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Energy absorption in **lattice structures** in dynamics: Experiments

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1 **Abstract**

2 **Lattice structures** offer the potential to relatively easily engineer specific
3 (**meso-scale properties (cell level)**), to produce desirable macro-scale mate-
4 **rial properties** for a wide variety of engineering applications including wave
5 filters, blast and impact protection systems, thermal insulation, structural
6 aircraft and vehicle components, and body implants. The work presented
7 here focuses on characterising the quasi-static and, in particular, the dy-
8 namic load-deformation behaviour of **lattice** samples. First, cubic, diamond
9 and re-entrant cube **lattice structures** were tested under quasi-static condi-
10 tions to investigate failure process and **stress-strain** response of such mate-
11 rials. Following the quasi-static tests, Hopkinson pressure bar (HPB) tests
12 were carried out to evaluate the impact response of these materials under
13 high deformation rates. The HPB tests show that the **lattice structures**
14 are able to spread impact loading in time and to reduce the peak impact
15 stress. A significant rate dependency of load-deformation characteristics was
16 identified. This is believed to be the first published results of experimental
17 load-deformation studies of additively manufactured **lattice structures**. The

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18 cubic and diamond lattices are, by a small margin, the most effective of those
19 lattices investigated to achieve this.

Keywords: lattice structures, impact and blast protection, Hopkinson
pressure bar (HPB)

20 1. Introduction

21 The choice of material for a given structural problem requires a careful
22 balance of strength, stiffness, cost, durability and relative static and dynamic
23 properties. Lattice structures are multi-functional materials that can offer a
24 range of these desirable properties. They are commonly constructed by dupli-
25 cating three-dimensional meso-scale unit cells, typically at the scale of a few
26 mm. The stiffness and strength of these materials depend on relative density,
27 strut aspect ratio (radius/length), unit cell geometric configuration, unit-cell
28 size, properties of parent material, and rate of loading (Ashby, 2006). By
29 changing the spatial configuration of struts and/or strut diameters, different
30 geometries with different material properties can be produced, which will be
31 explored herein the context of protection against blast and impact loading.

32 Although lattice structures are different from cellular materials, certain
33 concepts carry over from the well-studied cellular materials to the less well-
34 know lattice structures, especially under transient dynamic loading condi-
35 tions. It is thus worthwhile to review briefly the state of the art in cellular
36 materials.

37 Properties of cellular materials have been the subject of many studies
38 (Reid et al. (1983), Stronge and Shim (1987), Reid and Peng (1997), Desh-
39 pande and Fleck (2000), Elnasri et al. (2007)). The mechanical response of

40 cellular materials under intense blast and impact loading may result in lo-
41 calisation of deformation, densification and material resistance and stiffness
42 leading to propagation of the deformation by a process akin the development
43 of shock waves; this extreme localisation is typical for “sparse materials”
44 (Harrigan et al. (2010)) and not observed in bulk materials. In cellular
45 solids, shock wave propagation is frequently studied using one-dimensional
46 analytical models, spring-mass models or finite element (FE) models. Reid
47 et al. (1983) developed a theory for the propagation of structural shock waves
48 through one-dimensional metal ring systems in order to explain the experi-
49 mentally observed behaviour of such structures when subjected to end im-
50 pact. More detailed dynamic crushing experiments on tightly packed arrays
51 of thin-walled metal tubes were carried out by Stronge and Shim (1987).
52 Reid and Peng (1997) evaluated the enhancement of crushing strength of
53 wood samples under high velocity impact with a rate-independent simple
54 shock wave model. Since the cell sizes within wood are very small, the mate-
55 rial behaviour was homogenized by assuming a rigid perfectly plastic locking
56 (RPPL) material model for wood to determine the strength enhancement
57 due to shock wave propagation. Two important parameters, namely plateau
58 stress σ_{pl} and densification or lock-up strain ϵ_D , were used to characterize
59 the constitutive behaviour of the material. By assuming a certain level of
60 strength enhancement, critical impact velocities, at which shock propaga-
61 tion effects become important and the response becomes dependent upon
62 the impact velocity, were defined (e.g. Deshpande and Fleck (2000) adopted
63 a criterion of a 20 % elevation in strength for foams). Since these parameters
64 cannot be easily identified from stress-strain data for shock enhancement pre-

65 diction, a simple power law densification model was proposed to replace the
66 RPPL model (Pattofatto et al., 2007). Tan et al. (2005) used the efficiency
67 of cellular material in absorbing energy to compute σ_{pl} and ϵ_D .

68 In addition to shock wave propagation, strength increase in cellular solids
69 under dynamic loading conditions may be attributed to micro-inertial effects
70 (Deshpande and Fleck, 2000). Bending dominated (Type I) structures with
71 flat topped quasi-static stress-strain curve are slightly affected by micro-
72 inertial effects under dynamic conditions. Metallic foams generally behave
73 as Type I structures. Deshpande and Fleck (2000) verified rate insensitive
74 behaviour of two particular types of aluminium foam under high strain rates
75 by split Hopkinson pressure bar (HPB) and direct impact tests. Elnasri et al.
76 (2007) reported the existence of shock front in cellular structures under high
77 strain rate impact loading at low critical velocities by comparing the results
78 of direct Hopkinson bar and Hopkinson bar-Taylor tests. On the other hand,
79 stretch dominated (Type II) structures show sharp softening behaviour after
80 peak load. In contrast to bending dominated structures, stretch dominated
81 structures are significantly influenced by micro-inertial effects (Calladine and
82 English, 1984). Strength enhancement of square tubes in successive folding
83 mechanisms under impact loading was attributed to the higher strain in
84 edge-areas of the tube because of inertia (Zhao and Abdennadher, 2004).

85 Recent technological advances, i.e. additive manufacturing techniques,
86 allows us to create periodic metallic **lattice** structures with an efficient ge-
87 ometry which, **in principle, can minimise the material usage whilst opti-**
88 **misising the desired mechanical properties of the material. One potentially**
89 **promising application is the use of bespoke metallic lattices as sacrificially**

90 energy-absorbing layers in protection systems against blast and impact load-
91 ing. However, as a sub-class of cellular solids, lattice structures are quite
92 new materials for blast, ballistic and impact protection applications, and ex-
93 perimental and numerical studies on the dynamic response of such materials
94 are very limited. McKown et al. (2008) experimentally evaluated the quasi-
95 static response and dynamic progressive collapse behaviour of steel lattice
96 structures under impulsive loads and their associated failure modes, without
97 focusing on the effect of lattice structures on the temporal spreading of im-
98 pulse. Hasan et al. (2010) compared the drop weight impact performance
99 of sandwich panels with aluminium honeycomb and titanium alloy lattice
100 structures in terms of specific impact energy versus dent depth. Smith et al.
101 (2010) conducted an extensive study to characterise the response of steel lat-
102 tice structure samples to blast. They presented quantitative deformations of
103 qualitative damage as a function of blast impulse. However, to date, no ex-
104 perimental data on the dynamic load-displacement characteristics of cellular
105 metallic lattice materials has been presented in the literature.

106 In the current work, the energy absorption behaviour and failure modes
107 of lattice structures under quasi-static and dynamic loading conditions are
108 studied. In order to maximise the freedom in creation of potentially complex
109 lattice structures, additive layer manufacturing techniques, where a struc-
110 ture is built up progressively by the selective melting of specific regions in
111 successive layers of metal powder are used. Titanium alloy (Ti6Al4V) is
112 preferred, due to its high specific properties, and availability of data to al-
113 low modelling of mechanical response (U.S. Department of Transportation
114 Federal Aviation Administration DOT/FAA/AR-00/25, 2000), (Shao et al.,

115 2010). Lattice structures with different unit cell geometries are fabricated
116 using the Electron Beam Melting (EBM) technique. A series of experimental
117 tests performed on the lattice structure samples. First, the load-deflection
118 response and associated failure modes of such structures were captured by
119 quasi-static compression tests. Following the compression tests, the impact
120 response of lattice structures under high deformation rates was evaluated by
121 HPB tests to assess the ability of such materials to spread impact loading in
122 time and to attenuate peak response.

123 The outline of this paper is as follows. Section 2 summarizes the manu-
124 facturing process of lattice structures. In Section 3, quasi-static stress-strain
125 curves and associated failure modes of lattice structure samples are assessed.
126 The experimental impact response of lattice structure samples is discussed in
127 Section 4. Finally, in Section 5 some implications of the work are discussed.

128 A numerical modelling study of the quasi-static and dynamic collapse of
129 these lattice materials has been conducted in parallel and the results of this
130 will be published in a forthcoming paper.

131 2. Manufacturing process

132 A range of Additive Manufacturing techniques have been developed, and
133 equipment is commercially available. The names used vary with equipment
134 supplier, and there are fundamental differences between some of the tech-
135 niques; for example, Selective Laser Melting (SLM) uses a laser as the di-
136 rectable heat source, while Electron Beam Melting (EBM) uses a high-energy
137 beam of electrons. In this case EBM has been selected for use as the beam
138 can be split and moved around the build area more rapidly, meaning sam-

139 ples can be produced in less time. The EBM technique can be used for the
140 production of metallic materials of arbitrary shape. This technique does not
141 require additional treatments (thermal, machining etc) to obtain the final
142 shape or mechanical properties (Al-Bermani et al., 2010).

143 In this work, lattice samples are manufactured from spherical grade 5
144 Ti6Al4V powder with 45-110 μm particle size using an ARCAM S12 EBM
145 machine. Three unit cell geometries of increasing complexity, shown in Figure
146 1, are chosen for the lattice samples. For the cubic lattice geometry (Figure
147 1-(a)), struts run along the edges of the unit cell. The other geometries are
148 diamond (Figure 1-(b)), where the struts are arranged in directions similar
149 to the interatomic bonds in the atomic lattice of diamond, and re-entrant
150 cube (Figure 1-(c)), where all edges and diagonal struts across the faces bent
151 towards the centre. The repeating unit cell is kept as a 5 mm side length
152 cube for all three lattice structures. Square strut cross-sections were chosen
153 for the cubic and diamond lattices with diagonal lengths of 1.3 and 1.0 mm,
154 respectively, whereas the strut diameter of the re-entrant cube is 0.48 mm.
155 Figure 2 shows single layer cubic, diamond and re-entrant cube samples prior
156 to testing.

157 Figure 3 presents Scanning Electron Microscopy (SEM) images of an in-
158 dividual unit-cell strut of a diamond lattice specimen. The layered nature of
159 a strut along the length and its roughly square cross-section can be observed
160 in Figures 3-(a) and (b).

161 The relative density $\bar{\rho}$, which is the ratio of the measured lattice density
162 ρ to the density of the titanium alloy ρ_s , is given by:

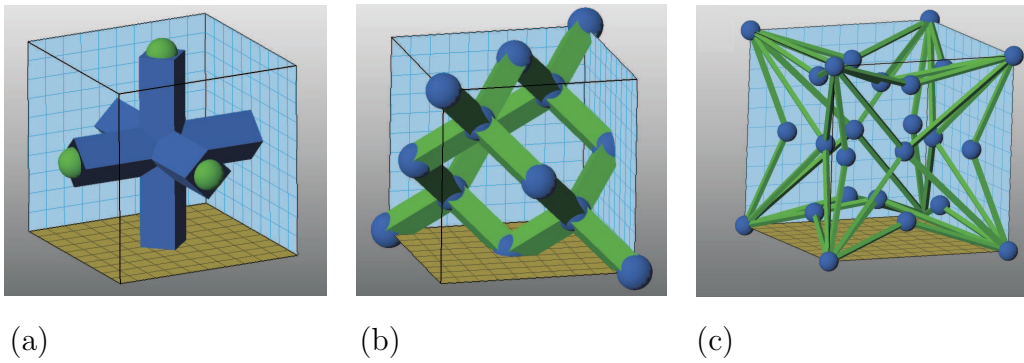


Figure 1: Representative unit cells of (a) cubic, (b) diamond and (c) re-entrant cube lattice structures. When built, the unit cell side length in the lattices is 5 mm.

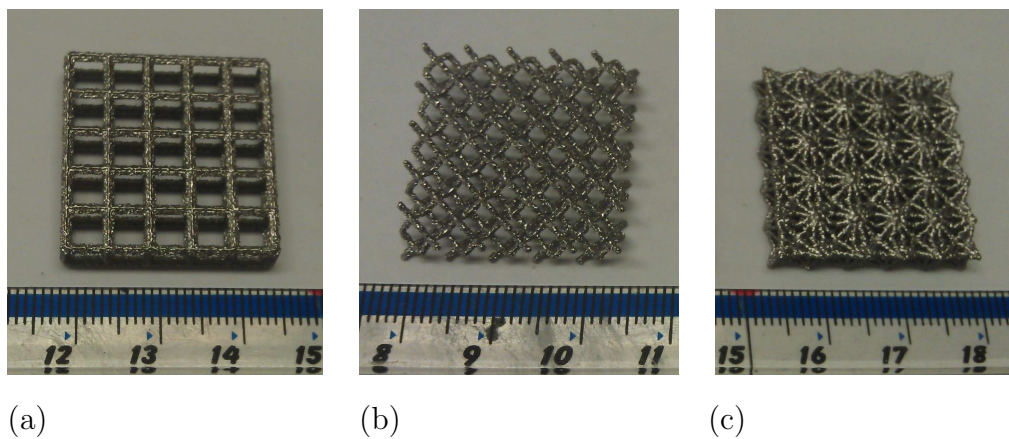


Figure 2: View of single layer (a) cubic, (b) diamond and (c) re-entrant cube lattice structures prior to testing

$$\bar{\rho} = \frac{\rho}{\rho_s} \quad (1)$$

163 Relative densities of the ideal structures for cubic, diamond and re-entrant

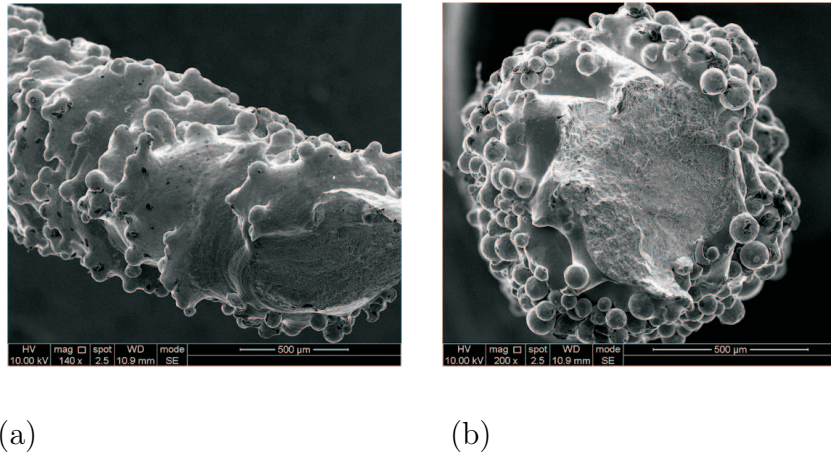


Figure 3: SEM photographs of (a) an individual unit-cell strut along the strut length, (b) its square cross-section

164 cube unit cells are 0.139, 0.137 and 0.166, respectively.

165 3. Quasi-static response of **lattice structures**

166 Single-layer and five-layer samples of **lattice structures** were tested under
 167 conventional quasi-static conditions using a Houndsfield TX0038 universal
 168 test rig **with compression platens which were verified before testing to have**
 169 **a misalignment below 0.5°.**

170 3.1. *Quasi-static response of single layer **lattice structures***

171 Single layer square samples of **lattice structures** with edge length of 25
 172 mm and a height of 5 mm were compressed at a crosshead speed of 0.2
 173 mm/min. For each sample type, three quasi-static tests were carried out. The
 174 **engineering stress-strain** curves of cubic, diamond and re-entrant cube **lattice**

175 **structure** samples following the quasi-static compression tests are shown in
 176 Figure 4. Initial offset, due to some of the struts coming into contact with the
 177 test platens before others, as either the samples are not exactly rectilinear, or
 178 they are not exactly aligned, is eliminated from the experimental **stress-strain**
 179 curves.

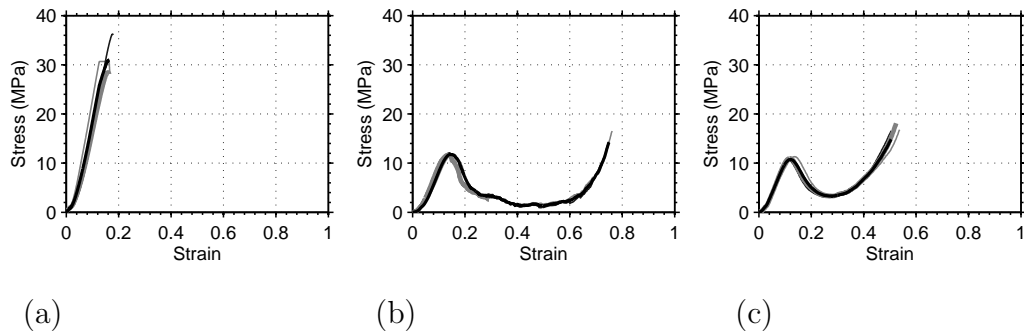


Figure 4: The **engineering stress-strain** curves of single-layer (a) cubic, (b) diamond and (c) re-entrant cube samples obtained following compression test 1 (thin grey line), test 2 (thin black line) and test 3 (thick grey line), and average of these curve (thick black line).

180 The quasi-static **stress-strain** response of the cubic lattice structure, shown
 181 in Figure 4a, is effectively elastic before brittle failure; this is to be expected,
 182 from the unit cell geometry, which does not encourage plastic deformation.
 183 Instead, the failure mechanism is similar to that shown for a brittle foam by
 184 Ashby (2006), with shear fracture occurring at the joints between the lon-
 185 gitudinal and lateral struts. The diamond Figure 4b and re-entrant Figure
 186 4c unit cell **stress-strain** relationships show a **relatively constant** initial stiff-
 187 ness, followed by post-peak softening, and later stiffness increase due to final
 188 densification of the material. This is typical of Type II (stretch dominated)

189 response which appears to be the predominant deformation characteristic of
190 the diamond lattice. However, in the case of the re-entrant **lattice structure**
191 unit cell, pronounced post-peak softening is observed despite the deformation
192 involving significant flexural deformation, because the re-entrant geometry
193 leads to a loss in stiffness once rotation of the nodes commences.

194 *3.2. Quasi-static response of multi-layer **lattice structures***

195 Next, five-layer square samples (**each consisting of 5 by 5 unit cells**) of
196 diamond and re-entrant cube **lattice structures** with an edge length of 25 mm
197 and a height of 25 mm were manufactured to be tested at a cross-head speed
198 of 0.2 mm/min and 0.1 mm/min, respectively. The **stress-strain** curves of
199 **lattice structure** samples following quasi-static compression tests are shown
200 in Figure 5. The curves show distinct peaks at low platen displacements for
201 both diamond and re-entrant cube samples. At higher platen displacements,
202 peaks become less clear. Each of these peaks observed on the **stress-strain**
203 curve of the re-entrant cube **lattice structures** corresponds to the failure of
204 one particular layer at a time; however, **this failure of layers** occurs in an
205 arbitrary order. Small deviations are observed between **stress-strain** curves
206 carried out on different samples. Peak responses of single and multi-layer re-
207 entrant cube samples are very close. Therefore, re-entrant **lattice structures**
208 exhibit more predictable behaviour. Compared to re-entrant cube samples,
209 the deformation of diamond **lattice structures** is less constrained by the par-
210 ticular configuration of struts, and therefore their **stress-strain** curves show
211 a more random behaviour. Failure in diamond **lattice structures** develops
212 and propagates in the weakest parts of the sample. Load is resisted by a

213 longer diagonal path in five-layer diamond lattices, see also Figure 6 below.
 214 Therefore, the peak response of the five-layer diamond lattices is higher than
 215 that of single-layer samples.

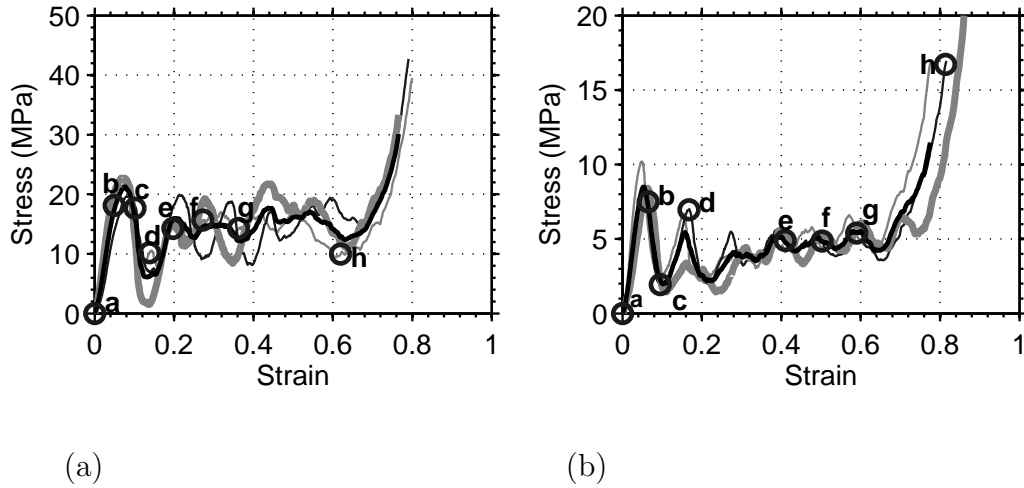


Figure 5: The **stress-strain** curves of five-layer (a) diamond and (b) re-entrant cube samples obtained following the compression test 1 (thin grey line), test 2 (thin black line) and test 3 (thick grey line), and average of these curves (thick black line).

216 The **stress-strain** responses of the diamond **lattice structures** shown in
 217 Figure 5-(a) is correlated with the images taken during the compression test
 218 in Figure 6. Each of these images corresponds to a different point on the force-
 219 displacement curve of compression test 1. Figure 6-(a) shows the undeformed
 220 diamond sample. The onset of the failure of the struts at the first layer is
 221 shown in Figure 6-(b). Figure 6-(c) illustrates failure of struts touching the
 222 bottom platen. Figure 6-(d) corresponds to the onset of the development
 223 of localised failure of struts along a diagonal on the lower right part of the

224 sample. As the sample is more compressed, shear failure becomes clearer
225 (Figures 6-(e) and (g)). Figure 6-(h) corresponds to the onset of densification.

226 The images taken during the compression test of a re-entrant cube sample
227 are shown in Figure 7. Again, each of the images corresponds to a different
228 point on the force-displacement curve of compression test 2 shown in Figure 5-
229 (b). The undeformed sample is shown in Figure 7-(a). Figure 7-(b) illustrates
230 the onset of failure of the struts at the first layer. Load on the second layer
231 starts increasing after point (c) as shown in Figure 5-(b). The onset of the
232 failure of the struts at the second layer of the re-entrant cube sample coincides
233 with point (d) as represented on Figure 7-(d). Figures 7-(e) and (f) show
234 failure of the third layer. The onset of failure of the final layer of the sample
235 is given in Figure 7-(g). Figure 7-(h) shows the state of the sample during
236 densification. Comparing Figures 6 and 7, it is clear that failure of the re-
237 entrant lattice occurs in a much more systematic, layer-by-layer fashion than
238 failure of the diamond lattice.

239 Elastic modulus E , yield stress σ_y and absorbed energy (up to densifica-
240 tion) of the single and multi-layer samples obtained following the quasi-static
241 tests are summarized in Table 1. This table also gives the actual density of
242 the lattices, which matches the density of the designed structures very well.
243 It must nevertheless be noted that processing defects can lead to departures
244 in some additively manufactured porous materials (Hernandez-Nava et al.,
245 2015), and that test orientation relative to build direction (which was con-
246 stant here) can also have an effect (Amendola et al., 2015). Strain limits up
247 to 30 % and 60 % are chosen to compute absorbed energy for the single-layer
248 re-entrant cube lattices and other sample types, respectively. These values

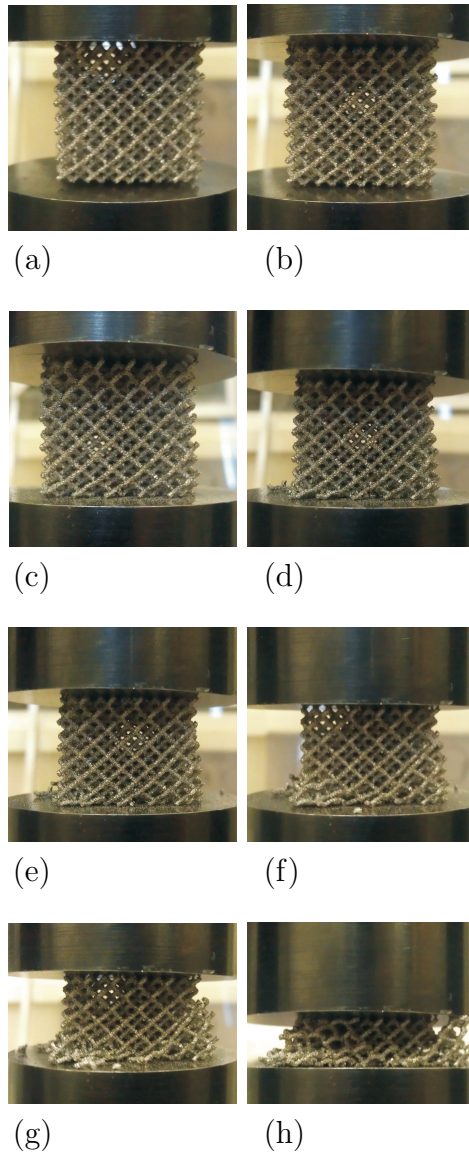


Figure 6: The images taken during the quasi-static compression test of the five-layer diamond sample correspond to the points of **stress-strain** curve observed during compression test 1 as shown in figure 5-(a).

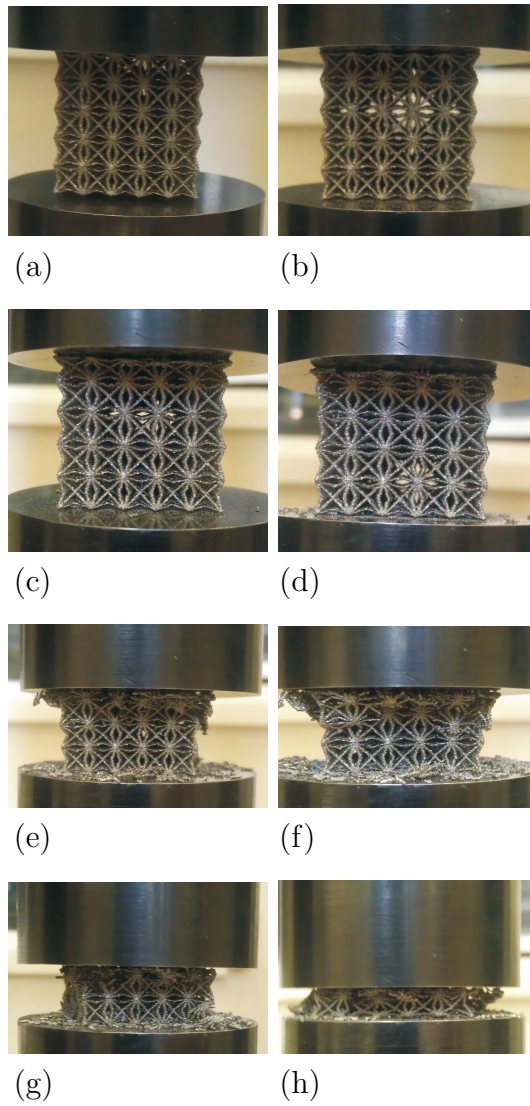


Figure 7: The images taken during the quasi-static compression test of the five-layer re-entrant cube sample correspond to the points of **stress-strain** curve observed during compression test 2 as shown in figure 5-(b).

249 are chosen such that **the unbounded** energy absorption associated with the
250 densification stage is ignored. The multi-layer samples offer a significantly
251 higher elastic modulus than the single-layer samples. A tentative explanation
252 for this unexpected phenomenon could be the difference in stiffness between
253 internal layers and boundary layers. Internal layers can be expected to have
254 full stiffness, whereas boundary layers are weakened by imperfect contact
255 conditions and buckling of struts in the contact zone, **especially for the di-**
256 **amond samples**. In multi-layer samples, the stiffness reducing effects of the
257 boundary layers are relatively less important, thus the overall stiffness is
258 larger than for a single-layer sample. Similarly, the yield stress of diamond
259 lattices increases significantly with the number of layers, while re-entrant
260 cube lattices do not exhibit such behaviour. Diamond samples can absorb
261 more energy than re-entrant cube samples under quasi-static conditions, al-
262 though the relative density of the re-entrant cube samples is higher than
263 that of diamond lattices. Both explanations require further study, possibly
264 by studying samples with different number of layers.

265 **4. Impact characteristics of lattice structures**

266 The impact response of **lattice structures** under high deformation rates
267 was evaluated by HPB tests. The motivation behind all the tests is to in-
268 vestigate how the presence of a **lattice structure** specimen influences the
269 load-time history generated by the impact of the projectiles described be-
270 low. Tests were first carried out in the absence of the **lattice** specimen at
271 the impact face of the HPB to establish baselines for the loading generated
272 by the bare impactor. Impact tests were then repeated in the presence of

Lattice structure	N. of layers	$\bar{\rho}$	E	σ_y	Absorbed energy
		[-]	[MPa]	[MPa]	[MJ/m ³]
Diamond	1	0.137	132.2	11.8	2.32
Diamond	5	0.137	399.5	21.3	8.39
Re-entrant cube	1	0.166	126.6	10.8	1.65
Re-entrant cube	5	0.166	216.4	8.51	2.51

Table 1: Averaged material properties obtained following the quasi-static tests.

273 single layer **lattice structures** of the same diameter as the impactor in order
274 to establish the ability of the **lattice structures** to extend the duration of the
275 impact load and to reduce peak response. Finally, five-layer samples are used
276 to examine the temporal spreading of load.

277 4.1. Rationale for choice of impact loading

278 Suitable magnitudes and rates of loading for the impact tests were iden-
279 tified considering a 10 kg TNT detonation at distances of 1.75 m and 2.5 m.
280 This would produce specific reflected impulses of 9000 and 3000 kPa · msec,
281 respectively (Hyde (1991)). If these impulses were imparted to a steel plate
282 target of thickness 5 mm, the resulting kinetic energies areal density in the
283 plate would be in the range 100-1100 kJ/m². The same order of magnitude
284 kinetic energy and impulse can be imparted to the target **lattice** specimens
285 using a steel bar projectile **or a Nylon 66 impactor in order to differentiate**
286 **between low and high velocity impact. In this study, we have used** a 25
287 mm diameter and 250 mm long EN24T steel bar with mass of 963 g fired

288 at velocities in the range 5-21 m/s for *low-velocity* impact tests, as well as a
289 27 mm diameter and 31 mm long Nylon 66 projectiles with mass of 19.3 g
290 fired at velocities in the range 80-250 m/s for *high-velocity* impact tests. The
291 specific impulse and kinetic energy density delivered to the target specimen
292 was thus in the range 10000-40000 kPa · msec and 25-400 kJ/m² for the steel
293 bar impactor and 3000-9000 kPa · msec and 115-1150 kJ/m² for the Nylon
294 66 impactor. All impacts were conducted by firing projectiles from a single
295 stage gas gun.

296 4.2. The HPB Test set-up

297 **Impact response of lattice structures under high deformation rates was**
298 **evaluated using HPB tests.** The Hopkinson pressure bars used in this work
299 were all custom made, from EN24(T) cylindrical bar. All bars are 3.4 m
300 long and have a 0.025 m diameter. Optical records of all tests were recorded
301 by a Phantom v 4.2 high speed digital video camera **with 256 x 112 pixels,**
302 operating typically at 40-50 μ s per frame. The velocity of the impactor during
303 the impact event and the displacement vs time record of the compressed
304 specimens can therefore be established using the high speed video footage.

305 A single strain gauge station positioned 250 mm from the impact face of
306 each bar, comprising 4 orthogonally placed high gauge factor Kyowa KSP-
307 2-120-E4 semi-conductor strain gauges, linked in such a way as to eliminate
308 bending effects in the output strain. The output of the strain gauge stations
309 checked by the application of a known impulse which was compared to the
310 integrated load-time data at the strain gauge station, by means of an impact
311 test with a known impact mass and impact/rebound velocities of the im-

312 pactor recorded using a high speed digital video camera. Density and elastic
313 modulus of the bars were determined using elastic wave propagation tests,
314 and found to be 7850 kg/m^3 and 210.2 GPa , respectively.

315 It is possible in principle to perform frequency domain correction of the
316 signals recorded at a strain gauge station on the bar to account for dispersion
317 effects as the pulse propagates along the bar, and hence to reconstruct the
318 load-time history at the impact face of the bar. However, it is known that
319 there is an upper limit to the frequency of Fourier components for which
320 standard dispersion correction methods are applicable. Tyas and Watson
321 (2001) note that this upper limit is $1250/a \text{ kHz}$, where a is the radius of
322 the bar in mm. In the experimental signals recorded in this study, there was
323 typically significant energy present at frequencies well in excess of this value,
324 and therefore dispersion correction was not applied. Instead, the dispersed
325 signals recorded at the strain gauge location in the experimental work are
326 presented.

327 Two testing configurations were considered for the HPB tests: In the
328 first case, the specimen was placed on the impact face of the HPB and the
329 projectile was fired onto the specimen. Therefore, the strain gauge station
330 recorded the strain on the distal face of the lattice structure specimen (Figure
331 8-(a)). This test configuration is called a distal-face test. In the other case,
332 the test specimens were fixed to the impact face of the projectile (Figure 8-
333 (b)). In these tests, the stress recorded on the face of the HPB was from the
334 impact face of the specimen which experiences a sudden change of velocity
335 on impact. This test configuration is called an impact-face test. The purpose
336 of these tests and their comparison is to determine whether the stress in the

337 specimen was effectively uniform throughout the specimen length, or whether
 338 there were significant variations between the distal and impact faces. The
 339 difference between the impact and distal face loads shows the effectiveness of
 340 the **lattice structures** were they to be used as a cushioning layer to protect
 341 rear structure. The specimens were laterally unconfined in all cases. No
 342 correction was made for dispersion in propagation of the pulse from the
 343 impact face of the HPB to the strain gauge station.

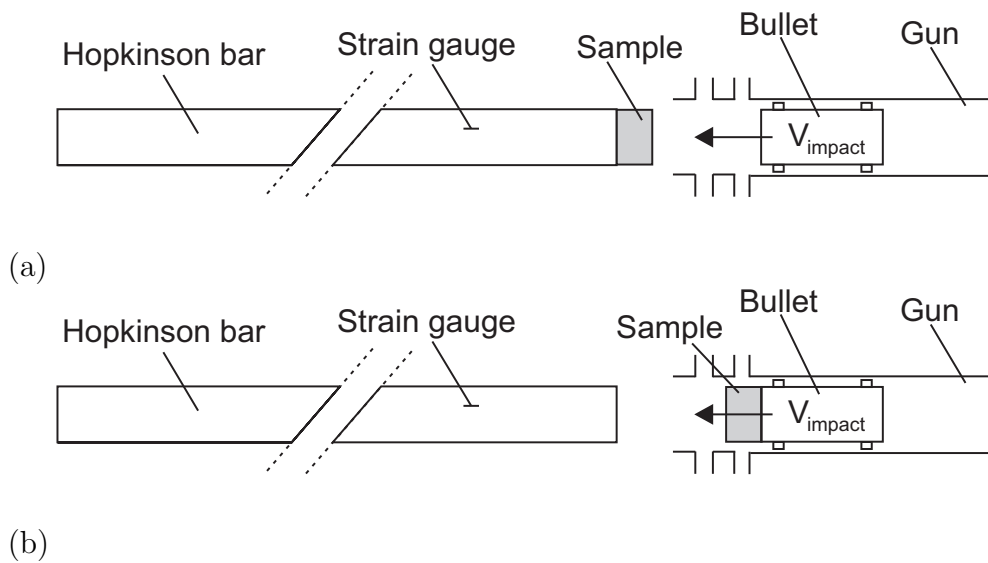


Figure 8: Two testing configurations for the HPB tests: (a) the distal face test and (b) impact face test.

344 4.3. The HPB tests in the absence of **lattice structure** specimens

345 These tests were conducted to establish the baseline impact stress-time
 346 histories when the impactors struck the HBP with no **lattice structure** spec-
 347 imen present. Tests were carried out using the steel impactor at velocities

348 of 7.3-8.9 m/s and the Nylon 66 projectiles at velocities of 175-191 m/s.
349 Examples of typical stress-time histories are shown in Figure 9.

350 The key points to note here are the high magnitude of the peak stresses,
351 which are 135 MPa for the steel impactor and 240 MPa for the Nylon 66
352 impactor, and the very short durations of the main impact pulse of 50-100
353 μ s. For the case of the steel impactor, the main impact is followed by a small
354 amplitude stress pulse. This verifies that the impactor hits the HPB obliquely
355 with a very small angle due to experimental errors in alignment. For the case
356 of the Nylon 66 projectile, two peaks in the impact stress time history (Figure
357 9-(b)) show that the impactor undergoes inelastic deformations. It should
358 be noted that these two peaks were cropped during the measurement.

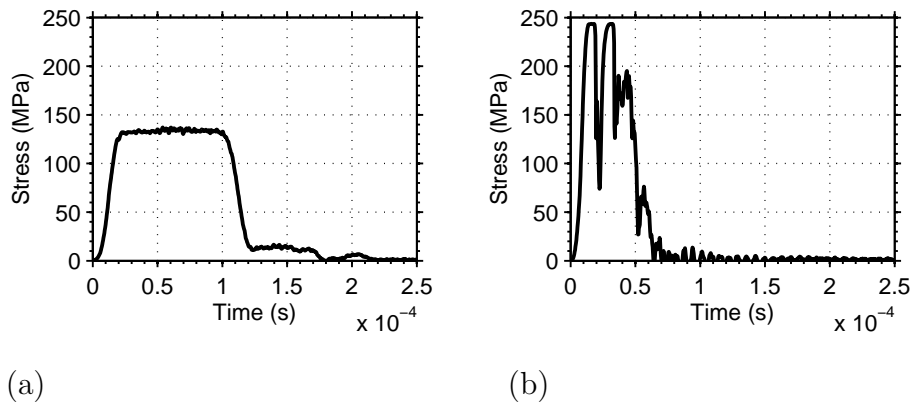


Figure 9: Impact stress time histories in the absence of **lattice structure** specimen generated by the (a) steel and (b) Nylon 66 impactors fired at velocities of 7.6 and 178 m/s, respectively.

359 4.4. The HPB tests on single layer specimens

360 This group of tests were conducted on 5 mm thick cylindrical single layer
361 re-entrant cube samples, with diameter 25 mm. Examples of stress and cu-
362 mulative impulse time histories developed on the distal and impact faces
363 induced by the steel impactor and the Nylon 66 projectile are shown in Fig-
364 ures 10 and 11, respectively. Cumulative impulse time histories are obtained
365 by calculating the area under the impact force versus time plot. Impulse
366 starts to increase when the impactor comes into contact with the HPB and
367 remains unchanged following the rebound of the impactor.

368 Taking into account the difference in impact velocity from test to test,
369 the impact and distal face stress-time histories from both the low-velocity
370 and high-velocity impact tests are quite similar (Figures 10 and 11).

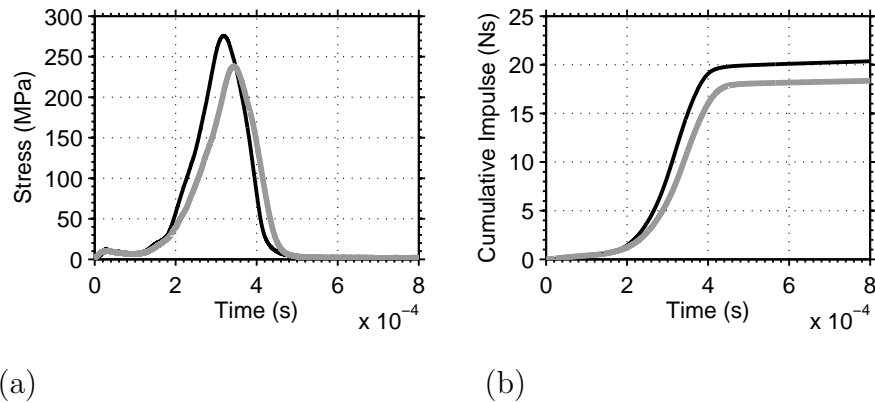


Figure 10: Distal face (black line) and impact face (grey line) (a) stress and (b) cumulative impulse time histories of the single layer re-entrant cube lattice structure specimen induced by the steel impactor fired at velocities of 18.8 and 17.7 m/s, respectively.

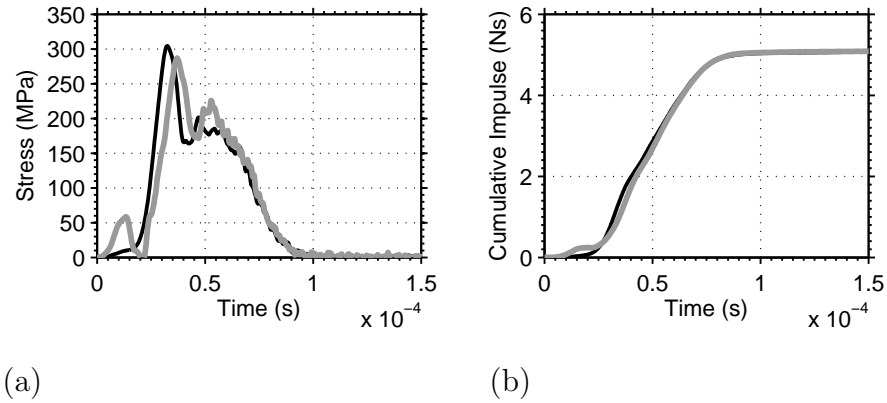


Figure 11: Distal face (black line) and impact face (grey line) (a) stress and (b) cumulative impulse time histories of the single layer re-entrant cube **lattice structure** specimen induced by the Nylon 66 impactor fired at velocities of 200 and 187 m/s, respectively.

371 *4.5. The HPB tests on five-layer specimens*

372 Cylindrical samples of nominal dimensions 25 mm long by 25 mm diame-
 373 ter were used to test the ability of the **lattice structures** to laterally spread
 374 impact load. First, distal face impact stress-time histories of five-layer cubic,
 375 diamond and re-entrant cube samples are compared in order to find out the
 376 most effective lattice type for impact protection. Examples of typical stress
 377 and cumulative impulse time histories for lower and higher end velocities of
 378 the two impactors are shown in Figures 12-15. In all cases, the presence of
 379 the lattice specimen significantly attenuates the peak impact stress transmit-
 380 ted to the bar, and significantly extends the duration of the load pulse. In
 381 the case of the low velocity steel impactor tests (7-9 m/s), the peak stress is
 382 reduced to around 20 % of that experienced in the bare impact tests whilst
 383 the duration of the load pulse is increased by around 2000 %.

384 In the higher velocity Nylon 66 projectile tests (170-190 m/s), the peak
385 stress is attenuated to $\sim 35\%$ compared to the bare impact test by cubic
386 and diamond micro-lattice samples, and to $\sim 50\%$ by the re-entrant cube
387 specimen. The duration of the load was extended by $\sim 350\%$ by the cubic
388 and diamond specimens and by $\sim 250\%$ by the re-entrant cube specimens.
389 The cubic and diamond lattices appear to be marginally more efficient in
390 temporally spreading the load than the re-entrant cube lattice. This differ-
391 ence would be magnified on a weight-specific basis, as the re-entrant cube
392 specimens have higher density.

393 In the low kinetic energy tests (i.e. the low velocity 7-9 m/s- steel im-
394 pactor tests), the specimens experienced plastic work or damage along only
395 part of their lengths and consequently the specimen did not begin to den-
396 sify and stiffen, a process well known from quasi-static testing of foams and
397 lattices generally, which occurs as the lattice structure collapses and the spec-
398 imen density begins to approach that of the parent metal (Figure 12). In
399 more energetic impacts (the high velocity 16-20 m/s- steel impactor tests) the
400 cellular structure collapsed along the entire length of the specimen and densi-
401 fication begins to occur as the specimen loses its energy dissipation capacity
402 (Figure 13). Thus, the specimen stress-time curve comprises a reasonably
403 constant plateau load during cell collapse, followed by a much greater mag-
404 nitude stress spike towards the end of the pulse. This feature is even more
405 pronounced in the very high energy impacts of the Nylon 66 projectiles (Fig-
406 ures 14 and 15). In all cases, oscillations can be seen on the plateau load.
407 The high speed video records shows that these oscillations are associated
408 with the collapse of the individual cell layers. Similar features were seen on

409 the traces from all the specimen types.

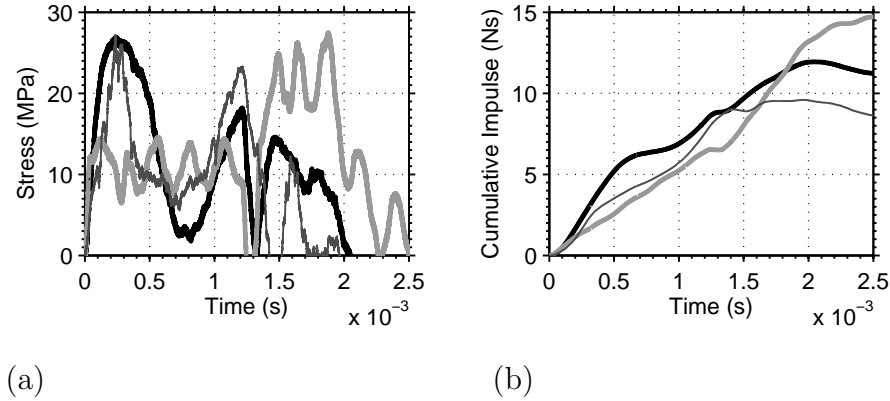


Figure 12: Experimental distal face (a) stress and (b) cumulative impulse time histories of the five-layer cubic (thin black), diamond (thick black) and re-entrant cube (thick grey) **lattice structure** specimens induced by the steel impactor fired at velocities of 7.4, 7.7 and 9.4 m/s.

410 Examples of the impact face stress compared to the distal face stress mea-
411 surements developed on the diamond and re-entrant cube samples are shown
412 in Figures 16–19. Considering the difference in impact velocity from test to
413 test, the impact and distal face stress-time histories from the low-velocity
414 steel impactor tests are quite similar (Figures 16 and 18). For both **lattice**
415 types, the plateau stress is approximately equal at the two faces, indicat-
416 ing that this is purely a function of the resistance of the lattice. There are
417 differences in the densification spike, but these may be explained primarily
418 through differences in the impact velocity.

419 At higher velocity, there is a marked difference between the distal and
420 impact face loads, unlike in single-layer samples (Figures 17 and 19). In

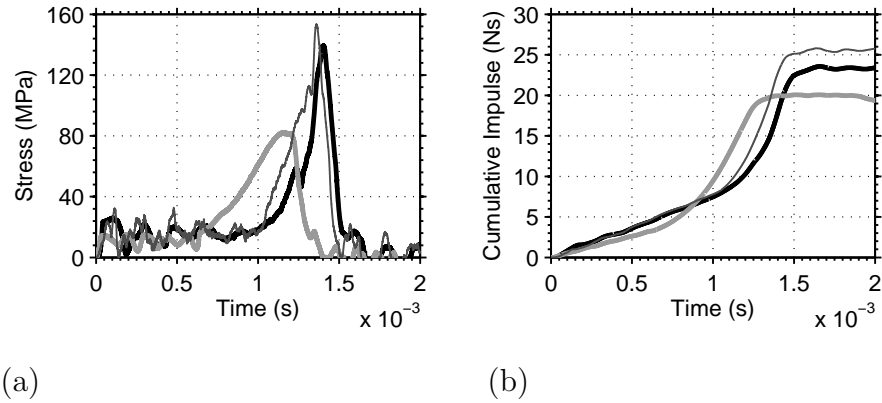


Figure 13: Experimental distal face (a) stress and (b) cumulative impulse time histories of the five-layer cubic (thin black), diamond (thick black) and re-entrant cube (thick grey) **lattice structure** specimens induced by the steel impactor fired at velocities of 20.6, 19.4 and 16.8 m/s.

421 the case of the diamond lattice, the impact face load shows a pronounced
 422 initial peak, followed by a plateau load which is some 60-75% greater than
 423 the plateau load measured on the distal face in a slightly slower impact. The
 424 final densification peak is also significantly higher in magnitude than that
 425 measured at the distal face. In the case of the re-entrant cube lattice, the
 426 difference is even more pronounced. The impact face load shows a series of
 427 five clear peaks prior to the final densification peak. These peaks are assumed
 428 to be associated with the collapse of the five individual cell layers. The distal
 429 face trace shows a smooth plateau load followed abruptly by the densification
 430 peak. Similar behaviour was observed on the single layer samples.

431 Analysis of the high speed video footage shows that, in the lower velocity
 432 (steel impactor) tests, the failure of cell layers does not occur sequentially

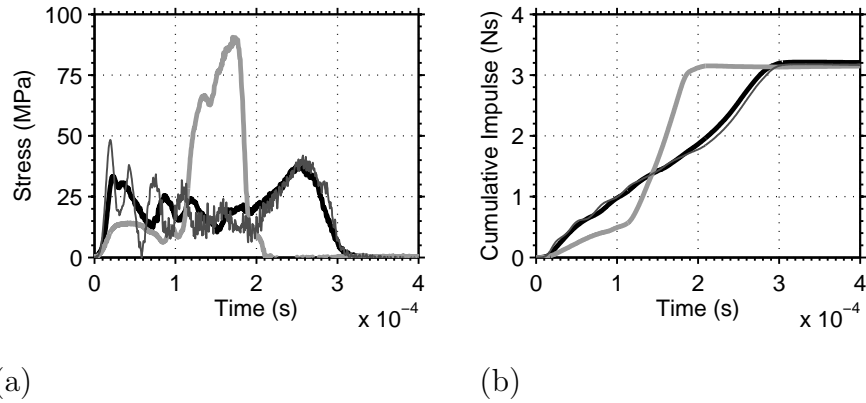


Figure 14: Experimental distal face (a) stress and (b) cumulative impulse time histories of the five-layer cubic (thin black), diamond (thick black) and re-entrant cube (thick grey) lattice structure specimens induced by the Nylon 66 impactor fired at velocities of 130, 140 and 134 m/s.

433 from one end to the other. Instead, the order of cell layer collapse appears
 434 random similar to the quasi-static tests of Section 3. Figure 20 shows a
 435 example of this non-sequential collapse in the re-entrant cube specimen taken
 436 during the distal face HPB test where the steel impactor was fired at velocity
 437 of 16.8 m/s. Red arrows on the images show the compressing layer. As can be
 438 seen from these images, numbering the layers from left to right, the sequence
 439 of collapse of layers is one, four, three, two and five. It is likely that when
 440 the loading is applied sufficiently slowly for the entire length of the specimen
 441 to experience roughly equal load, the order of cell layer collapse is governed
 442 by the relative strength of the cell layers and small strength perturbations
 443 (caused, for example by variations in strut thickness along the length, as can
 444 be seen in Figure 3) lead to a random order of collapse. This is evidenced by

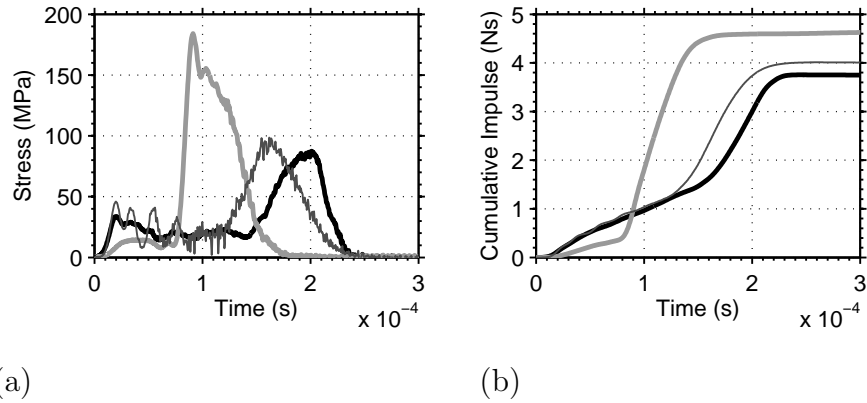


Figure 15: Experimental distal face (a) stress and (b) cumulative impulse time histories of the five-layer cubic (thin black), diamond (thick black) and re-entrant cube (thick grey) **lattice structure** specimens induced by the Nylon 66 impactor fired at velocities of 195, 178 and 190 m/s.

445 the near equivalence of the distal and impact face loads. Similar behaviour
 446 is observed generally in the quasi-static testing of foams Tan et al. (2005).

447 **Conversely**, high speed video footage of the higher velocity (Nylon 66
 448 impactor) tests shows the cell layer collapse invariably running from impact
 449 face to distal face. Figure 21 shows a example of this layer-by-layer collapse
 450 in the re-entrant cube specimen taken during the distal face HPB test where
 451 the Nylon 66 impactor was fired at velocity of 104.0 m/s. This indicates
 452 that equilibrium of load throughout the length of the specimen is not estab-
 453 lished at these higher velocities. The initial elastic deformation propagates
 454 through the specimen at high speed, resulting in the distal face approaching
 455 its plateau load. However, collapse is initially localized at the impact face,
 456 until such time as the cell layer at the impact face has densified and stiffened,

457 produced increased resistance to the impact and propagated the deformation
 458 to the next cell layer. Hence, whilst the impact face sees a series of high
 459 load spikes due to the collapse and partial densification of each cell layer, the
 460 distal face sees only the initial, pre-collapse elastic load until the collapse is
 461 driven through to the final cell layer at the distal face.

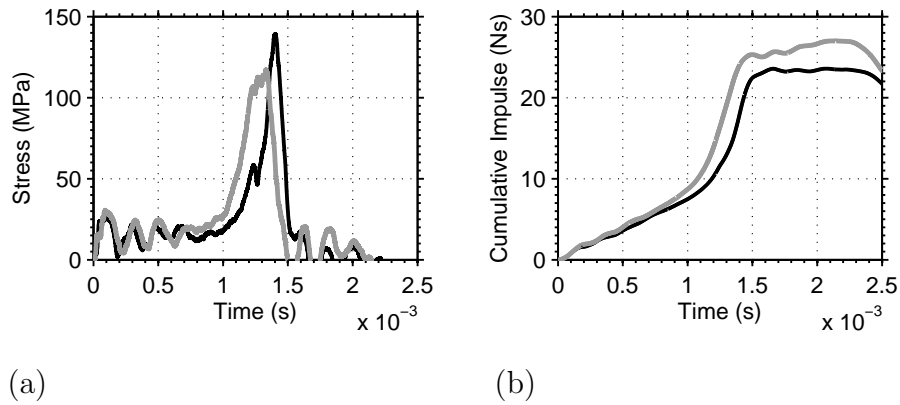


Figure 16: Experimental distal face (black line) and impact face (grey line) (a) stress and (b) cumulative impulse time histories of the five-layer diamond lattice structure specimen induced by the steel impactor fired at velocities of 19.4 m/s and 16.6 m/s, respectively.

462 5. Discussion

463 Lattice structures have very regular periodic morphologies in contrast to
 464 the metallic foams which are stochastic, highly heterogeneous and contain
 465 many significant imperfections. Lattice structures with such a well-defined
 466 micro-structure allow us to easily pick out features on the load-deformation
 467 time histories and relate them to collapse of specific layers.

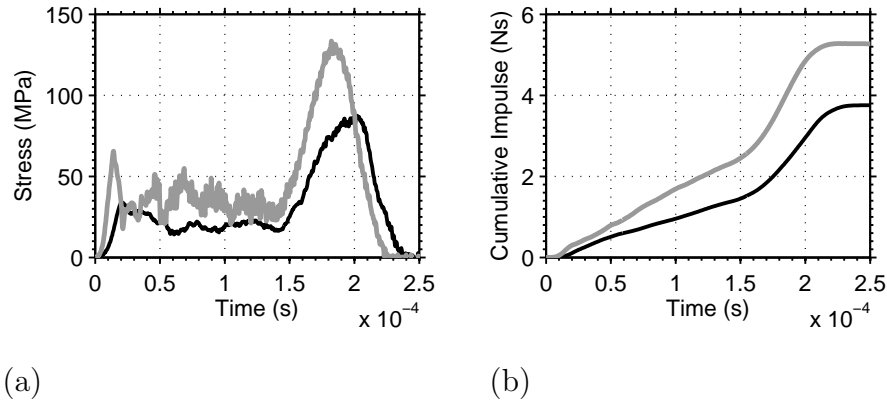


Figure 17: Experimental distal face (black line) and impact face (grey line) (a) stress and (b) cumulative impulse time histories of the five-layer diamond **lattice structure** specimen induced by the Nylon 66 impactor fired at velocities of 178 m/s and 165 m/s, respectively.

468 High rate impact experiments conducted in this work provide critical data
 469 for interpretation the dynamic response of **lattice structures**. The low veloc-
 470 ity HPB tests with the steel impactor on re-entrant cube samples showed
 471 that the failure of the cell layers occurred randomly without following any
 472 sequence from one end to the other. This indicates that slow application
 473 of loading causes equal distribution of load over the sample and the order
 474 of the collapse of the cell layer is controlled by the distribution of imper-
 475 fections in the sample. On the other hand, the high speed HPB tests with
 476 the Nylon 66 impactor on re-entrant cube samples show that the cell layer
 477 collapse invariably runs from impact face to distal face. This indicates that
 478 load equilibrium in the specimen is not established at these higher velocities.
 479 Similar observations were reported for closed-cell Cymat/Hydro foams under
 480 dynamic loading conditions by Tan et al. (2005). Examination of crushed

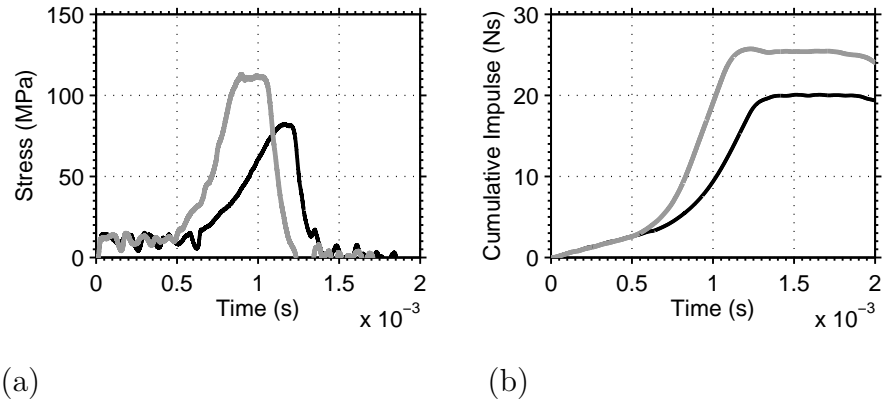


Figure 18: Experimental distal face (black line) and impact face (grey line) (a) stress and (b) cumulative impulse time histories of the five-layer re-entrant cube **lattice structure** specimen induced by the steel impactor fired at velocities of 16.8 m/s and 19.5 m/s, respectively.

481 specimens following the impact tests on Cymat/Hydro foams showed that
 482 deformation is through the cumulative multiplication of discrete crush bands
 483 for static loading and for dynamic loading at sub-critical impact velocities.
 484 At super-critical impact velocities, specimens show a shock-type deformation
 485 response, where the deformation is localised behind a travelling crushing in-
 486 terface. Samples deform by progressive cell crushing from the impact surface.
 487 **This bears analogies with propagating Lüder's bands in metal plasticity un-**
 488 **der dynamic loading.** Tan et al. (2005) attributed the enhancement of the
 489 dynamic plastic collapse stress at sub-critical velocities to micro-inertial ef-
 490 fects. In this velocity regime, the dynamic strength properties are affected
 491 by the the specimen cell-size and cell morphological defects. At super-critical
 492 impact velocities, inertia effects associated with the dynamic localisation of

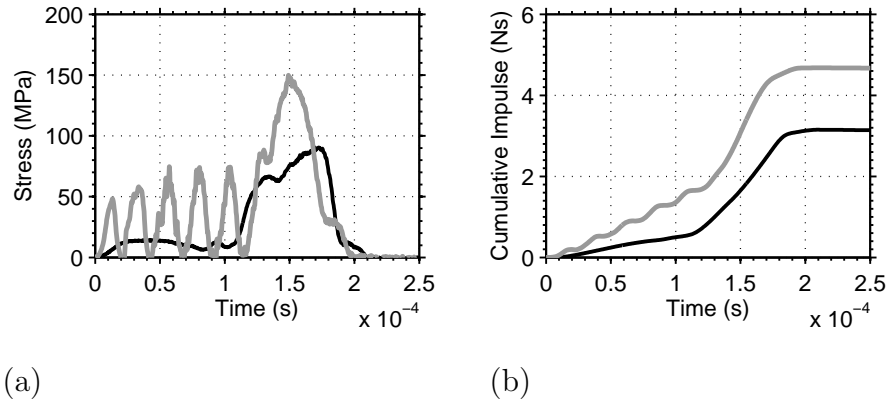


Figure 19: Experimental distal face (black line) and impact face (grey line) (a) stress and (b) cumulative impulse time histories of the five-layer re-entrant cube **lattice structure** specimen induced by the Nylon 66 impactor fired at velocities of 134 m/s and 136 m/s, respectively.

493 crushing are responsible for the enhancement of the dynamic strength prop-
 494 erties. The effects of specimen size and cell morphological defects on the
 495 measured dynamic properties are insignificant. Similarities in the dynamic
 496 response of the Cymat/Hydro foams and re-entrant cube **lattice structures**
 497 may be explained by the similar quasi-static response of such structures which
 498 shows sharp softening behaviour following to the peak load as observed in
 499 stretch dominated (Type II) structures.

500 Shock-like deformation response has also been observed in cellular struc-
 501 tures with regular periodic geometries. Reid et al. (1983) describe the lo-
 502 calisation behaviour of a 1-D arrangement of collapsing steel rings. The
 503 mechanism described in Figure 4 of that paper, one of collapse of the unit
 504 cells propagating from the impact face to the distal end of the specimen un-

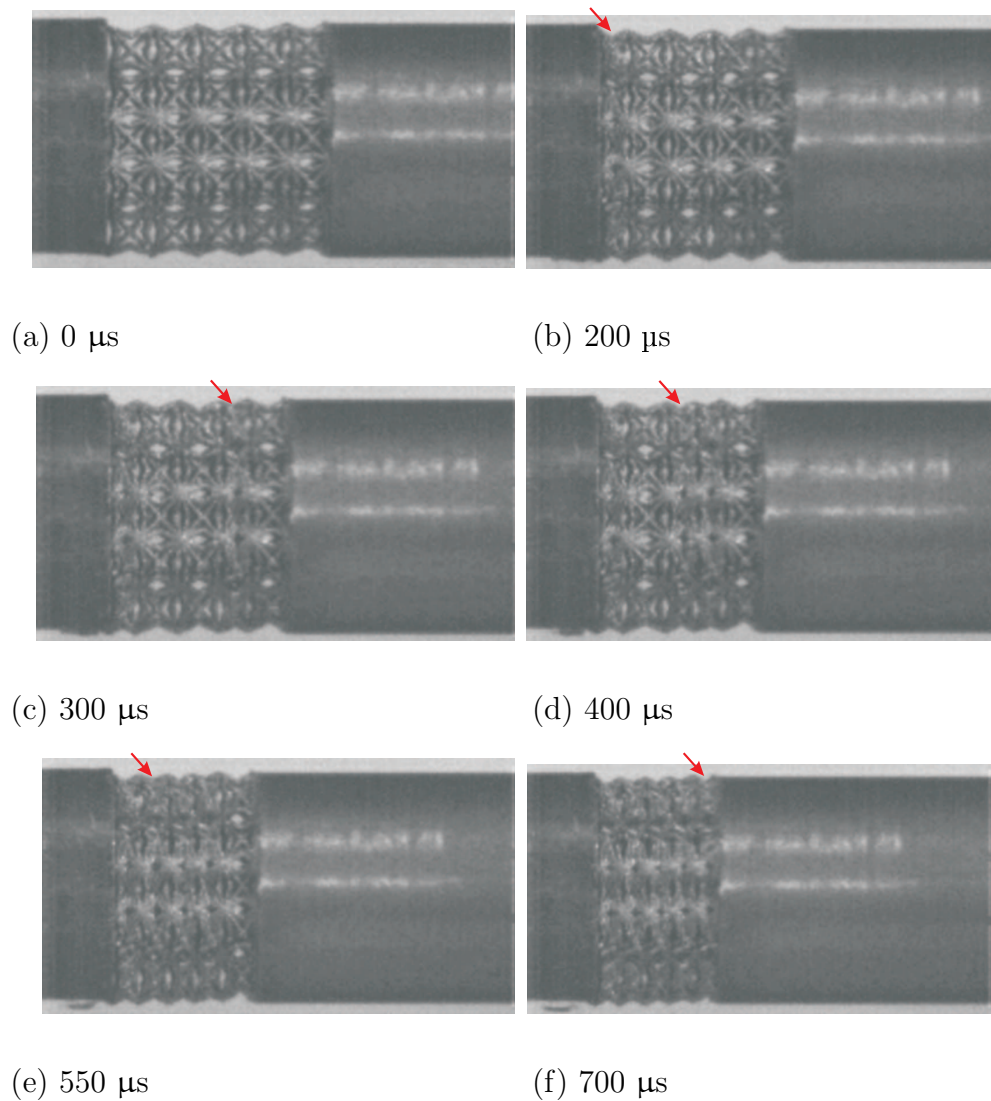


Figure 20: High speed video footage of re-entrant cube specimen showing random collapse of the cell layers. The steel impactor was fired at velocity of 16.8 m/s.

505 der high-speed impact loading is similar to that seen in this study for Type
 506 II unit cells (Figure 21). When the impact velocity is sufficiently high to

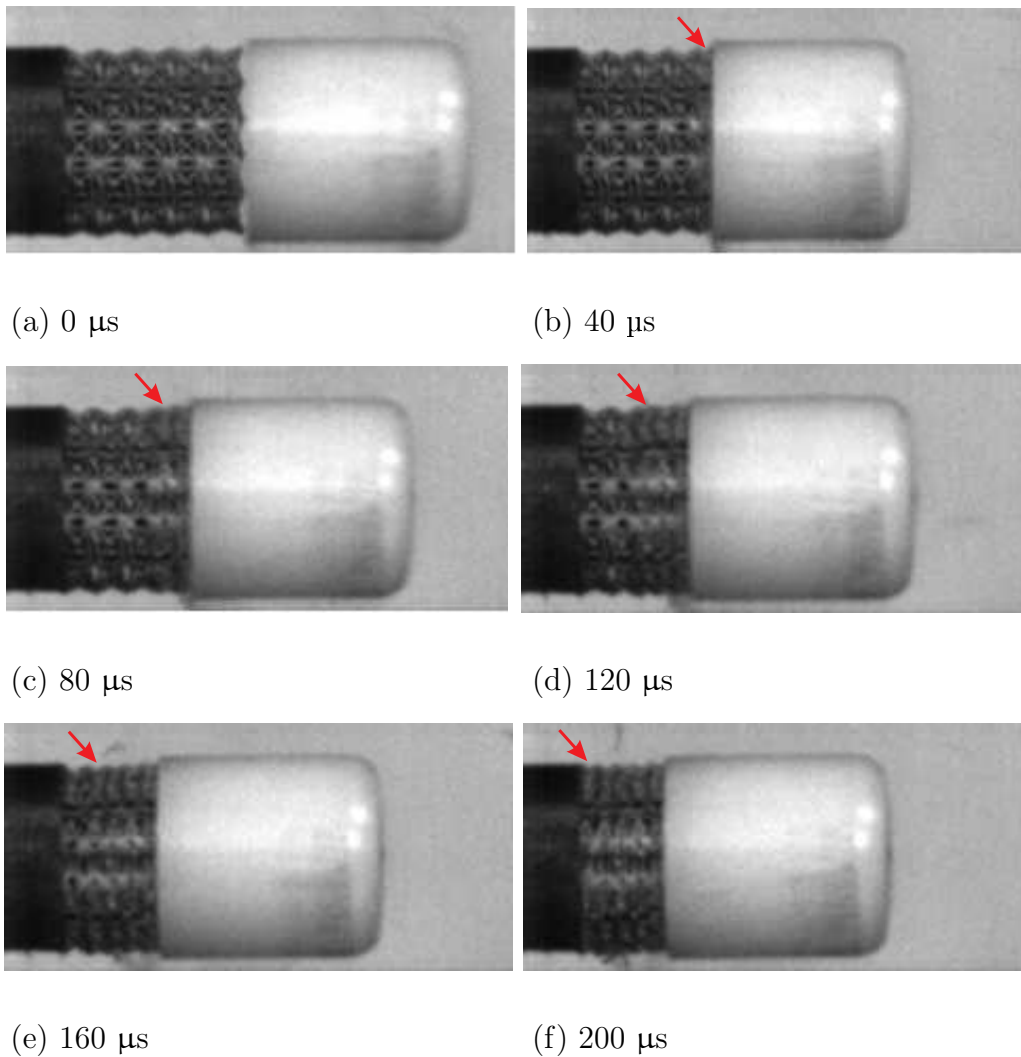


Figure 21: High speed video footage of re-entrant cube specimen showing layer-by-layer collapse of the cell layers. The Nylon 66 impactor was fired at velocity of 104.0 m/s.

507 produce this shock-like behaviour, the successive collapse of the unit cells re-
 508 sults in a train of loading pulses on the impact face of the specimen (Figures
 509 17-(a) and 19-(a)). These features would presumably occur in any cellular

510 structure collapsing under shock conditions, but are visible here due to the
511 relatively large size of the unit cells ¹. It appears that a simple RPPL-type
512 model will be unable to capture this shock behaviour.

513 6. Conclusions

514 An experimental study has been presented, detailing quasi-static and dy-
515 namic **stress-strain** behaviour of **lattice** specimens. The dynamic behaviour
516 shows clear evidence of an emergent rate-**dependence**, with significant differ-
517 ences in behaviour at low and high velocities. Specifically, effectively identical
518 impact and distal face load-time histories are seen for low velocity impacts,
519 and significantly different response at the two faces for higher velocities. This
520 is due to the "shock-like" response of the specimen at high velocity impacts.
521 Whilst this in itself is not a new phenomenon, having been previously seen
522 in experimental work on cellular polymeric and metallic foams, the relatively
523 large and geometrically consistent form of the unit cells in this study allows
524 direct measurement to be made of the loading features associated with the
525 deformation and collapse of each cell layer.

526 Whilst previous studies have assessed the relationship between the im-
527 pulse applied to a **lattice** specimen under dynamic loading, and the conse-
528 quent structural deformation, the results presented here show how the load-
529 time history is altered by the presence of a **lattice structured** cushioning layer.

¹Presumably these features would have been apparent in the work conducted by Reid et al. Reid et al. (1983), but they didn't record the load-time history on the faces of the specimens.

530 In design of sacrificial protective systems, this information is necessary to al-
531 low the designer to assess the effect of the reduction in intensity of loading on
532 a protected structure. This work also demonstrates that there is significant
533 scope for **lattice structures** to serve in a number of protective applications.

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539 **References**

- 540 Ashby M. The properties of foams and lattices. *Philosophical Transactions*
541 *of the Royal Society A* 2006;364:15–30.
- 542 Reid S, Bell W, R.A. B. Structural plastic shock model for one-dimensional
543 ring systems. *International Journal of Impact Engineering* 1983;1(2):175–
544 91.
- 545 Stronge W, Shim V. Dynamic crushing of a ductile cellular array. *Interna-*
546 *tional Journal of Mechanical Sciences* 1987;29:381–400.
- 547 Reid S, Peng C. Dynamic uniaxial crushing of wood. *International Journal*
548 *of Impact Engineering* 1997;19:531–70.
- 549 Deshpande V, Fleck N. High strain-rate compressive behaviour of aluminium
550 alloy foams. *International Journal of Impact Engineering* 2000;24:277–98.

- 551 Elnasri I, Pattofatto S, Zhao H, Tsitsiris H, Hild F, Girard Y. Shock en-
552 hancement of cellular structures under impact loading: Part I experiments.
553 *Journal of the Mechanics and Physics of Solids* 2007;55:2652–2671.
- 554 Harrigan J, Reid S, S. YA. The correct analysis of shocks in a cellular
555 material. *International Journal of Impact Engineering* 2010;37:918–927.
- 556 Pattofatto S, Elnasri I, Zhao H, Tsitsiris H, Hild F, Girard Y. Shock en-
557 hancement of cellular structures under impact loading: Part II analysis.
558 *Journal of the Mechanics and Physics of Solids* 2007;55:2672–2686.
- 559 Tan P, Reid S, Harrigan J, Zou Z, Li S. Dynamic compressive strength
560 properties of aluminium foams. part i experimental data and observations.
561 *Journal of the Mechanics and Physics of Solids* 2005;53:2174–2205.
- 562 Calladine C, English R. Strain-rate and inertia effects in the collapse of two
563 types of energy-absorbing structure. *International Journal of Mechanical*
564 *Sciences* 1984;26(11–12):689–701.
- 565 Zhao H, Abdennadher S. On the strength enhancement under impact loading
566 of square tubes made from rate insensitive metals. *International Journal*
567 *of Solids and Structures* 2004;41:6677–6697.
- 568 McKown S, Shen Y, Brookes W, Sutcliffe C, Cantwell W, Langdon G, et al.
569 The quasi-static and blast loading response of lattice structures. *Int Jour-*
570 *nal of Impact Engineering* 2008;35(8):795–810.
- 571 Hasan R, Mines R, Shen E, Tsopanos S, Cantwell W, Brooks W, et al.
572 Comparison of the drop weight impact performance of sandwich panels

573 with aluminium honeycomb and titanium alloy micro lattice cores. Applied
574 Mechanics and Materials 2010;24–25:413–8.

575 Smith M, Cantwell W, Guan Z, Tsopanos S, Theobald M, Nurick G, et al.
576 The quasi-static and blast response of steel lattice structures. Journal of
577 Sandwich Structures and Materials 2010;13(4):479–501.

578 U.S. Department of Transportation Federal Aviation Administration
579 DOT/FAA/AR-00/25 . Experimental investigations material models for
580 ti-6al-4v titanium and 2024-t3 aluminum. 2000.

581 Shao F, Liu Z, Wan Y, Shi Z. Finite element simulation of machining of ti-6al-
582 4v alloy with thermodynamical constitutive equation. The International
583 Journal of Advanced Manufacturing Technology 2010;49(5):431–9.

584 Al-Bermani S, Blackmore M, Zhang W, Todd I. The origin of microstructural
585 diversity, texture, and mechanical properties in electron beam melted ti-
586 6al-4v. Metallurgical and Materials Transactions A 2010;41.

587 Hernandez-Nava E, Smith C, Derguti F, Tammam-Williams S, Leonard F,
588 Withers P, et al. The effect of density and feature size on mechanical
589 properties of isostructural metallic foams produced by additive manufac-
590 turing. Acta Materialia 2015;85:387–395.

591 Amendola A, Hernandez-Nava E, Goodall R, Todd I, Skelton R, Fraternali F.
592 On the additive manufacturing, post-tensioning and testing of bi-material
593 tensegrity structures. Composite Structures 2015;131:66–71.

594 Hyde D. Conventional Weapons Program (ConWep). U.S Army Waterways
595 Experimental Station, Vicksburg, USA; 1991.

596 Tyas A, Watson A. An investigation of the frequency domain dispersion cor-
597 rection of pressure bar signals. *International Journal of Impact Engineering*
598 2001;25(1):87–101.