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25 **Abstract**

26

27 Additive manufacturing (AM) enables production of geometrically-complex elastomeric
28 structures. The elastic recovery and strain-rate dependence of these materials means they
29 are ideal for use in dynamic, repetitive mechanical loading. Their process-dependence, and
30 the frequent emergence of new AM elastomers, commonly necessitates full material
31 characterisation; however, accessing specialised equipment means this is often a time-
32 consuming and expensive process. This work presents an innovative equi-biaxial rig that
33 enables full characterisation via just a conventional material testing machine (supplementing
34 uni-axial tension and planar tension tests). Combined with stress relaxation data, this
35 provides a novel route for hyperelastic material modelling with viscoelastic components.
36 This approach was validated by recording the force-displacement and deformation histories
37 from finite element modelling a honeycomb structure. These data compared favourably to
38 experimental quasistatic and dynamic compression testing, validating this novel and
39 convenient route for characterising complex elastomeric materials. Supported by data
40 describing the potential for high build-quality production using an AM process with low
41 barriers to entry, this study should serve to encourage greater exploitation of this emerging
42 manufacturing process for fabricating elastomeric structures within industrial communities.

43

44 **Keywords**

45 *Elastomeric Polymer Characterisation; Hyperelastic; High strain-rate FEA analysis; Cellular*
46 *Structures; Viscoelastic*

47

48 **1. Introduction**

49

50 Thermoplastic elastomers (TPEs) are co-polymeric materials that exhibit both thermoplastic
51 and elastomeric properties, with their functional advantages meaning they are used across a
52 broad range of applications. Tooling costs associated with traditional manufacturing
53 methods typically constrains TPE production to high volume components only, limiting
54 opportunities to lever a performance advantage. The emergence of additive manufacturing
55 (AM), with unrivalled design freedom and the economic-viability of one-off production,
56 provides new opportunities to employ TPEs in environments demanding low-volume, high-
57 performance, or both.

58

59 Finite element analysis (FEA) simulations are well-established in the design, testing and
60 evaluation of new and novel applications. Emerging techniques including topology
61 optimisation and cellular lattice generation have supplemented this process, guiding
62 designers with an over-riding objective function that prescribes the ultimate mechanical
63 performance [1, 2]. These approaches are now being used in a series of, predominantly
64 metal-based, weight-sensitive applications [3, 4].

65

66 The success of optimisation techniques is inherently governed by the accuracy of the
67 material behaviour defined within the simulation. Where the analytical descriptor of a
68 material's behaviour correlates poorly with its physical performance, the simulation will likely
69 deliver an inaccurate solution. TPEs, which exhibit a hyper-elastic (HE) response, can be
70 particularly challenging to characterise due to phenomena such as the Mullin's effect [5],
71 where stress-softening occurs based on the previous level of strain experienced by the
72 material. This results in the material's primary response (i.e. that to the first loading) differing
73 from that of subsequent loading cycles (i.e. the stabilised response). Determining if one, or

74 both, of these responses are of importance to an application, is key to accurately simulating
75 HE events.

76

77 The non-linear HE response of TPE materials means they cannot be characterised by a
78 single data-point. Established constitutive models comprise a series of coefficients
79 associated with strain energy density functions capturing the variation of stress versus strain,
80 with advanced FEA software enabling the end-user to identify the model with the strongest
81 correlation to experimental data. Coefficients describing AM-produced materials typically
82 differ from traditionally manufactured equivalents [6, 7]. Whilst characterisation of AM
83 metallic structures have now been reported [8, 9], no studies quantify the rate-dependant
84 behaviour of HE AM material properties when simulating dynamic events. The technical
85 demands of such characterisation, with laboratories rarely having the requisite facilities
86 including a stand-alone equi-biaxial testing apparatus [10], risks constraining the
87 development and uptake of new TPE AM filaments and powders.

88

89 This study describes a novel experimental approach to characterise TPE materials for
90 applications experiencing strain-rates in excess of quasistatic conditions (referred to as
91 dynamic strain-rate applications), using solely a commonplace uniaxial testing machine.
92 Primary, stabilised and rate-dependant responses were captured and then fitted with an
93 appropriate HE/viscoelastic material model. Computational analysis of an exemplar TPE AM
94 structure within a dynamic strain-rate environment demonstrates both the validity of this
95 characterisation process, and the potential to enable high-performance designs.

96 **2. Materials and Methods**

97

98 Uniaxial, equi-biaxial, and planar tension data was collected to define the HE behaviour, for
99 both primary and stabilised responses. Rate-dependant behaviour was defined by stress
100 relaxation data. For uniaxial, equi-biaxial and planar tests, strain in the gauge area was
101 measured using non-contact video-extensometry (iMetrum CAM028, UK). All stresses and
102 strains are reported as nominal (i.e. engineering) data.

103

104 **2.1. Materials**

105

106 *Table 1. Printing parameters used for this study*

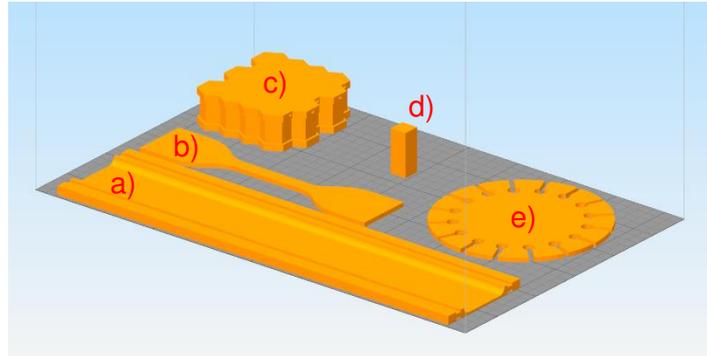
Nozzle Diameter	0.4 mm	Extrusion Multiplier	1.4
Print speed	2000 mm/min	Layer Height	100 μm
Bed Temperature	40 $^{\circ}\text{C}$	Active cooling	Yes
Extruder Temperature	210 $^{\circ}\text{C}$	Infill extrusion width	125%

107

108 SOLIDWORKS (Dassault Systems, France) was used to design coupons for each test
109 method that were manufactured in NinjaFlex (NinjaTek, US), a readily available TPE filament
110 selected as an exemplar AM material. A fused filament fabrication printer was used (2017
111 Flashforge Creator Pro printer), retrofitted with high-specification extrusion control (Diabase
112 Engineering, USA) and using processing parameters tuned to achieve a high extrusion
113 density. Simplify3D (Simplify3D, US) was used to define print settings and slice the .STL
114 files for printing. The common rectilinear pattern was adopted for in-filling the parts and X-
115 ray microscopy (XRM)/microcomputed tomography (μCT) was used to confirm successful
116 fusing of the infill extrudate. Infill was set to 100% and the extrusion settings tuned to ensure
117 fusing of the extrudate, allowing confidence that the infill pattern would have minimal effect

118 on experimental results. A honeycomb was also designed and manufactured for use as a
119 case study to demonstrate the validity of this novel characterisation methodology, with part
120 quality assessed via μ CT. Print orientation is shown in Figure 1.

121



122 *Figure 1. Test part build orientations. a) Planar, b) Uniaxial, c) Honeycomb geometry, d)*
123 *Cuboid for μ CT Scanning, e) Equi-biaxial*

124

125 2.2. Methods

126

127 A preliminary simulation was undertaken to establish the minimum/maximum strains
128 experienced during the loading of the honeycomb structure. This allowed identification of
129 the appropriate cycled strain during mechanical testing, used to describe the stabilised
130 response of the TPE material. A linear elastic model [11] was applied to the honeycomb
131 structure, which was compressed within ABAQUS to densification. The recorded strain was
132 approximately ± 0.3 throughout the simulated densification of the honeycomb (to $\sim 60\%$ of
133 its original height). This guided the adoption of an upper strain threshold of 0.4 for
134 mechanical testing.

135 During the preliminary simulation, a mesh sensitivity study was undertaken. Varying the
136 element size from one-quarter, to twice, the wall thickness, achieved near-identical force-

137 displacement curves and little variation in predicted energies, which is consistent with other
138 studies investigating dynamic compression of cellular structures [12].

139 Five samples were manufactured for each test setup described in section 2.2.1.

140

141 *2.2.1. Mechanical Testing*

142

143 *Uniaxial (Tension) Testing*

144

145 Testing was performed using an electromechanical uniaxial testing machine (Zwick Z50,
146 Germany), following ISO 37 [13] with a reduced crosshead speed (100mm/min), to minimise
147 strain rate sensitivity. Test coupons were designed and fabricated as per tensile testing
148 specimen type 1 [13]. Investigation was performed over cyclical loading to 0.4 strain.

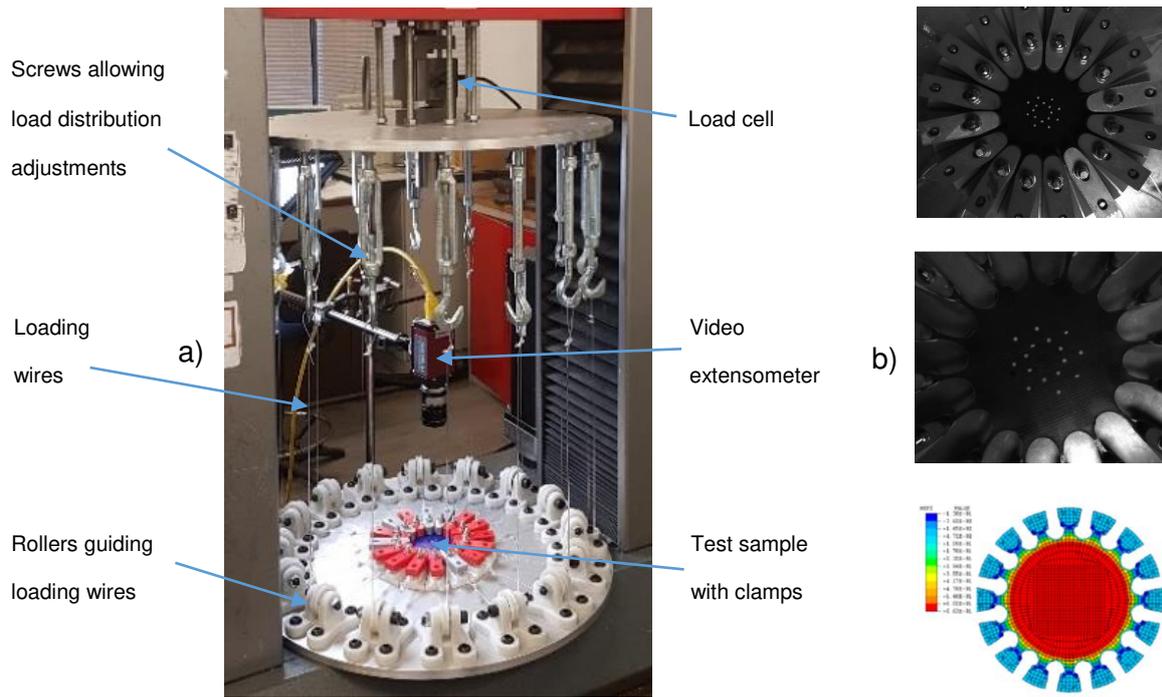
149

150 *Equi-Biaxial (Tension) Testing*

151

152 An equi-biaxial test apparatus was designed and built in-house, to enable multi-axial data
153 generation from a single uniaxial testing machine. Novel test coupons were designed and
154 manufactured, including 16 clamping tabs that enabled uniform application of a multi-axial
155 load, generating equi-biaxial strain in the coupon centre (Figure 2 a & b). These test
156 specimens have been shown to be appropriate for equi-biaxial testing [10], with FE analysis
157 showing little influence of geometry on the state of stress in the central gauge section.
158 Machine parameters and cycled strain were consistent with the uniaxial setup.

159



160 *Figure 2: a) Equi-biaxial test rig, b) Stretching of Equi-biaxial sample in this study, and FEA*
 161 *validation of sample performed by Day, J. (reproduced from [10])*

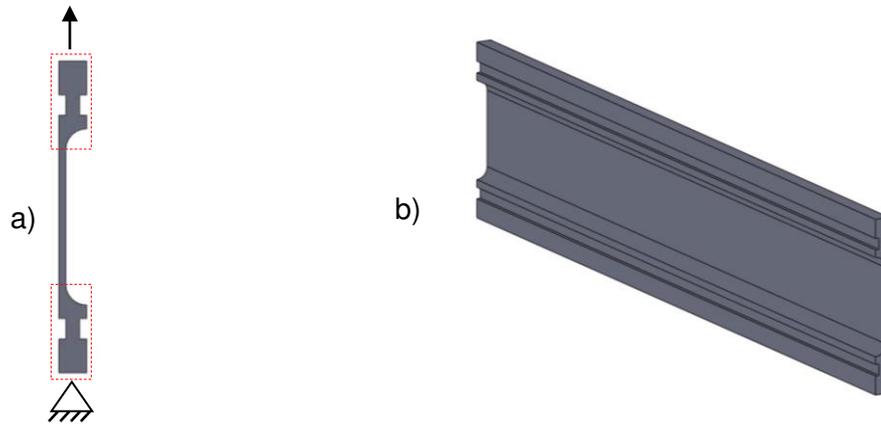
162

163 *Planar (Tension) Testing*

164 Shear data is valuable when modelling hyperelastic materials, which is derived from planar
 165 tension testing [14, 15]. Novel planar coupons were designed to include ridges, which
 166 improved gripping and ensured load distribution into the test gauge area (Figure 3 a & b).
 167 Machine parameters and cycled strain were again consistent with the uniaxial setup.

168

169



170 *Figure 3: a) Side profile highlighting ridges/added geometry on planar sample, b) 3D*
 171 *visualisation of planar sample*

172

173 *Stress Relaxation Testing*

174

175 The uniaxial test geometry was used to measure stress relaxation, performed at the
 176 maximum available cross-head speed (600mm/min), to a strain of 0.4 and followed by a
 177 100s relaxation period. Stress relaxation experiments cannot achieve an instantaneous step
 178 input and will always include an initial loading ramp, as well as inertial effects from the test
 179 equipment loading. The user must compensate for these effects when analysing the data,
 180 by back-calculating to a theoretical instantaneous load point, as has been performed here.

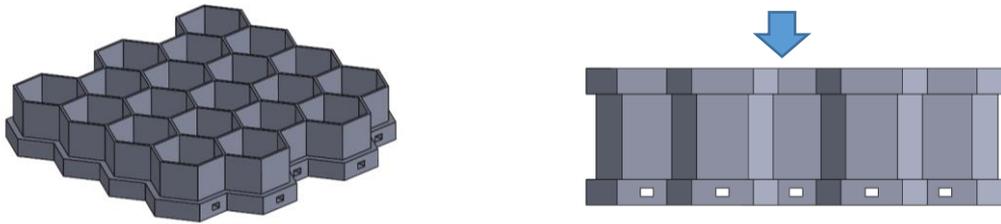
181 *Mechanical Testing of Exemplar TPE AM Honeycomb*

182

183 A NinjaFlex hexagonal honeycomb was designed and manufactured to validate the above
 184 characterisation process and to demonstrate the potential of AM TPEs to produce structures
 185 for high performance applications. The honeycomb structure consisted of a 4x5 unit cell,
 186 with each cell having a side length of 5.8mm, 10mm height and 0.4mm wall thickness. Two
 187 3mm thick solid sections were designed onto the upper and lower surfaces of the
 188 honeycomb, to achieve well-defined boundary conditions. Exhaust channels (1mm

189 diameter) were designed in to the lower solid section, enabling release of air trapped within
190 the honeycomb cavities during compression and impact testing.

191



192 *Figure 4. a) sectioned view of the honeycomb part, b) indication of load direction on part*

193

194 The honeycomb structure was cyclically compressed to densification (~60% of its original
195 height) at 100mm/min (i.e. quasistatically). Industrial-strength adhesive tape (Tesa 64621)
196 was used to adhere the solid sections to the compression platens, ensuring consistent
197 boundary conditions. Dynamic testing was then performed to evaluate the relative
198 performance of the TPE AM honeycomb in a dynamic strain rate environment. A guided
199 drop tower (Instron 9250HV, US) was used to strike the honeycomb test geometry with a
200 3.53kg impactor at 1.4 m/s. This velocity ensured the honeycomb compressed to >60% of
201 its overall height. An in-line accelerometer (Kistler 8715A, Switzerland) was used to record
202 the acceleration-time pulse. Boundary conditions were defined by the lower solid section of
203 the honeycomb geometry being adhered to the anvil, and the impactor and upper solid
204 section of the honeycomb being covered with sandpaper. The impactor was released from
205 0.01m, allowing dynamic compression of the honeycomb to 60% of its original height.
206 Acceleration-time pulses were converted using standard formulae into force-displacement
207 and displacement-time data.

208

209 *Statistical Analysis*

210

211 Results of each test method are displayed as a mean value, with error bars representing the
212 standard deviation (SD). All testing was performed through 5 cycles/impacts, to account for
213 stress softening behaviour in the material, which decreased markedly after the second cycle
214 and was cycled a further three times to ensure a stabilised response.

215

216 *2.2.2. Computational Analysis and Validation*

217

218 ABAQUS 6.14 (Dassault Systems, France) was used first to curve-fit an appropriate material
219 model to the primary and secondary responses (for dynamic simulations the viscoelastic
220 component was added to these material models), before enabling analysis of the primary
221 and stabilised performance of an exemplar honeycomb structure. An appropriate material
222 model was then selected based on the closest correlation with the test data. Explicit
223 Dynamic Analysis was used and, in addition to any other boundary conditions/interactions
224 defined in the simulation, a global frictionless contact was defined to prevent self-penetration
225 of the honeycomb. Incompressibility was assumed (i.e. Poisson's ratio = 0.475, as this is
226 the maximum allowable in ABAQUS) and enhanced hourglass control implemented. Hyper-
227 elastic material models were fitted separately to primary and stabilised datasets. Ogden 1st
228 to 6th order, Polynomial 1st and 2nd order and Reduced Polynomial 1st to 6th order models
229 were investigated for each state. The viscoelastic component of the material model was
230 defined using normalised stress relaxation data, fitted by ABAQUS to a Prony series with
231 0.001 minimum allowable root-mean-square error. A continuum element hex-dominated
232 mesh was proliferated throughout with a seed equal to the measured average wall thickness
233 of the honeycomb (0.45 mm); however, the 3mm thick upper and lower sections of the test

234 part were partitioned and given a larger (default) edge seed of 0.72 mm, to reduce the
235 computational cost.

236

237 Due to the honeycomb walls being the same thickness as the extrusion nozzle, it was
238 expected the manufactured wall thickness would increase. Average wall thickness was
239 measured by μ CT and used to update the honeycomb CAD for ABAQUS simulations. This
240 ensured identical geometry of the simulated and mechanically tested parts.

241

242 Quasistatic compression was computationally modelled with the honeycomb component
243 sandwiched between two rigid flat plates. The upper plate was tied to the upper solid
244 section of the honeycomb and prescribed a deflection of 0.6mm, over 1s. The lower plate
245 was fixed in space and tied to the lower honeycomb face. Viscoelastic material properties
246 were not included, whilst a mass scaling of 20 considerably reduced simulation time with
247 minimal influence on accuracy. The force-time and displacement-time histories were
248 extracted from a reference node at the centre of the upper rigid plate, enabling direct
249 comparison with mechanical testing results.

250

251 For simulated validation of the impact tests, the honeycomb was again sandwiched between
252 two rigid flat plates in ABAQUS. The upper plate was now assigned a 3.53kg point mass
253 and prescribed a pre-impact velocity observed during experimentation. A sliding frictional
254 coefficient of 1 was defined between the upper honeycomb surface and adjacent plate, to
255 represent a sandpaper-sandpaper contact. The lower honeycomb face was tied to the
256 bottom plate, which was fixed in space. The acceleration-time and displacement-time
257 histories were extracted from a reference node at the centre of the upper rigid plate, for
258 comparison with mechanical testing results. Acceleration-time was converted to force-time
259 using Newton's second law of motion.

260 2.2.3. X-ray Microscopy (XRM)/Microcomputed Tomography Scanning (μ CT)

261

262 Porosity analysis was performed using a nominal cuboid structure (7.5 x 7.5 x 20 mm)
263 manufactured from NinjaFlex and by adopting the established processing parameters.
264 Analysis was performed via XRM using a lab-based Zeiss Xradia 520 (Carl Zeiss XRM,
265 Pleasanton, CA, USA) X-ray Microscope, using a CCD detector system with scintillator-
266 coupled visible light optics and tungsten transmission target. To achieve a higher resolution
267 over the entire part height, the specimen was imaged along its 20 mm length at high
268 resolution, using an overlap-scan and stitching procedure including five individual scans,
269 with 15% overlap between each scan. An X-ray tube voltage of 60 kV and a tube current of
270 80 μ A were used, with an exposure of 1000 ms and a total of 3201 projections. An objective
271 lens giving an optical magnification of 0.4 was selected with binning set to 2, producing an
272 isotropic voxel (3-D pixel) sizes in the range 11.862 μ m. The tomograms were reconstructed
273 from 2-D projections using a Zeiss commercial software package (XMReconstructor, Carl
274 Zeiss), a cone-beam reconstruction algorithm based on filtered back-projection.
275 XMReconstructor was also used to produce 2-D grey scale slices for subsequent analysis.
276 A threshold size of 2 voxels was implemented, reflecting the boundary between pore (gas)
277 and material of the smallest pores. Excluding data below this threshold avoids inaccurately
278 including smaller pores during the segmentation process.

279

280 The honeycomb sample was imaged using a lab-based Nikon XT H225 microfocus X-ray
281 microtomography (μ CT) system, with a 1.3 Megapixel Varian PaxScan 2520 amorphous
282 silicon flat panel digital X-ray imager, in reflection mode with a molybdenum target. An X-ray
283 tube voltage of 60 kV and a tube current of 130 μ A were used, with an exposure of 1000 ms
284 and a total of 3015 projections, with a voxel (3-D pixel) size of 15.05 μ m. The tomograms
285 were reconstructed from 2-D projections using a Nikon commercial software package
286 (CTPro version 3.0, Nikon Metrology), a cone-beam reconstruction algorithm based on

287 filtered back-projection. The commercial software VGStudio Max 2.1.5 was used to view the
288 reconstructed data and produce 2-D grey scale slices in TIFF format. These were imported
289 into Avizo Software (ThermoFisher Scientific, Waltham, MA, USA), where post-processing
290 including reorientation, binarization and segmentation allowed extraction of pore size and
291 volume. Honeycomb average wall thickness was measured using Vernier callipers, as well
292 as digitally via the μ CT data using SOLIDWORKS (Dassault Systems, France) and used to
293 update the equivalent CAD/FEA model used for computational simulation.

294

295 **3. Results**

296

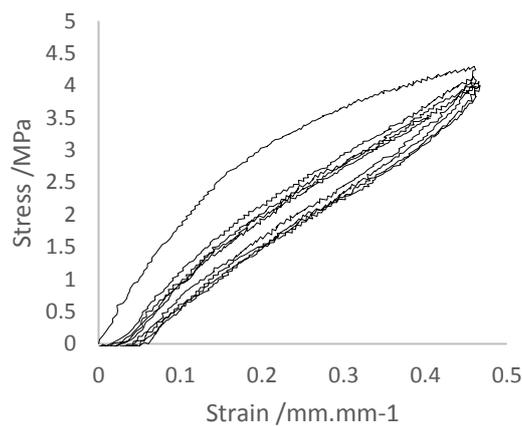
297 **3.1. Mechanical Testing**

298

299 The test results showed that the equi-biaxial response generated a higher stress than the
300 planar response, which was greater than the uniaxial response, at any given strain (Figure
301 6). This trend was consistent when considering both the primary and stabilised response.

302 Stress and strain for uniaxial and planar testing are presented based on the direction of the
303 loading.

304



305 *Figure 5. cyclic behaviour of NinjaFlex under uniaxial loading*

306

307 **3.1.1. Primary HE response**

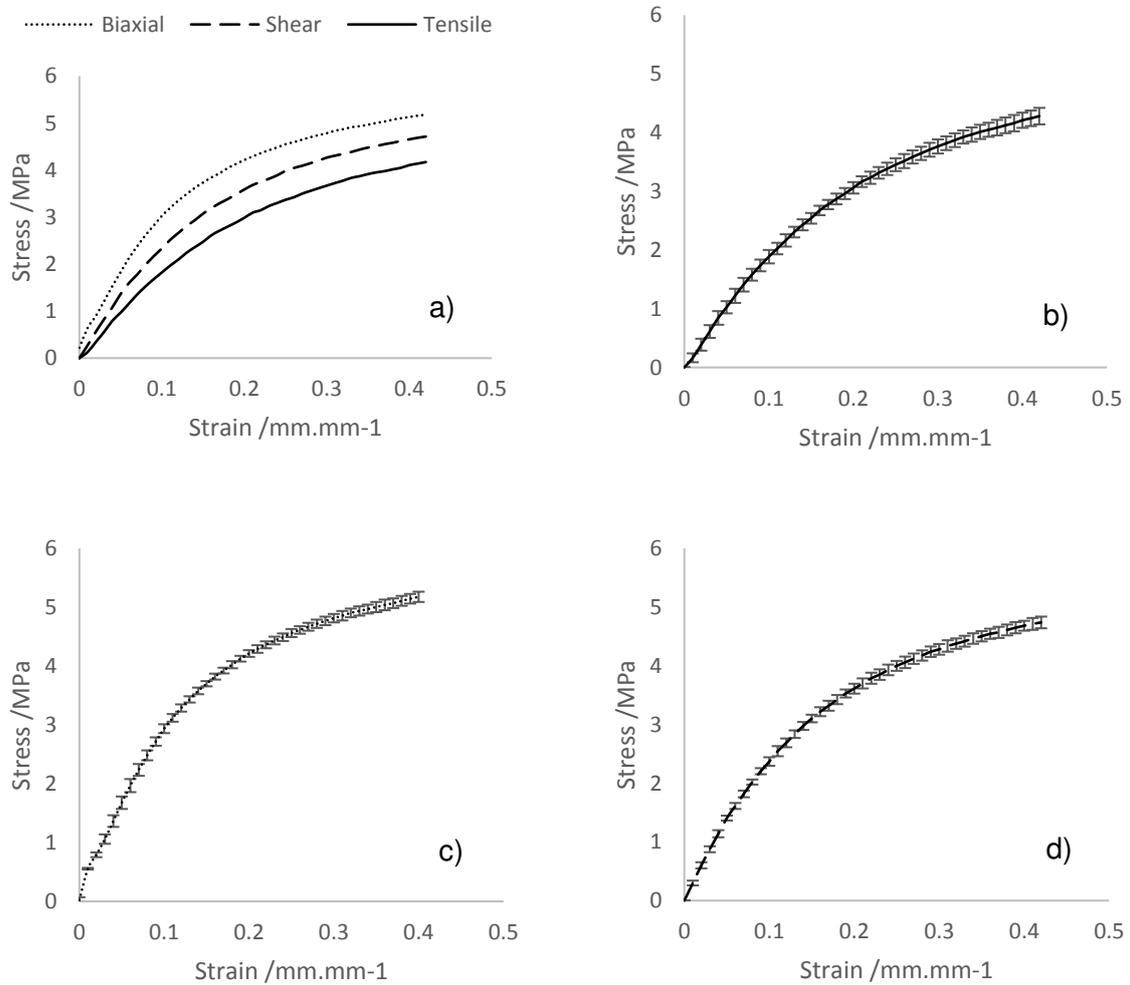
308

309 All datasets demonstrated non-linear behaviour typical of elastomeric materials. Uniaxial
310 testing gave an average initial modulus of 18.2MPa, when considering strains from 0 to 0.1.

311 The average initial planar modulus was 28% greater than uniaxial and the average initial
312 equi-biaxial modulus 66% greater. At a strain of 0.4, uniaxial stress was 4.11 MPa, planar

313 stress was 4.66 MPa and equi-biaxial stress was 5.13MPa. The full data curves showing the
 314 average mechanical test data are displayed in Figure 6.

315



316 *Figure 6 Mechanical testing for average primary response of: a) Combined data sets, b)*
 317 *Uniaxial only, c) Equi-biaxial only, d) Planar only. Error bars = SD*

318

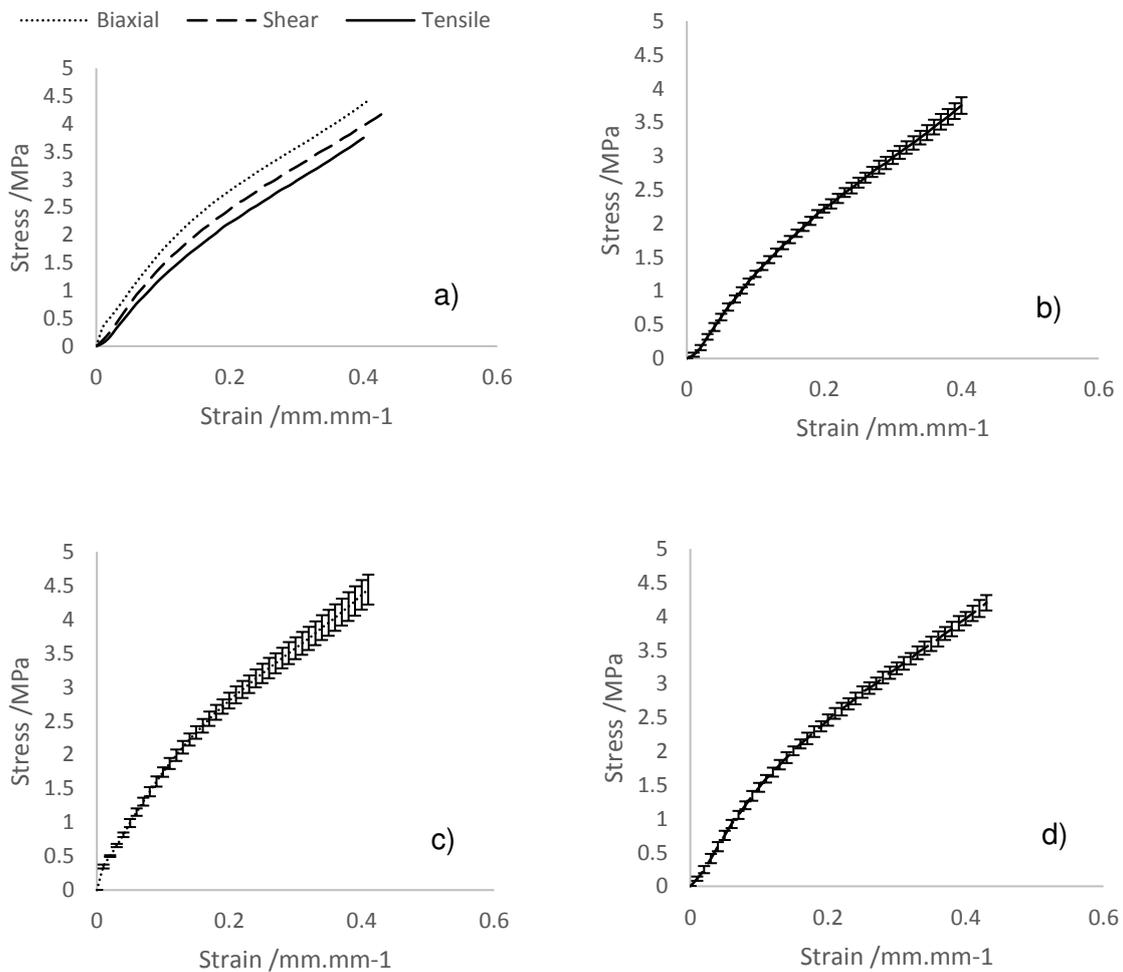
319 3.1.2. Stabilised HE response

320

321 The planar data trend was closer to the uniaxial, than equi-biaxial, response. Uniaxial
 322 testing gave an average initial modulus of 12.5MPa, when considering strains from 0 to 0.1.

323 The average initial planar modulus was 18% higher than uniaxial, with the average initial
 324 equi-biaxial modulus 39% higher. At a strain of 0.4, uniaxial stress was 3.75 MPa, planar
 325 stress was 3.97 MPa and equi-biaxial stress was 4.36 MPa. Variance between the 5 test
 326 samples for each stress state of the stabilised response was minimal, though larger than the
 327 primary response data (Figure 7).

328



329 Figure 7 Mechanical testing for the average stabilised response of: a) Combined data sets,
 330 b) Uniaxial only, c) Equi-biaxial only, d) Planar only. Error bars = SD

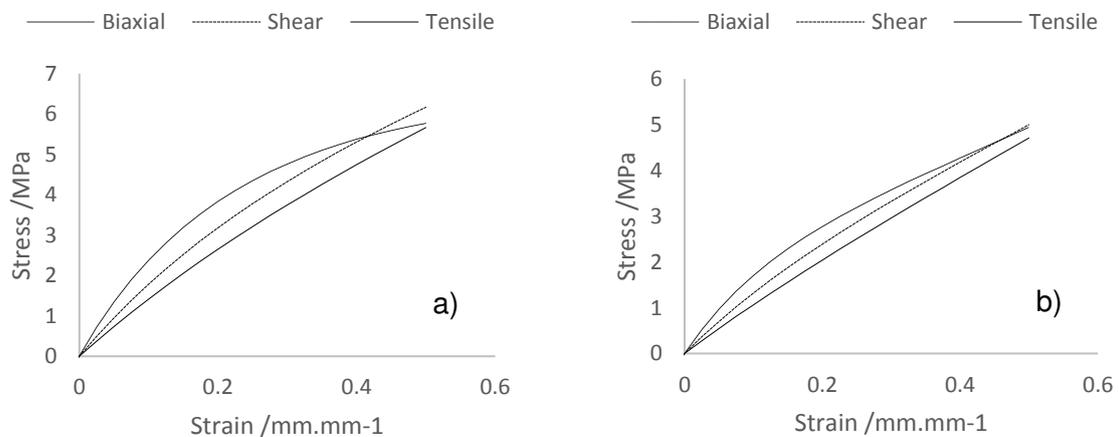
331

332 3.2. Curve-fitting

333

334 The ABAQUS-based curve fitting procedure for the primary and stabilised responses are
335 presented in Figure 8. The Mooney-Rivlin model provided the most appropriate fit to the
336 primary response, whilst the 2nd order Ogden model provided the best fit for the stabilised
337 response.

338



339 *Figure 8 Graphs showing combined fit for: a) Primary response, b) Stabilised response*

340

341 The coefficients for the primary and stabilised responses material models are presented in
342 Table 2 and Table 3. These models are mathematically stable, both fitting well to
343 experimental extension data and sensibly predicting the compressive behaviour, for the
344 positive and negative strain (+/- 0.3) estimated in the preliminary unit cell investigation
345 (Section 2.2.1). It should be noted that outside of the predicted strain range both models
346 become increasingly inaccurate.

347

348 *Table 2 Primary response – Mooney-Rivlin material model coefficients*

$C10$ /MPa	$C01$ /MPa
2.93	0.363

349

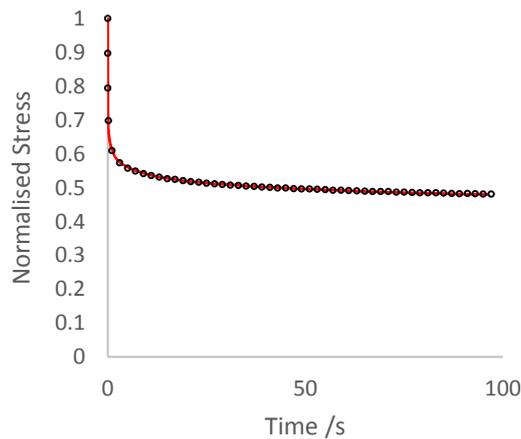
350 *Table 3 Stabilised response – 2nd order Ogden material model coefficients*

	$\mu1$ /MPa	$\alpha1$
1	12.2	1.87
2	8.41	1.19

351

352 Due to the specified low root mean square (RMS) error (0.001), the Prony series were
 353 calibrated closely to the experimental data (Figure 9). Examining the experimental data
 354 trend enables estimation of a long-term normalised modulus between 0.4 - 0.5. The Prony
 355 coefficients that define the curve presented in Figure 9 are quantified in Table 4.

356



357 *Figure 9 Normalised uniaxial stress relaxation data, with Prony series curve fit*

358

359 *Table 4 Viscoelasticity Prony series*

	<i>G /MPa</i>	<i>K /MPa</i>	<i>tau /s</i>
1	0.196	0.0000	1.27E-03
2	0.129	0.0000	8.30E-02
3	7.67E-02	0.0000	0.894
4	6.03E-02	0.0000	6.51
5	7.10E-02	0.0000	54.6

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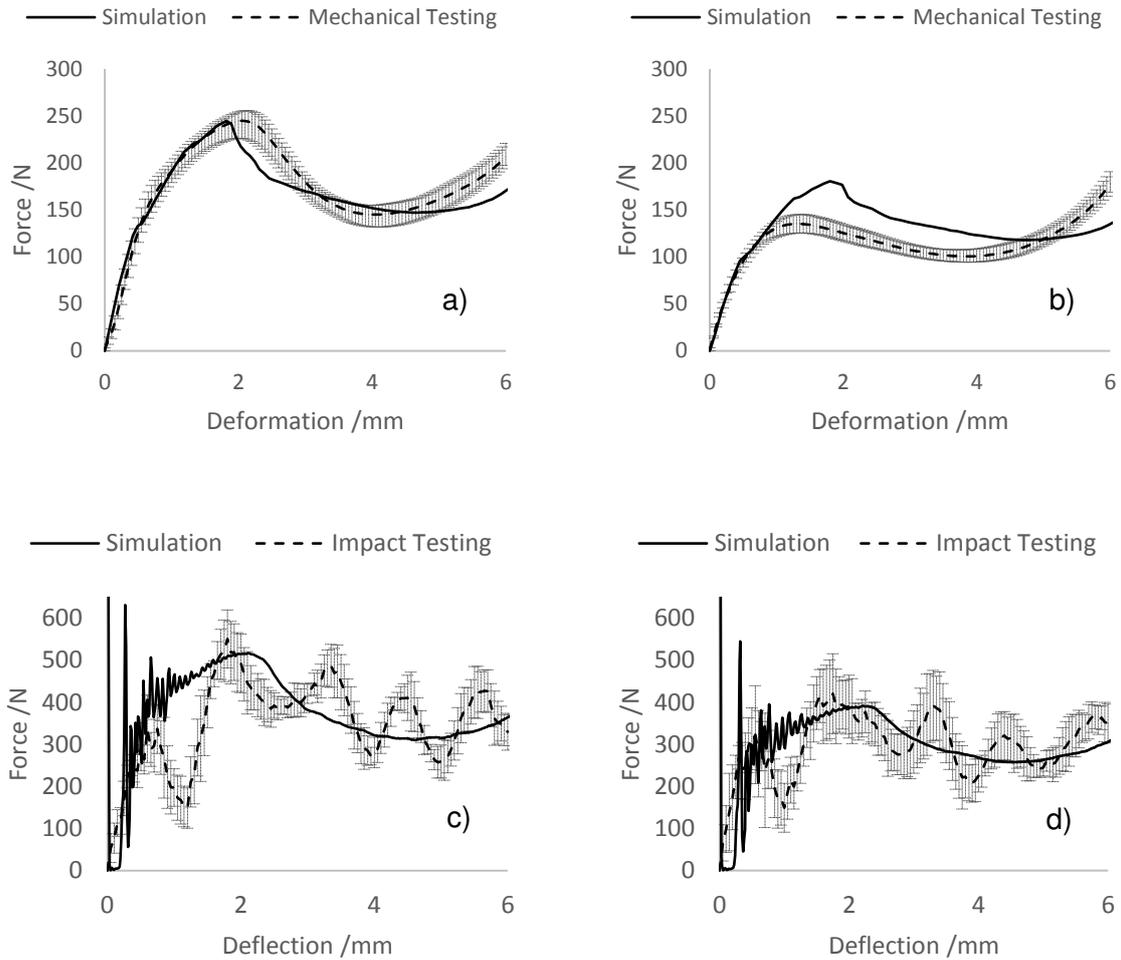
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381

382 3.3. Honeycomb testing



383 *Figure 10 Honeycomb validation, plotting mechanical test data alongside related simulations:*

384 *a) Primary quasistatic, b) Stabilised quasistatic, c) Primary impact, d) Stabilised impact.*

385 *Error bars = SD*

386

387 *Quasistatic Honeycomb Compression*

388

389 The plateau region varies between experimental and simulation results, influencing the

390 energy absorbed by each structure prior to densification (Table 5). For the simulated

391 primary response, agreement exists between the experimental and simulation peak forces

392 and absorbed energy; however, an increase in peak displacement of 11% was observed in

393 the experimental results. The stabilised energies for the simulated and experimental results
 394 were within 10% of one another.

395

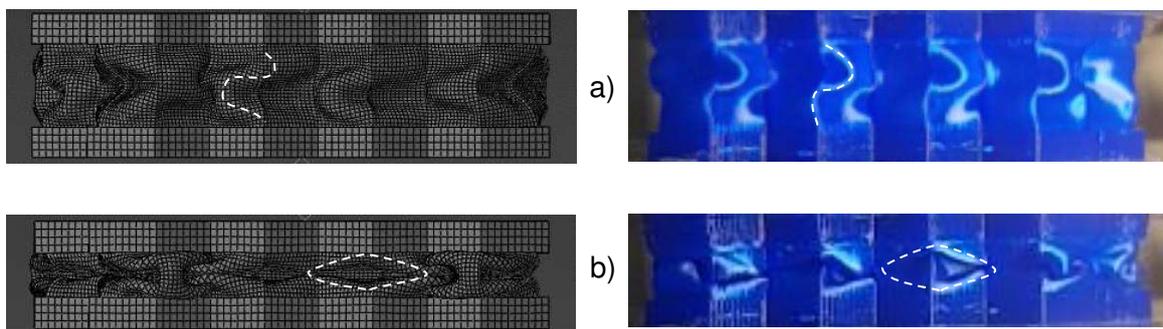
396 *Table 5 Peak quasistatic forces/displacements at commencement of plateau region + energy*
 397 *absorbed by structure prior to densification*

	<i>Peak force pre- plateau /N</i>	<i>Displacement of peak force /mm</i>	<i>Energy absorbed by 6mm /J</i>
<i>Simulation Primary response</i>	245	1.82	1.00
<i>Mean Experimental Primary response</i>	245	2.05	1.04
<i>Simulation Stabilised response</i>	180	1.80	0.77
<i>Mean Experimental Stabilised response</i>	137	1.25	0.69

398

399 At 2mm, similar s-shaped and arrow-shaped deformation patterns were observed in
 400 experimental testing and simulation (Figure 11). At greater levels of compression (2 –
 401 6mm), the structure begins to fold inside itself with elongated diamond-shaped patterns.

402



403 *Figure 11 Comparison of simulated and experimental deformation during quasistatic*
 404 *compression: a) 2mm, b) 6mm. Note, simulated images have been flipped horizontally to*
 405 *better highlight the similar deformation patterns.*

407

408 *Data describing the plateau regions is presented in*

409 Table 6. Experimental and simulated peak forces, displacements and energies absorbed
 410 were all within 10% of one another for the dynamic primary and stabilised responses, except
 411 the stabilised peak displacement, where the mechanical testing was 30% lower.

412

413 *Table 6 peak forces/displacements at commencement of plateau region + energy absorbed*
 414 *by structure prior to densification dynamic*

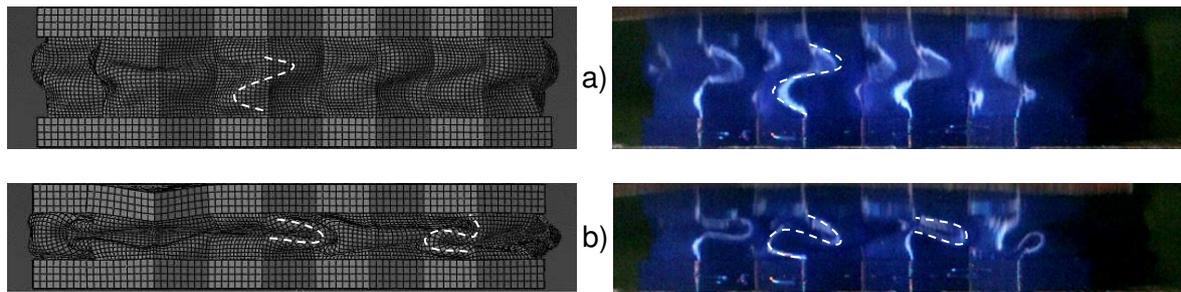
	<i>Peak force pre- plateau /N</i>	<i>Displacement of peak force /mm</i>	<i>Energy absorbed by 6.5mm /J</i>
<i>Simulation Primary response</i>	515	1.97	2.21
<i>Mean Experimental Primary response</i>	550	1.80	2.10
<i>Simulation Stabilised response</i>	391	2.20	1.75
<i>Mean Experimental Stabilised response</i>	420	1.75	1.77

415

416 Distinct s-shaped deformation was identified both in experimental testing and simulation, at
 417 2mm compression (Figure 12). At 6mm, the experimental testing and simulation
 418 demonstrated distinctive arrow-shaped and s-shaped deformation patterns; however, the
 419 simulation also had outer walls folding into the centre of the structure, similar to observations
 420 during quasistatic compression (Figure 11).

421

422



423 *Figure 12 Comparison of simulated and experimental deformation during impact: a) 2mm, b)*
 424 *6mm. Note, simulated images have been flipped horizontally to better highlight the similar*
 425 *deformation patterns.*

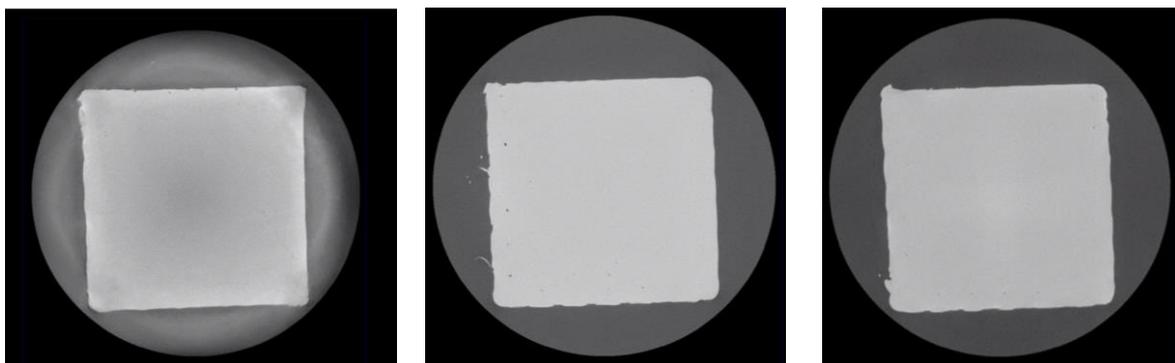
426

427 3.4. XRM/μCT Analysis

428

429 μCT scanning demonstrated that manufactured parts were largely homogenous, meaning
 430 successful fusion of the extruded material (Figure 13). Additionally, the outline bounding the
 431 internal rectilinear patterning was continuous, with no pores observed throughout its height.

432



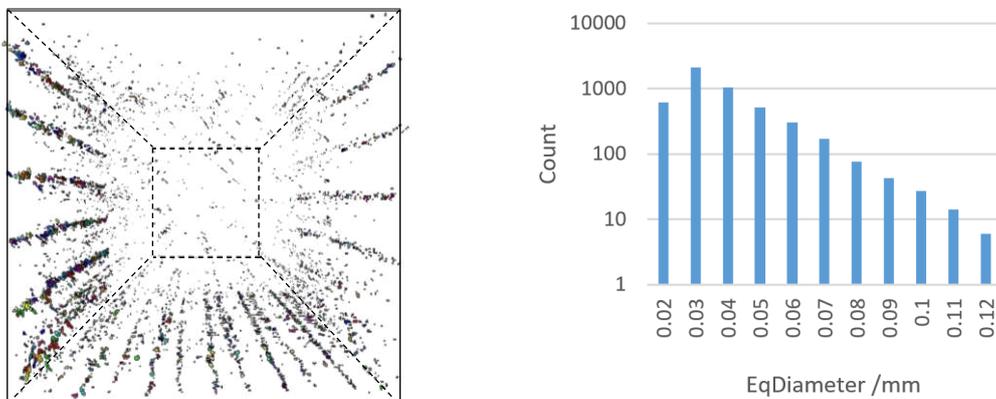
433 *Figure 13 CT scanned cross-sections of cuboid geometry. Left-right: bottom, centre, top*

434

435 When analysing the pores within the scanned cuboid, those of equivalent diameter ≤ 2 voxels
 436 (equivalent to $23.7 \mu\text{m}$) were excluded. This was due to the potential lack of accuracy when
 437 detecting pore edges of such small pores. Analysis of the remaining pores suggested the

438 cuboid was 99.97% dense, with an average pore size of 38 μm and a max pore size of 119
439 μm . Only ~10% of the pores were 60-119 μm , which appeared concentrated between the
440 rectilinear fill forming the cuboid centre and the outline forming the perimeter. The
441 distribution of the pores within the cuboid and the pore diameter histogram, are presented in
442 Figure 14. A one-point perspective view down the length of the cuboid illustrates the pore
443 distribution (Figure 14a). The largest pores are located at the boundary of the outline and
444 the infill pattern, in lines running the height of the cuboid.

445



446 *Figure 14 a) 3D image of pores within the cuboid structure, with a bounding outline to show*
447 *the approximate position of the cuboid exterior, b) histogram showing the effective length of*
448 *each pore*

449

450 The μCT scan and supporting vernier measurements of the honeycomb walls gave an
451 average thickness of 0.45mm (versus 0.4mm for the CAD design) with a SD of 0.01 mm.
452 The averaged value was used to simulate a part of constant wall thickness within ABAQUS,
453 based on the minimal deviation. Some material could be observed drooping as the upper
454 surface 'bridged' over the honeycomb cell wall; however, this appeared minimal and did not
455 affect adhesion between these two features.

456

457 **4. Discussion**

458

459 The mechanical performance of TPE AM materials are known to vary with processing
460 parameters, whilst new products regularly enter the market; hence, there is an increasing
461 need to perform full characterisation, though the requisite equi-biaxial facilities remain
462 scarce.

463

464 This study has demonstrated success with a novel approach to material characterisation,
465 validated by the comparable trends achieved when experimentally and computationally
466 compressing a honeycomb structure. When applying the material models to a multi-strain
467 rate and state application, a close correlation between predicted and experimental data was
468 observed (Figure 10). The stress-softening characteristic of the Mullin's effect is evident
469 when comparing Figure 6 and Figure 7. Even at a relatively low strain (0.4), the initial
470 stiffness of the primary response is 31% higher than that of the stabilised response, and
471 15% higher stress at maximum strain. This reinforces the importance of understanding and
472 selecting the correct material response when simulating TPEs in specific applications. This
473 study has also highlighted the need to characterise multiple responses for a single material,
474 with both primary and stabilised responses being required to validate consecutive dynamic
475 compressions of a honeycomb structure (Figure 10).

476

477 Good correlation was achieved between the HE material models and experimental data
478 across both the primary ($r^2 = 0.97$) and stabilised ($r^2 = 0.99$) response. Such strong
479 correlation provided a robust platform to investigate dynamic strain-rate applications. The
480 low RMS error requirement placed on the stress relaxation data meant that the viscoelastic
481 portion of the material model closely followed the experimental response. Consequently,

482 these material models accurately simulate NinjaFlex behaviour in dynamic applications of a
483 similar strain (i.e. +/-0.3).

484

485 Applying the material model to the honeycomb structure achieved strong comparability
486 between simulation and experimental data. This strong correlation validates this novel
487 method for TPE characterisation, whilst also demonstrating the potential for use in complex
488 geometries within dynamic environments. The mechanical response (Figure 10) and
489 deformation patterns (Figure 11 and Figure 12) demonstrated excellent prediction of a
490 complex HE buckling event. The quasistatic stabilised experimental and computational
491 investigations exhibited the weakest correlation. This may be caused by the residual strain
492 accumulated during stabilising loading cycles which, in combination with the fixed boundary
493 condition created by the adhesive tape, resulted in a period of tensile loading as the actuator
494 returned to the datum. Whilst this was noted and appropriately adjusted for during data
495 analysis, this additional loading regime could have triggered a unique response within the
496 material, meriting future investigation.

497 The experimental and simulated honeycombs exhibited discrepancies between their
498 deformation patterns during dynamic loading (Figure 12). Whilst the honeycomb walls
499 appeared to all form s-shaped profiles during experimental testing, a combination of s-
500 shaped and inward folding behaviour was observed in the simulated deformation patterns.
501 This appears to be focussed around the bending of the upper thick section's profile within
502 the simulation, causing inward folding to occur underneath. AM inherently results in
503 inconsistent wall thickness, minimal variation was evident and strong correlation existed
504 between the simulated and experimental stress-strain behaviour; however, such
505 manufacturing variability could still have influenced the observed deformation patterns.
506 Additionally, the buckling in the structures is a non-trivial event and, therefore, some
507 deviation in deformation patterns was expected between the simulated and experimental
508 behaviour. Structural response can also be influenced by contact behaviour; however, this

509 study investigated pre-densification behaviour and, when running these simulations with a
510 general frictional contact (as opposed to frictionless), minimal change in stress-strain
511 behaviour was observed.

512

513 This study assumed linear viscoelasticity and, whilst the use of non-linear viscoelastic
514 models may help to further fine-tune the prediction of varying strain rate behaviour, this
515 comes at a substantial computational time cost. In the light of this drawback, the close
516 correlation of predicted behaviour presented here serves to justify the assumption of linear
517 viscoelasticity. In the light of mainstream adoption due to low machine costing, fused
518 filament fabrication (FFF) is considered by many to be a rudimentary/entry level technique.
519 The potential of FFF to produce high quality components is, however, demonstrated here,
520 with an excellent cuboid part density of 99.97%. This exceeds previously reported densities
521 achieved via Selective Laser Sintering (SLS) TPE components (~95%) [16] and is
522 comparable to injection moulded parts. Accounting for 94% of the cumulative pore volume,
523 the largest voids (70-119 μ m) are technically challenging to eliminate in FFF builds and
524 existed between the rectilinear fill and bounding outline of the cuboid. During tuning of
525 processing parameters, attempts to reduce these voids included the use of concentric
526 (instead of rectilinear) fill, increasing extrusion multiplier, and increasing overlap between the
527 inner rectilinear fill and bounding outline. These methods introduced their own issues such
528 as the concentric fill generating significant voids in the centre of the part, whilst increasing
529 overlap/extrusion multiplier resulted in distortion of printing parts. It should be noted that the
530 threshold size of 20 μ m was selected to ensure the pores within the entirety of the cuboid
531 could be captured in a single scan. Whilst this provides a suitable indicator of the porosity of
532 the part (as the pores circa 70-110 μ m accounted for 94% of the measured pore volume),
533 this has the potential to filter out smaller pores that could have an undetermined influence on
534 material behaviour.

535 It is known that the layer-by-layer AM build process produces component anisotropy, with
536 this behaviour frequently noted in the literature perpendicular to the layer deposition [17-19].
537 This behaviour is highly dependent on manufacturing build quality as this logically effects the
538 inter-layer bonding. As complex printed components can be exposed to different strain
539 states, potential exists for loadings to be applied parallel and perpendicular to inter-layer
540 bonding, even if the overall structure is only under compressive loading. Due to the lack of
541 notable voids, similar deformation patterns/mechanical responses and good correlation
542 between stress-strain behaviour of the honeycomb structure, no further investigation of
543 anisotropy was performed in this study. AM manufacture also means that thin some
544 geometric features comprise only a single track of extruded filament (i.e. as per the entire
545 honeycomb structure), creating the potential for a different mechanical response than parts
546 with infill patterning (e.g. test parts used to characterise NinjaFlex). This risk was mitigated
547 against by using process parameters that achieved minimal voids in the recti-linear fill
548 pattern, with good correlation evident between the simulated honeycomb response (using
549 infill patterning characterisation) and the mechanical testing (of single extrudate honeycomb
550 print).

551 **5. Conclusions**

552

553 This study has achieved a greater understanding of the behaviour of TPE AM materials,
554 enabling more effective exploitation of this emerging technology. A novel approach to
555 efficiently and robustly characterise TPE materials has been presented. The importance of
556 considering strain-softening has also been demonstrated, along with the potential to design
557 and analyse AM structures for high performance applications. Highlighted findings include:

- 558 • Multi-state strain data to define a material model has been acquired using a standard
559 uni-axial testing machine.
- 560 • A material model has been fitted to the TPE test data, including viscoelastic effects.
561 This model is then successfully validated through its application to a case study of a
562 traditional hexagonal honeycomb at varying strain rate.
- 563 • The level to which the TPE material was strained had significant effects on
564 subsequent straining of the material, an important consideration when developing
565 material models for applications involving multiple cycling events.
- 566 • When dynamically compressed, the viscoelastic properties significantly affect the
567 recorded forces, demonstrating a significant degree of strain-rate dependence.
568 These strain-rate effects carried over to the manufactured parts, resulting in a
569 significant increase in recorded force when dynamically compressed, compared to
570 quasistatic compression.
- 571 • FFF has been used to fabricate TPU components of high homogeneity (material
572 density of 99.97%), with expected manufacturing considerations spreading material
573 at the extruder nozzle, resulting in an increased wall thickness.

574

575

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577

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583

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