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Terminal Ballistics Simulation of the Rod – Plate Interaction

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Abstract

Terminal ballistics considers the dynamic processes of mechanical interaction between the projectile and the target and has a wide area of applications. One of them is safety and vulnerability of military vehicles, aircrafts, space shuttles and civilian transport systems. In this paper a finite element model of a projectile – target interaction has been developed. Dynamic properties of the materials have been evaluated by taking into account high strain rates. Special attention has been devoted to the validation of the computational model by comparing the computational results against the experimental ones. The analysis has been carried out by using the explicit dynamics finite element software LSDYNA.
KEY WORDS: *terminal ballistics, high velocity impact, finite elements, explicit dynamics*

1. Introduction

Investigation of terminal ballistic processes has a wide area of applications. Though they originate from the military field, also in civilian technologies a lot of problems can be formulated involving the ballistic impact interactions. As an example, one of important applications is aircraft and aerospace industry. The requirement for safe and cost-effective design of products is demanding a thorough understanding of materials and structures behavior during very short duration impulse loads.

For many years the terminal ballistics was mainly a field of an experimental research. The behavior of some materials during short duration loads has been studied up to 10^3 s^{-1} strain rate loads [1, 3]. Basing on experimental results, empirical relations of terminal ballistics applications have been estimated [3]. Material behavior at high strain rates and material erosion due to the projectile – target interaction are undergoing studies.

3D terminal ballistics simulation by using finite element (FE) analysis codes becomes more and more widespread today. Reliable computational models can be built only if proper material behavior models and good estimations of the material constants are available. The estimation of the dynamic properties of the material in terms of material constants is also one of the most important issues in the process of the model validation. As check-points between computed and experimental results the conditions at which the projectile – target ballistic limit is reached are widely used [2].

The aim of this work is to build FE models of steel rod - plate interaction producing credible computational results against experimental ones at interaction velocities in the range of 700 and 1300 m/s.

2. Material model

The strain rate dependent theory of the material behavior is based on the relation [2, 3]:

$$\sigma = f(\varepsilon, \dot{\varepsilon}) \tag{1}$$

A number of materials models have been implemented into LSDYNA [4]. For terminal ballistics simulation we chose *MAT_PLASTIC_KINEMATIC model suitable for presenting the isotropic and kinematical hardening laws of plasticity. This material model also enables to evaluate the strain rate dependence, failure and erosion of elements. The Dynamic effects caused by high strain rates are taken into account by scaling the static yield stress value in accordance with Cowper – Symonds relation [1, 2, 4]:

$$\frac{\sigma_{d_y}}{\sigma_y} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p} \quad , \tag{2}$$

where σ_{d_y} – dynamic yield stress; σ_y – static yield stress; $\dot{\varepsilon}$ – strain rate; *C, p* – constants.

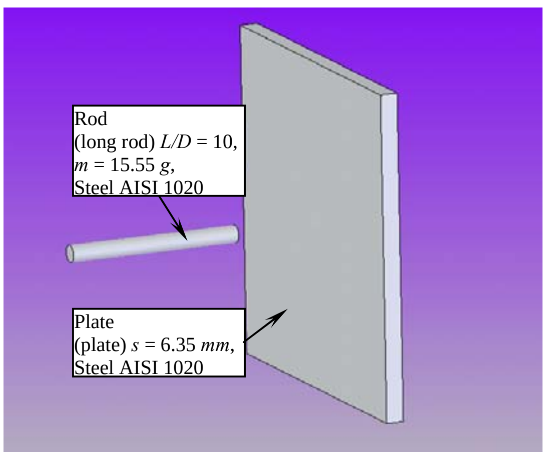
The dynamic yield stress described by the kinematical, isotropic hardening law or the combination of the two reads as [4]:

$$\sigma_{d_y} = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}\right]\left(\sigma_y + \beta E_p \varepsilon_{ef}^p\right) \quad , \tag{3}$$

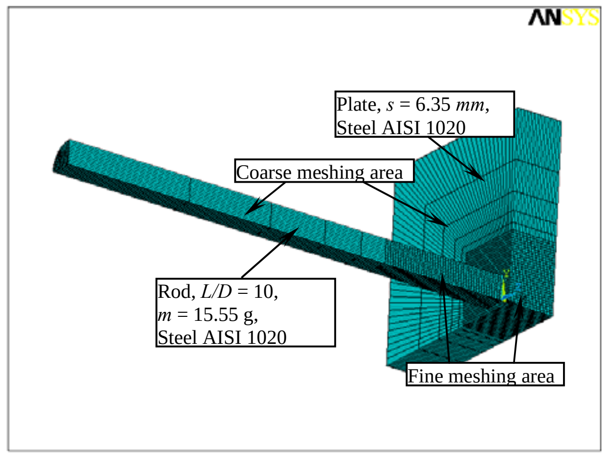
where coefficient $0 < \beta < 1$ specifies the "amount" of the isotropic hardening law against the kinematical one, $E_p = \frac{E_t E}{E - E_t}$ – plastic hardening modulus, E – elastic modulus, E_t – tangential modulus, ε_{ef}^p – effective plastic strain.

3. Terminal ballistics computational model

For the terminal ballistics analysis the computational model has been built consisting of a long steel rod (projectile) and a steel plate (target), Fig.1a. Both parts are made from the same material steel AISI 1020. The mechanical properties of steel AISI 1020 were recalculated from the available 'nominal' values into the 'actual' ones. The contact surface is perpendicular to the direction of motion of the rod. In the preliminary analysis we assumed the friction in the contact being negligible.



a)



b)

Fig. 1 Terminal ballistics computational model: a) rod – plate interaction system; b) quarter symmetry 3D FE computational model

For the validation of the model the experimental results presented in [3] have been used, Table 1.

Table 1

Experimental initial and residual velocities of the rod [3]

Initial velocity, *m/s*	**Residual velocity, *m/s***
738	543
1290	1226

The computational FE model has been presented in ANSYS by using Ansys Parametric Design Language (APDL) and transformed into LSDYNA keyword file by means of the APDL statement EDWRITE, TAURUS, <FILENAME>, K.

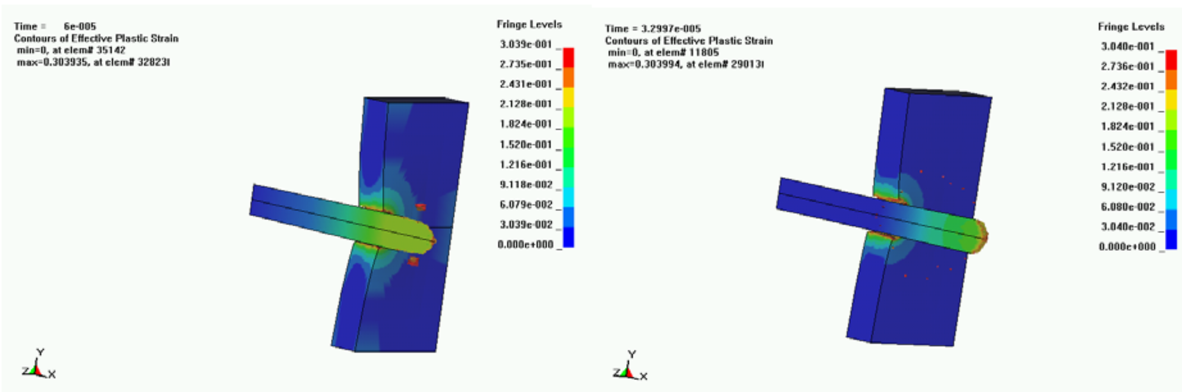
We use two symmetry planes (quarter symmetry model) and the butterfly meshing technique (Fig. 1b). The refined mesh zone has been established after making several trials. The main criterion was that the failure of the material had to take place in the refined mesh zone only. Finally the FE model size was 40442 elements, 45119 nodes and the FE edge length in the refined mesh zone ~ 0.3 mm - a relatively small FE model for this kind of simulation. The contact between the projectile and the target was described in LSDYNA as an interaction between the two parts by using the 'master-slave' method where the rod was the master. The friction in the contact has been assumed to be dependent on the relative velocity of the surfaces participating in the contact interaction as [4]:

$$f = f_D + (f_S - f_D)e^{-DC|V_{rel}|} \quad , \tag{4}$$

where f_D – dynamic coefficient of friction; f_S – static coefficient of friction; DC – exponential decay coefficient; V_{rel} – relative velocity.

4. Terminal ballistics simulation and estimation of the material constants

After a number of trial simulations and comparisons against the experimental results the constants of Cowper – Symonds relation (2) have been chosen as C = 495.5 s^{-1}, p = 3 and the isotropic plasticity hardening law has been selected. The failure criterion was the failure strain value 0.304. Terminal ballistic process was simulated at two initial velocity values 738 m/s and 1290 m/s at which the experimental data were available, see Table 1. These values were chosen as check-points for the validation of the computational model. Some simulation results are presented in Fig. 2.



a) b)

Fig. 2 Contour plots of the effective plastic strain. Vertical plane x0y used as reflection plane for visualization purposes:

a) initial velocity of the projectile 738 m/s, residual velocity 544.8 m/s;
b) initial velocity of the projectile 1290 m/s, residual velocity 1219.8 m/s

By comparing the FE analysis and experimental results good correlation has been obtained. The difference the results was in a range of 0.3 – 0.5 % (presented in Table 2).

Table 2. Comparison between experimental and FE analysis results

Parameters	Results		Percentage difference
	FE analysis	**Experimental test**	
Initial velocity (first point)	738	738	–
Residual velocity (first point)	544.8	543	0.34 %
Initial velocity (second point)	1290	1290	–
Residual velocity (second point)	1219.8	1226	0.51 %

It is not easy to predict the necessary refinement of the model. The usage of very refined meshes does not necessarily lead to better results when compared with the experimental ones. Generally, the material model and its constants should be adjusted for a certain level of refinement of a mesh. In the investigated case changing the FE edge length invoked changing of the calculated residual velocity. This required a re-estimation of the Cowper –Symonds relation constants set. The comparative analysis of the performance of different meshes has been carried out in the next section of this article.

In preliminary computations the friction between interacting parts was assumed as negligible. Later on we checked the influence of the mesh refinement and friction. The influence of friction has been analyzed by using four different values in relation (4): three static values f_S = 0, 0.2, 0.5 and one set of dynamic coefficient values f_S =0.2, f_D = 0.02, DC = 0.0135. As a result, we obtained that the influence of friction was negligible. The reason for this apparently is a very simple and regular geometric shape of the model and very short duration of the load.

5. Computationl analysis of the ballistic limit

The influence of the mesh size upon the Cowper – Symonds relation constants has been investigated. The criterion for the comparison of different models was the difference between the obtained initial and residual velocity values. The friction between contact surfaces was estimated by (4) with constants values f_S =0.2, f_D = 0.02, DC = 0.0135. Table 3 presents the results of analysis of two finite element models and the Lambert residual velocity prediction model [3] by using which the estimations of the residual velocity values have been made. The ballistic limit (V_{bl}) and residual against initial velocity curves are presented in Fig. 3.

Table 3. Ballistic limit analysis results by using different models

FE model size	Cowper – Symonds constants	Ballistic limit
40442 elements, 45119 nodes, element edge length ~ 0.3 mm (mesh V_{bl})	C = 495.5 s^{-1}, p = 3	556 m/s
With 89808 elements, 97513 nodes, element edge length ~ 0.19 mm (mesh V_{b2})	C = 618 s^{-1}, p = 3	535 m/s
Lambert's residual velocity prediction model		535 m/s

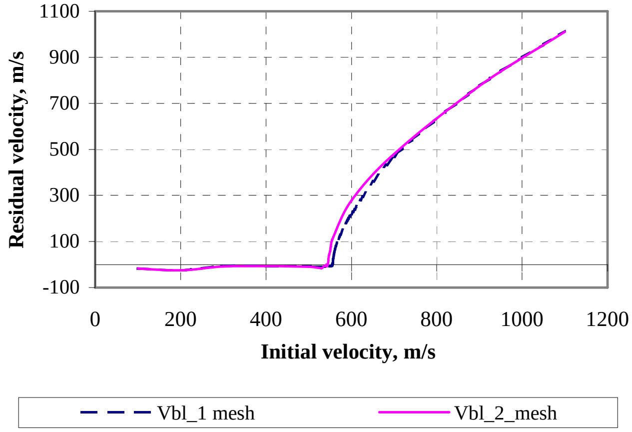


Fig. 3 Residual velocity against the initial velocity curves for two FE models

The lowest value of the ballistic limit was obtained by using the Lambert's residual velocity prediction model. However, in this model the projectile is considered as a rigid body and therefore the ballistic limit value is intentionally diminished. The ballistic limit value obtained by using the two FE models is very similar. When the initial velocity exceeded 700 m/s, practically no difference between the two residual velocities could be observed.

6. Conclusions

The analysis of the rod–plate terminal ballistic interaction has been carried out by using the LSDYNA explicit dynamics software and the experimental test results. The following conclusions could be made:

- In the range of high strain rates the adequate simulation results can be obtained only adjusting properly the finite element mesh edge length and material constants values. Moreover, the values of the constants are slightly different for each individual range of the interaction velocity;
- The results of the investigation of the cylindrical rod – plate terminal ballistic system demonstrated that the influence of friction between interacting surfaces is very small and can be neglected in practical computations. The reason for this apparently is a very simple and regular geometric shape of the investigated model and very short duration of the load;
- In the initial interaction velocity range of 700-1300m/s the recommended mesh edge length is ~0.3 mm. The conclusion is valid when the target thickness and projectile diameter values are close to each other. For steel AISI 1020 the recommended values of Cowper – Symonds constants are C=495.5 s^{-1} and p=3;
- The model enabled to predict the residual velocity of the rod for initial velocity range 700 – 1300 m/s with the accuracy 0.3 – 0.5 %. Higher accuracy values are obtained for lower initial velocities;
- For initial velocity values higher than 1300 *m/s* Cowper – Symonds relation constants should be re-estimated. In this velocity range the thermal softening influence becomes more significant and the influence of Cowper – Symonds relation should be decreased.

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