Impulse Transfer during Sand Impact with a Cellular Structure

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Abstract

Compressible cellular metal sandwich structures made from a 3D assembly of square cross section 6061 T6 aluminum alloy tubes, and face sheets of the same alloy have been attached to a vertical pendulum and impacted by synthetic wet sand with an incident velocity of $\sim 300 \text{ ms}^{-1}$. The transmitted impulse of samples with thick (relatively rigid) and thin face sheets are compared to that transferred by an incompressible solid aluminum test block of the same dimensions. A discrete particle-based simulation method was used to simulate the experiments and to investigate the soil particle – structure interaction with the cellular structures. The simulated results agreed very well with experimental data; both showed that the impulse transferred to cellular structures with a 22 MPa core strength was 10-15% less than that transferred to a solid block of similar dimensions. However, the simulations reveal that some of this apparent mitigation resulted from a subtle sand interaction between the bottom of the test structure and the sand box used for the tests. When this sand box effect was eliminated in the simulations, a small impulse reduction from cellular structures with thin face sheets was still observed. However, this was found to be a result of dynamic deflection of the edges of the front face sheet. When this effect was eliminated (by the use of a rigid front face), the simulations showed a small (5%) impulse reduction occurred for cellular structure whose compressive strength was much less than the pressure applied by the sand. This was a consequence of rapid core compression which increased the travel distance (and lateral spreading) of late arriving sand during the sand loading process. Weak cellular structures, that suffered significant crushing, also reduce the impulse transfer rate.

Key words: 6061 Aluminum, Blast loads, Cellular structures, Discrete particles, Sand ejecta

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1 Introduction

Compressible cellular materials are widely used for protecting structures from impulsive loads created by impacts^{1,2}. For example, light, low compressive strength polymeric foams are used as a part of packaging systems to protect fragile objects during transport, and in helmets as a key component of a strategy to reduce the risk of traumatic brain injury³. In each application, the stress applied to the protected object is controlled by the compressive strength of the cellular material⁴. When these cellular materials are integrated into structures with strong faces, localized (impact) loads are spatially and temporally dispersed, further reducing the risk of damage or injury⁵. The emergence of compression resistant, metallic cellular structures^{6,7} led to an interest in the extension of these concepts to the protection of structures from high intensity impulsive loads caused by nearby explosions^{8,9,10,11, 12}.

Several studies have investigated impulse transfer by cellular structures, configured as the cores of sandwich panels, during underwater impulsiveload^{13,14,15}. The impact of one of the face sheets by a water propagated shock was shown to result in a transfer of momentum to the face sheet that was governed by a fluid structure interaction (FSI) resulting from shock reflection at the face sheet - water interface^{16,17,18}. For (rigidly supported) face sheets that remained stationary during shock reflection, the momentum transferred to a structure was twice the incident value. However, the reflection coefficient (and transferred impulse) was reduced when the face sheet was allowed to move during the shock reflection process. This could be achieved by decreasing the mass per unit area of the impacted face sheet, and the ratio of the core compressive strength to shock pressure. In well-designed structures, the ensuing motion of the impacted face sheet was arrested by reaction forces activated by core compression and face sheet and core stretching as the sandwich panel suffered out of plane deflection. These forces could be controlled by the cellular core topology, its relative density and by the mechanical properties of the material used to fabricate it. The use of light (thin) front face sheets, and weak cores whose dynamic crush strength was less than the pressure applied by the shock front, enabled significant (up to 50%) reductions in impulse transfer to the protected structure^{19,20,21}. However, when the shock pressure to core strength ratio was too high, complete core densification was predicted. The ensuing “slap” event (as the front face sheet and densified core were accelerated against the rear

1 of the structure), could then lead to impulse magnification; especially if the shock loading was
2 in-phase over a large area of the face sheet (planar shock fronts impinging flat face sheets at zero
3 obliquity)¹¹.
4

5 Underwater experiments utilizing instrumented Hopkinson pressure (or Kolsky) bars
6 attached to back supported, impulsively loaded structures have been used to study pressure (and
7 impulse) transmission during quasi-planar underwater shock front loading of cellular core
8 sandwich structures^{22,23}. Many core topologies for these studies were fabricated from corrosion
9 resistant stainless steels^{24, 25,26} including honeycombs²³, corrugated structures²², and lattices with
10 a pyramidal truss arrangement²⁷. All were able to significantly reduce the transferred impulse
11 and pressure. These studies showed that significant reductions in transmitted pressure (and
12 momentum) could be realized when weak core systems were utilized. They also showed that
13 when the shock pressure was sufficient to completely collapse (densify) the cellular structure,
14 slap of the front face sheet against the densified core did cause a rise in pressure and impulse
15 transfer, but this was much less than model predictions.
16

17 Efforts to extend the cellular structures approach to edge restrained test configurations
18 revealed the important role of the core in supporting panel stretching¹⁷. Since the pyramidal
19 lattice offered little in-plane stretch resistance, square or triangular honeycomb cores²⁸ were
20 preferred, but were more difficult to fabricate. Related studies have also investigated the
21 response of edge clamped sandwich panels to explosive shock loading in air, and led to the
22 experimental discovery of significant reductions of back face sheet deflection compared to
23 equivalent monolithic plates^{29,28}, even though the FSI effect was weaker in air^{30,31}.
24

25 Recently, experimental work has begun to characterize momentum and pressure transfer
26 during the impact of explosively accelerated soil against sandwich structures with compressible
27 cores^{32, 33, 34, 35,36,37}. Discrete particle based simulation approaches have also been used to model
28 the transfer of momentum from high explosive reaction products to air and soil particles, and
29 from these to model test structures³⁸. This same model approach was later used to investigate
30 soil interactions with an edge restrained aluminum sandwich structure³⁹. These studies showed
31 that significant reductions in back face panel deflection could occur when a solid plate was

1 redistributed to form a strong core sandwich panel, consistent with other studies³⁵. Sand impact
2 with aluminum sandwich panels also revealed the existence of a strong coupling between local
3 compressions of the core, dynamic deflection of the impacted face sheet and the local impulse
4 transfer mechanism. Local surface concavities more strongly reflected the sand
5 particles, resulting in a locally higher momentum transfer to that region. The higher local loading
6 of the sandwich by sand particle reflection during dynamic evolution of the panel's surface
7 topology, amplified local core crushing and face sheet stretching leading to fracture, and focused
8 attention upon the need for a deeper understanding of the soil structure interaction (SSI) effect.
9

10 The impact of sand particle columns against rigid surfaces at zero obliquity has been
11 experimentally investigated by Park et al⁴⁰. Using wet and dry sand column's with impact
12 velocities up to 100 ms^{-1} , they found that the pressure applied by the sand was hydrodynamic and
13 approximately equal to ρv^2 (where ρ was the sand column density and v its incident velocity); the
14 stagnation pressure of the sand. This inertial loading then transferred its incident momentum to
15 the test structure with very little amplification (less than 10%) from sand particle reflection. This
16 observation has been recently confirmed for explosively accelerated wet sand impact (at a
17 velocity of $\sim 300 \text{ ms}^{-1}$) against a solid aluminum test block⁴¹. Coupled discrete particle/finite
18 element simulations of the impact of sand columns against back supported cellular structures by
19 Lui et al.⁴² identified the existence of a small ($<10\%$) reduced impulse transfer regime when the
20 compressive strength of the core was less than the stagnation pressure applied by the sand, but
21 not so small that face sheet slap occurred. These simulations also indicated that the effect was
22 sensitive to the axial density gradient and length of the sand column, and the thickness of the
23 core.
24

25 Here, a recently proposed 3D cellular structure, made from square cross section Al 6061-
26 T6 tubes,⁴³ is utilized to experimentally investigate the impulse and pressure transfer mechanisms
27 to a back supported cellular core sandwich structure impacted by soil. The quasi-static⁴³ and
28 dynamic compression⁴⁴ of the 3D tube core structure has been previously examined in detail, and
29 the structure's response was shown to be rate independent for the compression rates of interest.
30 We investigate the compressive response of this structure when attached to both thin and thick
31 impact face sheets, as it is subjected to approximately planar loading by explosively accelerated

wet silica glass micro-spheres. The experiments were conducted in the same vertical pendulum recently used to study the sand-structure interaction with a back supported solid block⁴¹. Differences in the response of the cellular and solid block structures could therefore be observed and quantified. The same discrete particle based simulation used to analyze solid block interactions with sand is then used to interpret the experiments, and to more fully investigate the soil-cellular structure interaction process.

2. Test sample fabrication

The study utilized three test samples shown schematically in Figure 1. The solid block used in the previous study of the soil – structure interaction is shown in Figure 1(a). The cellular structures were manufactured by first laying down a co-linear layer of 6061 aluminum alloy square tubes each spaced a tube width apart. A second, similarly spaced layer was then orthogonally placed on the first, and the assembly sequence repeated to create a $[0^\circ/90^\circ]_2$ structure. The 3D topology was assembled from the 2D array by inserting identical tubes in the out-of-plane (vertical) void space between the cross-ply oriented tubes. The 3D core was attached to either 12.7 mm or 4.7 mm thick front face sheets to create the two other sample types tested, Figure 1(b) and (c). All the structures were attached to 4.7 mm thick back face sheet with a pre-drilled set of holes that permitted attachment to the test rig. The out-of-plane tubes in the 3D cellular structure were notched to facilitate complete fluid penetration during a subsequent dip brazing operation used to bond the various components of the test structure. After brazing the structure was heat treated to the T6 (peak aged) condition. A full description of the sample fabrication and mechanical properties of the cellular structure has been previously reported⁴³.

The geometry and mass of the 3D test structures investigated here are summarized in Table 1, and Figure 1. The core of the sandwich structures occupied a volume of $3.14 \times 10^{-3} m^3$ while the aluminum in the 3D core occupied a volume of $6.3 \times 10^{-4} m^3$ resulting in a core relative density $\bar{\rho} = 20.1\%$. The solid aluminum block, Figure 1(a), had the same volumetric dimensions as the cellular core structure. Both structures in 1(b) and 1(c) had identical cores; however, the different thickness front face sheets led to the thickness of the three

structures to vary, as shown in Figure 1. The core compressive strength was 21.8 MPa and independent of strain rate^{43,44}.

3. Blast Loading Test Procedures

The cellular structures were loaded by explosively accelerated wet synthetic sand in the same vertical impulse loading facility used to study impulse transfer by the same sand to solid block samples⁴¹. Figure 2 shows a schematic representation of the vertical impulse test apparatus. The reader is referred to Holloman et al.⁴¹ for a detailed description. The separation distance, δ , between the front face of the three test structures and the outside surface of the top plate of the steel sand box enclosure (Figure 2) varied during this study as a result of the different test structure thicknesses, Figure 1. The gap, δ , for the solid block was 8.1 mm; 9.7 mm for the thin face sheet cellular structure, and 1.8 mm for the thick face sheet cellular structure. Figure 2 shows the test geometry for a thin face sheet cellular structure.

A 50.4 mm thick layer of synthetic sand (consisting of 150-200 μm diameter amorphous silica particles) with 80% water saturation, was placed on top of a 300 g planar layer of explosive about 3 mm in thickness that rested on a polymer foam foundation. This charge was detonated using an array of five detonators connected by 5, 10 g C4 explosive boosters, to create a planar impulsive load that accelerated the wet sand towards the test structure at a velocity of $\sim 300 \text{ ms}^{-1}$. The sand that passed through a square aperture in a solid steel plate on top of the sand enclosing box then impacted the lower surface of each test structure. The standoff distance between the top of the explosive sheet and the bottom of the test structure was varied between 14 and 40 cm to change the impulse applied by the sand. The samples were attached to an apparatus that could be used either as a vertical pendulum or to measure the pressure waveform applied by the sand. In the latter mode, the pressure was determined using strain gauges located at the four pressure bar locations shown in Figure 2.

4. Experimental results

4.1 Vertical pendulum mode

The impulse transmitted by the sand to the cellular core sandwich structures were first deduced from the pendulum jump height and mass are summarized in Table 2 and compared with analogous data for the solid block sample. The impulse transferred to the solid aluminum block and cellular structure with a thick face sheet is shown as a function of standoff distance in Figure 3(a). The impulse applied to the solid block was experimentally observed to decrease from approximately 14 kPa·s, for a standoff distance of 14 cm, to approximately 8 kPa·s at a standoff distance of 40 cm. The impulse acquired by the cellular structure with a thick face sheet was less than that of the solid block; it decreased from approximately 12.5 kPa·s at a standoff distance of 14 cm, to approximately 8 kPa·s at a standoff distance of 40 cm. The error bars shown with the data were estimated from the uncertainty in pendulum height during the exposure time of a high speed video image and from estimates of the parallax error. The impulse transferred to the solid block decreased linearly with standoff distance, and had a slope $= -0.20 \text{ kPa} \cdot \text{s} \cdot \text{cm}^{-1}$. The impulse transferred to the thick front face covered cellular structure also decreased linearly with standoff distance, but with a slightly smaller slope $= -0.16 \text{ kPa} \cdot \text{s} \cdot \text{cm}^{-1}$. The impulse of the thin faced sandwich structure decreased from approximately 11.5 kPa·s at a standoff distance of 14 cm, to approximately 8 kPa·s at 40 cm, Figure 3(c). The impulse of the thin faced sandwich structure decreased linearly with standoff distance with a slope of $-0.14 \text{ kPa} \cdot \text{s} \cdot \text{cm}^{-1}$.

4.2 Hopkinson pressure bar mode

The pressure-time responses for the thin face cellular structures (measured at the strain gauge locations on the four Hopkinson pressure bars) are shown in Figure 4 (solid black lines) for each standoff distance. Time $t=0$, corresponded to detonation of the test charge. All the pressure-time signals exhibited an initially sharp rise to a peak pressure that decreased with increasing standoff distance. Following the initial pressure peak, a period of declining pressure was observed before the first reflected signal arrived at the strain gauge locations (shown on the figures). Its slope decreased with standoff distance, and at the largest standoff distance, the slope of this region was almost flat (a plateau), Figure 4(d). There was an abrupt drop in pressure

1 corresponding to the arrival of the first (sign converted) reflected signal at the sensor location,
2 followed by elastic reverberations of the Hopkinson bars.

3
4 The pressure-time curves shown in Figure 4(a)-(d) were integrated to calculate the
5 impulse-time curves shown in Figure 5 (solid black lines). The time at which the first distal
6 reflection and the second reflected signals reached the sensor on the Hopkinson bars ($558 \mu s$
7 and $748 \mu s$ respectively) are shown for each standoff distance. The first reflection was sign
8 converted upon reflection from the top of the bar and its arrival caused a sharp drop in pressure,
9 and inflection in the impulse-time response. The second reflection had undergone two sign
10 reversals, and was in phase with the continuing direct signal. Its arrival therefore caused the
11 impulse to again start rising.

12
13 The peak pressures for each standoff distance are summarized in Table 3, and plotted
14 against standoff distance in Figure 6(a). Table 3 and Figure 6(a) also shows that the peak
15 pressures recorded for the solid aluminum block were greater than those for the cellular structure
16 at the same standoff distance. The pressure applied to the solid block was observed to decrease
17 from approximately 28 MPa at a standoff distance of 14 cm, to approximately 10 MPa at a
18 standoff distance of 40 cm. At the shortest standoff distance of 14 cm, the initial peak pressure
19 transmitted by the cellular structure was 19.4 MPa. This fell with increase in standoff distance to
20 7.2 MPa at a standoff distance of 40 cm. The pressure applied by the solid block decreased
21 linearly with standoff distance with a slope $= -0.7 \text{ MPa} \cdot \text{cm}^{-1}$. The pressure applied by the thin
22 front face cellular structure also decreased linearly with standoff distance, but with a slope $=$
23 $-0.5 \text{ MPa} \cdot \text{cm}^{-1}$. The cellular structures crush strength (21.8 MPa) has been previously
24 reported⁴³ and is shown on Figure 6(a).

25
26 Integration of the pressure data acquired up to the arrival of the first bar reflection, Figure
27 5, indicated that a substantial fraction of the full impulse was acquired during the first $558 \mu s$ of
28 sand impact. The initial slope of pressure time response gives an estimate of the impulse transfer
29 rate, $\dot{I}$. Using the data shown in Figure 5, $\dot{I} = 18.8 \text{ MPa}$ at a 14 cm standoff and fell to 6.9 MPa at
30 a 40 cm standoff distance; consistent with the average pressure during the first $558 \mu s$ pressure
31 measured with the Hopkinson bars, Table 3. The impulse rate for the comparable solid

1 aluminum block is also presented in Table 3 and exceeded that of the cellular structure. The
2 impulse obtained by integrating the pressure waveform for 558 μs after the first direct arrival is
3 summarized in Figure 6(c). The measured impulse transmitted by the cellular structure was 2-3
4 kPa·s lower than that transmitted by the solid block, Figure 3(c).

5
6 The test samples were sectioned and photographed to reveal their mid-plane deformation,
7 Figure 7 and 8. The collapse mechanisms shown in Figures 7 and 8 are consistent with those
8 found during the previous quasi-static⁴³ and dynamic⁴⁴ studies. Core crushing was initiated by
9 the onset of buckling of the tubes oriented in the through thickness direction, and was nucleated
10 at the notches in the out of plane tubes. The vertical side walls of the in-plane tubes then began to
11 buckle and constrained the amplitude of the vertical tube buckling. This led to repeated folding
12 of the vertical tubes and a plateau-like stress-plastic strain response. The change in core
13 thickness was used to calculate the core plastic strain caused by sand impact with both the thick
14 and thin front faced cellular structures. These results are shown as a function of incident impulse
15 (taken to be that transferred to the solid block samples at each standoff distance) for both sample
16 types in Figures 9(a) and (b). The core strains of the thin face samples were approximately the
17 same as those of samples with a thick front face sheet. Examination of Figures 7 and 8 show that
18 the sides of the face sheets, especially for the most severely loaded samples, had been dent
19 upwards by the sand impact, and the impacted surface therefore acquired a slightly convex shape
20 (when viewed from below).

21
22 The difference in impulse transferred by the solid block and cellular structures has been
23 divided by the impulse transferred by the solid block and is plotted against incident impulse
24 transferred to the solid block in Figures 9(c) and (d) for samples with thick and thin faces. It can
25 be seen that the reduction in impulse transferred by the cellular structures increased with incident
26 impulse (i.e. with reduction in standoff distance), and that samples with thinner face sheets
27 suffered a large change.

28 29 **5. Numerical simulations**

30

1 The commercial IMPETUS Afea Solver⁴⁵ was used to simulate the experiments
2 conducted with the vertical impulse test apparatus. A detailed description of its implementation
3 to analyze the vertical impulse test facility and earlier experiments with the solid block sample
4 can be found in Holloman et al.⁴¹. Briefly, the code uses particle based methods to simulate the
5 detonation of an explosive from a single detonation location, and track momentum transfer from
6 high pressure explosive reaction products to surrounding air and sand particles. These particles
7 then interact with each other, and eventually contact the test structure and sample surfaces,
8 applying contact forces to them. The resulting deformation of the test structure and samples is
9 then modeled using a finite element method⁴⁶.

11 A convergence study was conducted to determine the optimum number of discrete
12 particles. From this study convergence was reached with 2,000,000 discrete particles. These
13 particles were distributed by the IMPETUS Afea Solver as 45,595 air particles, 1,941,610 soil
14 particles, and 12,795 high-energy explosive reaction product particles based on prior work by
15 Borvik et al.³⁸

17 **5.1 The cellular structure model**

19 The geometry and relative density of the modeled cellular specimens was the same as
20 that reported in Table 1. Following usual practice^{47, 48, 49}, small imperfections were incorporated
21 in the models to account for manufacturing defects (such as tube misalignment and tube wall
22 thickness variability) in the tested specimens that tripped tube wall buckling under compressive
23 loading. The imperfections were introduced as a displacement to each tube wall with a spatial
24 distribution corresponding to the lowest order buckling eigenmode. For all the modeled
25 structures, the first order eigenmode amplitude was set at 0.1 times the tube wall thickness.

27 **5.2 Material properties**

29 The experimentally determined Cauchy stress-true strain response of the Al 6061-T6
30 alloy used to make the test specimens was presented in Holloman et al.⁴⁴ The uniaxial Cauchy

stress, σ , versus true strain, ϵ , relation for an elastic-plastic material under uniaxial straining can be written:

$$\epsilon = \epsilon_e + \epsilon_p = \frac{\sigma}{E} + \epsilon_p \quad (1)$$

where ϵ_e and ϵ_p are the elastic and plastic components of strain and E is Young's modulus. The true stress versus plastic strain curve was tabulated and used to determine an isotropic strain hardening relation needed for FE simulations. The transition from elastic to plastic behavior was set at a Cauchy stress of 230.7 MPa. The hardening tabulation was implemented in the IMPETUS Afea Solver using the general piecewise linear hardening constitutive model with optional thermal softening and strain rate hardening. The yield stress of this model is defined in the form:

$$\sigma_y = f(\epsilon_{eff}) \left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right) \left(1 + \frac{\dot{\epsilon}_{eff}}{\dot{\epsilon}_0}\right)^c \quad (2)$$

where $f(\epsilon_{eff})$ is the piecewise linear hardening function of the effective deviatoric strain, which was obtained from the hardening curve behavior. The thermal softening component was defined by the current temperature, T , the reference temperature, T_0 , the melting temperature, T_m , and the thermal softening parameter, m . The strain rate hardening component of Eq (2) was defined by a reference strain rate, $\dot{\epsilon}_0$, and a strain rate hardening parameter, c . The coefficients used in conjunction with Equation 2 to model the material are given in prior work⁴⁴. We note that the thermal softening and strain rate hardening components made a negligible contribution to the flow stress. This was primarily defined by the piecewise linear hardening function $f(\epsilon_{eff})$ modeled using a von Mises yield criterion with isotropic hardening.

To account for softening resulting from tube wall fracture on the tensile side of severely buckled tubes, the Cockcroft-Latham failure criterion⁵⁰ was implemented for all the simulations. In this approach, failure is defined to occur when a damage parameter, D , reaches unity. The damage parameter was calculated as:

$$D = \frac{1}{W_c} \int_0^{\epsilon_{eff}} \max(0, \sigma_1) d\epsilon_{eff} \quad (3)$$

where σ_1 is the first principle stress. The critical damage parameter, $W_c = 85$ MPa was obtained by fitting the simulated measured stress-strain response of a single laterally compressed tube tested in the prior work⁴⁴. The general node splitting feature in the IMPETUS code was turned on.

1 This feature allowed the damage variable to evolve without change to the constitutive response
2 of the Al 6061-T6 alloy until $D=1$. At that instant, the Al6061-T6 alloy was assumed to have
3 failed and nodes of the elements where this failure had occurred were split.

4 The FE model was constructed from 7,104 cubic and 19,608 linear hexahedra elements
5 with 246,216 nodes. The Hopkinson bars and all connecting parts were modeled with a coarse
6 mesh since material failure was not seen experimentally. The solid test block was modeled with
7 a finer mesh since some local deformation (thought to be associated with sand fingers) was
8 observed experimentally. The solid block was constructed from 16,944 8-node 3rd-order linear
9 hexahedra elements. The cellular structure sample with a thin front face sheet was constructed
10 with 19,278 8-node 3rd-order linear hexahedra elements and the cellular structure sample with a
11 thick front face was constructed from 15,568 8-node 3rd-order linear hexahedra elements. A
12 mesh sensitivity study was performed for all three sample types to confirm solution convergence
13 with this level of discretization.

15 **6. Simulation Results and Discussion**

17 **6.1 Comparisons with experiments**

18
19 The IMPETUS code enables a direct computation of the momentum incident upon the
20 front face of a test structure. This feature was used to calculate the impulse transferred to the
21 solid Al block and to the cellular samples with thick and thin impact faces. The simulated
22 impulse transferred to the solid block and thick front cellular samples is shown as a function of
23 standoff distance in Figure 3(b). Similar data for the thin faced sample is shown in Figure 3(d).
24 The magnitudes of the simulated impulses for both the solid and cellular structures were in good
25 agreement with those measured with the vertical pendulum, and declined with increasing
26 standoff distance. Within the experimental range of standoff distances, the impulse transferred by
27 the cellular structures was usually less than that transferred by the solid block, and the difference
28 was slightly large for the thin faced samples, Figures 3(a) and 3(c). To more clearly establish the
29 trends with standoff distance, additional simulations were performed at shorter and longer
30 standoff distances, and this data is shown on Figures 3(b) and 3(d). These simulations show that
31 at large standoff distances (low incident impulse levels), where no core compression occurs,

1 there is no difference in the impulse transferred to the solid and cellular structures. Decreasing
2 the standoff distance below 14 cm confirms that substantial impulse mitigation continues to
3 occur, especially for the cellular structure with the thinner impact face.

4
5 Additional simulations were conducted to determine the pressure versus time history at
6 the Hopkinson bar sensor locations. The average of the signals recorded on the four bars is
7 shown in Figure 4 for the cellular structures with a thin impact face. Before the arrival of the first
8 reflection, the simulated and measured pressure histories (and especially the peak pressures) are
9 in good agreement. Past the first reflected wave, reverberations within the Hopkinson bar
10 dominated the response, and it was difficult to accurately simulate the response in part because of
11 poorly known reflection coefficients and dissipation processes of the bars. The most notable
12 discrepancy between the measured and simulated pressure waveforms was the time at which the
13 pressure began to rise. This occurred earlier in the simulations, and was most noticeable at longer
14 standoff distances. This phenomenon was observed in the earlier study of the solid block
15 response and was attributed to the arrival of (anomalous) high velocity spalled sand⁴¹, due to
16 insufficient momentum transfer from sand to air particles. Figure 6(b) provides a summary of the
17 simulated peak pressure predictions for the solid block and thin front face cellular structure. The
18 simulated peak pressure was slightly higher than that observed experimentally as a consequence
19 of the higher sand front velocity.

20
21 The impulse was obtained by integration of the simulated pressure waveforms, and is
22 shown in Figure 5 for the cellular structures with a thin front face. Again, relatively good
23 agreement with measured results was obtained up to the first reflected wave arrival. Following
24 the first (sign reversed) reflected wave arrival, the impulse plateaued or decreased, before again
25 rising when the twice reflected, non-sign reversed signal arrived ($190\ \mu\text{s}$) after the first reflected
26 arrival. Reverberation and dissipation within the bars was not as well modeled by the simulation
27 methodology, but even so, the general trend of rising impulse towards a final value was evident
28 in the simulated data, Figure 5. The impulse obtained by integration (for $558\ \mu\text{s}$) of the measured
29 and simulated pressure waveforms is plotted versus standoff distance in Figure 6(d). By
30 extending the simulations to larger standoff distances than those used in experiments, it can be
31 seen that the reduction in early stage impulse decreased to zero as the standoff distance was

1 increased. The simulated change in impulse versus incident impulse for samples with a thick
2 impact face is shown in Figure 9(c) and for those with a thin impact face in Figure 9(d). The
3 simulated results again agree well with both sets of measurements.
4

5 The effective plastic strain distribution and overall deformation of the two sets of cellular
6 test structures are shown in Figures 7 and 8. The buckling collapse of the core and the convex
7 deflection of the thin face sheet samples are well predicted. However, the simulations
8 overestimated the convexity acquired by the impact face of the thick face samples. This may be a
9 result of the use of a single (central) detonator location in the simulations rather than the five in
10 the experiment which would have produced a slightly more spatially uniform impulse
11 distribution. The plastic compressive strain of the cores is shown versus incident impulse in
12 Figure 9(a) and (b) for both types of cellular structure. It can be seen that there was very good
13 agreement between the measured and simulated core strains.
14

15 **6.2 Sand impact visualization**

16

17 A sequence of sand(brown) and detonation product (burgundy) particle position snap
18 shots for the solid block, thin faced, and thick faced cellular structures are shown for the 14 and
19 40 cm standoff distance tests in Figures 10 and 11. Twenty spherical virtual particle “monitors”
20 each with a radius of 0.508 cm were positioned 2.5 cm below the lower surface of the solid
21 block, and distributed in a line across the full mid-plane of the specimen, Figures 10(a) and
22 11(a). The monitors (not shown in the simulations) were positioned at the same positions within
23 the box lid aperture opening for the cellular structure simulations. This resulted in the monitors
24 being initially located 2.7 cm below the thin face specimen front face sheet and 1.9 cm below the
25 thick face sheet sample. In all three cases, it can be seen that the explosively accelerated sand
26 above the explosive traveled in (predominantly) the upwards direction. A small lateral
27 acceleration was also imparted to the synthetic sand layer causing it to widen over time (and
28 distance of propagation). The upward accelerated sand acquired a range of velocities as a result of
29 loading by a combination of shock reflection and the push from the expanding detonation
30 products. It therefore increased in thickness with distance travelled.
31

At the 14 cm standoff distance, the fastest sand began to load the samples at ~ 0.24 ms after detonation, Figure 10(b), and at about 0.6 ms for the 40 cm standoff distance, Figures 11(a) and (b). The test samples then began to suffer an upwards displacement as the solid block and Hopkinson bars were elastically compressed, and the cellular structures began to plastically crush. The upward motion of the sand that impacted the solid block was arrested and displaced laterally across the flat surface. As it reached the sides of the sample it was forced to propagate through the narrow gap between the sand box lid and the bottom of the sample. Initially, sand accumulated just below the sample since the sand particle arrival rate exceeded that of escape through the gap. The upward motion of the impacted surface of the samples increased the gap with the lid and eventually enabled more rapid sand escape. However, sand particle impact with the underside of the lid also caused it to suffer an initially upward displacement during the experiment. The gap separation was controlled by vertical displacement of the sample (due to compression and extension of the samples and test structure) and oscillation of the sand box lid which are shown in Figure 12 for the three topologies at a 14 cm standoff distance. The evolution of the position of the lid and impacted surface of the samples is shown in Figure 13(a) and the gap separation in Figure 13(b). The gaps for the cellular samples were wider than those of the solid because of plastic core compression. The sides of the face sheet of the thin faced cellular sample were also more significantly bent by the escaping sand than the sample with the thick front face, Figure 12, and so their gaps with the sand box lid surface were larger throughout most of the sand loading process.

The effect of increasing the standoff distance can be seen by comparing Figures 10 and 11. The sand layer was more significantly stretched as the standoff distance increased. This decreased the sand arrival rate, and in turn decreased the pressure on the test structure and its initial upward deflection, and also resulted in less plastic core compression for the two cellular structures, Figure 14. As a result of these off-setting effects, substantial sand accumulated beneath the three sample types, but was again more rapidly relieved in the thin front face structure by opening of the gap, Figure 15.

More insight into the sand loading process can be gained by examining the monitor deduced sand velocity – time profiles, Figures 16(a) and 17(a). Apart from small random

deviations and the slight difference in distance to the test sample, these were identical for the three sample types. At a 14 cm standoff distance the sand particles reached a peak velocity of approximately 400 ms^{-1} at 0.2 ms after detonation. Figure 10(a-b) shows that this highest velocity was associated with spalled sand traveling at the sand front's leading edge. The most significant difference in the sand velocity of the three topologies was observed at ~ 0.4 ms after detonation when the main sand layer arrived. The monitors positioned below both cellular structures had a sand velocity of approximately 200 ms^{-1} at this time, whereas the solid block sand velocity was substantially lower (approximately 100 ms^{-1}), consistent with extra accumulated sand that had stagnated against the sample. This difference is highlighted in Figure 10(d) where the sand contacting the solid block had limited opportunities to escape while the core crushing and the face sheet edge deformation allowed the sand to more easily flow past the steel box top. When the standoff distance was increased, the sand velocity exhibited less deviation between topologies, Figure 17(a). This is visually apparent in Figures 11(c and d) where less core crushing occurred, and the cellular structures acted more like the incompressible solid block.

The sand density – time profiles at the monitors differed more significantly than the velocity – time outputs for the three topologies. At a 14 cm standoff distance the sand density at the monitors below the cellular structures reached a higher value ($1400\text{-}1600 \text{ kgm}^{-3}$) than the solid block during the time (0.3-0.5 ms) of core crushing, Figure 16(b). After reaching a maximum, the sand density fell most rapidly for the thin faced cellular structure. The drop in density is visually apparent in Figures 10(c and d), and corresponded with rapid sand flow from the steel box as the cores crushed and the gap, δ , increased. The incompressible solid block forced much of the sand to stagnate against the impact face. A similar effect occurred for the thick front face sheet sample which suffered smaller plastic compression than the sample with the thin face sheet. At the 40 cm standoff distance, the density – time outputs from the monitors exhibited similar trends, Figure 17(b). Once again, this was directly controlled by the separation distance with the sand box structure. The slower drop in sand density for the thin face sheet cellular structure at the 40 cm standoff distance (compared to that at 14 cm) was due to less core crushing.

The hydrodynamic pressure (P_h) applied by the sand particles, could be calculated from the numerically measured sand density, ρ , and velocity, v , with the spherical monitors using:

$$P_h = \rho v^2 \quad (4)$$

The sand velocity and density data obtained with the monitors, Figures 16(a) and (b) and 17(a) and (b) can be used to estimate the pressure applied to the front of the sample. This is shown in Figures 16(c) and 17(c) for the two standoff distances. The pressure for the 14 cm standoff distance test increased rapidly to a first peak, and then decreased before rising again to a second peak for both cellular structures. This second peak was less apparent for the solid block. The first pressure peak amplitude was 30 MPa for the solid block, 25 MPa for the thick face cellular structure, and 20 MPa for the thin face cellular structure. These peak pressures were nearly identical to the pressures of the initial pressure spike measured using the Hopkinson pressure bars, Table 3, and corresponded to arrival of the fast (spalled) sand at the sample surface. A second, lower pressure of approximately 15 MPa occurred at 0.5 ms after detonation for both cellular structures, and corresponded to the arrival of the more densely packed sand slab at the monitors. Increasing the standoff distance to 40 cm, led to a reduction in sand density (due to axial and lateral stretching of the sand) and a slightly reduced velocity (because of sand-air particle collisions), Figure 17 (a) and (b). This resulted in disappearance of the first pressure spike, Figure 17(c); consistent with the disappearance of the initial spike in pressure observed experimentally, Figure 4, as the standoff distance was increased.

By integrating the hydrodynamic pressure, the impulse-time relation for sand particles could also be calculated, Figures 16(d) and 17(d). At 14 cm, the impulse rose rapidly upon arrival of the sand, and for the solid block reached a maximum of ~13 kPa·s within approximately 2 ms of detonation. The impulse also rose rapidly for both cellular structures, but reached a lower maximum value of approximately 10 kPa·s. This agreed reasonably well with vertical pendulum measurements. Figure 17(d) shows that at a 40 cm standoff distance, the impulse's at the monitor locations were also similar to those measured with the vertical pendulum.

The impulse applied by the particles to the front face of the solid block (located 2.5 cm above the monitors) and both cellular structures (located at 2.7 cm and 1.9 cm above the monitors for the thin and thick face cellular specimens respectively) could be directly obtained from an

output file of the IMPETUS Afea post processor, Figure 18. Good agreement between the vertical pendulum measured and these simulated impulses was seen for all the standoff distances. The impulse-time signals calculated with the contact algorithm exhibit three distinct regions. Region I was associated with impact of the spalled sand at the sand front leading edge. For each standoff distance, the impulse acquired in Region I was almost identical for all three sample types. The slight differences were due to the differing thicknesses of the specimens which slightly changed the standoff distance from that of the solid block. Region II corresponded to impact by the dense sand slug, and was the region most responsible for the impulse differences between the three sample types. Figures 10(d) and 11(d) indicate that Region II corresponds to the period where the separation gap between the steel top plate and the front face of the specimen was rapidly increasing. Recall that the gap for the solid block was smaller than for the cellular structures, and provided less room for sand to escape, and the impulse to remain higher than the crushable cellular structures. Sand loading rapidly decreased in Region III, and corresponded to a regime where the sample to sand box gap was the widest.

6.3 Mechanisms of impulse transfer reduction

(a) Test geometry effects: It has been shown that the combination of the sand box lid deflection, core crushing, and elastic compression (and extension) of the Hopkinson bars all contribute to the gap through which sand flowed away from the sample and escaped the system. To better understand the consequences of this critical aspect of the experiment, the lid was removed from the simulations, keeping the rest of the model unchanged. This allowed the effect of the lid-sample aperture upon the transmitted impulse to be more clearly understood, and reveal the process by which the three samples interact with an unperturbed sand front. Figure 19 shows the transferred impulse (calculated using the sample contact algorithm) to the three sample types at standoff distances of 14 and 40 cm with the sand box lid removed. At a 14 cm standoff, Figure 19(a), the impulse for all three sample types was less than that with the lid in place, Figure 18(a) because of sand reflection from the inclined periphery of the sand box aperture towards the sample.

1
2 These results indicate that the lid aperture substantially affected the impulse transfer, and
3 the mechanisms responsible for this are explored using sand position snap shots shown in Figures
4 20 and 21. At the 14 cm standoff distance there is no noticeable difference between the
5 simulation with a steel lid and without a steel lid at 0.16 ms after detonation, Figures 10(a) and
6 20(a). At 0.24 ms after detonation, the spalled sand began to interact with the front face of the
7 sample and the only noticeable difference between the simulation with and without a lid can be
8 seen at the right and left edges of the sand front, Figures 10(b) and 17(b), where the inclined
9 surface defining the aperture is lid has reflected sand into the aperture. At 0.48 ms after
10 detonation the sand's peak density with a lid was calculated to be approximately $300 \text{ kg} \cdot$
11 m^{-3} higher than that with no lid present for the three test samples. The monitors calculated no
12 noticeable sand velocity change when the lid was removed. A comparison between Figure 10(c)
13 and Figure 20(c) shows the presence of inclined surface around the aperture of top lid forced
14 some sand that would have otherwise missed the edge of the sample, to coalesce under and then
15 impact the sample. Without a lid, the accumulated (densified) sand below the sample surface
16 assumed a convex shape, and the edges of this dense sand front reflected some of the sand in a
17 manner that allowed a fraction of its vertical impulse to be retained. Continued sand loading at
18 0.80 ms after detonation showed that without a lid the sand more easily rolled off the sample's
19 edge, Figure 20(d), rather than stagnating and eventually escaping as the gap separation
20 increased, Figure 10(d). The formation of this virtual convex sand shape combined with the
21 smaller fraction of the sand slug that impacted the sample resulted in reduced impulse transfer to
22 the sample.

23
24
25 **(b) Impact face deformation effects:** It is interesting to note that the solid block and the
26 thick face cellular structure acquired a nearly identical impulse once the sand box lid was
27 removed, Figure 19. Figure 20(d) shows that the thick face sheet sample remained nearly planar
28 during sand loading, and the sand flowed off its surface in a similar fashion to the solid block.
29 However, the impulse transmitted to the thin face sheet sample was less than that transmitted to
30 the solid block, Figure 19. Examination of Figure 20(d) shows that the thin face sheet underwent
31 significant deformation upon spalled sand impact, and its sides were quickly bent upwards to a

1 shape that allowed the subsequent (Region II) sand slab to be only partially arrested before
2 flowing around the specimen. To explore the consequence of this dynamic front face deflection
3 phenomenon, the front face of the thin face cellular structure was again modeled as a 6061
4 aluminum alloy, but with a greatly increased yield strength (23 GPa) and modulus (7000 GPa)
5 which caused it to remain rigid throughout the simulation.

6
7 The red dashed (thin/strong face) line in Figure 19(a) represents the impulse-time
8 response for a cellular sample with a strong thin face sheet that was not allowed to deform. The
9 impulse at 14 cm was increased to that of the solid block, and the thick face cellular structure. It
10 is therefore clear that face sheet deformation was able to promote sand flow around the sample
11 and only partial vertical momentum transfer to the specimen. It is noted that even though the
12 impulse-time response of the three samples reached the same plateau value when the face sheet
13 did not deform, a slight difference in the slope in Region II of the impulse-time response
14 remained, Figure 19(a). The impulse-time response in Region II occurs during core compression,
15 and so the core's contribution to impulse transfer was explored next.

16
17 **(c) Core strength effects:** The cellular structure core has been simulated to this point using
18 an aluminum alloy yield strength of 230 MPa resulting in a core peak crush strength of 21.8 MPa.
19 Since the crush strength of the core scales linearly with that of the alloy's yield strength, the
20 alloy yield strength was progressively decreased in the simulations to investigate how easier core
21 collapse affected the transmitted impulse and applied pressure. The alloy yield strength was
22 decreased to half (115 MPa), a fourth (58 MPa), and an eighth (29 MPa) of its original value, and
23 the core compressive strength calculated using the finite element model developed in the previous
24 study⁴³. These core strengths are summarized in Table 4. The sand impact simulations were then
25 repeated without a sandbox lid and a rigid front face was used for all simulations.

26
27 Figure 22(a) shows the impulse-time response for cellular structure cores with core
28 compressive strengths between 21.8 and 2.8 MPa. Decreasing the compressive strength of the
29 cellular structure resulted in a slightly reduced plateaued impulse from 11 kPa·s (for the original
30 core strength of 21.8 MPa) to approximately 10.5 kPa·s for weakest core samples. The
31 approximately 5% decrease in impulse only occurred when the core was sufficiently weak to

1 permit significant core crushing, Figure 22(b-d). The majority of the core crushing occurred
2 during Region I by impact of the spalled sand at the sand front. This allowed the distance
3 between the impact face and the explosive charge original location to rapidly increase (by the
4 product of the original core height and the compressive strain). This increased the standoff
5 distance for later arriving (Region II) sand, and was responsible for the reduction in impulse. To
6 illustrate, if a 7.6 cm thick core were compressed 50%, the increased standoff distance would be
7 3.8cm, and using the slope of the impulse – standoff response for the solid block, Figure 3(a) of
8 $0.2 \text{ kPa.s.cm}^{-1}$, the reduction of impulse if all the sand had impacted at the longer standoff
9 distance would be 0.76 kPa.s compared to the 0.5 kPa.s change of the simulation.

10
11 The collapse sequence in Figure 22(b-e) shows that cellular structures with lower
12 compressive strengths were fully densified 0.8 ms after detonation at a 14 cm standoff distance,
13 Figure 22(e). The maximum velocity attained by the front face during the core crushing Region
14 I response was $\sim 100 \text{ ms}^{-1}$. During the Region I response, the rate of impulse transfer decreased
15 with reduction of core strength, Table 4, because of the decrease in sand impact velocity (and
16 thus stagnation pressure) measured in the front face sheet frame of reference. This result
17 indicates that when a core can be easily compressed by sand impact, the pressure transmitted to
18 the structures distal side can be decreased. We also note no slap enhancement of impulse was
19 observed, even when the core was compressed beyond its densification strain.

20 21 **7. Concluding Remarks**

22
23 A vertical pendulum test apparatus has been used to experimentally investigate the
24 impact of explosively accelerated wet sand with back supported Al 6061-T6 cellular test structures
25 attached to thin and thick face sheets, and compared to the response of a solid (incompressible)
26 6061-T6 aluminum block test specimen. The apparatus could be used as a vertical pendulum
27 for determination of the impulse transferred to the specimens when detonation of a 300 g sheet of
28 explosive was used to accelerate a 5.08 cm thick layer of wet silica (sand) particles towards
29 samples whose flat impact face was inclined at perpendicular to the sand propagation direction.
30 The cellular structures were fabricated from extruded Al 6061-T6 square tubes that were arranged
31 in a rectilinear pattern and had a relative density of $\bar{\rho} = 20.1\%$. Instrumented Hopkinson bars

1 attached to the rear face of the samples also enabled the pressure exerted on the sample to be
2 measured. Integration of these pressure waveforms over time enabled an independent estimate
3 of the transferred impulse for 558 μ s after the start of sand impact to be measured. By varying
4 the distance between the surface of the explosive layer and the samples front face from 14 to 40
5 cm, the transferred impulse and pressure were found to decrease with distance for all tested
6 samples. A particle base simulation implemented in the IMPETUS Afea Solver was used to
7 model the experiments and excellent agreement was observed between the experimental and
8 simulation results. This validated code was then used to investigate the mechanisms of the sand-
9 structure interaction with cellular structures. It has been found that:

- 10
11 1. When cellular structures were placed just above the aperture in the lid of the sand
12 containment box, the transmitted impulse to cellular structures was reduced by
13 approximately 10-15% compared to that transmitted to a solid block at the closest
14 standoff distances. This change decreased to zero as the standoff distance increased
15 and was correlated with reduced sample compression. The pressure transmitted to the
16 distal end of the specimen was also shown to be reduced by cellular structure that
17 underwent significant plastic compression.
- 18 2. Particle based simulations accurately predict the impulse transferred during the
19 vertical mode tests and the pressure waveforms recorded with the instrumented
20 Hopkinson pressure bars. In addition, the cores deformation modes were accurately
21 predicted along with the percentage of core strain and the change in impulse.
- 22 3. The simulations provided a means to investigate the soil structure interaction and
23 revealed that the gap between the samples front face and the sand box top was largely
24 responsible for the reduction in impulse. The separation gap acted as a valve to allow
25 sand to escape from the system and release sand pressure. Compressible structures
26 with easily deformed faces were shown to enable a more significant opening and
27 greater impulse reduction.
- 28 4. By making the thin front face sheet rigid and removing the sand box lid in the
29 simulations, it has been shown that strong core cellular structures transferred the same
30 impulse as a solid block. Identical cores with soft impact faces transferred less

- 1 impulse than the solid block because they dynamically deformed to a convex shape,
2 which reduced the vertical component of sand momentum transferred to the specimen.
- 3 5. As the core crush strength was reduced in simulations, a small (~5%) sand-structure
4 interaction was observed with the sand box lid removed and the thin front face forced
5 to be rigid. This effect resulted from a dynamic increase in standoff distance due to
6 core compression. A weak core was also shown to decrease the impulse transfer rate
7 (and therefore acceleration) applied to the distal end of the specimen.
- 8 6. The study has shown that in contrast to underwater shock loading at zero obliquity,²²,
9 ²³the impact of explosively accelerated sand against a soft (compressible) structure
10 that remains planar during impact, results in no significant reduction of the
11 transferred momentum. More substantial reductions in the rate of momentum transfer
12 (and thus pressure applied to the protected structure) can be accomplished by thick
13 core cellular structures with core strengths that are 0.1-0.5 that of the hydrodynamic
14 pressure applied by the sand.

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18

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