3D Numerical Simulations of Penetration of Oil-Well Perforator into Concrete Targets

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Abstract

The oil-well perforator and its interaction with concrete targets are simulated with fluid-structure coupling algorithm and the new mesh motion option of the multi-material ALE formulation of LS-DYNA[1] in Version 960. Comparison of the simulation results to the experimental test data has been conducted. The simulation results show good correlation with data in tests and indicate that LS-DYNA can be used as an engineering tool to help in the prediction of perforation depth.

Keywords: oil-well perforator penetration multi-material ALE fluid-structure coupling

1. Introduction

The action of oil-well perforator approximately includes: explosive detonation, liner collapse, jet formation and stretch, crater and penetration. It concerns large-deformation dynamics containing multi-materials interaction over very short time intervals, at strain rates of 10^4-10^7 /s. The Lagrangian code can only simulate the initial stages of jet formation because of the elem ent distortion problem which forces the calculation to be terminated. The multi-material Eulerian method has several advantages in solving this type problem but faces some questions, such as the large amounts of computational grid, smaller time step at the order of 10^{-2} μs and the material dissipation throughout the computational grid. To overcome these difficult, new methods must be employed to simulate the jet formation and its interaction with fluid-filled porous media.

This paper use multi-material ALE method of the dynamic finite element program LS-DYNA in version 960 to calculate the jet formation and stretch and its penetration into concretes. In the new method, the explosive and liner are modeled as Eulerian material which are filled into void (air) mesh with the preprocessor LS-INGRID, the concrete target is modeled as Lagrangian grid. A penalty based fluid-structure coupling algorithm which is defined to preserve the total energy of the system as well as possible is used to investigate the jet-target interaction. A new ALE-option allows to prescribe the motion of Eulerian mesh, independently. Numerical results are compared with observations in tests.

2. Basic model of numerical simulation

The physical model for a typical oil-well perforator consists of a liner, explosive and outer case, as illustrated in Figure 1.The parabolic shaped liner is made of powdered copper without sintering. The outer case is made of ordinary steel. The concrete target modeled is on the basis of the test used with a standoff of 10 mm.

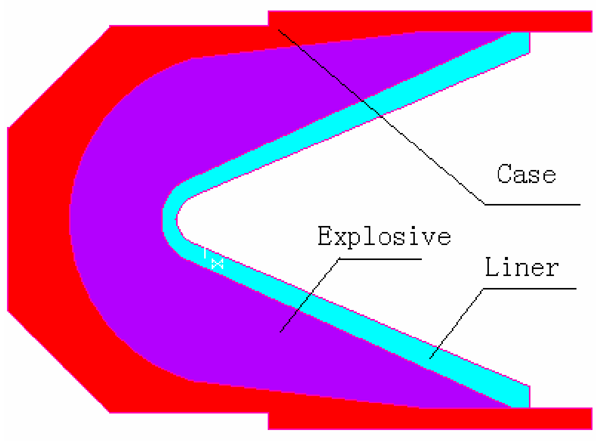

Fig. 1. The oil well perforator configuration

2.1 FE model

The FE-model is generated with the preprocessor LS-INGRID in version 35b.One quarter of the perforator and target is modeled with two symmetry planes, seen in Figure 2.2. The liner and explosive material are filled into the Eulerian grid (void) where eight-node solid elements are used for all the parts included. For the multi-material Eulerian formulation, the Eulerian mesh (air) with the element number of 171687 must be produced to enclose the all Lagrangian target (concrete) during the whole perforation event, see the red fringe in Figure 2.3. The multi-material ALE formulation only encloses one portion of the concrete in a mesh following its motion according to pre-defined load curves. The total number of ALE elements is 111687，illustrated in Figure 2.4-2.6.

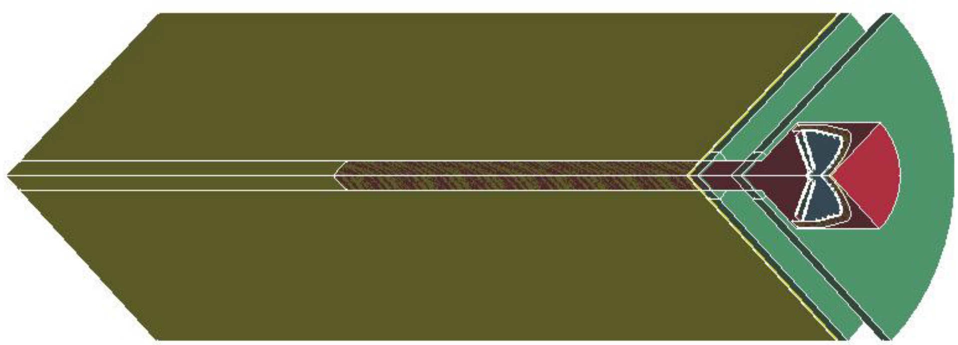

Figure 2.2 FE-model of the oil well perforation problem

Figure 2.3 FE-model for the multi-material Eulerian formulation

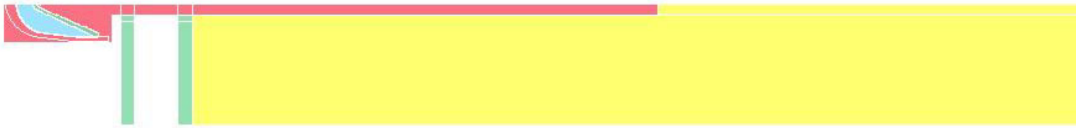

Figure 2.4 FE-model for the multi-material ALE formulation

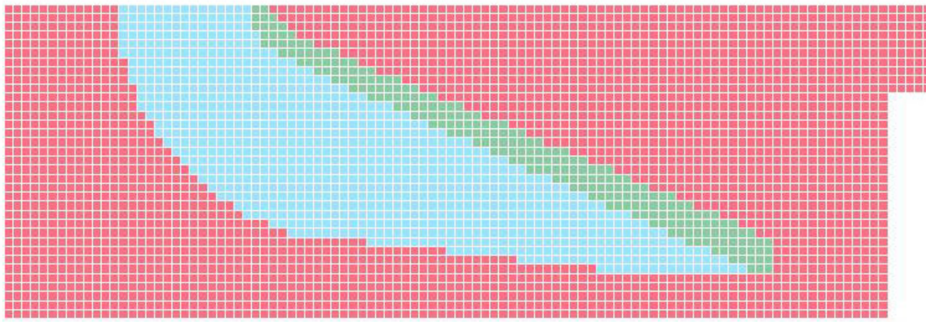

Figure 2.5 Eulerian meshes for the liner, explosive and void (air) on the symmetry section

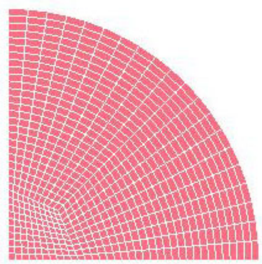

Figure 2.6 Eulerian meshes for the liner, explosive and void (air) on the cross section

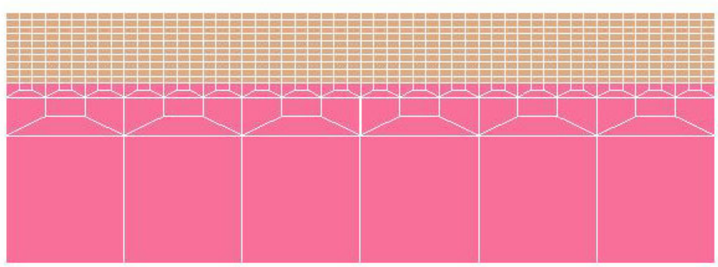

Figure 2.7 Concrete target mesh on the symmetry section

2.2 Material models

The explosive used is Composition A-3 . The material model, Type 8, “High Explosive Burn” with an equation of state, Type 2, “JWL” is used for the explosive. The material parameters for the explosive are listed in Table 1.

Table 1 Parameters for the explosive

ρ (g/cm³)	D (cm/μs)	P_{c-j} (Mbar)	A (Mbar)	B (Mbar)	R_1	R_2	ω	E_0 (Mbar)
1.65	0.8300	0.3	6.113	0.1065	4.4	1.2	0.32	0.089

High-strain-rate material properties for the powdered copper liner and target must be obtained as input data. For these purpose, the SHPB (Split Hopkinson Pressure Bar) and flyer plate impact tests are conducted to obtain uni-axial stress-strain relations for high strain rate and Hugoniot shock EOS (diagrams for the shock pressures and the particle velocities) for simulating jet penetration at very high velocities of 7~8 km/s. The detail experimental technique is not described in this paper. The typical stress-strain curves for the liner and concrete are illustrated in Figure 2.8-2.9. Moreover, the measured material data are adjusted and validated according to the perforation depth from tests, seen in Table 2. These data are used as input parameters for the material model Type10 plus EOS Type 4 in LS-DYNA. This model is adopted because of its simplicity and the erosion option useful for penetration problems.

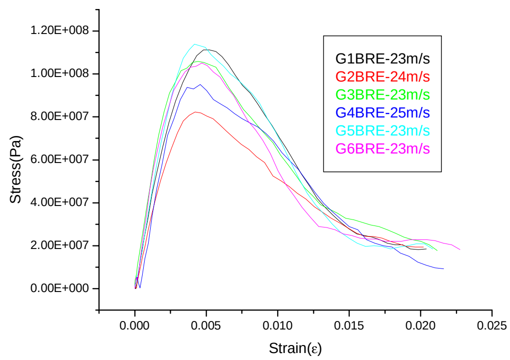

Figure 2.8 Stress-strain relations for concrete at different impact velocities

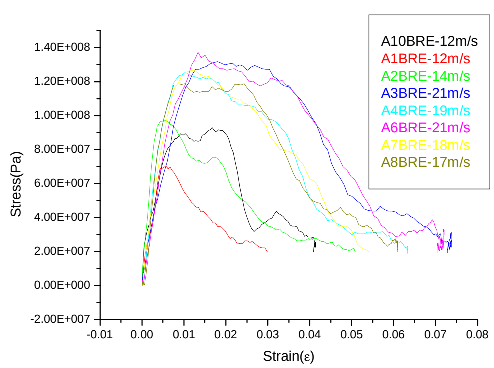

Figure 2.9 Stress-strain relations for the copper liner at different impact velocities

Table 2 Parameters for the material model Type10 and EOS Type 4

Material No.	Parameters for material model 10				Parameters for Eos 4	
	ρ (g/cm³)	G (Mbar)	σ_y (Mbar)	fs	C (cm/μs)	S_1
liner	8.93	0.03	1.4e-3		0.385	1.48
concrete	2.3	0.08	2.7e-4	0.1	0.15	1.4

3. Results

The jet formation process is depicted in Figure 3.1. When the explosive charge is initiated, a spherical wave propagates outward from the point of initiation. As the detonation wave spreads, the liner material is accelerated and collapsed under the high pressure. The collapse of the liner material on the centerline makes a portion of the liner to flow in the form of a jet where the jet tip can travel in excess of 6.4 km/s. Figure 3.2 shows the shape of jet when the jet will strike the first layer of steel plate. Figure 3.3 describes that the jet just penetrates into concrete after the jet crater is formed. Figure 3.4 shows the penetration depth when the jet penetration ends. By contrast with Figure 2.4, Eulerian mesh has covered the target in the height direction of the concrete target.

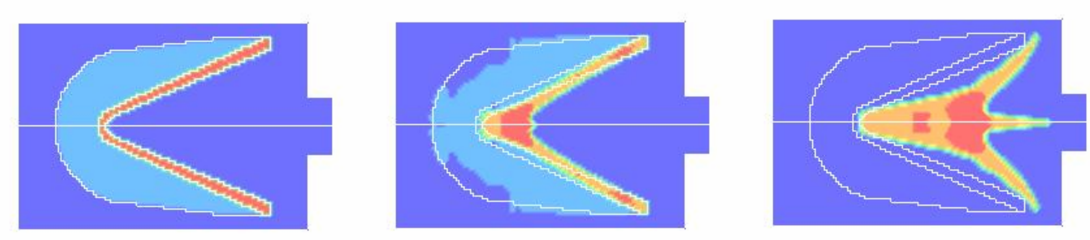

Figure 3.1 Density distribution during jet formation（t=0、4、8 μs ）

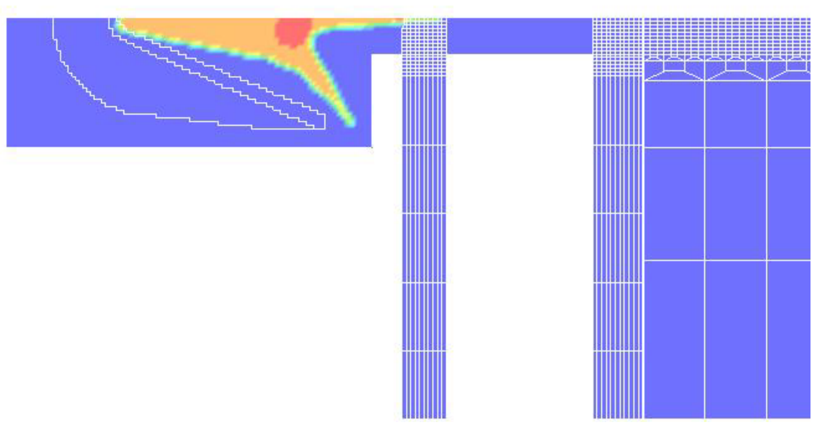

Figure 3.2 The jet penetration into the first layer of steel plate （t=10 μs ）

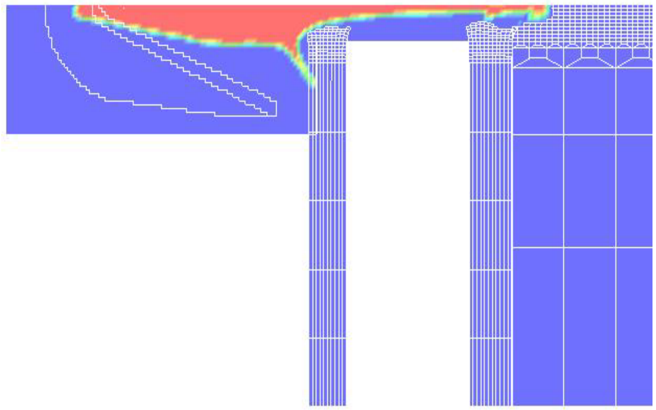

Figure 3.3 The initial crater profile by the jet penetration t=20 μs

Figure 3.4 Ultimate Eulerian mesh and perforation depth t=204 μs

Table 1 Comparison of experimental and calculating values

Jet tip velocity km/s		penetration depth mm	
Computational value	Experimental value	Computational value	Experimental value
6.42		377.52	358.4

4. Summary

Numerical studies of the whole action process of the oil-well perforator were presented using LS-DYNA. The use of multi-material ALE-mesh motion and fluid-structure coupling algorithm makes the numerical simulation accurate and economic. The results indicate that numerical simulation provides a helpful tool to design products for the oil well application.

References

1 LS-DYNA KEYWORD USER'S MANUAL, Version 960, March 2001, LSTC