High intensity impulsive loading by explosively accelerated granular matter

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\textbf{A B S T R A C T}

The mechanism by which a spherical shell of granular matter is accelerated by an internal explosion together with its subsequent loading of a high ductility, edge clamped steel plate is investigated by a combination of instrumented experimentation and particle-based simulation. By using a large spherical explosive charge to drive the expansion of a water saturated synthetic sand shell, it has been possible to create sand front impact speeds with a test plate that exceeded 1200 m/s. Direct observations of the evolution of the sand front were made using a pair of high speed video cameras, and revealed rapid initial acceleration of the sand accompanied by the formation of locally faster sand spikes, followed by deceleration. The pressure evolution and specific impulse during particle impact were measured using the Kolsky bar. A discrete particle-based numerical simulation method implemented in the IMPETUS Afae code was then used to simulate the pressure and impulse applied to the Kolsky bar and to model dynamic deformation of the plate and its support structure. The simulation analyzed the interactions between the explosively accelerated high explosive, air, and sand particles and the shock fronts that propagated though each interface after detonation. The impulse applied to the test plate and its support structure were well reproduced by the simulation. The simulations also revealed significant dispersion of the sand, with some sand particles attaining radial velocities that were almost 50\% higher than that of the main front. They also identified the presence of an experimentally unobservable instability at the energetic material-wet sand interface. The deceleration of the sand with distance of propagation was found to be the result of momentum transferring collisions with the background air, resulting in the formation of a strong air shock ahead of the sand front. This process resulted in the eventual transfer of all the sand momentum to the air and significantly influenced the dynamically changing topology of the sand-air interface. While the differential acceleration of the sand particles to form a dispersed front, and their deceleration by air drag were well modeled, the topology of the sand instabilities at the sand front-air interface were not resolved by the simulations.

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1. Introduction

Soil can be accelerated to very high velocity by the detonation of a shallow buried explosive [1]. The impact of this soil against a nearby structure applies large impulsive loads resulting in inelastic deformations and even rupture of the structure [2,3]. The experimental assessment of potential mitigation strategies can be a difficult, time-consuming challenge, especially as the severity of the impulsive load increases. The problem is further complicated because the transient deformations responsible for failure are very difficult to directly observe due to obscuration by the ejecta [4]. Numerical simulations provide a complementary means for investigating potential mitigation concepts, provided the physics of soil acceleration [5–7], its impact loading of the structure [8–11], and the structures dynamic mechanical response are properly captured. The study presented here uses a combination of instrumented experimentation and particle-based simulation to investigate the dynamic loading and response of a model test structure following detonation of a spherically symmetric granular material encased test charge.

The detonation of an energetic material results in conversion of a solid or liquid material to its gaseous detonation products across a high-pressure detonation front that travels through the explosive at the energetic materials characteristic detonation velocity [12]. For a buried event, this detonation front eventually reaches the interface between the explosive and the surrounding granular media [13], compressing it across a shock front that propagates away from the detonation at the granular media's shock velocity [3,5,10,13]. This...
compressive shock eventually reaches the granular matter - air interface. The high shock impedance difference at this interface results in a strongly reflected (sign converted) tensile (release) shock returning towards the detonation center [13]. To conserve momentum during this reflection, the granular medium is accelerated (spalled) from the reflecting surface with a velocity that can approach twice that of the incident shock. The spalled ejecta travels from the surface, and eventually impacts a target leading to its impulse loading [3]. For some combinations of depth of burial and soil properties, the majority of the impulse that loads a nearby structure results from soil particle impact rather than the momentum transferred by the air shock or detonation products [13].

The impulse created during buried explosive tests at outdoor test ranges can be sensitive to the composition, moisture content, temperature, and degree of compaction of the foundation beneath the test charge [4,14]. Many of these factors are difficult to control, and the resulting irreproducibility of such tests greatly complicates experimental assessment of mitigation strategies. Dharmasena et al. [15] recently developed an experimental set-up to controllably load test structures with explosively accelerated sand. In this approach, a suspended spherical explosive charge was encased by an annular shell of silica particles (synthetic sand) of known mass, particle size and shape, and water content. Detonation of explosive charges with a mass of 0.1–0.3 kg encased in 5 cm thick sand shells resulted in sand front velocities of 300–600 m/s [15,16]. While the deformation of structures tested this way are readily measured after testing, the dynamic interaction of the sand with the structure was much more difficult to monitor because of obscuration by incident and reflected sand, and by escaping detonation products. Simulations do not suffer from such problems.

Several numerical techniques have been proposed to simulate the blast loading of structures [17–23]. The widely used LS-DYNA code [24] allows several different approaches to be used for blast modeling [22] including pure Lagrangian approaches, sequential Eulerian followed by Lagrangian simulations, and fully coupled Eulerian-Lagrangian simulations. Fully coupled simulation allows the blast loading and structural response to be simulated during dynamic deformation of the structure where fluid-structure interactions can be significant [22,25]. In this approach, the response of the soil to impulsive loading by the detonation event and the loads applied by the soil to the test structure are calculated using a soil constitutive model. Many empirical continuum soil models have been proposed for this purpose [7,26,27], but all require careful calibration [6,14,26], and causality between soil structure/composition and impulse loads is obscured.

Deshpande et al. [5] proposed a soil constitutive model based upon a particle-particle contact mechanics analysis that defined interactions between soil particles. This granular model examined two regimes of particle interaction corresponding to the dispersed and high-density particle packing limits. For dispersed particles, typical of conditions during soil propagation through air, the model defined particle contact law was analogous to that for gas molecule collisions in the kinetic theory of gases. The high packing density limit corresponded to a regime of semi-permanent contacts dominated by particle deformation and friction, which is representative of conditions during impact of the particles with a structure. Related corpuscular simulations have begun to be used for explosive loading simulations [23,28]. They use the discrete particle approach to model the momentum transfer via contact forces between particles and between particles and a structure. This approach uses different rigid, spherically symmetric particles to represent high explosive detonation products, the surrounding air, and the soil. The contact laws governing interactions between the various particles, and with a structure, result in contact forces that are used in a finite element analysis to predict dynamic structural response. This approach has recently been implemented in the IMPETUS Afea Solver [23], and several studies have begun to investigate the accuracy of predicted structural responses [15,23,28–30]. In these studies, the explosive charges were small (less than 0.5 kg), sand front velocities were usually comparable to the speed of sound in air, and the effects of momentum transfer from the soil to the surrounding air did not appear to be significant. In this regime, once the soil particle contact model parameters were established, the simulated responses were in good agreement with the experimental observations.

The present study investigates the acceleration and impact of sand particles created by a model explosive event that launched a dispersed sand front with velocities of more than 1200 m/s, and explores the validity of particle-based simulations of the test. The study investigates the response of a 2.54 cm thick high ductility stainless steel edge clamped plate to loading by a spherical, water saturated (synthetic) sand encased high explosive test charge whose center was suspended above the center of the plate. The temporal evolution of pressure applied by the sand particles was measured by simultaneously stagnating the sand against the end of an instrumented Kolsky bar. A pair of high speed video cameras were also used to make a full observation of soil front fragmentation and propagation towards the structure. The IMPETUS Afea code was then used to analyze the impulse loading of the Kolsky bar and the plate, and to examine the dynamic response of the test structure to which the plate was attached. The combination of sand impulse measurement, observations of the sand front evolution, and the measured plate deflection then enabled identification of the important physical phenomena associated with high intensity impulsive loading by granular media, and an assessment to be made of the extent to which a particle-based code is able to analyze them.

2. Experimental setup

A high intensity soil impact loading experiment was conducted at an outdoor testing facility operated by the NEWTEC Services Group, Inc. (Edgefield, SC). A schematic illustration of the test setup is shown in Fig. 1, with additional details given in Fig. 2. The test utilized a rigid platform to support a square edge clamped test plate. The detonation of a suspended high explosive sphere encased within a spherical annulus of water saturated synthetic sand provided the impulse loading. A 3.81 m long, strain gauge instrumented, maraging steel Kolsky bar system was used for measurement of the sand impact pressure and impulse applied at a location symmetrically equivalent to the center of the test plate.

2.1. Test platform

A test platform was designed to enable the testing of edge clamped square test plates, Fig. 1. A square support base with an overall footprint of 122 cm × 122 cm was constructed using a single layer of cinder block laid down on a concrete pad. Several wooden beam layers were placed on the cinder block to raise the platform to a height that enabled unobstructed observation of the test. A 0.95 cm thick rubber mat was placed on the wooden supports to cushion impacts, and reduce damage to the support structure. The rest of the platform was then assembled by positioning a square picture frame constructed from welded, 15.3 cm deep, A-36 steel I-beams on the support structure. To avoid test plate shear-off near the test plate edge clamping, a 3.8 cm thick, 122 cm × 122 cm, A-36 steel support plate with an 80 cm × 80 cm square, center cutout was attached to the steel I-beam picture frame assembly, Fig. 2. The test plate was then attached to the periphery of this support plate where its center, 80 cm × 80 cm opening defined the span during test plate testing, Fig. 2. This enabled the total length of the edge clamped region to be large enough that the pull-in stresses at the edge attachment location were maintained below the yield strength of the test
plate, thereby avoiding otherwise difficult to analyze edge effects during the test [15,16].

2.2. Test plate target

The test plate target consisted of a 2.54 cm thick, 132 cm × 132 cm, 304L grade stainless steel plate, Fig. 3. The plate was supplied by Rolled Alloys, Inc. (Temperance, MI) and was tested in the (as received) hot rolled, annealed and pickled (HRAP) condition. Very large forces must be supported at the gripped edges of the test sample. Furthermore, studies with square plates that utilized edge grips that extended above the top surface of the plate were found to create very significant local impulse amplification due to the reaction momentum created during upward redirection of soil [15]. To prevent plate pull-in at its gripped edges during center impact loading, while also avoiding out-of-plane sand reflection at the periphery of the structure, 5.1 cm wide, 2.54 cm thick, rectangular cross section 304 grade stainless steel bars were welded in a picture frame pattern along the four edges of the eventual underside of the test plate, Fig. 3. To further strengthen the edge restraint system, a series of holes were drilled through the edges of the test plate and the picture frame to enable insertion of ~19 mm diameter, press-fitted tool steel dowel pins. This combination of welded and pinned bars robustly connected the 2.54 cm thick test plate to the picture frame support, Fig. 3. This edge reinforced test plate was secured to the test platform with four 19 mm diameter, Grade 8 steel bolts located near the corners of the test plate, Fig. 2.

2.3. Test charge design and assembly

A high explosive charge was suspended directly above the center of the test plate. The charge was constructed using two thin wall, acrylic plastic, concentric sphere assemblies with thicknesses ranging from 4.8 mm at the equator to 1.6 mm at the poles of each hemisphere. The concentric test charge was assembled by filling a 160 mm diameter, inner sphere with 3 kg of C-4 explosive [31]. A thin walled cylindrical plastic pipe with an internal diameter of 10 mm penetrated a pole of one of the hemispheres for subsequent

Fig. 1. Schematic illustration of the test geometry. A spherical test charge consisting of an annular shell of wet sand encasing an explosive sphere was suspended a distance \( H \) over the center of an edge clamped test structure with a Kolsky bar positioned a similar distance from the center of the charge. To ensure that similar ejecta from the charge impacted the center of the plate and the face of the Kolsky bar, the detonator was placed at a position that bisected the directions from the charge center to the test plate center and to the Kolsky bar axis.

Fig. 2. Schematic illustration of edge constrained test panel geometry showing the location of the Kolsky bar (including its strain gauge location), the test charge geometry and the standoff distances to the Kolsky bar \( (H_k) \) and test plate \( (H_p) \) at the instant of detonation.
placement of a detonator in contact with the explosive surface, Fig. 4 (a). The explosive sphere was then centered inside a 304 mm diameter, outer sphere with a carbon fiber reinforced polymer (CFRP) suspension rod passing through the center of both spheres for eventual positioning of the charge above the test plate. The outer sphere was again constructed from two hemispheres, each with a 3.8 cm flange around the equator which aided in the test charge assembly but resulted in a ledge around the sphere. The approximately 72 mm wide annular space between the two spheres was filled with 18.8 kg of glass microspheres with a diameter of 150–200 μm, Fig. 4(b). Grade GL-0191 soda-lime glass spheres were obtained from Mo-Sci Corporation (Rolla, Missouri), and were identical to those used in previous studies by Hollomon et al. [29] and by Borvik et al. [23] for sand model calibration. Finally, 5.0 kg of water was added to fill the void spaces between the packed silica microspheres forming a water saturated model test “soil”, Fig. 4(c). An instantaneous (0 ms delay) model SP/SM (12-0) detonator with a 3.5 m copper lead wire manufactured by Dyno Nodel Inc. (Salt Lake City, Utah) was inserted into the explosive through the plastic pipe just prior to testing.

To ensure that the center of the Kolsky bar and center of the test plate were subjected to similar impulsive loads, the orientation of the sphere was adjusted such that the detonator axis was at an angle of 45° to both the test plate normal and the axis of the Kolsky bar. The center of the spherical charge was initially suspended 45 cm above the center of the top surface of the test plate and at the same standoff distance from the Kolsky bar end face. However, after the sphere was suspended, sufficient time elapsed during placement of the detonator for a small displacement of the charge to occur. The actual standoff distances (shown in Fig. 2) to the plate and Kolsky bar could be measured from the high speed camera images captured immediately before detonation. These measurements indicated the test charge was displaced 1.8 cm downward towards the plate and 3.5 cm further away from the Kolsky bar prior to the detonation. The actual standoff distance from the charge center to the end of the Kolsky bar was $H_k = 48.5$ cm. If the top surface of the plate is taken to lie in the X-Y coordinate plane with the X-axis parallel to the Kolsky bar and origin at the plate corner, the coordinates for the center of the test plate are located at $X = 66$ cm and $Y = 66$ cm. The actual location of the charge center above the plate was $X = 69.5$ cm and $Y = 66$ cm, and the standoff distance from the charge center to the plate surface was $H_p = 43.2$ cm.

2.4. The Kolsky bar

The pressure applied by impact of the water saturated sand was measured using a 2.54 cm diameter, 3.81 m long, age hardened C-350 grade, maraging steel Kolsky bar (Fig. 1). Plastic bushings were placed around the Kolsky bar where it was attached to a series of pedestals to minimize energy leakage of the elastic modes of the Kolsky bar [32]. The end of the Kolsky bar was positioned so that a spherically expanding wet sand front reached the test target and the Kolsky bar almost simultaneously. Even though the charge had
shifted slightly and was not equidistant to the test plate and end of the Kolsky bar, the Kolsky bar measurement still provided a quantitative measure of the pressure and impulse loading experienced near the center of the test plate. The simulation of its response provided a critical test of the validity of the numerical simulation approach. To minimize plastic deformation during impulsive loading, the maraging steel bar was aged before use at a temperature between 480 and 510 °C for a period of 6 hours to achieve a Rockwell scale hardness value of 58 (equivalent to a tensile strength of 2.07 GPa). Strain gauges were mounted on the Kolsky bar to enable the impact pressure to be measured, Fig. 5. Two, T-rosette type strain gauges were mounted on the Kolsky bar to enable the wet sand front to be observed after detonation of the charge. A plan view of the X-Y plane, Fig. 6, shows the experimental set-up with the locations of the cameras (placed side by side). An expanded view of the test plate in the X-Y plane indicates the distances to the plate center and the charge center location from the edge of the test plate (measured with the cameras). To provide a reference for distance and velocity calculations, a 20 cm long section of the front end of the Kolsky bar, and the full width of 132 cm wide test plate front side were spray painted in white prior to the experiment. One camera provided a wide view of the entire event with a 640 × 480 pixel resolution and a 30 µs exposure time at 142 µs intervals. The second camera used a 512 × 256 resolution and 20 µs exposure time at 47 µs intervals to provide a magnified image of the test charge. These images were used to measure the sand front position. The cameras spatial resolution was reduced to allow the capture of more frames per second and therefore increase the temporal resolution. The higher magnification camera captured images that were 1.14 × 0.57 mm² in area, with each pixel corresponding to 2.23 × 2.23 mm² area in the observation plane.

3. Simulation methodology

The suspended charge test geometry was simulated using the IMPETUS Afea Solver [23]. This code employs a discrete particle based method using air, high explosive (HE), and soil particles. A particle contact interaction model was used to determine the interaction between these discrete particles while contact forces created by particle impact with the test structure were coupled to a finite element (FE) model of the test plate and support structure to determine dynamic deformations. The particle model approach used here considers only the translational degrees of freedom of the system. Particle rotation is not addressed, which is equivalent to ascribing an infinite angular moment of inertia to the particles. The discrete particle method used here was first described by Borvik et al. [22] and Olovsson et al. [28], and has been validated as an analysis tool for low soil velocity loading by several studies [15,23,29,30].
Tagged contact parameter calibration was performed by Borvik et al. [23] with data from an experimental study [15] using spherical, sand encapsulated, 150 g high explosive charges. The sand in those tests was identical to that used here.

The simulation model used the geometry of the experimental setup with a charge suspended over a 2.54 cm thick, edge gripped solid plate that was bolted at its four corners to a steel support plate placed on an I-beam picture frame base structure, Fig. 7. A 3.81 m long Kolsky bar was placed 45 cm above the test plate to determine the predicted pressure and impulse loading. The spherical charge was constructed with an inner sphere of high explosive material surrounded by an outer annular region of wet sand particles contained within a 3 mm thick acrylic plastic shell of 152 mm radius. The ledge around the outer shell was not modeled as it appeared to have no effect on the loading of the Kolsky bar or test plate as a result of its inclination. The inner sphere was also confined in a 3 mm thick acrylic plastic shell with a radius of 80 mm. The inner sphere was filled with sufficient HE particles to represent a 3 kg charge with the properties of C-4. This concentric sphere charge was suspended in air at a vertical standoff distance of 43.2 cm from the center of the charge to the top of the solid plate. The horizontal standoff distance from the center of the charge to the front of the Kolsky bar was 48.5 cm. Both distances were consistent with those measured from the experimental high speed video images just prior to detonation. This data set the center of the charge at $X_D=69.5$ cm, $Y_D=66$ cm, and $Z_D=43.2$ cm. The detonation point was defined at a 45° angle from the top center of the spherical charge and at the edge of the C-4, located on the opposite side of the Kolsky bar. One additional simulation test was performed with a second Kolsky bar positioned at the center of the test plate location ($X_D=66$ cm, $Y_D=66$ cm, and $Z_D=0$ cm with the front of the Kolsky bar in the X-Y plane 45 cm below the center of the test charge). It confirmed that the impulse applied to both Kolsky bars (when each was placed at a 45 cm standoff distance from the test charge center) were the same, validating the assumption that radial expansion and loading are equivalent in these two directions, and confirming that the horizontal Kolsky bar could be used as a witness of the blast load near the center of the test plate.

### 3.1. Particle model

The air and HE particles used by the solver were modeled as rigid particles each representing many actual particles that transfer momentum via collisions. Following Olofsson et al. [28], particle...
Fig. 6. Plan view of the X-Y plane showing camera locations. An expanded view of the test charge and plate shows the plate center, the charge center at detonation, and the point of maximum plate deflection (X = 71.3 cm and Y = 66.0 cm) after the event. The location of the section cut used to obtain a plate deflection profile is also shown. The origin of the coordinate system used for the study was at the front (lower) left corner of the test plate.

Fig. 7. A cross-section through the mid-plane of the FE model geometry used for the IMPETUS Afea discrete particle based simulation. The coordinate axis origin was located at the front left corner of the top of the test plate (out of the plane of this Fig.) as shown in Fig. 6.
interactions between air and HE particles were taken to be elastic, consistent with Maxwell’s kinetic theory of gases [33]. In this approach, IMPETUS models the air particles as an ideal gas with density \( \rho = 1.3 \text{ kg/m}^3 \), initial internal energy \( E_0 = 253 \text{ kJ/m}^3 \), and a ratio of specific heats \( \gamma = 1.4 \) with initial directions and velocities distributed at the start of the simulation according to the Maxwell-Boltzmann distribution [29]. The IMPETUS code has several predefined HE particle options that have been calibrated by Borvik et al. [23] by iterative simulation of a standard explosive filled pipe test. For the simulations reported here, the C-4 high explosive option was selected with predefined parameters of initial density \( \rho_0 = 1601 \text{ kg/m}^3 \), initial internal energy \( E_0 = 8.78 \text{ GJ/m}^3 \), ratio of heat capacities \( \gamma = 1.4 \), particle initial solid-fill fraction \( b = 0.35 \), and a detonation speed \( D = 8190 \text{ m/s} \). The explosion was initiated at the detonator location by releasing HE into motion at a release time \( R/D \) where \( R \) was the radial distance from the point of detonation and \( D \) the detonation velocity [23].

The water saturated (wet) sand was modeled with a penalty based (soft-particle) inter-particle contact law governing the behavior of the soil particles [23]. This contact model comprised a linear spring \( k \), in parallel with a linear dashpot with a damping constant \( c \), which were in series with a Coulomb friction component characterized by a coefficient of friction, \( \mu \). The values selected for the normal spring constant and the damping parameter govern the normal motion while a horizontal spring constant and the friction coefficient govern the tangential motions during inter-particle contact. The sand input parameter model was calibrated for \( 150 \pm 200 \mu \text{m} \) diameter, silica glass microspheres (density of \( 2700 \text{ kg/m}^3 \)) for both dry and water saturated (wet) sand. The dry sand fill fraction was 60% for the glass spheres with initial density \( \rho = 1620 \text{ kg/m}^3 \). The solver, rather than directly modeling the water in the wet sand, accounts for water effects by modifying the sand particle contact friction, contact stiffness, and damping as proposed by Borvik et al. [23]. The wet sand was given an initial density \( \rho = 2020 \text{ kg/m}^3 \). The calibrated wet sand parameters include the soil-soil particle contact stiffness \( k_0 = 4.0 \text{ GN/m} \), the soil-soil particle contact coefficient of friction \( \mu = 0.0 \), and soil-soil particle damping coefficient \( \xi = 0.005 \).

To analyze the sand particle distribution, the sand particle density was calculated at specified time steps after detonation. The simulated volume was segmented into approximately \( 1 \text{ cm}^3 \) volume rectangular cells in a radial direction of interest. The number of simulated sand particles in each cell was determined to calculate the simulation particle density, \( \left( \frac{\text{N}}{\text{cm}^3} \right) \) (number of particles/cm\(^3\)) where \( \text{N} \) is the number of sand particles in the segmented cell \( i \). The sum of the particles in all cells was also calculated, \( \sum \left( \frac{\text{N}_i}{\text{cm}^3} \right) \). The particle density was then divided by the total number of simulated sand particles to calculate a particle probability density, \( \left( \frac{\sigma}{\text{cm}^3} \right) \).

A convergence study indicated the simulation converged at 2 million total particles divided (by the solver) into 803,849 air, 439,911 sand, and 756,240 HE particles. For the 2 million particle simulation results shown here, one simulated sand particle was equivalent to approximately 5200 actual sand particles.

### 3.2. Finite element model

A cross sectional view of the model and the suspended spherical charge with the model coordinate system defined is shown in Fig. 7. The coordinate axis origin was located at the top front left corner of the test plate, shown in Fig. 6. The 3.81 m long Kolsky bar was modeled using the IMPETUS Afea Solver finite element package as a series of four cylindrical parts each of diameter 2.54 cm merged together, using the merger option in the solver. A 2.54 cm length cylindrical section located at the front of the bar was used to measure the impact force on the front of the Kolsky bar. The second cylindrical part was 47.86 cm in length and ended at the location of the strain gauges where the pressure was experimentally measured. The third part consisted of a 4 mm cylinder representing the region where strain gauges were located and was used to measure the bar pressure. The fourth cylindrical section covered the remaining length of the bar. The full bar model was constructed from 39,000 linear hexahedra elements with 43,248 nodes.

The 2.54 cm thick solid plate with in-plane dimensions of 132 cm × 132 cm, was supported on a test platform consisting of a 3.8 cm thick support plate, with an 80 cm × 80 cm center opening on top of an I-beam picture frame structure. To clamp the edges of the plate securely to the test platform, an outer (5.1 cm wide and 2.54 cm thick) picture frame was merged to the solid 2.54 cm thick plate to represent the four rectangular bars that were welded and pin reinforced to the test plate. The bottom plane of the model was constrained in the X, Y, and Z directions using a fixed boundary condition. A mesh sensitivity analysis was performed to determine the number of elements needed for solution convergence. The final full model geometry, including the inner and outer spherical acrylic shells, test plate, test platform, attachment bolts, and the Kolsky bar, was meshed with a total of 44,284 elements; 288 linear pentahedra elements, 42,320 cubic, and 1676 linear hexahedra elements with 129,432 nodes. The test plate used a more refined mesh than the support structure and the Kolsky bar to better observe the plate deflection during impulse loading. The full test plate with rectangular bars forming the picture frame edge consisted of 1676 cubic hexahedra elements with 62,964 nodes.

#### 3.2.1. Material models

The test plate, support frame, bolts, and Kolsky bar were all modeled as isotropic, Johnson-Cook materials. The IMPETUS Afea Solver uses the Johnson-Cook (J-C) constitutive model to calculate the von Mises flow stress defined by [29],

\[
\sigma_f = (A + B((\varepsilon_eff)^n)) \left( 1 + C \ln \frac{\varepsilon_eff}{\varepsilon_0} \right) \left( 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right)
\]  

(2)

where \( A, B, n, C, \) and \( m \) are material constants and \( \varepsilon_0 \) is the effective plastic strain of the material. The strain hardening constant parameters are the initial yield strength \( A \), the two hardening parameters \( B \) and \( n \), the strain rate parameter \( \varepsilon_0 \), and the strain hardening parameter \( C \). The J-C model also included the ambient temperature \( T_0 \), melting temperature \( T_m \), and the thermal softening parameter \( m \) for the material. The J-C model parameters for 304SS were reported by Dean et al. [34] and by Mori et al. [35] for annealed 304SS. For the A-36 steel constitutive model, the model parameters for ASTM-A36 were assumed [36]. The J-C parameters for 350 grade, maraging steel were taken from parameters for a similar VascoMax 300 alloy [37], assuming approximately equivalent material properties with an adjusted yield strength parameter for 350 grade steel. The reported value for the yield strength of 350-grade commercial maraging steel is 2.195 GPa with an ultimate tensile strength of 2.277 GPa [38]. The bolts were modeled as AISI 1040 carbon steel with J-C model parameters reported by Cohen et al. [39]. The J-C parameters used with Eq. (2) are summarized in Table 1 for the three materials. There was no fracture of the test plate so a failure model for 304SS was not included in the simulation model.

The acrylic polymer spherical shells used for both the inner shell (containing the HE) and the outer shell (containing the wet sand), were modeled using a linear elastic constitutive model with acrylic plastic values of density \( \rho = 1.18 \text{ kg/cm}^3 \), Young’s modulus \( E = 2.80 \text{ GPa} \), and Poisson’s ratio \( \nu = 0.37 \). The failure criteria for the plastic model was set at an effective geometric strain of 10%. When
elements in the geometric shell, reached the failure strain $\varepsilon_{\text{fail}} = 0.1$, they were eroded.

4. Sand shell expansion

4.1. High speed video observations

Fig. 8 shows a sequence of images of the test charge recorded with the wide field of view camera following detonation. Both the white painted side of the test plate and 20 cm length end of the Kolsky bar can be seen. The $t = 0$ s image in Fig. 8(a) corresponds to the moment of detonation. The image was used to confirm that the test charge was displaced to the right of the plate center by $3.5 \pm 0.3$ cm and downwards from the Kolsky bar center axis by $1.8 \pm 0.3$ cm, resulting in actual standoff distances (measured from the test charge center) to the plate $H_p = 43.2 \pm 0.3$ cm and to the Kolsky bar end $H_k = 48.5 \pm 0.3$ cm. The white sand front expanded almost isotropically with only a slight asymmetry in sand front shape. It can be seen to impact the test plate between the images shown in Fig. 8(c) and (d) at approximately $t = 290$ $\mu$s, slightly before impact with the Kolsky bar; consistent with the reduced standoff distance to the plate surface. The lower part of Fig. 8(f) shows that after impact with the test plate the sand front had flowed laterally over the plate surface and off the edges of the test plate. This sand had a small upward component of motion consistent with sand reflection at an increasingly acute angle of impact near the plate periphery. Careful examination of the sand front images in Fig. 8 indicates the presence of locally faster sand spikes (sometimes referred to as “fingering”) similar to those observed by Holloman et al. [29] for buried explosive events. Fig. 8(e) shows a magnified region where the sand spikes/
fingers with small radius of curvature leading edges are more clearly observed. The images in Fig. 8(d) and (e) indicate significant (white) optical luminescence associated with the first sand finger impacts with various parts of the test plate and the Kolsky bar support structure. The significant additional mass of the acrylic polymer ledges around the equator of the test charge can be seen to have locally slowed the sand front. However, due to the inclination of the charge, this had no effect upon sand front expansion towards the test plate or end of the Kolsky bar.

Fig. 9 shows a similar sequence of images obtained with the higher magnification camera using the same definition of time as Fig. 8. Figs. 8(b) and 9(b) indicate that, at t = 72 μs, the sand sphere had already begun to radially expand. By backward extrapolation, it is estimated that the sand front began its movement at t = 40 ± 20 μs, consistent with the propagation of an explosive detonation front with handbook velocity of 8040 m/s [31] across the 160 mm diameter charge (in t = 20 μs) followed by the propagation of a shock through the 72 mm thick annular sand shell at a shock velocity of 3600 m/s [40,41]. The main sand front position is indicated with a black dotted line in Fig. 9(d), and shows the fast moving sand spikes well ahead of this main front. The image sequence in Fig. 9 shows the length of the sand front fingers increased with time consistent with their higher velocity. The images in Fig. 9(f) indicate the observable tips of the sand fingers had advanced between 2 and 5 cm ahead of the main, sand front at 453 μs after detonation. Impact of the stretching sand with both the end of the Kolsky bar and the center of the test plate was therefore distributed over time. Examination of the high speed video also showed that the sand front developed a fractal like topology consisting of outwardly propagating sand cones that themselves became composed of smaller diameter cones as the sand radially expanded. Fig. 10 shows the square region indicated in Fig. 8(f) where conical features in the sand front decompose into smaller diameter cones over time.

A full analysis of the main sand front position was performed in the Kolsky bar horizontal direction by assuming the observed radial expansion was in the plane formed by the charge diameter and the axis of the Kolsky bar. Since it was difficult to identify a consistent front for the sand fingers, particularly early in the expansion process, only the main spherical sand front expansion (indicated by the black dotted line in Fig. 9(d)) was measured. The experimentally deduced sand front location is plotted as solid black circles in Fig. 11(a). Numerical differentiation of the main sand front leading edge position data gave a sand front velocity that is also shown as solid black circles in Fig. 11(b). Error propagation analysis was used to estimate the uncertainty in sand front velocity [42], and resulted in a radial velocity error that decreased with time from ±96 m/s error for the earliest velocity estimate to ±15 m/s for the last data point.

It is evident from Fig. 11(b) that the main sand front was rapidly accelerated to a maximum velocity of ~1200 m/s at 110 μs after detonation, and was followed thereafter by a slower, but prolonged

![Fig. 9. Images of the sand using the higher spatial resolution high speed camera at times (a) t = 0 s (instant of detonation), (b) t = 72 μs, (c) t = 120 μs, (d) t = 168 μs, (e) t = 310 μs, and (f) = 453 μs. The sand progression towards the Kolsky bar, the main sand front expansion, and the sand fingering effect can be seen in (d).](image-url)
period of deceleration. Given a measured standoff distance of 48.5 cm from charge center to the edge of Kolsky bar, and an initial outer sand sphere radius (including polymer shell thickness) of 15.2 cm, the distance from the front of the initially stationary annular sand shell to the front of the Kolsky bar was 33.3 cm. The distance of sand front propagation to the front surface of the target plate was 28 cm, since the standoff distance to the plate was 43.2 cm. Projection of these propagation distances on the position vs. time plot, Fig. 11(a), shows that the main sand front required a time of \( \approx 330 \text{ ms} \) to reach the Kolsky bar and \( \approx 290 \text{ ms} \) to reach the target plate. Fig. 11(b) indicates that at these instances, the main sand front’s instantaneous velocity was beginning to decrease from its maximum value, and at impact with the Kolsky bar, the velocity was 1050 \( \pm 44 \) m/s, and 1100 \( \pm 50 \) m/s with the plate. The maximum estimated velocity of the fastest sand spike, \( v = 1470 \) m/s, shown in Fig. 9(d), is indicated by the horizontal dotted black line in Fig. 11(b). These sand spikes appear to be a manifestation of an interfacial instability that exists at high velocity granular matter-air interfaces [43–45].

4.2. Simulated sand front

The IMPETUS predicted HE and sand particle distributions for a sectional plane through the center of the plate and charge containing the axis of the Kolsky bar are shown in Fig. 12. This view is analogous to that of the experimental time sequence images shown in Fig. 9. Particle positions at the moment of detonation (\( t = 0 \) s) are shown in Fig. 12(a). The subsequent simulated images show that the sand shell velocity was slightly asymmetric with the fastest sand propagating in the (southwest) direction; normal to the expanding detonation front. Significant sand velocity dispersion was present in all directions with some sand particles having travelled significantly further (at substantially higher velocity) than others. To help visualize this effect, Fig. 12(e) shows the approximate location of the 1, 2 and 5% sand particle probability density contours at 310 \( \mu \text{s} \) after detonation (calculated using the procedure detailed in Section 3.1).

Fig. 12(e) and (f) also show the initial interaction of the sand particles with the test plate surface. They indicate that sand impact with the test structure occurred slightly earlier than that with the end of the Kolsky bar consistent with experimental observations. The sand particles that made impact near the center of the test plate at zero obliquity suffered weak reflection, and accumulated in this region. This was consistent with the results of previous calculations of the impact of unconstrained sand slugs with rigid beams where the incident momentum of the sand slug was transferred to the test structure with little amplification by reflection [46,47]. However, most particles did not behave in this manner. Instead, they made oblique impact with the plate, and were reflected along the plate surface with only a fraction of their incident momentum transferred to the plate. These sand particles eventually (not shown) left the surface as a thin sheet travelling radially outwards from the center of impact, consistent with the reflected sand identified in Fig. 8(f).

4.3. Sand acceleration

To better understand the sand shell acceleration process, Fig. 13 shows sand and HE particle positions for the first 45 \( \mu \text{s} \) following detonator activation. The dotted white line in Fig. 13(a) indicates the position of the detonation front at 10 \( \mu \text{s} \) after the initiation of...
detonation. The detonation shock front required $19.5 \pm 0.5 \mu s$ to propagate the 160 mm diameter of the inner HE sphere and reach the southwestern edge of sand/HE interface (diametrically opposite the detonation location). This gives a detonation velocity of $8205 \pm 210$ m/s; consistent with the detonation velocity parameter, $D = 8190$ m/s, given as input to the solver, and is close to the handbook value for the detonation velocity of the C-4 explosive (8040 m/s) [31]. A compressive shock wave was then launched into the 72 mm thick annular sand region, and can be seen as the line separating the darker (compressed) sand from the (original contrast) stationary sand, Fig. 13(b)–(e). The approximate sand shock location is indicated by the black dashed line in Fig. 13(b)–(e). The sand shock front reached the outer surface of the sand shell at $t = 38.5 \pm 0.5 \mu s$, corresponding to a wet sand shock velocity of $3790 \pm 100$ m/s which is consistent with reported shock velocities in water saturated sands [41]. The acrylic shell (not shown in Fig. 13) failed as the sand shock front reached the polymer shell inner boundary at $t = 38.5 \mu s$. At 45 $\mu s$ after initiation of detonation, Fig. 13(f), the sand shock had undergone reflection/sign conversion at the sand/acrylic interface and had begun to propagate back into the sand shell with concomitant spalling of the sand behind this release wave. The initial HE and sand front locations are indicated by dashed lines in Fig. 13(f) to show how far the sand particles had been displaced from their initial locations at this time.
Detailed examination of the simulations showed that the radial distance of propagation of the sand particles within the sand shell was not uniform in the circumferential direction. To illustrate this, Fig. 14 shows the displacement magnitude of the sand particles at $t = 50 \mu s$ after detonation. Spikes at the green to blue interface can be seen within the inner region of the sand shell. They are consistent with the development of a shock induced interfacial instability whose conditions for initiation were recently analyzed by Kandan et al. [45] and shown to be a manifestation of a Richtmyer–Meskov type instability.

4.4. Sand layer stretching

Fig. 12(c)–(f) showed the presence of a significant variation in the sand particle displacement, resulting in the development of a substantial sand particle density gradient. A significant fraction of sand was accelerated well ahead of the main sand front, while a trailing, much denser sand region existed directly in front of the expanding detonation products. To quantify the sand particle distribution, the simulated sand particle density was calculated (as

![Fig. 13](image1.png)

Fig. 13. A simulation sequence following detonation of the test charge. The propagation of a detonation front through the HE and the locations of compressive shock front within the annular wet sand shell are also shown. (f) Shows the distance the sand and HE particles were displaced from their initial locations at $t = 45 \mu s$ after initiation of detonation.

![Fig. 14](image2.png)

Fig. 14. Sand particle shell with color contours corresponding to the magnitude of the particle displacement at $t = 50 \mu s$ after detonation. The spikes in the green-blue contours are consistent with development of an instability at the interface between HE particles and the sand. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The sand probability density is shown for each time step in Fig. 15(b). The horizontal lines shown on the Fig. correspond to particle probability densities of 1, 2 and 5%. Their intersection with the probability distributions in Fig. 15(b) show the radial location of each probability density. These particle probability values were transposed as probability contours on the image shown in Fig. 12(e). The fastest sand (with a sand probability density of 1 to 2%) was consistent with the leading tips of the sand fingers (spikes) observed experimentally in Fig. 9, and had advanced well ahead of the main front with a 5% particle probability density. The positions of the 1, 2 and 5% sand probability density contours are also overlaid on the experimental sand front location data obtained with the high speed camera in Fig. 11(a). By comparing the simulated front locations at different time steps, it was also possible to calculate the sand probability density contour speed in the Kolsky bar direction, and this is overlaid on the experimentally estimated sand velocity in Fig. 11(b). It can be seen that both the experimental and simulated sand fronts accelerated, reaching a maximum velocity between 80 and 150 μs after detonation. The fastest (1% probability density) sand observed in the simulations reached a peak velocity of almost 1800 m/s while the denser (5% probability density) sand reached a peak velocity of 1250 m/s, almost identical to that observed experimentally (1200 m/s). Since a significant particle density would be needed to reflect sufficient light into a camera pixel to be registered as light from the sand particles, it is suspected that the fastest sand spikes observed with the high speed video cameras (approximately 1500 m/s) corresponded to regions with a particle density greater than 1%.

### 4.5. Sand deceleration

There was a well-defined decay in sand front velocity after the peak velocity was attained in both the experiment and the simulation data, Fig. 11(b). Examination of simulation results in which air particles are shown, Fig. 16, indicates the development of an air shock front (a dense air layer) in front of the sand. A red dashed line in Fig. 16(a) and (c) indicate the approximate location of this shock. The darker shade of blue indicates the presence of significantly higher air pressure behind the air shock front. This air shock had an estimated radial speed of approximately 1300 m/s. Examination of simulations conducted without air particles (Appendix A) showed no sand front velocity decay, indicating that the sand deceleration was a result of momentum-transferring collisions between sand and air particles associated with the formation of the air shock. Its presence in the experiment may also have contributed to the formation of sand fingers ahead of the main sand front; a hypothesis that is investigated by more appropriate shock instability analysis methods in a recent paper [45].

Kandan et al. [45] analyzed the propagation of a sand front moving with a velocity \( V_s \) into air at atmospheric pressure, \( p_o \), and ambient temperature. The front generates an air shock wave as it pushed through air. The shock pressure \( p_f \) at the front of the slug was shown to be related to \( V_s \) by;

\[
\frac{V_s}{a_s} = \frac{1}{\gamma} \left( \frac{p_f}{p_o} - 1 \right) \left[ \frac{2\gamma}{\gamma + 1} \right]^{1/2}
\]

where \( \frac{p_f}{p_o} \) is the normalized shock pressure and the air shock speed, \( c_f \), can be obtained from the ratio of specific heat, \( \gamma \), the speed of sound, \( a_s \), for air and the normalized air shock pressure;

\[
\frac{c_f}{a_s} = \frac{\gamma - 1}{2\gamma} + \frac{\gamma + 1}{\gamma + 1} \left( \frac{p_f}{p_o} \right)^{1/2}
\]

The main sand front approached the test plate with an incident velocity, \( V_s \), of \( \sim 1200 \) m/s, resulting in a shock pressure \( p_f \sim 2.3 \) MPa (23 times atmospheric pressure) and an shock speed of \( \sim 1520 \) m/s. The high air pressure loading on this hypersonic sand front (which scales with the sand front speed) results in an instability that causes breakdown of the front into an array of conical shaped protrusions [45]. We note that by increasing the standoff distance, momentum would be progressively transferred to the air shock from the sand, and the nature of test plate loading would increasingly be governed by the fluid structure interaction between the plate and an air shock [48–50].

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**Fig. 15.** (a) The variation in sand particle density and (b) the sand particle probability density as a function of distance from the charge center (measured in the Kolsky bar direction) at simulation times \( t = 102, 182, \) and \( 208 \) μs.
5. Kolsky bar response

5.1. Experimental measurements

The time corrected (with $t=0\ s$ corresponding to the moment of detonation) axial stress (pressure) within the Kolsky bar is shown in Fig. 17(a). Recall that observations at the strain gauge location were delayed by the time for a longitudinal elastic wave (with a speed of 4800 m/s for the C-350 maraging steel bar) to propagate 0.5 m along the bar (a time of 104 $\mu$s). The first (sign reversed) distal reflection from the end of the 3.81 m long Kolsky bar arrived 1.38 ms after the initial direct signal. The data from the Kolsky bar is therefore only plotted for the first 1 ms of recorded data and is not complicated by distal reflections. However, complex Pochhammer-Chree modes for the large diameter bar used here (to avoid buckling instabilities) resulted in a complex wavetrain that distorted the pressure response [51]. Fig. 17(a) shows that the first compressive stress whose amplitude significantly exceeded the background noise was detected by the Kolsky bar strain gauges at $\approx 420\ \mu$s after detonation. However, it was preceded by a sequence of very weak arrivals whose amplitude was no more than two times the background. The compressive stress associated with the first significant signal (at 420 $\mu$s) had an amplitude of less than 50 MPa, and was followed by similarly weak signals until a large compressive pulse with a peak pressure of $\approx 750\ \text{MPa}$ arrived at 560 to 575 $\mu$s after detonation. Integration of the pressure-time curve gave the specific impulse transmitted to the bar, Fig. 17(c). The impulse signal first began to rise very slowly between 350 and 400 $\mu$s, and was followed by small impulse jump of $\approx 0.4\ \text{kPa\ s}$ between 410 and 445 $\mu$s. This was followed by a $\approx 120\ \mu$s period of increasing impulse with an approximately constant impulse rate. The arrival of the large pressure pulse at approximately 575 $\mu$s after detonation caused a rapid rise in impulse to a final value of $\approx 9.5 \pm 1.5\ \text{kPa\ s}$ that persisted to the end of observation (1 ms). The plateau specific impulse is consistent with simple estimates of the impulse per unit area of 8.5 kPa s calculated by distributing the momentum for 23.8 kg of water saturated sand accelerated to an average velocity of 1050 m/s evenly over a sphere of 48.5 cm radius (the standoff distance to the end of the Kolsky bar).

5.2. Simulated response

The axial stress due to the simulated sand impact with the end of the Kolsky bar was calculated from the simulated force-time signal at the strain gauge location and the cross sectional surface area of the Kolsky bar (5.07 cm$^2$), Fig. 17(b). The impulse was then calculated as the time integral of the pressure-time response, and compares well with the experimental data in Fig. 17(c). Four response regimes can be identified and are indicated in Fig. 17(c): (i) an initial step in impulse arriving at the strain gauge position at approximately 400 $\mu$s after detonation and persisting for 20–30 $\mu$s, (ii) a
Tagged region of slowly rising impulse between approximately 430 and 560 μs, (iii) a rapidly rising impulse regime that began at 560 μs, and persisted for ~40 μs in the experiment and about twice this time in the simulation and (iv) a plateau region of no further increase in impulse that persisted from about 600 μs to beyond 1 ms. Again, careful examination of the response prior to region (i) reveals that the step in impulse was preceded by a weak, slowly rising impulse beginning approximately 360 μs after detonation.

The simulation can be used to calculate the impulse applied to the impacted end of the Kolsky bar by each particle type (air, HE, and sand). The impulse contribution to the signal at the strain gauge location for each of the different particle types is shown in Fig. 18. These sum to the specific impulse calculated at the strain gauge location in Fig. 17(c). The air shock initially impacted the Kolsky bar at approximately 250 μs after detonation resulting in a signal reaching the strain gauges at ~355 μs. This appears to be responsible for a very weak, slowly rising impulse prior to the onset of region (i) step response. Fig. 18 shows that the impulse from the air particle impacts leveled out at ~0.3 kPa s at ~400 μs after detonation. The first (fastest) sand particles impacted the front of the Kolsky bar at around 300 μs after detonation, Fig. 11, and their impulse signal began to be observed at the strain gauge at about 400 μs. This initial sand impact, when combined with the impulse from the air particles, led to the first jump in region (i) impulse. The region (ii) response in Fig. 17(c) corresponded with a period of impact by low density, but high velocity sand while region (iii) corresponded to impact by the densest sand front directly in front of the HE particles and ended at 600 ms after detonation. The HE particles began to impact the Kolsky bar at 470 μs with their associated impulse arriving at the strain gauge location at ~575 μs after detonation (as the last of the sand impulse was recorded). The HE particle impacts contributed very little additional impulse to the total response, consistent with a leveling out of impulse beyond 600 μs (the region (iv) response), Fig. 17(c).

Further insight can be gained by examining the position of only the sand and HE particles that eventually impacted the end of the Kolsky bar, Fig. 19. Radial stretching of the sand front with time (distance of propagation) can be clearly seen. The simulation sequence is analogous to that observed in a laboratory scale study of the impact of sand columns on a Kolsky bar [11]. The laboratory scale study also observed the sand column lengthening over time as it traveled through air. In both cases, this arose from progressive

Fig. 17. (a) The measured and (b) simulated Kolsky bar pressure versus time after detonation. (c) Shows the measured and simulated impulse versus time response and the four regions of impulsive loading.

Fig. 18. The simulated specific impulse contributions from the sand, air, and HE particles versus time at the strain gauge location.
spallation of sand at the sand/air interface during reflection of a sand shock launched here by the detonation wave. Examination of Fig. 19(b)–(d) clearly shows that the highest velocity sand particles had advanced well ahead of the main front while lower velocity sand accumulated directly ahead of the detonation products. Careful analysis of the simulations indicated that the fastest (1% contour) sand, shown in Fig. 12(e), reached the end of the Kolsky bar at approximately 280 μs after detonation, and was detected at the strain gauges at approximately 394 μs after detonation consistent with the simulation plot, Fig. 17(c). However, Fig. 18 showed the initial loading experienced on the bar was from the air shock particles at this time rather than the fastest moving sand. The 2% probability density contour arrived at the end of the Kolsky bar at ~300 μs. This is consistent with the first sand impact shown in Fig. 18 and, coupled with the loading from the air particles, the existence of a region (i) response ~400 μs after detonation (Fig. 17(c)).

The region (ii) response corresponds to the sand arrival with a probability density of ~5% or higher. The impulse loading from this sand reached the strain gauge location around 440 μs, consistent with a time during which the impulse was rising at a constant rate. This constant rate of loading persisted to 560 μs and was followed by a sharp jump in impulse to a plateau impulse of 9.2 kPa s. This region (iii) response corresponds to the time at which the sand directly in front of the HE particles impacted the bar. This region of lower velocity but higher density sand remained just in front of the detonation products, Fig. 19(f), and impacted the front of the Kolsky bar at about 450 μs after detonation and would therefore have begun to be detected at the strain gauges at ~555 μs after detonation. It is interesting to note that the arrival of the slower moving HE particles after the sand did not cause significant additional impulse to be transferred during region (iv); a consequence of efficient momentum transfer from lower mass HE particles to the denser sand.

There was good agreement between the measured (~9.5 ± 1.5 kPa s) and simulated plateau impulse (9.2 kPa s) results and the timing of the main features observed in the impulse waveform, Fig. 17(c). It is also noted that while the simulations showed significant interactions between the air and sand particles, when simulations were performed without air particles, only a small difference in the impulse transferred to the Kolsky bar was observed. Fig. 18 indicates that less than 10% of the impulse was transferred by air particles, and it is therefore concluded that the majority of the impulse loading occurred by the impact of sand.

6. Panel deflections

6.1. Experimental observations

The deformed 2.54 cm thick, 304SS plate was sectioned through the point of maximum deflection at X = 71.3 cm and Y = 66.0 cm as shown in Fig. 6. The deflection as a function of distance Y along the plate (with Y = 0 cm corresponding to the white painted near edge of the plate) is shown in Fig. 20(b) for the full 132 cm length of the test plate. A permanent center deflection, \( U_{\text{max}} = 3.56 \text{ cm} \) was measured near the midpoint of the section cut. This deflection profile was aligned with the cross-section image of the test plate, Fig. 20(a), and lines corresponding to the locations of the steel support frame and the I-beam picture frame are shown on the plot. The center of the test charge was located vertically above the Y = 66 cm line in Fig. 20(b) at X = 71.3 cm which was also the location of maximum permanent deflection. There was no evidence of fracture observed in the plate after impact or of permanent rotational deformations at the edge grips. However, the I-beam support structure did suffer plastic deformation (and in a subsequent test, the flange underwent partial rupture).

6.2. Simulated plate deformation

The calculated displacement response of the solid plate is shown in Fig. 21. It shows the transient damped oscillatory displacement as the plate asymptotes to a steady state permanent displacement of 3.51 cm; a 1.4% difference to the experimentally measured maximum experimental displacement at X = 71.3 cm and Y = 66.0 cm. The simulated plate was then virtually sectioned along the Y axis at X = 71.3 cm (the same as the section in the experiment). This simulated permanent deflection profile is compared with the measured profile in Fig. 20(b) and can be seen to be in excellent agreement with the measurement. The location of maximum simulated and measured deflection was slightly off the center of the plate due to the small drift in charge position prior to detonation.

Fig. 22 shows the specific impulse distribution applied to the plate during the first 1 ms of loading. The maximum specific impulse was registered along the Y = 66 cm (center) axis of the test plate at a value of X = 71 cm; directly beneath the center of the charge. This maximum impulse has a value, \( I_x = 12.8 \text{ kPa s} \); slightly higher than that incident upon the Kolsky bar because of the ~5 cm shorter standoff distance to the plate surface. The impulse then rapidly decayed with radial distance from this location falling to less than 1 kPa s at the corners of the plate as a result of the longer standoff distance (inverse square law spreading of the sand and its deceleration by interaction with the air) and the oblique angle of incidence which reduces the fraction of particle momentum transferred to the plate surface.

A simulation was performed without the test plate present to determine the hydrodynamic pressure, \( P = \rho v^2 \) (where \( \rho \) is the sand density and \( v \) its velocity) and the incident impulse at the surface of the plate directly below the charge center. A sand particle detecting “sensor” with a cross sectional area of 0.04 x 0.04 m² was placed at
tagged the location of maximum impulse in Fig. 22 and detected the passage of sand particles. The maximum calculated pressure was 560 MPa, similar to that observed experimentally. The incident impulse was calculated as $I_0 = 12.4$ kPa s resulting in a transmitted to incident impulse ratio $I_t/I_0 = 1.03$, consistent with weak sand particle reflection [46].

Fig. 23(a) shows the effective plastic strain on the top surface of the target plate, where the consequence of stretching of the plate during its impulsive loading can be seen along the diagonal lines connecting pairs of bolts. Fig. 23(b) shows the effective plastic strain on the back face of the test plate where the highest strain was found to be located directly beneath the charge center and at stress concentrations near the bolt hole locations. Black dotted lines show the location of the beam span defining support plate. Even though the loading to the plate was circularly symmetric in Fig. 22, the strain distribution was strongly influenced by the square symmetry of the test plate and edge grip system.

The simulation methodology also enables detailed analysis of the response of the test frame during sand loading. Appendix B shows that significant elastic rotation of the support frame accompanied later stages of the test. This resulted in a softened edge restraint. It also resulted in large inelastic deformations of some parts of the support structure indicating a need for a sturdier support structure for tests at this scale.

7. Concluding remarks

A suspended spherical test charge consisting of a 3 kg high explosive sphere surrounded by a 23.8 kg water-saturated annular sand shell has been detonated above a 2.54 cm thick edge clamped stainless steel plate to explore the impulse transfer mechanisms and dynamic response of a ductile plate. A combination of high speed video and instrumented Kolsky bar measurements during the test were used in conjunction with particle-based simulations to analyze the impulse loading response of the 304 stainless steel plate by high velocity sand. The fidelity of the predicted pressure and impulse distributions for scenarios in which particle velocities exceeded 1200 m/s have been confirmed, and therefore enabled sand front propagation and spreading to be investigated at a fundamental level. It has also allowed the contributions to the total impulse from air shock, sand, and HE particles to be evaluated.
The study has shown that for the test geometry used here, 90% of the impulse was delivered to the test plate by the impact of sand particles. During propagation of the sand through background air, a strong air shock developed immediately in front of the sand. This air shock delivered the majority of the remaining impulse. Eventual impact of the detonation product impacts was responsible for almost no impulse transfer for the test geometry investigated here.

The highest velocity sand particles acquired their momentum by spallation from the outer surface of the sand shell during reflection of a compressive sand shock front initiated by a detonation front that had crossed the HE charge. The experimental study showed that this fast sand was distributed in sand spikes (fingers) whose tip speeds significantly exceeded that of the main sand front. However, the majority of the impulse was carried by a denser sand front that...
was driven from the rear by repeated collisions with expanding HE particles. The main sand front was accelerated to a velocity of \(\sim 1200 \text{ m/s}\) during the first 130 \(\mu\text{s}\) of the event, but then began to decelerate. Simulations conducted with and without the presence of background air particles showed that the declaration resulted from momentum transfer from sand to air particles. The impact of the sand particles with the plate resulted in little outward reflection, and therefore transferred little more than the incident momentum for zero obliquity impacts directly beneath the charge.

The IMPETUS solver was also used to simulate the structural response of the I-beam frame support structure used for the test. The simulation identified a region on the I-beam flange where very large localized plastic strains were developed during rotation of the gripping system. This corresponded with the location of the support structure rupture during a subsequent test. The solver was therefore found to be well suited for the engineering level design of impulsive resistant test structures. While the simulations reproduced the impulse transfer from the detonation particles to the test plate well, they failed to provide insight into the origin of the shock induced instability at the sand/air interface, to capture the fractal-like evolution of the sand front topology, and predict the shape of sand spikes. The study of these phenomena will require the emergence of computational methods that can treat the coupling between the shape of the array of highly deformable sand front instabilities and the aerodynamic forces upon them in the hypersonic regime.

We note that the test conducted here was an example of a more general problem. During detonation, the release of the chemical (stored) energy of an energetic material creates an expanding shell of detonation products. While in any direction the detonation product momentum is high, the principle of conservation of momentum requires its integral about the charge center to be zero. Over time, the detonation product momentum in any direction is fully transferred to the sand shell, causing its rapid acceleration to a maximum value (dictated by detonation product momentum divided by the sand mass). For the test conducted here, most of the impulse was transferred to the structure by sand whose speed was near this maximum value. However, over time (or distance of propagation), the sand eventually transfers all its momentum to the surrounding air, and at large standoff distances, loading of a structure then occurs by air shock reflection. In this case, the impulse is sensitive to the air shock pressure created during the sand front expansion. Because of inverse square law spreading, the momentum transferred to a small area structure in this limit is likely to be low.

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Appendices

Appendix A

Simulations were run in the IMPETUS Afea Solver with and without air particles to understand the effects of the air particles in the simulation, and how these particles affect the sand particle propagation. Fig. A1 shows snapshots of a contour plot of the radial sand particle speeds for simulations with and without air particles present in the simulation. The presence of air particles significantly reduced the speed of the leading edge sand particles.

Fig. A1. Simulation snapshots indicating the radial sand particle speeds for simulations with and without air particles present in the simulation. The presence of air particles significantly reduced the speed of the leading edge sand particles.
speed for a simulation with air particles present (left) and without air particles (right) at equivalent times. Fig. A1(a) shows the fastest moving (red) sand particles in both simulations travelled in the south-west direction (direction of detonation). However, there was a higher fraction of fast sand particles in the airless simulation. As the sand expanded over time, Fig. A1(b)–(d), the radial sand speed of the simulations conducted with air particles decreased (less red particles) while in the airless simulation the sand speed appears to have been less affected. To quantify these differences, Fig. A2 shows the maximum radial sand speed for the fastest sand particles in both simulations. The two plots show that after almost instantaneously acquiring a maximum speed at around ~40 μs after detonation, the particle speed in the airless simulation remained constant while that with air reached a maximum velocity at between 80–150 μs after detonations and was followed by a prolonged deceleration, consistent with momentum transfer to the air.

Appendix B

Simulations of the test have revealed that shortly after sand impact with the test plate had been completed, the I-beam and support frame of the test facility was inelastically bent and suffered substantial rotation. Fig. B1(a) shows the edge of the test plate connected to the A-36 grade steel support plate and I-beam flange of the test facility structure. Fig. B1(b) shows the deformed geometry at 2.2 ms after detonation. This corresponded to the time required for the support plate to reach its maximum rotation (of about 5°) from the initial edge orientation. The maximum effective stress on the I-beam support frame predicted by the simulation was 535 MPa. Fig. B2(a) shows the time dependent displacement of three nodes located on the test plate, the support plate, and the I-beam picture frame. Fig. B1(b). The maximum displacement of node 22,570 on the I-beam picture frame was 7.3 mm with permanent deformation of 3.8 mm and the permanent deformation of the support plate (node 20,100) was 6.1 mm. Fig. B2(b) shows the corresponding angle of rotation at these nodes as the support frame rotated and bent after impact. This rotation of the I-beam support frame resulted in development of a slightly more compliant edge restraint during the period of test plate oscillation, Fig. 21.

In subsequent tests using a higher impulse loading, the I-beam flange near the corner of the picture frame support (parallel to the edge of the frame) ruptured, Fig. B3(b). Fig. B3(a) shows the effective

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**Fig. A2.** The maximum radial speed of sand particles as a function of time for simulations performed with and without air particles.

**Fig. B2.** (a) Nodal displacements for node 22,570 located on rotating I-beam picture frame, node 20,100 located on the support plate, and node 222 located on the 304 SS plate and (b) corresponding plot of the angle of rotation at the three nodes.

**Fig. B1.** Simulated bending and rotation of I-beam picture frame and support plate. (a) Shows the geometry prior to sand impact. (b) Shows the deformed structure at the time of maximum I-beam rotation (t=2.2 ms).
plastic strain on the meshed I-beam for the loading condition used here at 5 ms after detonation. This area of maximum strain coincided with that of rupture and was consistent with the location of the point of rotation of the I-beam, Fig. B3(b).

References


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