

Numerical simulations of near-field blast effects using kinetic plates

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Abstract. Numerical simulations using two hydrocodes were compared to near-field measurements of blast impulse associated with ideal and non-ideal explosives to gain insight into testing results and predict untested configurations. The recently developed kinetic plate test was designed to measure blast impulse in the near-field by firing spherical charges in close range from steel plates and probing plate acceleration using laser velocimetry. Plate velocities for ideal, non-ideal and aluminized explosives tests were modeled using a three dimensional hydrocode. The effects of inert additives in the explosive formulation were modeled using a 1-D hydrocode with multiphase flow capability using Lagrangian particles. The relative effect of particle impact on the plate compared to the blast wave impulse is determined and modeling is compared to free field pressure results.

1. Introduction

Advanced hydrocodes can be used, together with high-performance computing, to predict the response of structures subjected to blast loading environments [1]. Experimental tests can be designed to help validate the numerical results from these hydrocodes for scenarios of interest. A combined experimental and modeling effort has been implemented in order to explore the near-field blast effects on structures from different explosives, including explosive mixtures containing inert additives.

For explosive loading, accurate simulation of the impulse delivered by the charge is necessary to correctly predict structural response. Since the impulse transferred to a structure is the change in momentum for that structure, the former can be determined by measuring or calculating the latter. The newly developed kinetic plate test [2, 3] is designed to measure impulse in the near field by measuring the momentum imparted to a square steel plate by an explosive detonation at small standoff distance from the plate. Modeling the steel plate's response and comparing the numerical to experimental results helps assess the capabilities of the model when predicting the effects of explosives on structures.

2. Method

Square kinetic plate tests were conducted using spherical charges of C-4 [3], a C-4/sand mixture (80/20 weight ratio; [3]), potassium chlorate (KC)/fuel mixtures [3], and HMX mixtures [2]. Numerical simulations using either ALE3D [4] or STUN (a 1-D hydrocode that has been developed to provide rapid and accurate analysis of explosions with an inert additive) have been performed to compare with the tests.



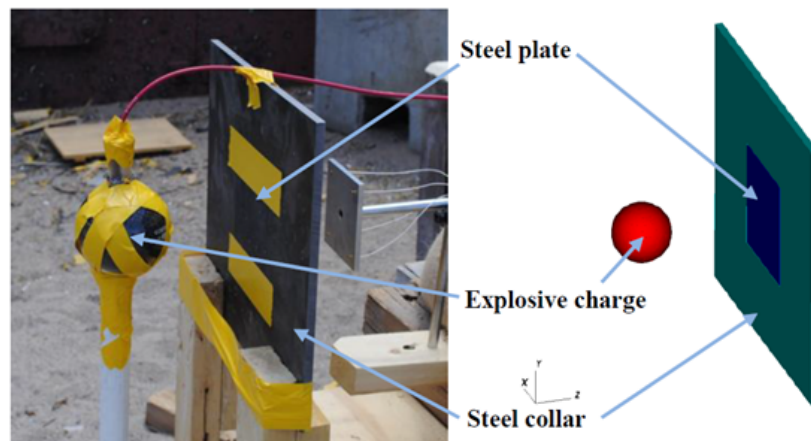


Figure 1. Kinetic plate test setup (left) and model (right).

2.1. Kinetic plate test experiments

In the experiments, a spherical charge is placed at a standoff distance of either 152 mm (6 in) [2, 3] or 254 mm (10 in) [2] from the steel plate, measured from the center of the explosive charge to the closest point on the plate. The steel plate is $127 \times 127 \times 12.7$ mm weighing 1584 ± 10 g. The plate is situated in a fixed outer steel collar (see figure 1) and allowed to accelerate in response to the blast loading. Four PDV (Photonic Doppler Velocimetry) probes are aligned opposite the charge and measure the resulting plate motion. Experimental velocity results reported here are based on curve fits to the PDV data. For several of the tests, pencil gauges at 1.52 m (5 ft) collect overpressure measurements. Further test details are available in [2] and [3].

2.2. Modeling of the Kinetic Plate Test with ALE3D

Detailed 3-D numerical simulations of the kinetic plate tests are conducted using the hydrocode ALE3D. Parameters in the model are matched as closely as possible to the experiment based on values reported, including plate mass, enabling a direct comparison with experimental results. The simulation had nominal mesh resolution of 3.175 mm. The Jones-Wilkins-Lee (JWL) equation of state model is used to calculate the explosive energy release. The calculated speed at the modeled plate's center of mass was used as the comparison to the plate speed measured in the experiments.

2.3. Modeling multiphase effects with 1-D hydrocode STUN

The experimental configurations with inert particles added to the explosive formulation (e.g. C-4 with sand) were modeled using a 1-D spherical hydrocode that has been shown to accurately predict multiphase effects. The STUN hydrocode [5] has been adapted to provide rapid analysis of an explosive charge in which inert solid particles are either embedded in the explosive material or packed at the periphery of the charge. The particles are initially modeled as a series of point-mass Lagrangian shells that are accelerated as spherical pistons by the pressure gradient developed in the explosive detonation. After expanding a prescribed amount, the explosion products can “break through” the dense shell of particles and from that point the particle motion is governed by the drag induced by the surrounding flow. The particles are modeled as spheres and interact with the surrounding flow but not with each other. Both particle and fluid motion are simulated in a Lagrangian frame. Mass, momentum and energy are strictly conserved. We have previously used the adapted STUN code to recreate several experimental tests with excellent agreement.

The experimental test charges are modeled in STUN as a charge of equivalent mass of explosive with ten particle groups representing the mass of the inert additive spatially distributed within the volume of the charge such that the appropriate density ratio is maintained. Explosive energy release is calculated using the JWL model. Impulse at the plate location is determined and used to estimate final plate velocity.

In order to determine plate motion, the total momentum calculated by STUN at the plate location is needed. The total effect is the sum of two components: the impulse delivered by the blast wave and the impulse delivered by the particles, or, in equation form:

$$M_{plate}(R, t) = [i_{BW}(R, t) + i_{Pa}(R, t)]a_{plate} \quad (1)$$

where R is the range from the charge center to the plate surface and a_{plate} is the surface area of the plate. The blast wave impulse per unit area, i_{BW} , is determined from the time integral of pressure and the impulse per unit area delivered by the particles, i_{Pa} , is determined from the particles' mass and velocity.

$$i_{BW}(R, t) = \int P(R, t)dt \quad i_{Pa} = \sum_j m_{P_j} U_{P_j} / a_{Pa} \quad (2)$$

The variable a_{Pa} is the cross sectional area of air through which the particles flow at the given R . For a spherical charge, $a_{Pa} = 4\pi R^2$.

While STUN gives accurate predictions of the flow field and particle motion, it cannot model the kinetic plate, and so the direct fluid/structure interaction cannot be simulated. Therefore, the effect of reflected pressure is not accounted for and the calculation described above underpredicts plate motion by nearly 50%. In order to determine an appropriate reflected pressure, a multiplicative factor for the blast wave component of impulse is determined by comparing ALE3D and STUN simulations of an equivalent explosive mass without inertial particles present. The ratio of the final ALE3D predicted impulse at the plate to the STUN prediction at the plate location is determined. The blast wave impulse calculated by STUN for the simulations with particles included is then multiplied by this factor and added to the particle impulse to determine the total value. This approach attempts to most accurately account for each phenomenon: the effect of energy transfer from the flow that accelerates the inert particles, the reflection of the blast wave off the plate, and the particle impact on the plate assuming inelastic collision. Since the STUN code is required to model the embedded particles at the time of this writing, this joint methodology is required to predict both the particle effect and fluid/structure interaction.

Finally, the 1-D nature of STUN allows for the propagation of the blast wave beyond the near-field with little computational burden; where applicable, overpressures at 1.52 m are calculated with STUN and compared to the experimental measurements.

3. Results

Experimental and numerical results are presented for an ideal explosive (C-4), an ideal explosive with an inert additive (C-4 with sand), and examples of non-ideal explosives (KC/fuel and HMX with aluminium). The variety of test charges gives an idea of which configurations can be modeled most accurately.

3.1. C-4 charges

Pemberton et al [6, 3] conducted a series of kinetic plate tests using C-4 charges at 152 mm standoff. These experiments were simulated using ALE3D. Figure 2 shows the plate velocity results versus charge size for the simulations as well as a fit to the experimental data [7]. The linear relationship between charge size and plate speed is consistent with the experimental results. The ALE3D simulations under-predict the plate velocity by 4-8% compared to the experiment.

3.2. C-4 with sand

Manner et al [3] tested C-4 charges at 152 mm standoff with 20% sand by mass added. The sand used was QUIKRETE Commercial fine grade sand with predominant grain size range of 0.2 mm to 0.6 mm. Particles are modeled in STUN as spheres with uniform 0.4 mm diameter after it was determined that the model results were not sensitive to particle size for this specified grain size range. Figure 3 shows excellent agreement between the experiment and simulation results for overpressure at 1.52 m. Plate velocity (V) results are shown in table 1.

The simulation over-predicts the resulting plate speed compared to the experimental values. However, this is to be expected since the simulation method assumes perfect coupling of impulse to the plate motion. The simple model has no way of accounting for losses present in the experiment, such as energy transfer to the plate which results in plate vibration or heating. Despite this approximation, there is good agreement between the experiment and the simulation. STUN predicts an overall increase in plate velocity of about 2% compared to a charge without sand. The experiments with sand showed an increase in plate velocity of 7.7% and 2.8% for the two test shots, with the larger percent increase occurring for the test with higher measurement uncertainty [3]. The percent of the total impulse due to particles compared to the blast wave cannot be determined from this test; however, STUN predicts that particle impacts account for about 4% of the total impulse imparted to the plate. Both the experiment and the simulation show that the presence of sand in the explosive mixture will not have a very significant effect on plate velocity.

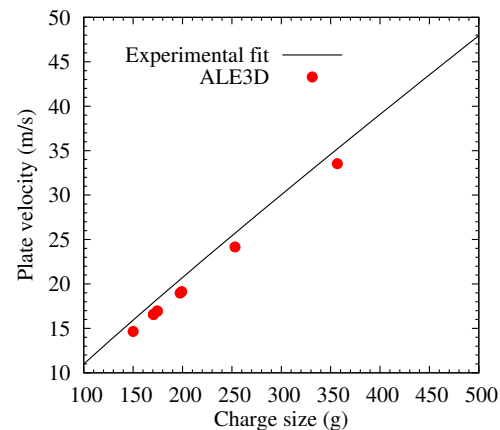


Figure 2. ALE3D kinetic plate simulation results for C-4 charges.

Table 1. Kinetic plate test simulation results for C-4 with sand.

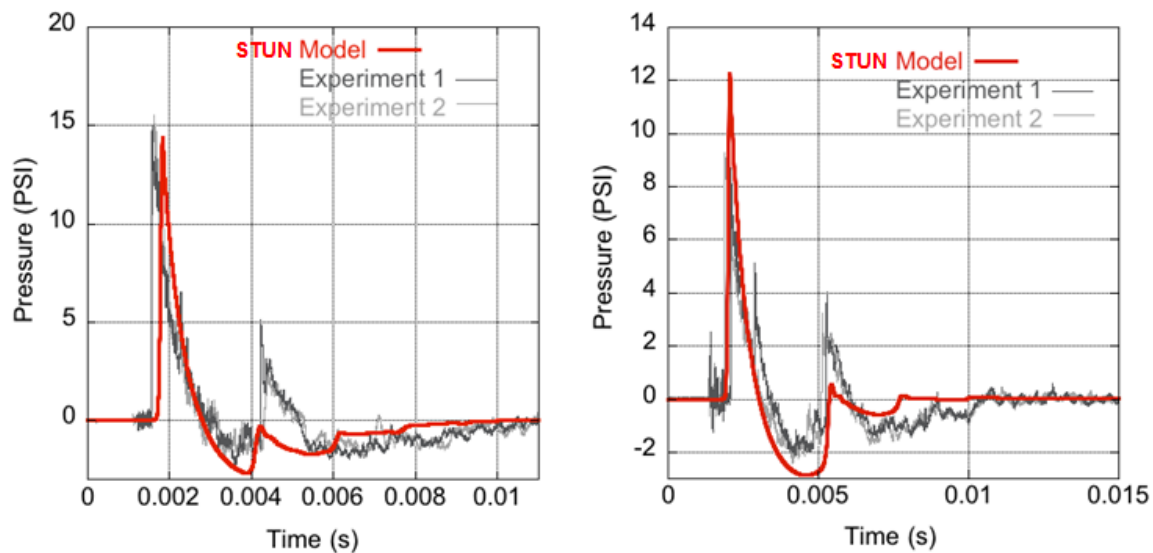
Simulation	i_{total} (N*s)	i_{Pa} (% of i_{total})	V (m/s)	% Error vs Exp	% Increase vs no sand
No sand	35.90	-	22.6	9.4	-
Run #1	36.56	3.8	23.1	3.7	2.2
Run #2	36.45	3.7	23.0	9.1	1.8

3.3. Non-ideal explosive: a KC/fuel mixture

The kinetic plate test was also used to determine the impulse imparted by a non-ideal explosive [3]. Two tests with a 245 g KC/fuel charge with no inert additive at 152 mm standoff were conducted, with resulting plate velocities of 18.1 and 18.6 m/s and measurement uncertainty of 1.1%. Simulation results using both hydrocodes are shown in table 2. Using the same JWL (derived from cylinder tests), both codes under-predict the resulting plate motion. STUN overpressure results at 1.52 m show good agreement with the experiment in initial pulse shape and duration (figure 3).

Table 2. Kinetic plate test and simulation results for a KC/fuel mixture.

Simulation	V (m/s)	% Error, shot 1	% Error, shot 2
STUN (1-D)	17.38	-3.9	-6.3
ALE3D (3-D)	16.42	-9.2	-11.5

**Figure 3.** Experimental and STUN numerical pressure results at 5' for a C-4 with sand (left) and KC/fuel (right).

3.4. HMX mixtures: effect of Al and varying standoff

In order to determine the near-field impulse transferred to a structure by non-ideal aluminized explosives, kinetic plate tests were conducted with HMX mixtures containing 15% (by mass) of either aluminium (median size $3.2 \mu\text{m}$) or lithium fluoride (an inert substitute with similar density, $< 5 \mu\text{m}$). Standoff distances of 152 mm and 254 mm are investigated. See [2] for further experiment details.

Table 3. Kinetic plate simulation results for HMX mixtures.

	Stand-off	V (m/s) ALE3D	% Error vs Exp (ALE3D)	V (m/s) STUN	% Error vs Exp (STUN)	Improve- ment
HMX-Al	6"	18.99	-1.71			
HMX-LiF	6"	15.49	-2.15	15.47	-2.24	None
HMX-Al	10"	10.44	11.78			
HMX-LiF	10"	8.49	19.24	8.12	14.0	5%

The tests are modeled in ALE3D using JWLL parameters determined by CHEETAH version 6.0 which accounts for the presence of Al or inert LiF. Therefore, the presence of Al in the simulation will affect the detonation energy release, but afterburn effects are not correctly accounted for. ALE3D results are shown in table 3, including the percent error compared to the experiment. The JWLL approximation gives good results at 152 mm standoff. At 254 mm standoff, the numerical results for both the Al and LiF mixtures show significantly higher velocities than observed.

The presence of inert particles in the explosive can affect the propagation of the blast wave as energy goes into accelerating the particles. The magnitude of this effect can be estimated using the STUN code. Treating the LiF particles as inert solid particles which do not change phase and using JWL parameters for HMX with no additives, the STUN simulation results are shown in the last three columns of table 3. The plate velocity for 152 mm standoff is about the same, and at 254 mm standoff the agreement is slightly better. However, the simulations still show significant over-prediction at this distance. This discrepancy may partially be due to the use of the JWL model, which will not account for non-ideal effects. Additionally, phenomena such as jetting and other non-homogeneities which can be present in the tests are not recreated in the simulation. These effects may be more apparent at larger standoff.

4. Conclusions

Comparison of numerical results to individual tests can help point out under what conditions the model is performing well. ALE3D simulations show good agreement to the C-4 test results. Using the STUN code gives overpressure at a distance for comparison to experiment and can be used to estimate the effects of inert particles in the explosive formulation on the kinetic plate motion. The addition of sand has very little effect on the total momentum imparted to the plate.

Poor agreement between the model and the experiment can help guide evaluation of the approximations that go into the simulations. In the case of the kinetic plate tests when the explosive is highly non-ideal, simulations using the JWL energy release may not capture the relevant physics and a different equation of state may be necessary.

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