



This is a repository copy of *Dynamic response of aluminium matrix syntactic foams subjected to high strain-rate loadings*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/191933/>

Version: Accepted Version

Article:

Alteneiji, M., Krishnan, K., Guan, Z.W. et al. (3 more authors) (2023) Dynamic response of aluminium matrix syntactic foams subjected to high strain-rate loadings. *Composite Structures*, 303. 116289. ISSN 0263-8223

<https://doi.org/10.1016/j.compstruct.2022.116289>

Article available under the terms of the CC-BY-NC-ND licence
(<https://creativecommons.org/licenses/by-nc-nd/4.0/>).

Reuse

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: <https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

Dynamic response of aluminium matrix syntactic foams subjected to high strain-rate loadings

M. Alteneiji^{1*}, K. Krishnan¹, Z. W. Guan^{1,2,4*}, W.J. Cantwell³, Y. Zhao⁴, G. Langdon^{5,6}

¹ Advanced Materials Research Centre, Technology Innovation Institute, Abu Dhabi, United Arab Emirates.

² School of Mechanical Engineering, Chengdu University, Shiling Town, Chengdu 610106, China

³ Department of Aerospace Engineering, Khalifa University, Abu Dhabi, United Arab Emirates.

⁴ School of Engineering, University of Liverpool, Brownlow Hill, Liverpool, L69 3GH, United Kingdom.

⁵ Department of Civil and Structural Engineering, University of Sheffield, Sheffield, S10 2TN, United Kingdom

⁶ BISRU, Department of Mechanical Engineering, University of Cape Town, Rondebosch 7701, South Africa.

Abstract

This paper presents experimental work to characterise the dynamic behaviour of aluminium matrix syntactic foams subjected to compression, Split Hopkinson Pressure Bar and terminal ballistic impact tests as well as blast loading. Numerical models have also been developed to simulate the dynamic response of the composite foams. The effect of strain-rate on their compressive crush behaviour has been investigated, given that the rate-dependent characteristics of these materials are required for designing dynamically loaded structures. Characterisation of the behaviour of the foam under high strain-rate loadings and the identification of the underlying failure mechanisms were also undertaken to evaluate their effective mechanical performance. The results show that the aluminium syntactic foam is sensitive to strain-rate in terms of initial stiffness, peak stress and plateau stress and show a pronounced high-rate dependence at a strain rate above 1000 s^{-1} . The concrete damage plasticity model with rate-dependent features were used to simulate the dynamic behaviour of the foams, with the failure modes being captured. The model was verified and validated against the experimental results, and predictions were made for the normal and oblique ballistic impact response. Overall, the level of agreement between the numerical simulations and the experimental results is encouraging.

Keywords: metal matrix syntactic foam; blasts; impact; strain-rate; finite element.

* M. Teneiji, email: malteneiji@tii.ae, * Z.W. Guan, email: zhongwei.guan@tii.ae

1. Introduction

31 The resistance of engineering structures to blast and impact loads is currently of great interest
32 within the engineering community. This is primarily due to the need for protective systems against
33 possible terrorist attacks. The development of lightweight, strong and impact-resistant materials to
34 manufacture special vehicles is a challenging task facing the materials community. When subjected to
35 blast or impact loading, a structure usually undergoes large plastic deformations, possibly leading to
36 partial or total failure. The important characteristics of such a structural response are related to: (1) the
37 impulse generated from explosion and the shock wave transferred, and (2) the deformation mode and
38 associated failure mechanisms, and (3) the energy absorption through plastic deformation and
39 progressive damage [1].

40 A relatively new classification of materials, known as metal matrix syntactic foams (MMSF),
41 has played an increasingly important role in the category of energy-absorbing materials [2-9]. These
42 syntactic foams can be considered as two-phase composite materials, where the primary material is
43 mostly a metal, and the secondary material is of a porous nature. These porous particles exhibit foam-
44 like properties, thus making them ideal candidates for energy-absorption applications [2]. MMSF
45 overcome some of the disadvantages of polymeric foams such as low heat resistivity, low modulus and
46 strength. MMSF have the potential to be used as low weight structural parts in automotive industry,
47 protective panelling in aerospace, naval, and deep-sea pipelines as well as in the packaging industry.

48 Aluminium alloys are the most commonly used matrix materials in metal matrix syntactic
49 foams, due to their light weight [3-6, 10-22]. Other common matrix materials used for such applications
50 are iron [8, 9], magnesium [23], titanium [24] and zinc [25-27]. Ceramic hollow spheres, usually made
51 of Al_2O_3 [12, 15, 18, 28-31] or SiC [32], are used as the porous phase in such syntactic foam structures.
52 Recently, structures known as bimodal syntactic foams are being manufactured with mixed fillers of
53 varying sizes and materials to produce the porous structures [19, 33]. The effects of functionally graded
54 syntactic foams under dynamic loading have also been studied and are reported to have superior
55 properties compared to non-graded foams [34-36]. These MMSF are manufactured using a variety of
56 novel techniques such as dispersion, infiltration, powder metallurgy and additive manufacturing
57 methods [22]. The pressure infiltration technique is by far the most employed process for manufacturing

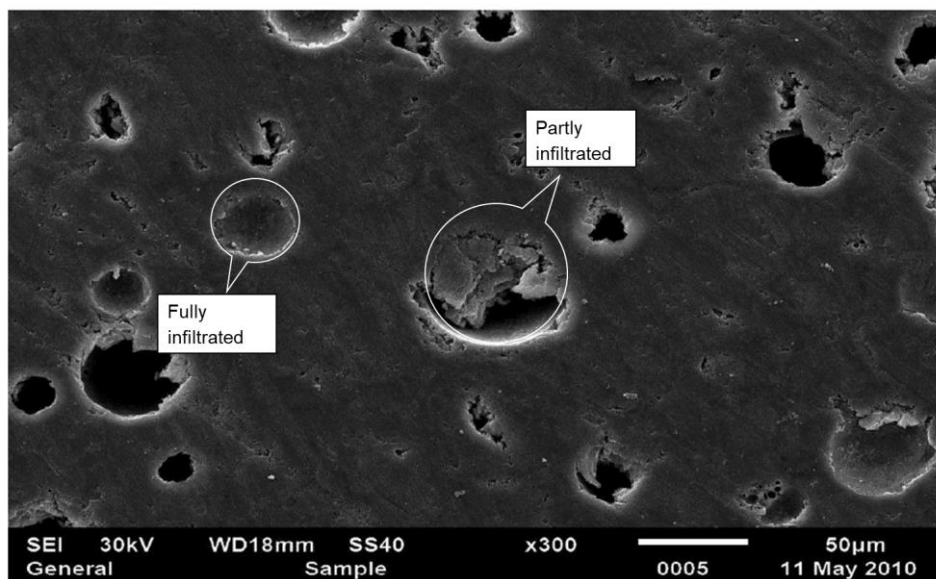
58 MMSF as it can incorporate a large range of reinforcement volumes compared to other methods [37,
59 38].

60 Metal matrix syntactic foams have been tested under dynamic compressive loading by a number
61 of workers [3-5, 7, 8, 14, 23, 27, 32, 34, 36, 39-45]. It was observed that at high strain-rates, aluminium
62 matrix syntactic foams experience higher plateau stress and peak stress values relative to those measured
63 through quasi-static tests [36, 39, 45]. This indicates that the dynamic energy absorption capability of
64 the aluminium foam is higher than the quasi-static value [4, 46]. Balch and Dunand [6] reported that the
65 rate sensitivity of the aluminium matrix induces a rate-sensitivity in the aluminium syntactic foam. They
66 found that the dynamic compressive strength of the aluminium syntactic foam was about 30–45 % higher
67 than that of its quasi-static counterpart. In contrast, Luong et al. [32] reported that A356/SiC syntactic
68 foam is insensitive to strain-rate. However, micro-inertia effects influence the rate-sensitivity of
69 syntactic foams [6]. In addition, Goel et al. [40] inferred that both the size of the ceramic micro-spheres,
70 as well as the fabrication method that was used, have an effect on the rate-sensitivity of a syntactic foam.
71 Wang et. al. [45] studied the impact resistance of Aluminium syntactic foams, highlighting the effect of
72 bio-inspired nacre like structure to mitigate damage propagation under impact loading. Aluminium foam
73 has also been investigated under blast loading using a ballistic pendulum [1]. Radford et al. [47] studied
74 the effect of the density of an aluminium foam core and the thickness of the cover plate on the blast
75 response of sacrificial cladding panels.

76 To date, detailed information on the dynamic response of aluminium matrix syntactic foams
77 subjected to high strain-rate loading is limited. The advantages of using MMSF structures as protective
78 panel for vehicular systems under ballistic and blast loading have also been barely investigated. In
79 response to this lack of information, this paper presents a series of experimental tests on aluminium
80 matrix syntactic foams subjected to various forms of dynamic loading, including drop-weight impact,
81 SHPB, ballistic impact and blast. In addition, finite element models are developed to predict the dynamic
82 responses of aluminium matrix syntactic foams subjected to these loading conditions. Finally, the
83 resulting numerical models are validated against the corresponding experimental results, in terms of
84 stress-strain relationships and failure modes. In addition, oblique impact response of the foams are
85 predicted using the validated model.

86 **2. Experimental Procedure**

87 In the present work, aluminium matrix syntactic foams based on ceramic spheres in the size
88 ranges (diameter) of 25–75 μm (CM(I)), 100–250 μm (CM(II)) and 250–500 μm (CM(III)) were
89 produced by pressure infiltration casting. The matrix was based on aluminium alloy Al7075-T. The
90 volume fraction of the ceramic microspheres within the foam was 66 % (weighing 6 g), with aluminium
91 matrix material representing the volume fraction of 34 % (weighing 45 g). Figure 1 shows a micrograph
92 of the aluminium matrix syntactic foam, which indicates that some ceramic micro-spheres were fully
93 infiltrated with molten aluminium.



94

95 Figure 1. Micrograph of the aluminium syntactic foam showing regions where the micro-spheres are
96 partly infiltrated with aluminium.
97

98 **2.1 Compression tests**

99 Uniaxial quasi-static compression tests were conducted on cube-shaped specimens having
100 dimensions of approximately $20 \times 20 \times 20 \text{ mm}^3$, i.e. with a height to width ratio equal to one. The thickness
101 of each specimen was therefore greater than seven times the size of the cells. Stress-strain curves were
102 recorded at a crosshead displacement rate of 1 mm/min. The displacements were measured from the
103 crosshead movement after the initial engagement of the sample with both the top and bottom platens.
104 The strain was approximately calculated by dividing the displacement by the original sample length,
105 whilst the stress was computed by dividing the applied load by the initial cross-sectional area.

106 **2.2 Split Hopkinson Pressure Bar (SHPB) Tests**

107 The SHPB apparatus employed in this study consists of two long slender bars, a striker and an
108 output system. The specimen is positioned between the bars and loaded by a transmitted wave generated
109 by the striker bar through the input bar. As the striker bar impacts the end of the input bar, an elastic
110 compression pulse is generated which travels through the input bar. At the sample interface of the input
111 bar, a portion of the pulse is transmitted to the output bar whereas the remainder is reflected. The
112 dynamic material properties can then be found from the superposition of the incident and reflected
113 pulses. Integration of the strain-rate in the specimen gives the corresponding strain. The stress in the
114 specimen can be determined using Kolsky's relation [48]:

$$115 \quad \sigma_s(t) = E \frac{A_0}{A} \varepsilon_t(t) \quad (1)$$

116 where $\sigma_s(t)$ is stress in the specimen, E is the elastic modulus of the pressure bar, A_0 is the cross-sectional
117 area of the output bar, A is the cross-sectional area of the specimen, and $\varepsilon_t(t)$ is the transmitted strain.

118 During Split Hopkinson Pressure Bar testing, a number of factors can affect the test accuracy
119 [48]. These include the dispersion of the longitudinal waves, the mismatch of the impedance between
120 the bars and the specimen and the transducer properties. However, the impedance was ensured to be
121 matched in the SHPB test. A basic rule in selecting bar materials is to use steel bars for the harder
122 materials (metallic ones) and aluminium bars for the softer materials (polymers, foams, etc.). Also, the
123 end faces of the bars need to be flat and parallel to each other. Therefore, the steel bar is used in the
124 current study. The strain in the specimen can be calculated as follows:

$$125 \quad \varepsilon_s = \frac{2c_o}{L} \int \varepsilon_r(t) dt \quad (2)$$

126 where c_o , ε_t , ε_i , ε_r are the longitudinal wave velocity, the transmitted strain, incident strain and the
127 reflected strain, respectively.

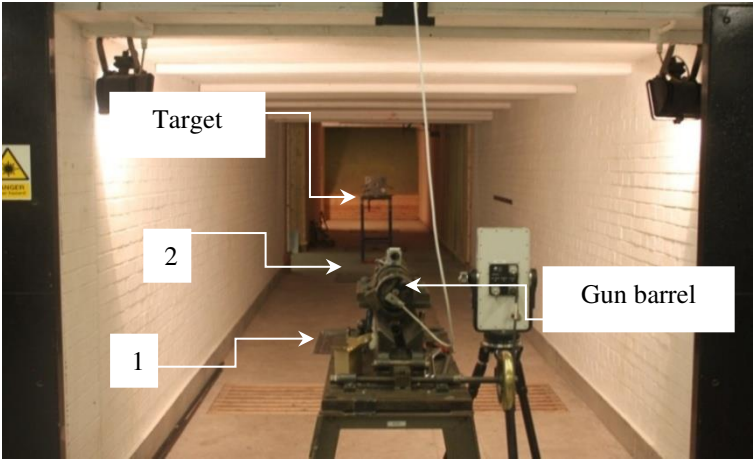
128 **2.3 Ballistic Impact Tests**

129 The ballistic tests were conducted using the firing range at Cranfield University. The length of
130 the indoor range is 20 metres. The range is equipped with an MS instrument ballistic computer, located

131 in an adjacent control room. A computer is connected to sensors mounted at 6 and 10 metres down the
132 range, which are used to measure the velocity of the projectiles. Figure 2 shows the views of the small
133 arms experimental range and the equipment used for the ballistic impact trials. A target disc of
134 aluminium matrix syntactic foam was fully bonded to peripheral surface of a hole in an aluminium plate,
135 which was fixed to the stand using a panel clamp.

136 The labels marked 1 and 2 in Figure 2(a) are the two velocity sensors. The projectiles used in
137 these tests were the Russian AK47 7.62 × 39 mm Kalashnikov with mild steel core [49]. The bullet
138 consists of four main components: the projectile, the propellant, the jacket or cartridge case and the
139 primer or igniter.

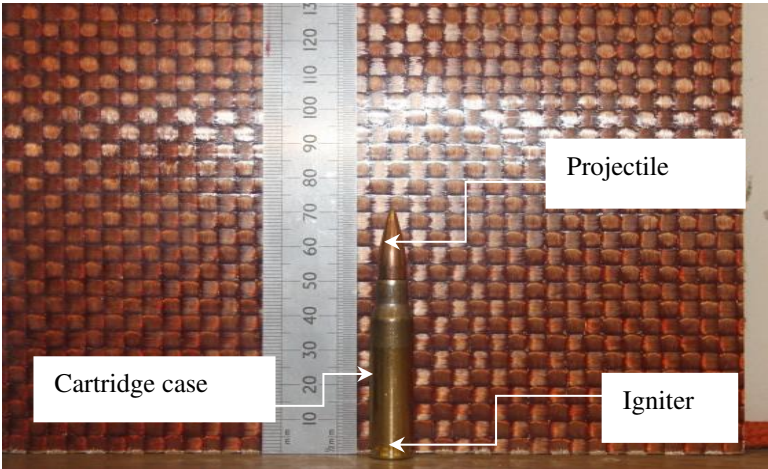
140



141

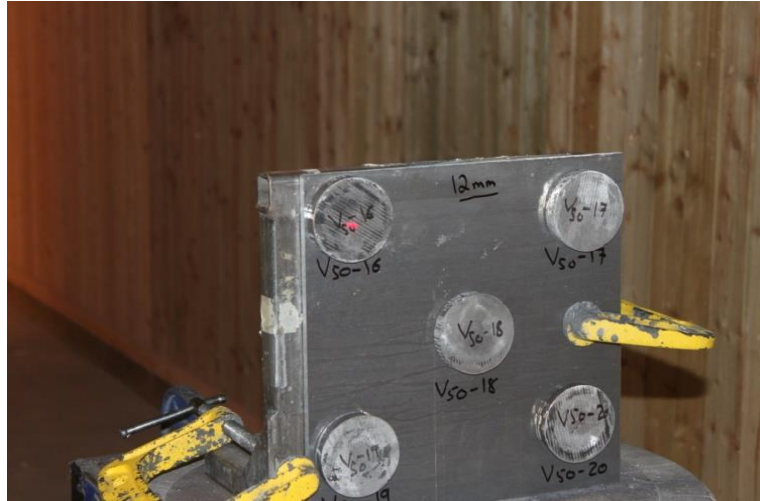
(a) Photograph of the ballistic range at Cranfield University.

142



143

(b) The 7.62 x 39 mm (NIJ level III).



144

145

(c) Target clamped to the stand.

146

Figure 2. Set-up for ballistic testing

147

148 **2.4 Blast Tests**

149

150

151

152

153

154

155

156

157

158

159

Blast loads were generated by detonating 20 mm diameter disks of plastic explosive PE4 using an electrical detonator. The specimens comprised discs of an aluminium syntactic foam of varying thickness. The blast tests were carried out on samples with a diameter of 90 mm and a thickness between 3 and 20 mm. Here, a ballistic pendulum [50] was used to determine the impulse transferred to the specimen, as shown in Figure 3a. The explosive was attached to a polystyrene disc (13 mm thick, 90 mm diameter). PE4 consists of 12 % of lithium and 88 % of RDX grease, has a nominal density of 1600 kg/m³, and can generate a wave velocity of 8200 m/s [51]. The blast load was directed along a 90 mm internal diameter, 180 mm long, steel tube to give a stand-off distance required and to ensure the impulse inferred from the pendulum swing was entirely directed at the panel, following [52, 53]. Steel clamps were used to provide a circular aperture and mount the specimen to the pendulum. The loading arrangement is shown in Figure 3b.

160

161

162

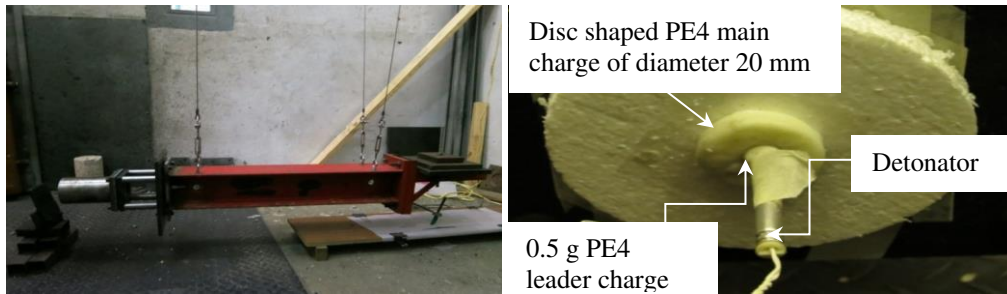
163

164

The ballistic pendulum consists of an I-beam that is suspended on 4 spring steel cables, which are attached by 4 screws that are adjustable in order to level the pendulum. Counter balancing masses are added to the end of the pendulum to ensure that each spring steel cable carries an equal load. The explosive charge generates an impulse through the centroid of the pendulum. The charge masses were 1.0, 1.5, 2.0, 2.5 and 3.0 grams with a leader of explosive fixed at 0.5 grams for the blast loading directly

165 onto the foam specimens (180 mm stand-off distance), For the panels with steel cover plates, the charge
166 masses were increased to be 10, 11, 12 and 12.5 g.

167



168

169 (a) the ballistic pendulum,

170 (b) disc-shaped PE4 explosive with a 0.5 g
171 leader attached to the detonator

171

172 Figure 3. Blast test setup

172

173 3. Finite element modelling

174 The commercial finite element (FE) code ABAQUS/Explicit [54] was used to model the
175 response of the aluminium matrix syntactic foam under the different loading conditions.

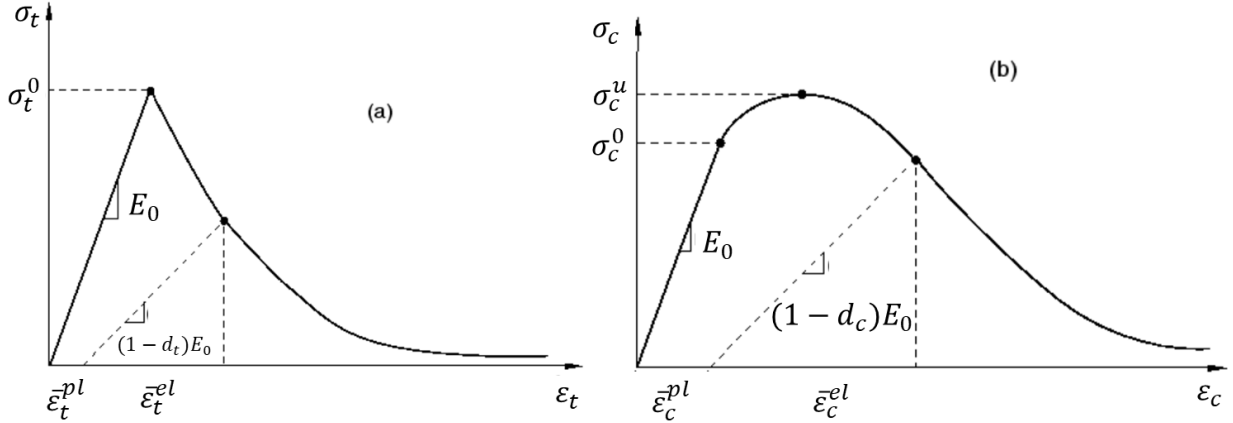
176 3.1 Plasticity model for quasi-brittle materials

177 The volume fraction of the ceramic microspheres within the foam was 66 %, corresponding to a
178 weight fraction of 88 %, which makes the deformation behaviour predominantly brittle in nature. A
179 detailed investigation of the experimental samples reveals typical damage observed in brittle materials,
180 such as ceramics, for instance micro-cracks and fracture. Constitutive models, such as Johnson-
181 Holmquist (JH) or Concrete Damage Plasticity (CDP), can be candidates to be adopted to predict brittle
182 fracture and the crack evolution observed in the experiments. However, the ability to input the stress-
183 strain data during compressive behaviour makes the CDP constitutive model a suitable candidate to
184 study damage in syntactic foams.

185 The concrete damage plasticity model provides a general capability for modelling brittle materials
186 using concepts of isotropic damaged elasticity combined with isotropic tensile and compressive
187 plasticity [26]. The model incorporates the two main failure mechanisms observed in brittle materials,
188 these being tensile cracking and compressive crushing. The evolution of the yield surface is controlled
189 by two hardening variables $\bar{\epsilon}_t^{pl}$ and $\bar{\epsilon}_c^{pl}$ linked to failure mechanisms under tension and compression

190 loading, respectively. The uniaxial tensile and compressive responses of a brittle material as
 191 characterised by damaged plasticity are shown in Figure. 4.

192



193

194 Figure 4. Uniaxial behaviour in concrete damaged plasticity model under (a) tension and (b)
 195 compression [54]
 196

197 The total strain-rate $\dot{\varepsilon}$ can be decomposed into its elastic and plastic counter parts, $\dot{\varepsilon}^{el}$ and $\dot{\varepsilon}^{pl}$, i.e.

$$198 \quad \dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl} \quad (3)$$

199 The elastic damage constitutive relationship is defined as,

$$200 \quad \sigma = (1 - d)D_0^{el} : (\varepsilon - \varepsilon^{pl}) = D^{el} : (\varepsilon - \varepsilon^{pl}) \quad (4)$$

201 where D_0^{el} is the undamaged elastic stiffness of the material, d is the damage factor with the value of
 202 zero indicating undamaged material and the value of one showing fully damaged one. The concrete
 203 damage plasticity model assumes non-associated potential plastic flow. The flow potential G used in
 204 this model is the Drucker-Prager hyperbolic function:

$$205 \quad G(\bar{\sigma}) = \sqrt{(e\sigma_{t0}\tan\psi)^2 + \bar{q}^2} - \bar{p}\tan\psi \quad (5)$$

206 where ψ is the dilation angle, σ_{t0} is the uniaxial tensile stress at failure, e is an eccentricity parameter
 207 and q is the equivalent stress. The material properties used in the brittle failure model were density =
 208 2296 kg/m³, Young's modulus = 4.00 GPa (corresponding to 66 % volume fraction of hollow ceramic
 209 microspheres) and Poisson's ratio = 0.29, dilation angle = 40°, eccentricity = 0.1, ratio of initial
 210 equibiaxial compressive yield stress to initial uniaxial compressive yield stress is 1.16. These material

211 constants were calibrated within the specified range values using the quasi-static compression test
 212 data[54]. The compressive stress-strain data were obtained from experiments as shown in Table 1.
 213 Concrete failure criterion is used to define the material failure based on tensile cracking strain. When it
 214 exceeds a critical value, element deletion will be triggered. Special care needs to be taken, while
 215 inputting the post damage strain values as Abaqus will issue error warning if the calculated plastic strain
 216 values are negative or decreasing with increasing cracking strain.

217 Table 1. Concrete compression and tension data for the brittle failure model

Compressive Behaviour		Tensile Behaviour		
Yield Stress (MPa)	Inelastic Strain	Yield Stress (MPa)	Cracking Strain	Damage Parameter
184.79	0	75	0	0
185	0.012717	70	0.00156	0.0010
186	0.061272	62	0.00257	0.0018
186.2	0.067052	56	0.00357	0.0025
186.4	0.077457	40	0.00453	0.0035
186.6	0.116763	44	0.00549	0.0050
191.977	0.216185	38	0.00645	0.0060
195.398	0.261272	32	0.00741	0.0070
196.6	0.285549	26	0.00837	0.0085
204.357	0.322543	20	0.00933	0.1000
222.092	0.378035	14	0.01029	0.2000
191.977	0.216185	8	0.01125	0.3000
195.398	0.261272	2	0.017	0.6500
260.725	0.440462	0	0.04	0.9000
307.025	0.493642			
363.203	0.542197			
409.452	0.576879			
457.883	0.60578			
380	0.63			
320	0.65			
260	0.67			
180	0.69			
90	0.71			
40	0.72			
10	0.73			

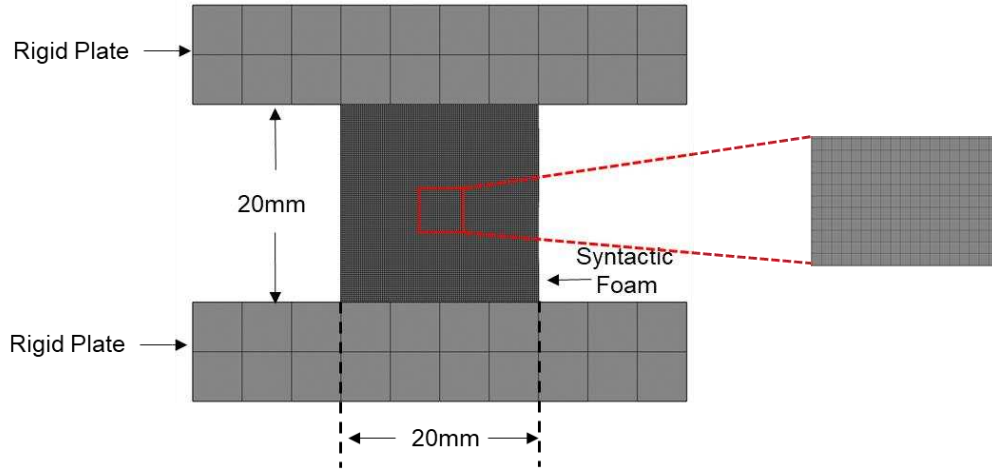
218

219 3.2 Finite element model setup

220 3.2.1 Modelling of the compressive behaviour of the syntactic foam

221 The setup for the compression test used for the simulations is shown in Figure 5. A 20×20×20 mm³
 222 cubic model was created, similar to the test sample. Very fine 8-noded hexahedral elements (C3D8R),
 223 with reduced integration and an element size of 0.2 mm, were used to capture the crack formation and
 224 damage evolution within the sample. The refined mesh, though computationally expensive, helps in

225 capturing crack propagation due to tensile failure without leading to any instabilities. The stress-strain
 226 values for the syntactic foam CM(I) were obtained from the compression test. Displacement was applied
 227 to the top rigid plate while the bottom rigid plate was fully constrained.



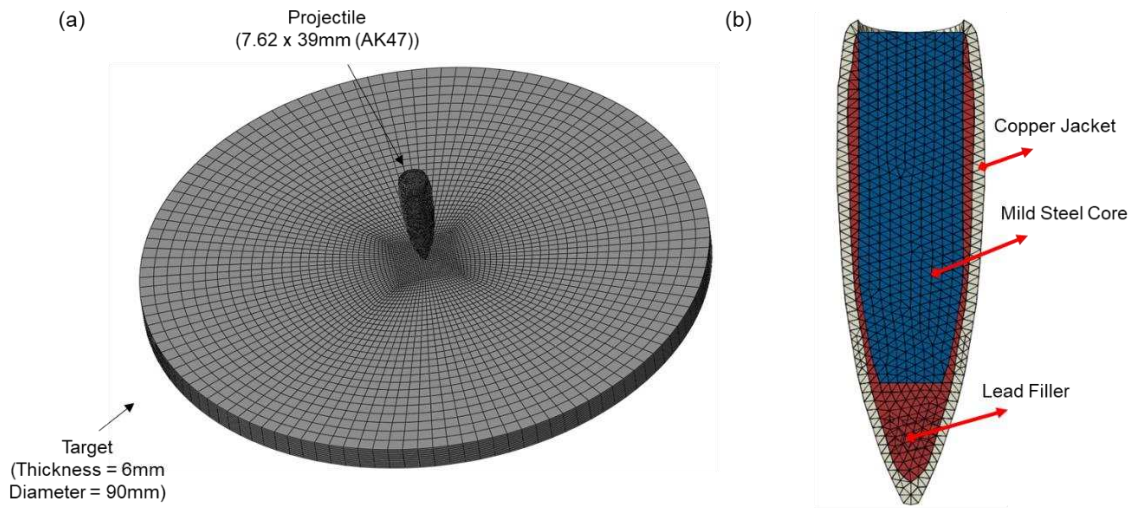
228
 229 Figure 5. Finite element model for the compression test

230 3.2.2 *Modelling ballistic impact*

231 Simulations of the ballistic tests were carried out to identify the minimum thickness of foam
 232 required to prevent perforation of a bullet. Boundary conditions similar to the experiments were used in
 233 the model. The mesh density in the central area of the sample was higher than that in the outer regions.
 234 The failed elements were removed during the penetration process. Figure 6(a) shows the finite element
 235 setup for the ballistic impact simulations. The outer surface of the sample was fully constrained. An
 236 initial velocity was applied to the projectile, equal to the impact velocity measured in the test. The
 237 residual velocity and depth of penetration were predicted using the model. The detailed bullet model is
 238 shown in Figure 6(b). The steel core, copper jacket and lead filler are modelled using Johnson-Cook
 239 constitutive model [55] and the parameters are summarised in Table 2. Effective plastic strain is used as
 240 the damage criterion with element deletion enabled in order to avoid excessive distortion.

241 Table 2. Johnson-Cook material properties for projectile components[56]

	A (MPa)	B (MPa)	C	n	m
Steel Core	234.4	413.8	0.0033	0.25	1.03
Copper Jacket	448.2	303.4	0.003	0.15	1.00
Lead Filler	10.30	41.3	0.001	0.21	1.03



243

244

245

246

Figure 6. Finite element model setup for terminal ballistic impact (a) FE mesh for the setup (b) Projectile mesh and components

247 3.2.3 Modelling blast behaviour

248

The numerical model was developed to simulate the blast response of the foam subjected to such the extreme loading condition. The mesh generation, shock pressure distribution and boundary conditions are shown in Figure 7. The model is subdivided into two separate zones over which different impulse pressures were applied. The outermost circular ring is clamped to simulate the boundary conditions used in the blast experiments. The pressure distributions for the two zones were proposed by the authors [57] and were adopted here.

254

$$P_{total} = P_1 + P_2 = \frac{0.85I_m}{2A_1t} + \frac{0.15I_m}{2A_2t} \quad (6)$$

255

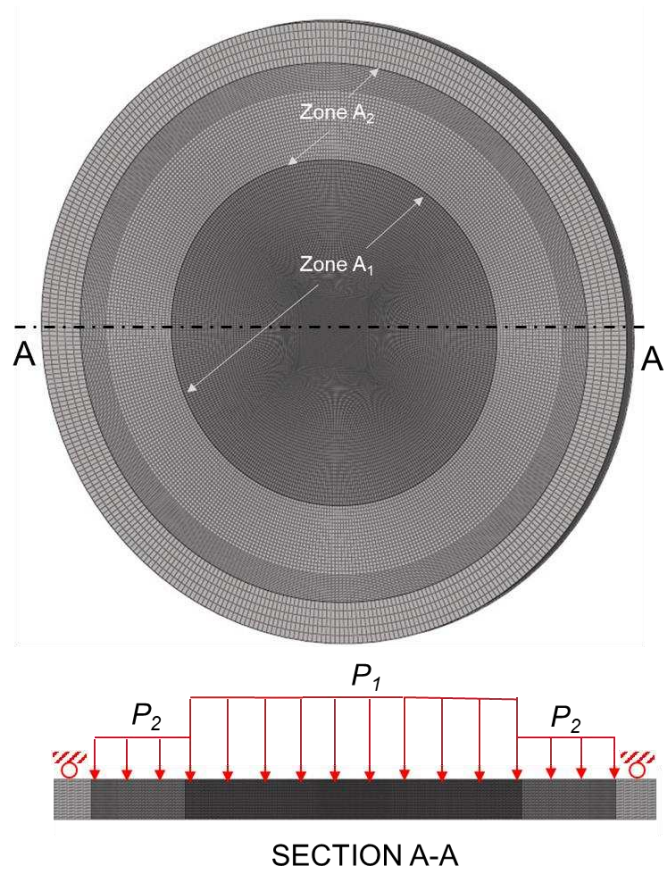
256

257

258

259

where I_m is the impulse obtained from experimental measurements, $A_1 + A_2$ is the total pressurised area and t is the blast time in microseconds. A highly refined mesh ($0.1 \times 0.1 \times 0.1 \text{mm}$) is used in the zone A_1 in order to capture the damage evolution of cracks during blast loading (Fig. 7). The area close to the clamped boundary was also locally refined to capture the damage observed in the adjacent regions, due to the high stress concentration there.



260

261 Figure 7. The finite element model setup showing the mesh generation, shock pressure zones and
 262 boundary conditions.

263 4. Results and Discussion

264 4.1 Experimental results

265 4.1.1 Compression test results

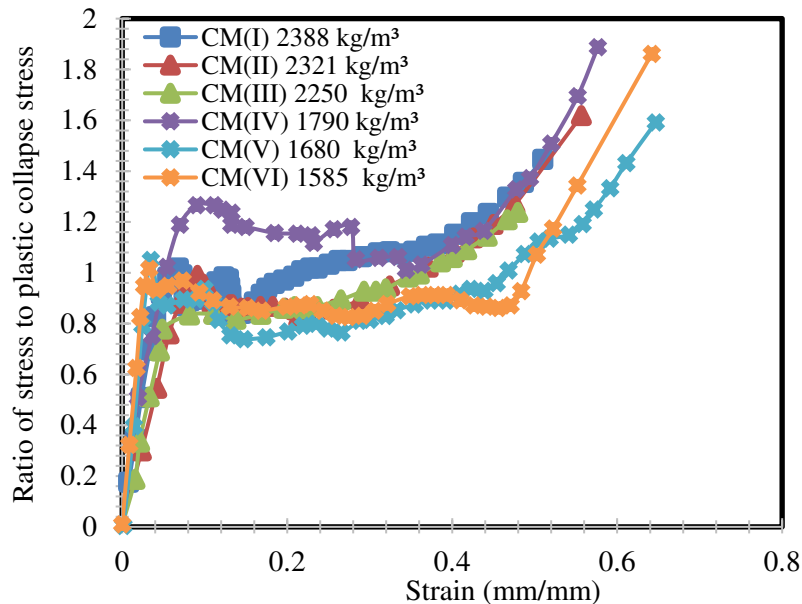
266 The compressive stress-strain curves of the different syntactic foams for the quasi-static and
 267 dynamic compression tests are shown in Figure 8. The stress values are normalized with respect to the
 268 plastic collapse stress to ensure consistency between the different material densities. There are three
 269 typical phases observed during the compression response of cellular solids. Initially, a linear elastic
 270 phase is observed, where the strain is less than 3 % and the stress-strain relationship follows Hooke's
 271 law. The slope of the first part is defined as the Young's modulus. This is followed by a section where
 272 the peak stress is reached, plastic deformation of the matrix starts and the load transfer between the
 273 matrix and ceramic micro-spheres reaches its maximum. This is where the compressive strength is

274 measured. Next, there is a small reduction in stress, due to the reduced load-bearing capacity caused by
 275 crushing of the ceramic micro-spheres and global instability. The second phase occurs between strains
 276 of 10 % and 43 %, characterised by a relatively constant plateau stress, where the micro-porosity in the
 277 ceramic micro-spheres densifies through crushing. Energy absorption is significant in this region, as the
 278 stress remains constant with increasing strain. The final phase is associated with densification, where
 279 the stress increases to a high value very quickly, while the strain increases slowly. The densification
 280 strain is located at the intersection between the tangents of the densification phase and the plateau phase.
 281 The mechanical properties of the syntactic foams are listed in Table 3, which are based on three repeated
 282 test results of each specimen.

283 Table 3. Average mechanical properties of aluminium matrix syntactic foams

ID	Density (kg/m ³)	Plastic Collapse Stress, σ_{pl} (MPa)	Compressive Modulus (GPa)	Steady State Stress, σ_{ss} (MPa)	Densification strain, ϵ_D (%)
CM(I)	2388	179	3.22	175	36
CM(II)	2321	167	2.83	150	41
CM(III)	2250	160	2.45	148	43
CM(IV)	1790	130	2.40	128	43
CM(V)	1680	101	2.25	78	44
CM(VI)	1585	75	2.10	65	50

284



285

286 Figure 8. Quasi-static stress–strain curves of the compression tests on the aluminium matrix syntactic
 287 foams

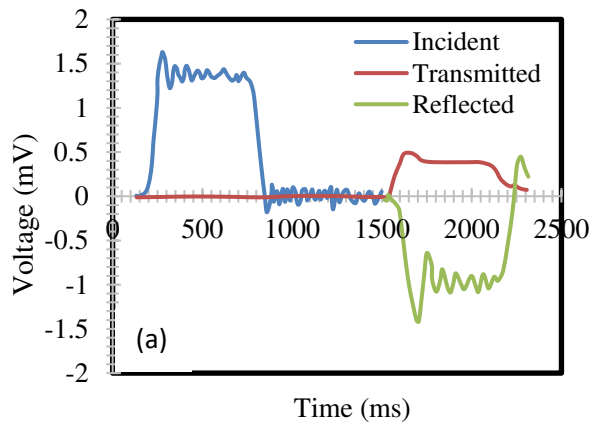
288

289 4.1.2 Impact response from Split Hopkinson Pressure Bar (SHPB) tests

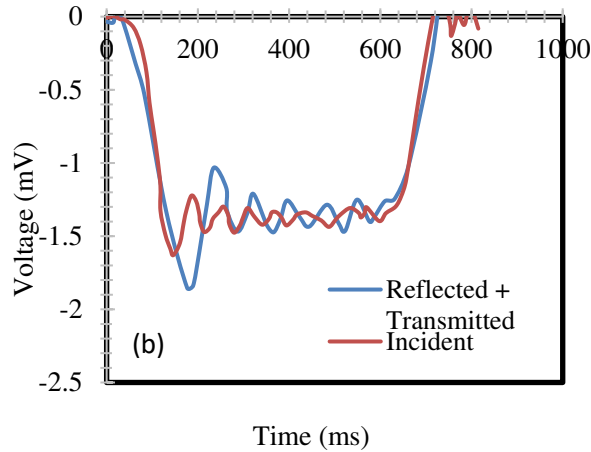
290 The dynamic properties of the aluminium syntactic foams are listed in Table 4. The failure
 291 modes observed in the aluminium syntactic foam at high strain-rates were associated with compressive
 292 failure, rather than shear failure. It is possible that the high strain-rate during the test hindered the
 293 formation of shear band. A strain-rate sensitivity parameter (Σ) was used to evaluate the effect of strain-
 294 rate on the material under dynamic loading, which can be calculated using the following equation [9]:

$$295 \quad \Sigma = \frac{\sigma_d - \sigma_q}{\sigma^*} \left[\frac{1}{\ln \frac{\dot{\epsilon}_d}{\dot{\epsilon}_q}} \right] \quad (8)$$

296 where σ is the flow stress, σ^* is the static stress at 5% strain at a strain-rate of 10^{-3} s^{-1} for foam materials,
 297 $\dot{\epsilon}$ is the strain-rate and d and q are subscripts that refer to dynamic and quasi-static testing, respectively.
 298 The peak stress reached in compression is used to calculate the sensitivity parameter, although these
 299 peak stresses appear at slightly different strains. The strain-rate sensitivity parameters of various
 300 aluminium alloys are varied between 0.006 and 0.06. Table 4 shows that the sensitivity parameter of the
 301 aluminium syntactic foams lies between 0.018–0.204, which indicates that this type of the aluminium
 302 syntactic foam is sensitive to strain-rate. Figure 9(a) shows the strain pulses obtained from the incident
 303 and transmitted bars used to compute stress, strain and strain rate. The combined reflected and
 304 transmitted strain pulses are plotted along with the incident pulse, as shown in Figure 9(b), to identify
 305 any potential losses in the specimen while testing. The close match ensures that the losses are not
 306 significant during the tests.



307



308

309 Figure 9. Split Hopkinson Pressure bar test results for a representative Aluminium syntactic foam
 310 showing (a) strain signals from incident and transmitter bars (b) comparing strain signals to analyse
 311 losses in the specimen
 312

313 Table 4 Average high velocity impact properties of the aluminium matrix syntactic foams (CM (I),
 314 CM (II) and CM (III)).

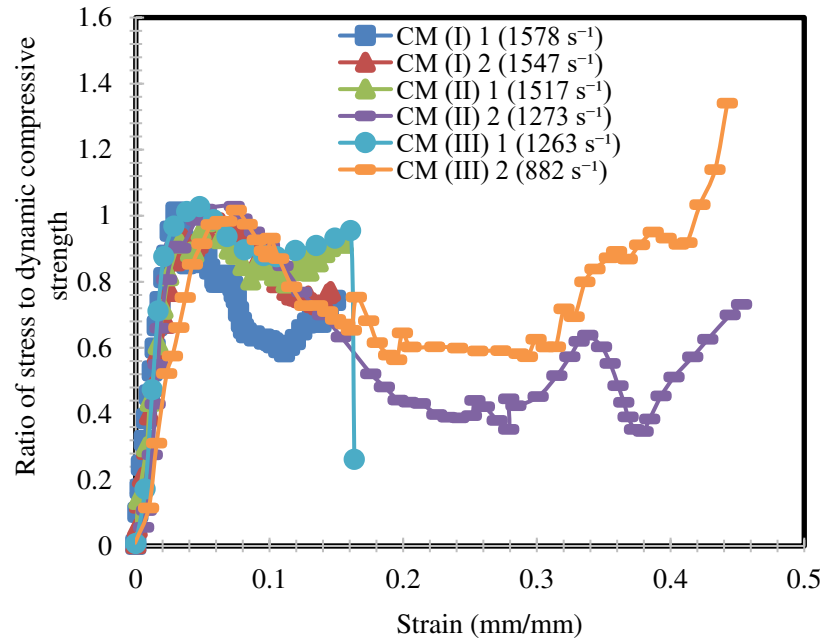
ID	Young's Modulus (GPa)	Dynamic compressive strength (MPa)	Dynamic strain rate (1/s)	Relative density, (ρ/ρ_s)	Relative yield strength, (σ/σ_s)	Relative Young's modulus, (E/E _s)	Sensitivity parameter Σ
CM(I) ₁	14.22	601.4	1578	0.891	0.752	0.151	0.204
CM(I) ₂	13.95	574.9	1547	0.890	0.719	0.148	0.192
CM(II) ₁	13.16	487.9	1517	0.889	0.609	0.139	0.151
CM(II) ₂	12.87	461.0	1273	0.880	0.922	0.184	0.140
CM (III) ₁	11.93	265.0	1263	0.797	0.650	0.099	0.043
CM(III) ₂	9.04	203.0	882	0.755	0.490	0.057	0.018

315 *E_s, σ_s and ρ_s of aluminium Al 7075-T6 are 94.4 GPa, 646 MPa and 2810 kg/m³, respectively [20].

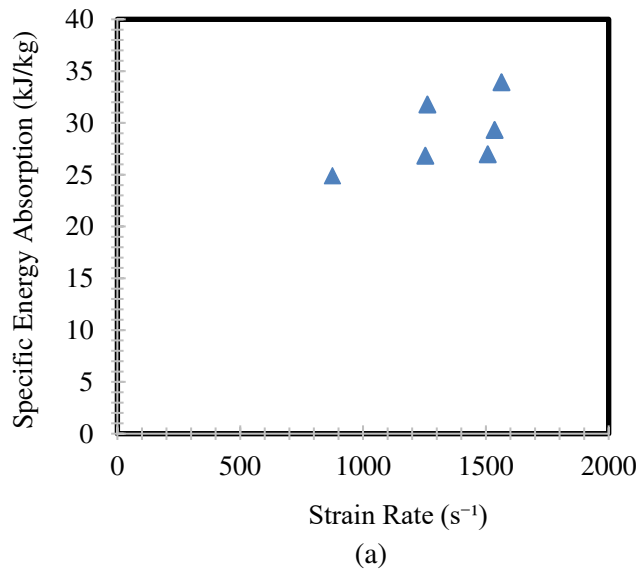
316 *_{1,2} refer to the same type of material at different strain rates.

317 Figure 10 shows the dynamic compressive stress–strain curves for materials CM (I), CM (II)
 318 and CM (III). The stress values are normalized with respect to the dynamic compressive strength to
 319 ensure consistency between the different material densities. The results highlight the rate-sensitivity of
 320 the foams. For example, the peak stress for CM (III)₂ increased from 203 MPa at 882 s⁻¹ to 601 MPa at
 321 1578 s⁻¹ CM (I)₁. The peak stress is shifted to lower strains at higher strain-rates, as are the fracture
 322 strains, primarily due to the strain-rate sensitivity of the foam matrices (change of foam densities also
 323 plays some role). It was found that those syntactic foams with a higher percentage of metal matrix were
 324 more rate-sensitive. The results presented in Figure 11 show the influence of strain-rate on specific
 325 energy absorption, the plateau stress and the peak stress, respectively. The results confirm the
 326 dependency of the properties of the syntactic foam on strain-rate. An increase in the strain-rate leads to

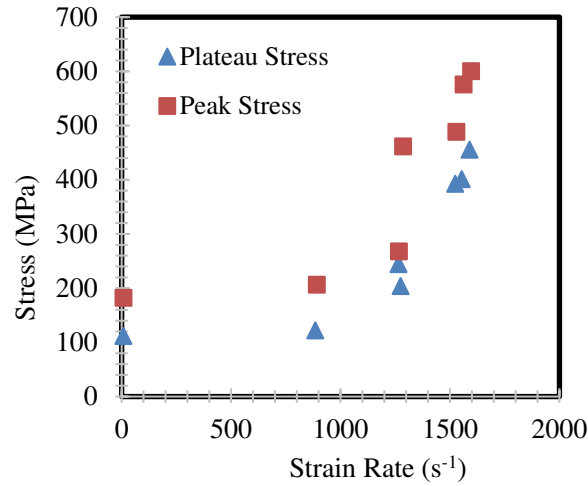
327 an increase in the specific energy absorption, peak stress and plateau stress. In addition, the peak stress
 328 appears to be more sensitive to strain-rate than the plateau stress, which is likely due to the prolonged
 329 plateau stage. However, the strain-rate dependence is not significant until values of 1000 s^{-1} and above,
 330 where both the plateau and the peak stresses exhibit a strong rate-dependence (Figure 11(b)).



331
 332 Figure 10. Compressive stress–strain curves for the aluminium matrix syntactic foam at high
 333 strain-rates
 334



335
 336
 337



(b)

Figure 11. Strain-rate dependence of CM (I) foams (a) The variation of specific energy absorption with strain-rate (b) the variation of plateau and peak stress with strain-rate.

338
339
340
341
342
343
344

4.1.3 Ballistic impact behaviour

346 The ballistic response of different thicknesses of aluminium matrix syntactic foams was
347 investigated using ballistic impact tests. A summary of the results from the ballistic tests is shown in
348 Tables 5 and 6. The penetration resistance of foam CM (I) follows a linear relationship with velocity,
349 which can be expressed as

$$350 \quad \text{DOP}_{\text{Al7075-T6 (75 } \mu\text{m)}} = 0.5627 + 0.4187 v_s \quad (9)$$

351 where $\text{DOP}_{\text{Al7075-T6 (75 } \mu\text{m)}}$ is the depth of penetration (DOP) into the foam and v_s is the impact velocity.

352 Table 5. Average properties and DOP for the aluminium matrix syntactic foam subjected to impact
353 velocities up to 20 m/s.
354

ID	Thickness (mm)	Impact velocity (m/s)	DOP (mm)	Areal density (kg/m ²)
G1	13.2	20	8.94	18.35
G2	14	17	7.60	19.46
G3	15	14	6.50	20.85
G4	15.6	11	5.24	21.68
G5	15.6	8	3.27	21.68

355 Table 6. Average terminal ballistic properties of the aluminium matrix syntactic foam with same
356 density but different thickness.

ID	Thickness of the sample (mm)	Impact velocity (m/s)	Residual velocity (m/s)
T1	6	812	740
T2	6	815	742
T3	6	845	760
T4	8	850	830
T5	8	750	727

T6	8	650	625
T7	10	550	520
T8	10	450	415
T9	10	350	310
T10	12	250	203
T11	12	150	81
T12	12	120	33

357

358

359

360

361

362

363

364

The penetration of a target by a projectile depends on the material properties, impact velocity, projectile shape and target position. In addition, the prediction of target and projectile failure is required in order to design a target with the minimum areal density to defeat the projectile. The parameters that control perforation include the thickness of the target, the radius of the projectile and the impact velocity. If the ratio of the target thickness to the radius of the projectile is greater than one, the target plate is considered to be thick, whereas if the ratio is less than one, it is considered to be thin.

4.1.4 Blast response

365

366

367

368

369

370

371

372

A summary of the blast tests is given in Table 7, detailing the mass of explosives used for each test, the impulse measured and the permanent resulting displacement. The results show that the measured impulses lie between 3.09 Ns and 6.12 Ns. These results are lower than those reported by Teeling-Smith and Nurick [58] for steel, due to the longer stand off distance employed in the experiments. Many of samples fractured or exhibited small permanent displacements, reflecting the extremely brittle nature of aluminium syntactic foam materials. The foam failed by radially cracking in several locations. This is discussed more fully in relation to the finite element modelling results in Section 4.2.3. The results also indicate that the charge mass increased the damage on the target, as expected.

373

374

Table 7. Summary of the blast tests (the stand-off distance was 180 mm).

ID	Sample thickness (mm)	Mass of PE4 (g)	Impulse (Ns)	Mid-point deflection (mm)
B1	3.07	1.5	3.82	*
B2	5.8	1.5	3.36	*
B3	9.12	1.5	3.09	0.45
B4	9.18	2.0	4.50	*
B5	10.0	1.0	4.20	0.50
B6	10.2	2.0	4.30	0.35
B7	10.5	2.0	4.32	*
B8	12.5	2.0	3.72	0.48
B9	12.8	2.5	5.4	*
B10	14.0	2.5	4.82	0.50
B11	16.0	2.5	4.79	0.45

B12	20.0	3.0	6.12	0.60
-----	------	-----	------	------

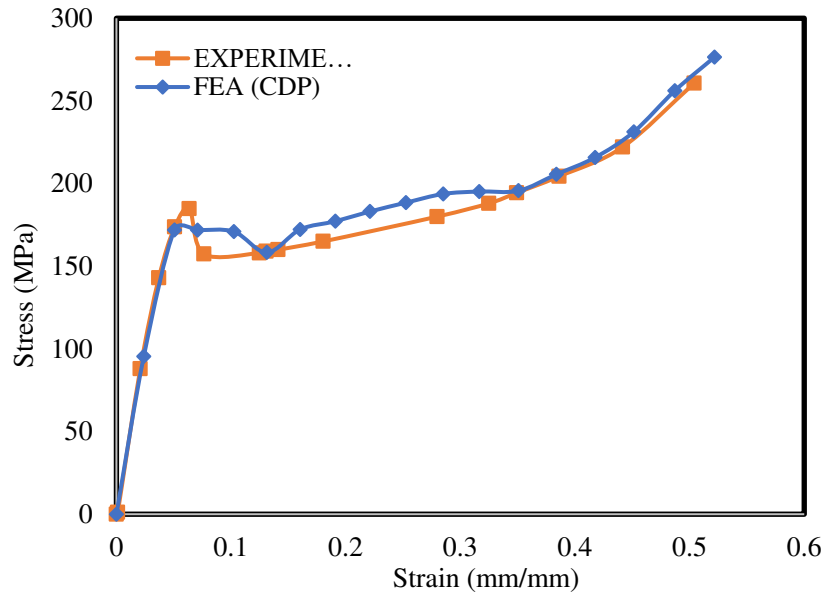
375 * Sample completely failed

376 *4.2 Finite element modelling results*

377 The concrete damage plasticity (CDP) material model is mostly used to study the compressive
378 behaviour of concrete and other reinforced brittle materials. The implementation of the CDP model to
379 study syntactic foams needs to be justified through a series of verification and validation simulations in
380 order to use it as a predictive tool for further studies. The verification study is conducted by comparing
381 the compressive test results obtained from the finite element models with the experimental stress-strain
382 curves. The finite element model is then verified using ballistic test results from tests on 6 mm thick
383 syntactic foam sample as well as the blast response of a 10 mm thick foam. The validated model is then
384 used to predict the impact response of different thicknesses of syntactic foam subjected to normal and
385 oblique impacts.

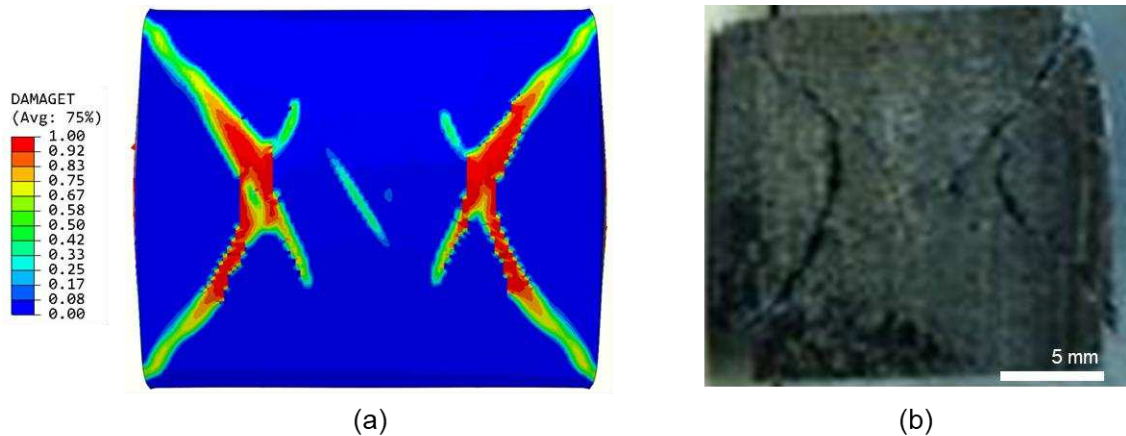
386 *4.2.1 Modelling quasi-static compression behaviour of the syntactic foam*

387 The comparison between the finite element results and the experimental compression stress-
388 strain curve is shown in Figure 12. The FE model is capable of capturing the predominant features of
389 the compressive behaviour, such as the plastic collapse stress, the compressive modulus as well as the
390 steady state stress. Furthermore, the contour plots for tensile damage, as shown in Figure 13, show a
391 good degree of correlation with the damage observed in the tested sample. The cracking occurs along a
392 characteristic shear plane at 45⁰ to the loading direction, which is consistent with the damage observed
393 in metal matrix syntactic foams subjected to compression [59, 60]. Comparisons of the experimental
394 and predicted compressive stress-strain curves, as well as the failure mode can be used to verify the
395 numerical model as well as the input parameters. The plateau and peak stress values for the quasi-static
396 stress-strain data can be scaled for testing at strain-rates related to dynamic loading using the strain-rate
397 dependency shown in Figure 11(b).



398
399
400

Figure 12. Verification of the FE model using the compression test experimental data



401

Figure 13. Crack propagation during the compression test (a) FE results showing tensile damage contour (b) Experimentally failed sample.

402

403

404
405 4.2.2 Modelling the ballistic impact response of the syntactic foam

406 The finite element models developed were validated against the ballistic impact and blast test

407 results. The objective was to compare the results obtained from the finite element simulations with the

408 experimental data without changing any of the material parameters. The syntactic foam samples with a

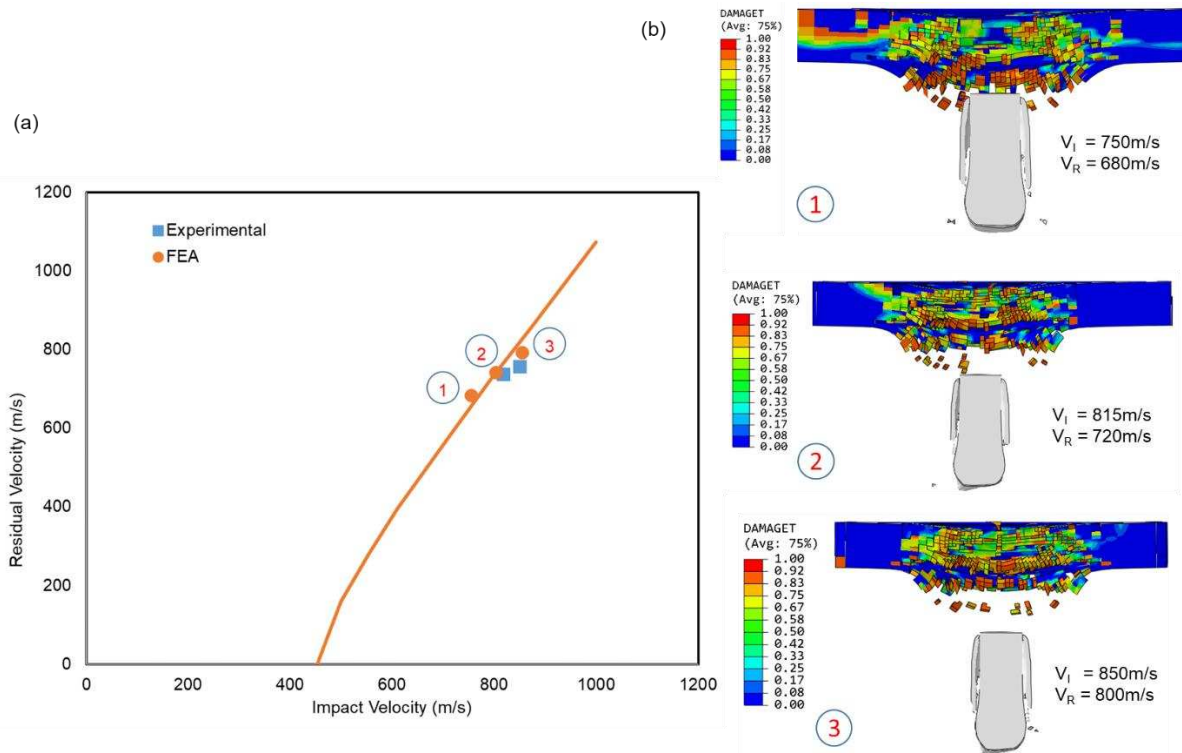
409 thickness of 6 mm, were impacted at velocities of 800, 750 and 700 m/s and the corresponding residual

410 velocities were predicted using the model. The FE simulations are compared with the experimental

411 results in Figure 14. The predicted damage modes of the foam as well as the projectile exiting the panel

412 are shown in Figure 14(b). As there are only two measured residual velocities, three predicted residual

413 velocities are obtained using the validated FE model. The method of least squares using the Lambert-
 414 Jonas equation (Eqn 10) [61] is used to apply a curve fit to the FE results, as shown by a solid line in
 415 Fig 14(a). The experimental results are then superimposed on the fitted curve generated from the
 416 simulations, which indicates reasonable correlation.

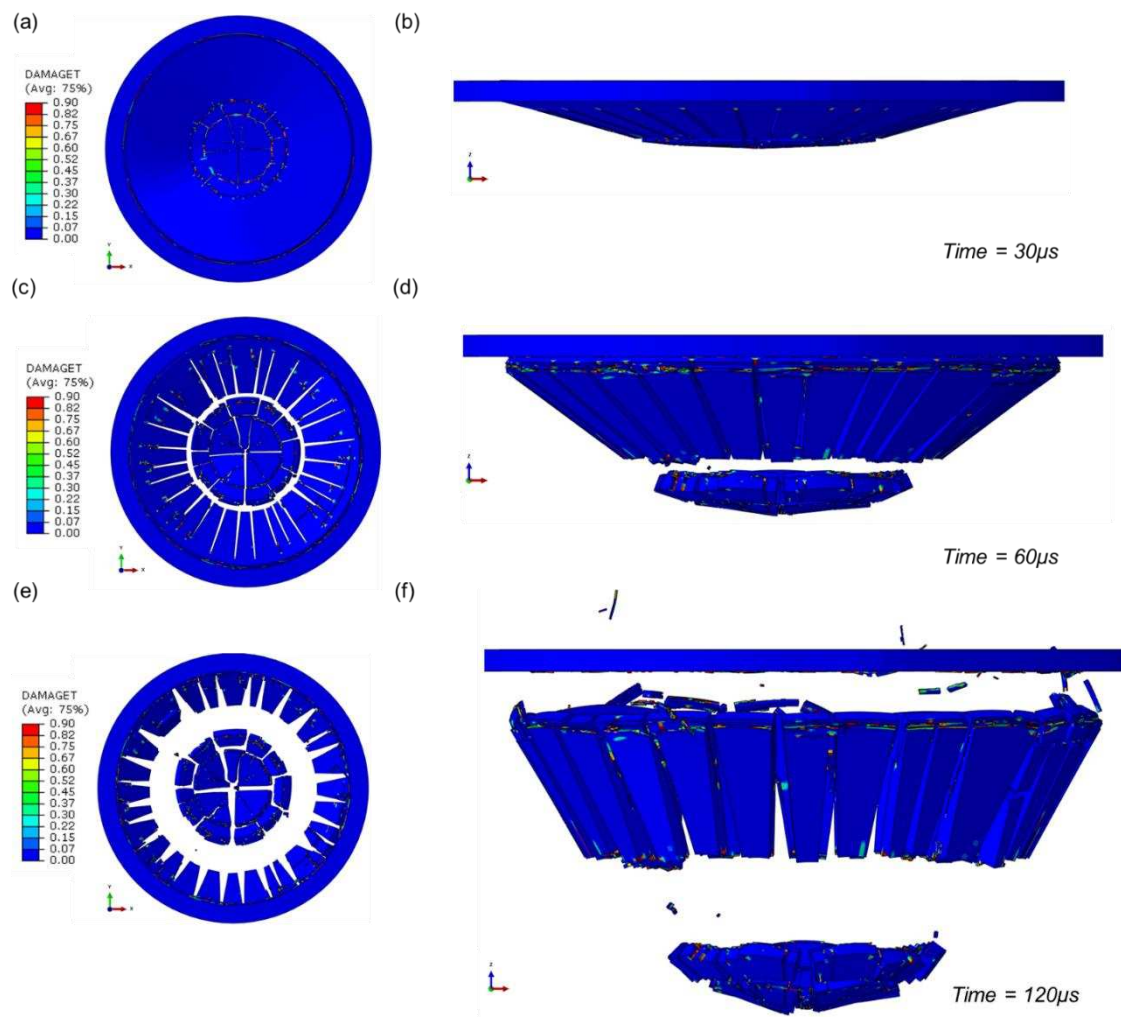


417
 418 Figure 14. Validation of the FE model using ballistic limit tests on 6 mm thick syntactic foam samples:
 419 (a) residual velocity, (b) the simulated failure modes (V_I = impact velocity, V_R = residual velocity).

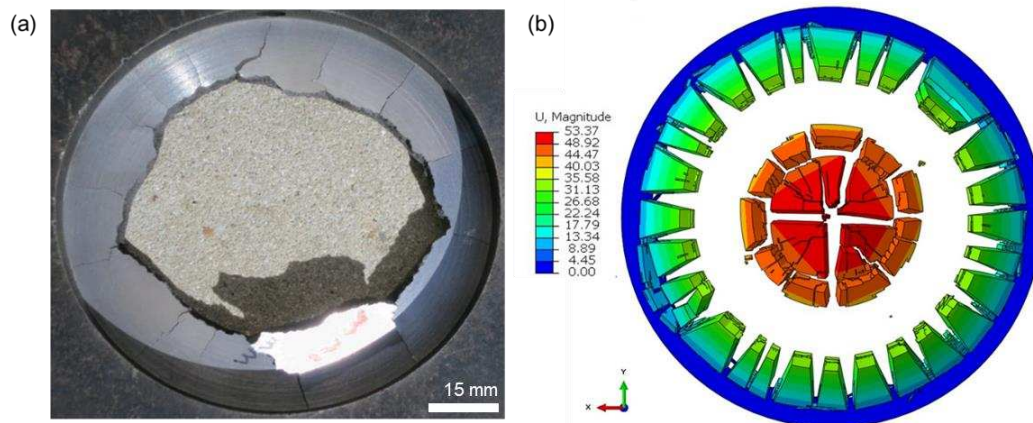
420
 421 4.2.3 Modelling blast response

422 The simulations for blast tests were performed for the syntactic foams with two different
 423 thicknesses in order to predict different damage patterns observed during experiments. The validation
 424 was carried out on the damage profiles on the front and back face of the foam panels. Firstly, a thin
 425 sample (thickness = 3 mm) subjected to an impulse of 2 Ns was simulated to validate the model for the
 426 target experienced a complete failure. The front face and side views of the failed foam panel after the
 427 blast simulation are shown in Figure 15. The thin target exhibits a complete failure in the central high-
 428 pressure zone as well as the area around the clamped boundary. The failed target is compared with the
 429 corresponding experimentally failed sample in Figure 16. The FE simulations shows good correlation
 430 with respect to the size of the crater and the radial cracks that are evident in the test sample. The

431 simulations show more uniform damage compared to the tests due to the uniformly applied boundary
 432 conditions and loads and homogenous modelling of the syntactic foams.

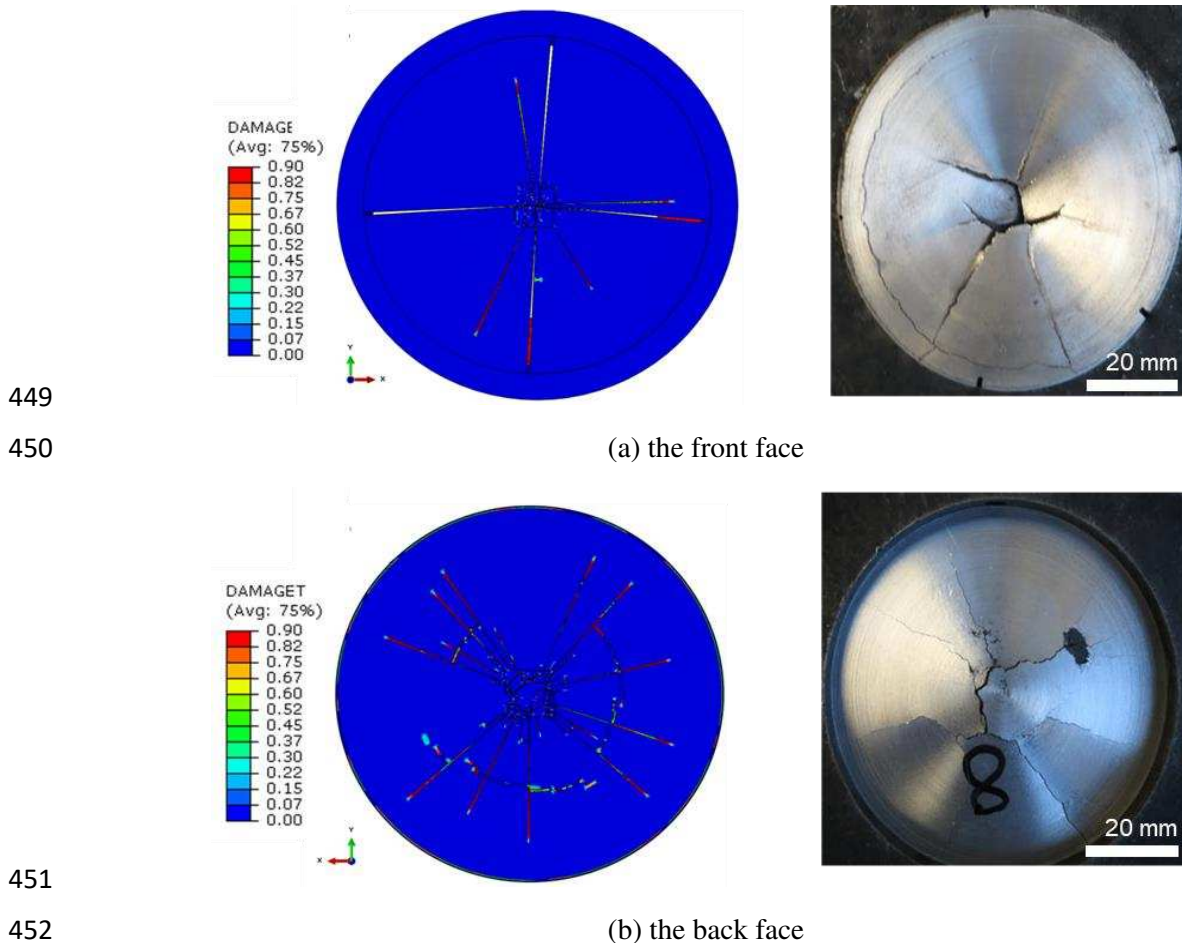


433
 434 Figure 15. Front face and side views of the damage profile of a 3 mm thick syntactic foam subjected to
 435 an impulse of 2 Ns detonated at a stand-off distance of 180mm at different time steps.



436
 437 Figure 16. Failure mode of a 3 mm thick syntactic foam subjected to a blast impulse of 2 Ns
 438 detonated at a stand-off distance of 180mm (a) Experimental and (b) FEA.

439 Secondly, the blast response of a thick foam panel (thickness = 14 mm) subjected to an impulse
 440 of 4.82 Ns was modelled for validation of the model to capture the related damage profile without the
 441 total failure. The simulated failure mode is compared with the experimental one, as shown in Figure 17.
 442 The front face shows the damage initiated in the centre with a few cracks propagating radially towards
 443 the clamping boundary, as shown in both the experimental and FE results (Fig. 17a). A circumferential
 444 crack can also be observed on both the tested and simulated panels where the specimen was clamped.
 445 The simulated damage profile on the back face (Fig. 17b) is similar to that on the front face, but with
 446 more radial cracks, which captures the experimental failure profile reasonably well. The foam panels
 447 tested, with non-homogenous nature, exhibit more random crack patterns in the damaged zones, whereas
 448 the homogenous FE models predict damage in a more uniform manner, as expected.



454 Figure 17. The predicted and experimental damage profiles of the 14 mm thick syntactic foam
 455 subjected to an impulse of 4.82 Ns detonated at a stand-off distance of 180mm.

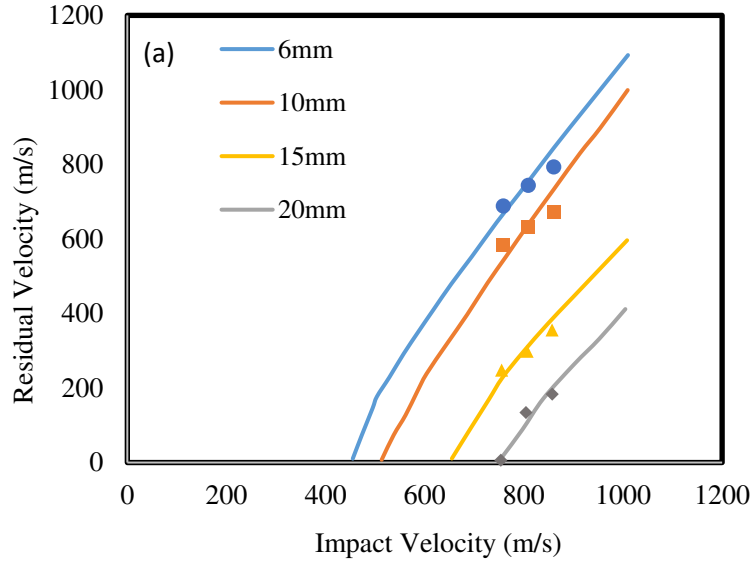
456

457 4.2.4 Prediction of ballistic response of syntactic foams subjected to normal and oblique impacts

458 The validated FE model was used to study the ballistic impact response of an AK47 projectile
 459 impacting on syntactic foams with four different thicknesses. The ballistic limits for these panels were
 460 determined to predict the thickness required to stop the projectile for NIJ III standard velocity (750
 461 m/s)[62]. The results for the ballistic limit studies are shown in Figure 18(a), the method of least squares
 462 using the Lambert-Jonas equation [61] is used to apply a curve fit to the FE results.

$$463 \quad V_R = a(V_I^b - V_{BL}^b)^{\frac{1}{b}} \quad (10)$$

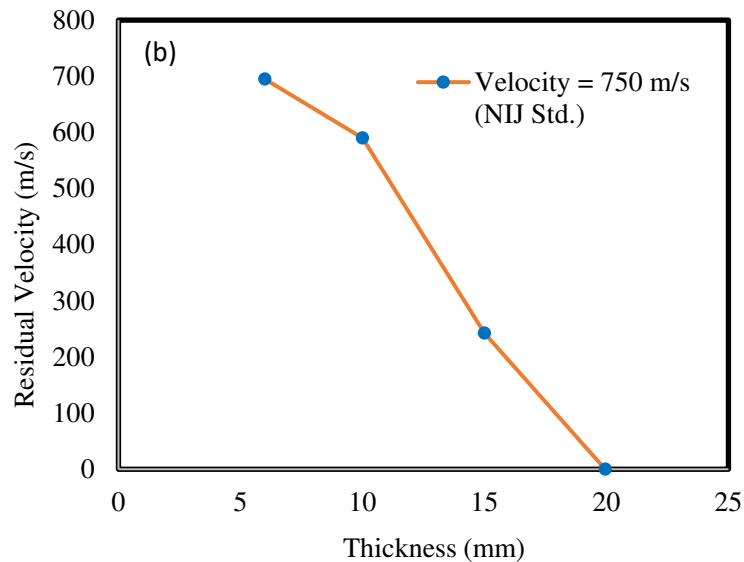
464 where V_R is the residual velocity, V_I is the impact velocity, V_{BL} is the ballistic limit, a and b are curve
 465 fitting constants. From Figure 18(a), it can be seen that in order to achieve a ballistic limit for an impact
 466 velocity of 750 m/s (NIJ standard), the required thickness is around 20 mm. The residual velocities for
 467 each of the four thicknesses impacted at 750 m/s are shown in Figure 18(b). The simulations of the
 468 ballistic impact behaviour using the validated models for normal and oblique impacts are discussed
 469 below.



470

471

(a)

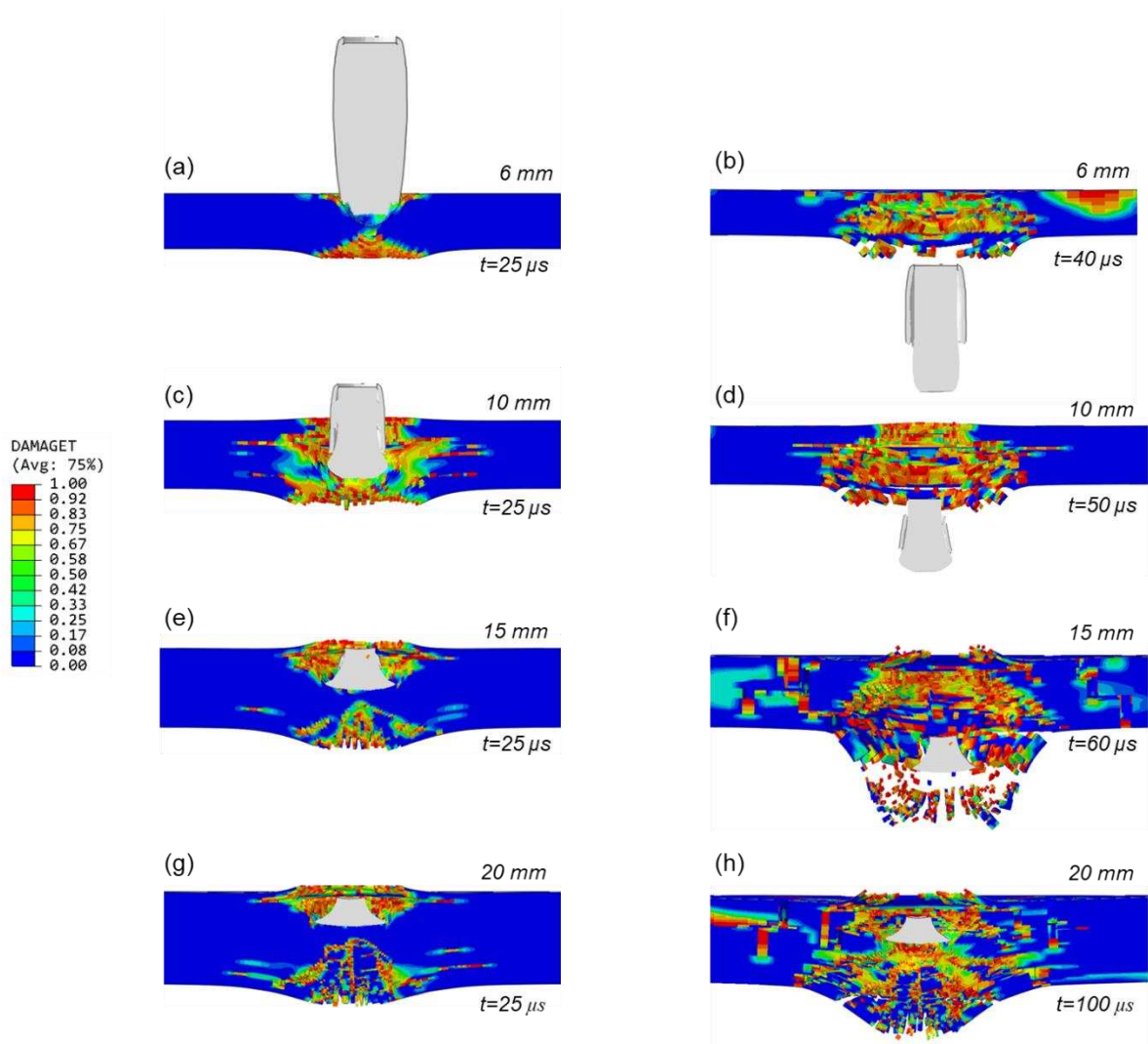


472

473 Figure 18. Determining the ballistic limits of different thicknesses (a) $V_R - V_I$ plot for 4 different
 474 thicknesses (b) V_R as a function of thickness for $V_I = 750$ m/s

475 Normal Impact (90°)

476 Most standard ballistic tests are conducted with the projectile impacting perpendicular to the
 477 target (normal impact). The FE simulation results for normal impact on the foam panels based on four
 478 thicknesses are shown in Figure 19. The contour plots for tensile damage are shown to help study the
 479 damage evolution through the various time steps. The 6 mm thick sample (Figures 19a-19b) was fully
 480 perforated with very little damage to the projectile. The mushrooming of the projectile core can be
 481 witnessed for the 10 mm thick sample (Figures 19c-19d). The projectile penetrates the target completely
 482 but with a lower residual velocity. Significant deformation of the projectile can be observed during
 483 impact on the foam panels with thicknesses of 15 and 20 mm, where the target is able to completely
 484 blunt and flatten the projectile front (Figures 19e-19h). The bullet is completely arrested in the 20mm
 485 thick sample, even though damage occurs in the back face of the target (Figure 19h). This phenomenon
 486 is common in brittle materials, where tensile damage can be seen on the back face even if the projectile
 487 is completely stopped. Hence, most armour configurations involving a ceramic front face have a ductile
 488 backing material to eliminate damage on the back face.



489

490 Figure 19. Ballistic simulation results for normal impact (90°) for 4 different thicknesses shown at 2
 491 different time steps.

492

493 Prediction of oblique Impact (30° and 45°)

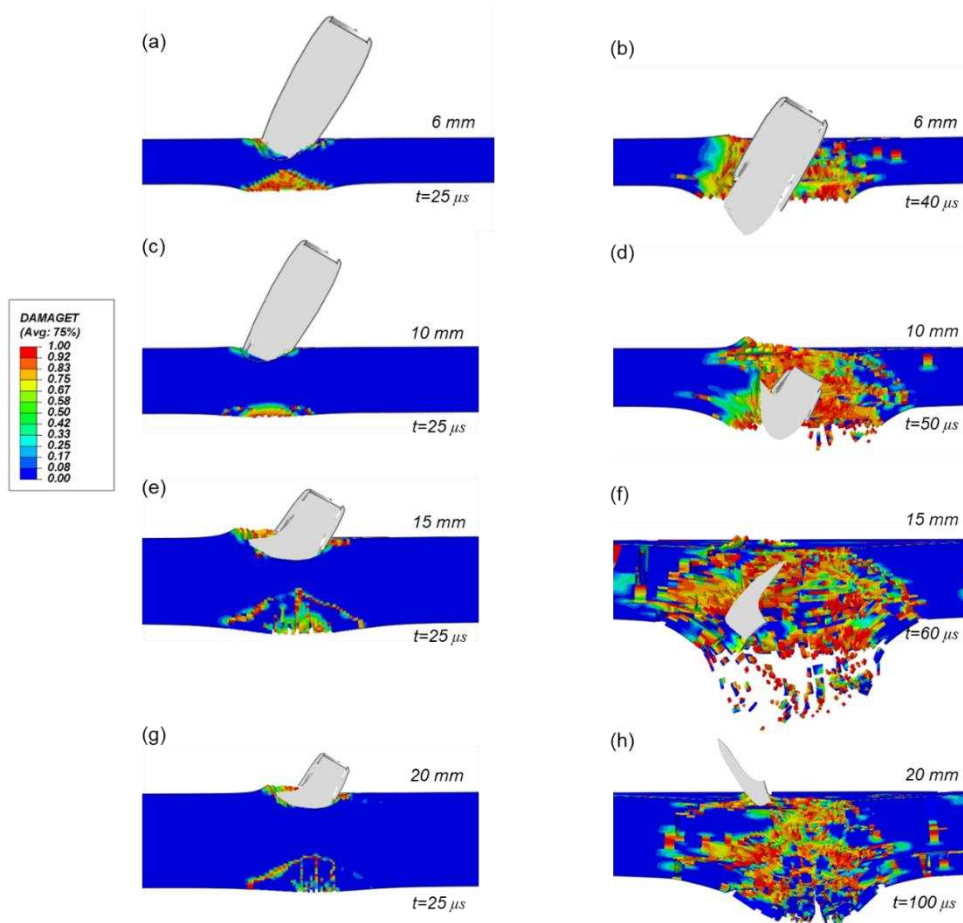
494 Ballistic tests performed under normal impact, though critical in determining the ballistic limit,
 495 fail to capture the ricochet effect when there are slight variations in the angle of impact. These studies
 496 become extremely important when we deal with armour configurations for vehicles and buildings. The
 497 FE model setup for oblique impacts at 30° and 45° are shown in Figure 20. The FE simulation results
 498 for these oblique impacts are shown in Figures 21 and 22. The 6 mm thick samples are easily perforated
 499 in both cases (Figures 21a-21b, Figures 22a-22b), as in the case of normal impact. The angle of impact
 500 causes considerable plastic deformation in the projectile and it starts to deform outwards, as can be seen
 501 for the foam panels with thicknesses of 10 mm and above. This phenomenon is more evident in 45°

502 oblique impact cases. The projectile completely perforates the 10 mm target in both cases, while in the
 503 15 mm target, the angle of impact causes the bullet to rotate within the target material (Figure 21f and
 504 Figure 22f). The rotated bullet finally bounces back and comes out from the front face of the foam panel.
 505 The ricochet effect can be seen in both the 30° and 45° oblique impacts for a target thickness of 20 mm.
 506 The effect is enhanced at higher angles where the bullet slides off the front face resulting in large plastic
 507 deformations (Figure 22h).



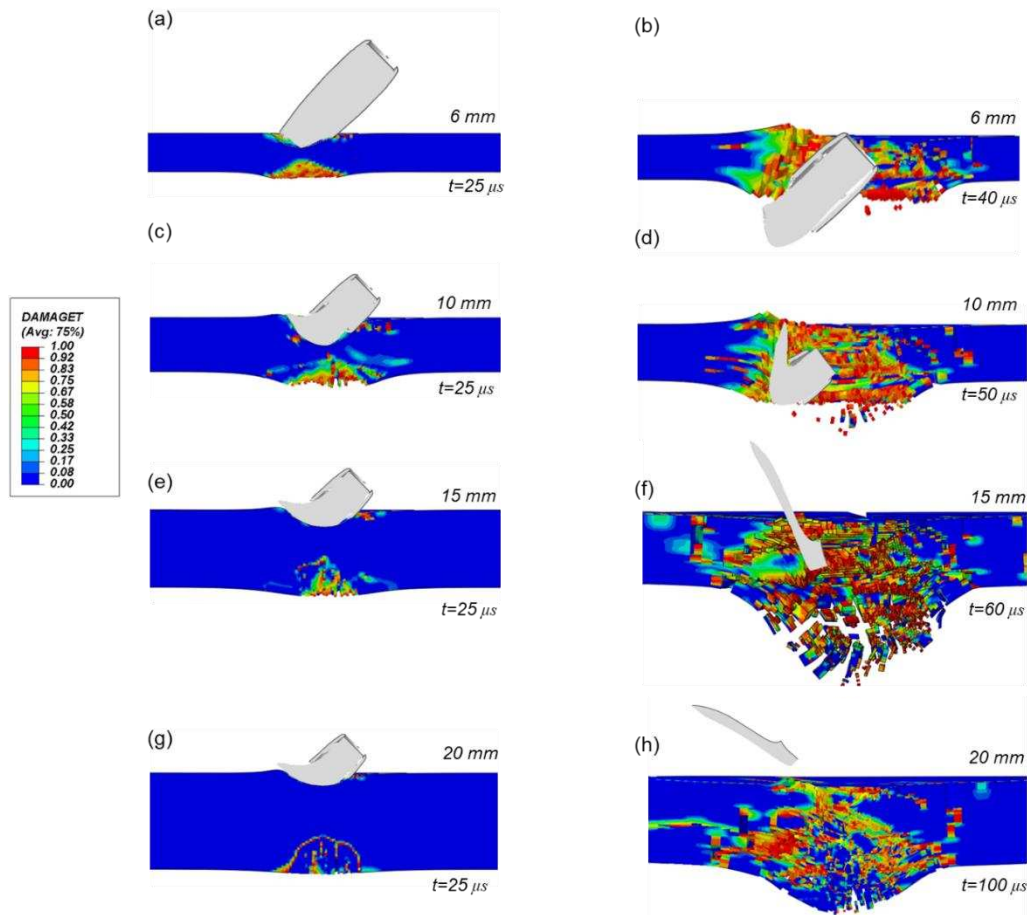
508
509

Figure 20. FE model set up for oblique impact (a) 30° impact (b) 45° impact



510
511
512

Figure 21. Ballistic simulation results for oblique impact (30°) on 4 different thicknesses of panel at 2 different time steps.



513

514 Figure 22. Ballistic simulation results for oblique impact (45°) on 4 different thicknesses of panel at 2
 515 different time steps.

516

517 The parametric studies using the validated FE model have provided interesting predictions of impact
 518 responses of aluminium matrix syntactic foams subjected to normal and oblique projectile impact,
 519 associated with the foams with various thicknesses. The outputs can be used to assisting design of such
 520 the foam panels with the homogenised modelling approach.

521 **5. Conclusions**

522 The dynamic response of aluminium matrix syntactic foams subjected to quasi-static and
 523 dynamic compression tests, Split Hopkinson Pressure Bar impact, terminal ballistic impact and blast
 524 loading have been investigated. Finite element models have been established using Abaqus/Explicit to
 525 simulate the dynamic response of the foam under compression, ballistic impact and blast loading. The
 526 concrete damaged plasticity model is shown to offer potential for modelling the damage evolution in

527 such the quasi-brittle materials. The simulations have shown that the FE models capture the essential
528 features of the response of the foams. The ballistic impact model was capable of accurately predicting
529 partial and full perforation of the samples. Parametric studies have been carried out to establish the
530 influence of sample thickness on the ballistic limit velocity. The effect of impact angle on the ballistic
531 performance of these samples has been studied in order to capture ricochet effects. The predictions from
532 the blast model are in a good agreement with the experimental tests. The experimental and modelling
533 studies have led to the following conclusions

- 534 (i) Experimental and modelling results for the compression test reveals formation of cracks
535 along a shear plane 45° with the base plane of the specimen consistent with the existing
536 research.
- 537 (ii) The SHPB results have shown that the dynamic Young's modulus and the yield strength
538 (peak stress) as well as plateau stress of the aluminium syntactic foams are rate-dependent,
539 with all of them increasing with increasing strain-rate. Such strain-rate sensitivity is even
540 more significant at strain-rates above 1000 s^{-1} .
- 541 (iii) The results of ballistic impact tests (normal impact) have shown that 13 mm thick
542 aluminium syntactic foams can stop a projectile at a velocity of 120 m/s. An aluminium
543 syntactic foam with a thickness of 20 mm is required to arrest the 7.62 x 39mm projectile
544 at a standard velocity of 750 m/s. Even though the projectile is arrested within the sample,
545 there is considerable damage at the back face of the specimen, indicating the requirement
546 of a backing material.
- 547 (iv) Finite element simulations of oblique impact at a velocity of 750 m/s on syntactic foams
548 show that thicker samples (greater than 10 mm) result in partial or complete rebounding of
549 the projectile, especially at higher impact angles. These studies can be used to identify
550 different strike/back face materials for ensuring the containment of a projectile within the
551 target.
- 552 (v) Blast test results have shown that foams with a thickness of 14 mm are able to withstand
553 only low blast loads. The aluminium syntactic foam is too brittle to sustain high blast loads
554 unless it is used as a core material in a sandwich structure.

555 **Acknowledgements**

556 The authors would like to thank Dr Gareth Appleby-Thomas who helps conduct ballistic impact tests in
557 Cranfield University.

558

559 **References**

560 [1] A.G. Hanssen, L. Enstock, M. Langseth, Close-range blast loading of aluminium foam panels,
561 *International Journal of Impact Engineering* 27(6) (2002) 593-618.

562 [2] N. Gupta, P. Rohatgi, *Metal matrix syntactic foams : processing, microstructure, properties and*
563 *applications*, 2015.

564 [3] I.N. Orbulov, K. Májlínger, Description of the compressive response of metal matrix syntactic foams,
565 *Materials & Design* 49 (2013) 1-9.

566 [4] L.C. Zou, Q. Zhang, B.J. Pang, G.H. Wu, L.T. Jiang, H. Su, Dynamic compressive behavior of
567 aluminum matrix syntactic foam and its multilayer structure, *Materials & Design* 45 (2013) 555–560.

568 [5] L. Licitra, D.D. Luong, O.M. Strbik, N. Gupta, Dynamic properties of alumina hollow particle filled
569 aluminum alloy A356 matrix syntactic foams, *Materials & Design* 66 (2015) 504-515.

570 [6] D.K. Balch, D.C. Dunand, Load partitioning in aluminum syntactic foams containing ceramic
571 microspheres, *Acta Materialia* 54(6) (2006) 1501-1511.

572 [7] D.K. Balch, J.G. O’Dwyer, G.R. Davis, C.M. Cady, G.T. Gray, D.C. Dunand, Plasticity and damage
573 in aluminum syntactic foams deformed under dynamic and quasi-static conditions, *Materials Science*
574 *and Engineering: A* 391(1) (2005) 408-417.

575 [8] L. Peroni, M. Scapin, M. Avalle, J. Weise, D. Lehmus, Dynamic mechanical behavior of syntactic
576 iron foams with glass microspheres, *Materials Science and Engineering: A* 552 (2012) 364-375.

577 [9] D.D. Luong, V.C. Shunmugasamy, N. Gupta, D. Lehmus, J. Weise, J. Baumeister, Quasi-static and
578 high strain rates compressive response of iron and Invar matrix syntactic foams, *Materials & Design* 66
579 (2015) 516-531.

580 [10] K. Myers, B. Katona, P. Cortes, I.N. Orbulov, Quasi-static and high strain rate response of
581 aluminum matrix syntactic foams under compression, *Composites Part A: Applied Science and*
582 *Manufacturing* 79 (2015) 82-91.

583 [11] D.P. Mondal, S. Das, N. Ramakrishnan, K. Uday Bhasker, Cenosphere filled aluminum syntactic
584 foam made through stir-casting technique, *Composites Part A: Applied Science and Manufacturing*
585 40(3) (2009) 279-288.

586 [12] M.M. Su, H. Wang, K.Y. Li, H. Hao, Microstructure and Compressive Properties of Al/Al₂O₃
587 Syntactic Foams, *Materials Science Forum* 933 (2018) 174-181.

588 [13] C.A. Vogiatzis, A. Tsouknidas, D.T. Kountouras, S. Skolianos, Aluminum–ceramic cenospheres
589 syntactic foams produced by powder metallurgy route, *Materials & Design* 85 (2015) 444-454.

590 [14] C. San Marchi, F. Cao, M. Kouzeli, A. Mortensen, Quasistatic and dynamic compression of
591 aluminum-oxide particle reinforced pure aluminum, *Materials Science and Engineering: A* 337(1)
592 (2002) 202-211.

593 [15] J.A. Santa Maria, B.F. Schultz, J.B. Ferguson, P.K. Rohatgi, Al–Al₂O₃ syntactic foams – Part I:
594 Effect of matrix strength and hollow sphere size on the quasi-static properties of Al-A206/Al₂O₃
595 syntactic foams, *Materials Science and Engineering: A* 582 (2013) 415-422.

596 [16] E. Lamanna, N. Gupta, P. Cappa, O.M. Strbik, K. Cho, Evaluation of the dynamic properties of an
597 aluminum syntactic foam core sandwich, *Journal of Alloys and Compounds* 695 (2017) 2987-2994.

598 [17] Y.M. Chordiya, M.D. Goel, Low Velocity Impact Behavior of Aluminum Cenosphere Syntactic
599 Foam, *Materials Today: Proceedings* 18 (2019) 3741-3748.

600 [18] Y. Zhang, Y. Zhao, Hysteretic energy dissipation in aluminium matrix syntactic foam under
601 intermittent cyclic compression, *Materialia* 6 (2019) 100286.

602 [19] I.N. Orbulov, A. Kemény, Á. Filep, Z. Gácsi, Compressive characteristics of bimodal aluminium
603 matrix syntactic foams, *Composites Part A: Applied Science and Manufacturing* 124 (2019) 105479.

604 [20] I.N. Orbulov, A. Szlancsik, A. Kemény, D. Kincses, Compressive mechanical properties of low-
605 cost, aluminium matrix syntactic foams, *Composites Part A: Applied Science and Manufacturing* 135
606 (2020) 105923.

607 [21] S. Sahu, M.Z. Ansari, D.P. Mondal, Microstructure and compressive deformation behavior of 2014
608 aluminium cenosphere syntactic foam made through stircasting technique, *Materials Today:*
609 *Proceedings* 25 (2020) 785-788.

610 [22] H. Dave, K. Samvatsar, A comprehensive review on aluminium syntactic foams obtained by
611 dispersion fabrication methods, *Materials Today: Proceedings* 47 (2021) 4243-4248.

612 [23] H. Anantharaman, V.C. Shunmugasamy, O.M. Strbik, N. Gupta, K. Cho, Dynamic properties of
613 silicon carbide hollow particle filled magnesium alloy (AZ91D) matrix syntactic foams, *International*
614 *Journal of Impact Engineering* 82 (2015) 14-24.

615 [24] D.P. Mondal, J. Datta Majumder, N. Jha, A. Badkul, S. Das, A. Patel, G. Gupta, Titanium-
616 cenosphere syntactic foam made through powder metallurgy route, *Materials & Design* 34 (2012) 82-
617 89.

618 [25] L. Pan, Y. Yang, M.U. Ahsan, D.D. Luong, N. Gupta, A. Kumar, P.K. Rohatgi, Zn-matrix syntactic
619 foams: Effect of heat treatment on microstructure and compressive properties, *Materials Science and*
620 *Engineering: A* 731 (2018) 413-422.

621 [26] A. Daoud, Effect of strain rate on compressive properties of novel Zn₁₂Al based composite foams
622 containing hybrid pores, *Materials Science and Engineering: A* 525(1) (2009) 7-17.

623 [27] S. Broxtermann, M. Vesenjajk, L. Krstulović-Opara, T. Fiedler, Quasi static and dynamic
624 compression of zinc syntactic foams, *Journal of Alloys and Compounds* 768 (2018) 962-969.

625 [28] M.Y. Omar, C. Xiang, N. Gupta, O.M. Strbik, K. Cho, Syntactic foam core metal matrix sandwich
626 composite under bending conditions, *Materials & Design* 86 (2015) 536-544.

627 [29] J.B. Ferguson, J.A. Santa Maria, B.F. Schultz, P.K. Rohatgi, Al–Al₂O₃ syntactic foams—Part II:
628 Predicting mechanical properties of metal matrix syntactic foams reinforced with ceramic spheres,
629 *Materials Science and Engineering: A* 582 (2013) 423-432.

630 [30] M.Y. Omar, C. Xiang, N. Gupta, O.M. Strbik, K. Cho, Data characterizing compressive properties
631 of Al/Al₂O₃ syntactic foam core metal matrix sandwich, *Data in Brief* 5 (2015) 522-527.

632 [31] M.Y. Omar, C. Xiang, N. Gupta, O.M. Strbik, K. Cho, Data characterizing flexural properties of
633 Al/Al₂O₃ syntactic foam core metal matrix sandwich, *Data in Brief* 5 (2015) 564-571.

634 [32] D. Luong, O. Strbik, V. Hammond, N. Gupta, K. Cho, Development of high performance
635 lightweight aluminum alloy/SiC hollow sphere syntactic foams and compressive characterization at
636 quasi-static and high strain rates, *Journal of Alloys and Compounds* 550 (2013) 412-422.

637 [33] M. Su, J. Li, M. Li, H. Hao, Microstructure and mechanical properties of bimodal syntactic foams
638 with different size combination and volume fraction of alumina hollow spheres, *Materials Science and*
639 *Engineering: A* 824 (2021) 141798.

640 [34] N. Movahedi, M. Vesenjak, L. Krstulović-Opara, I.V. Belova, G.E. Murch, T. Fiedler, Dynamic
641 compression of functionally-graded metal syntactic foams, *Composite Structures* 261 (2021) 113308.

642 [35] M. Salehi, S.M.H. Mirbagheri, A.J. Ramiani, Efficient energy absorption of functionally-graded
643 metallic foam-filled tubes under impact loading, *Transactions of Nonferrous Metals Society of China*
644 31(1) (2021) 92-110.

645 [36] M. Bhandari, K. Purohit, Dynamic Fracture Analysis of Functionally Graded Material Structures –
646 A Critical Review, *Composites Part C: Open Access* 7 (2022) 100227.

647 [37] I.N. Orbulov, Metal matrix syntactic foams produced by pressure infiltration—The effect of
648 infiltration parameters, *Materials Science and Engineering: A* 583 (2013) 11-19.

649 [38] A. S-de-la-Muela, L. Cambronero, J. Ruiz Román, Molten Metal Infiltration Methods to Process
650 Metal Matrix Syntactic Foams, *Metals* 10 (2020) 149.

651 [39] X.F. Tao, Y.Y. Zhao, Compressive behavior of Al matrix syntactic foams toughened with Al
652 particles, *Scripta Materialia* 61(5) (2009) 461-464.

653 [40] M.D. Goel, M. Peroni, G. Solomos, D.P. Mondal, V.A. Matsagar, A.K. Gupta, M. Larcher, S.
654 Marburg, Dynamic compression behavior of cenosphere aluminum alloy syntactic foam, *Materials &*
655 *Design* 42 (2012) 418-423.

656 [41] M. Altenaiji, Z.W. Guan, W.J. Cantwell, Y. Zhao, G.K. Schleyer, Characterisation of aluminium
657 matrix syntactic foams under drop weight impact, *Materials & Design* 59 (2014) 296-302.

658 [42] V.S. Deshpande, N.A. Fleck, High strain rate compressive behaviour of aluminium alloy foams,
659 *International Journal of Impact Engineering* 24(3) (2000) 277-298.

660 [43] K. Dharmasena, H.N.G. Wadley, Z. Xue, J. Hutchinson, Mechanical Response of Metallic
661 Honeycomb Sandwich Panel Structures to High-Intensity Dynamic Loading, *International Journal of*
662 *Impact Engineering - INT J IMPACT ENG* 35 (2008) 1063-1074.

663 [44] Z. Fan, F. Zhang, B. Zhang, T. He, P. Xu, X. Cai, Modelling the dynamic compressive response of
664 syntactic foam with hierarchical cell structure, *Cement and Concrete Composites* 124 (2021) 104248.

665 [45] Y. Wang, Q. Liu, B. Zhang, H. Zhang, Y. Jin, Z. Zhong, J. Ye, Y. Ren, F. Ye, W. Wang, Dynamic
666 compressive response and impact resistance of bioinspired nacre-like 2024Al/B4C composites,
667 Materials Science and Engineering: A 831 (2022) 142261.

668 [46] Z. Li, Z. Zheng, J. Yu, Low-velocity perforation behavior of composite sandwich panels with
669 aluminum foam core, Journal of Sandwich Structures and Materials 15 (2012) 92-109.

670 [47] D. Radford, G. McShane, V.S. Deshpande, N. Fleck, The response of clamped sandwich plates
671 with metallic foam cores to simulated blast loading, International Journal of Solids and Structures - INT
672 J SOLIDS STRUCT 43 (2006) 2243-2259.

673 [48] H. Kolsky, An Investigation of Mechanical Properties of Materials at Very High Rates of Loading,
674 Proceedings of the Physical Society. Section B 62 (2002) 676.

675 [49] I.G. Crouch, G. Appleby-Thomas, P.J. Hazell, A study of the penetration behaviour of mild-steel-
676 cored ammunition against boron carbide ceramic armours, International Journal of Impact Engineering
677 80 (2015) 203-211.

678 [50] N. Jacob, S. Chung Kim Yuen, G.N. Nurick, D. Bonorchis, S.A. Desai, D. Tait, Scaling aspects of
679 quadrangular plates subjected to localised blast loads—experiments and predictions, International
680 Journal of Impact Engineering 30(8) (2004) 1179-1208.

681 [51] R. Wharton, S.A. Formby, R. Merrifield, Airblast TNT equivalence for a range of commercial
682 blasting explosives, Journal of hazardous materials 79 (2001) 31-9.

683 [52] G. Nurick, G. Langdon, Y. Chi, N. Jacob, Behaviour of sandwich panels subjected to intense air
684 blast – Part 1: Experiments, Composite Structures - COMPOS STRUCT 91 (2009) 433-441.

685 [53] M. Yahya, The Blast Response of Fibre Reinforced Composites and Sandwich Structures,
686 University of Liverpool, 2008.

687 [54] Abaqus, Abaqus documentation, Version 6 (2014) 1-5.

688 [55] G.R. Johnson, W.H. Cook, Fracture characteristics of three metals subjected to various strains,
689 strain rates, temperatures and pressures, Engineering Fracture Mechanics 21(1) (1985) 31-48.

690 [56] L. Carbajal, J. Jovicic, H. Kuhlmann, Assault Rifle Bullet-Experimental Characterization and
691 Computer (FE) Modeling, Conference proceedings of the Society for Experimental Mechanics Series.
692 Experimental and applied mechanics 6 (2011).

693 [57] Z.W. Guan, A. Aktas, P. Potluri, W.J. Cantwell, G. Langdon, G.N. Nurick, The blast resistance of
694 stitched sandwich panels, *International Journal of Impact Engineering* 65 (2014) 137-145.

695 [58] R.G. Teeling-Smith, G.N. Nurick, The deformation and tearing of thin circular plates subjected to
696 impulsive loads, *International Journal of Impact Engineering* 11(1) (1991) 77-91.

697 [59] I. Kozma, D. Harangozó, H. Hargitai, I. Zsoldos, *DISPLACEMENT-BASED FAILURE*
698 *ANALYSIS OF METAL MATRIX SYNTACTIC FOAM*, 2019.

699 [60] I. Kozma, I. Zsoldos, CT-based tests and finite element simulation for failure analysis of syntactic
700 foams, *Engineering Failure Analysis* 104 (2019) 371-378.

701 [61] G.H. Jonas, J.A. Zukas, Mechanics of penetration: Analysis and experiment, *International Journal*
702 *of Engineering Science* 16(11) (1978) 879-903.

703 [62] A. Bhatnagar, 5 - Standards and specifications for lightweight ballistic materials, in: A. Bhatnagar
704 (Ed.), *Lightweight Ballistic Composites*, Woodhead Publishing 2006, pp. 127-167.

705