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Compressive properties of Advanced Pore Morphology (APM) foam elements

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Abstract. Advanced Pore Morphology (APM) foam elements have a spherical outer skin and a porous inner structure. APM foam is a product of the improved powder metallurgy FOAMINAL[®] process. The present work investigates the mechanical properties of single APM foam elements under quasi-static and dynamic compressive loading. By means of μ CT techniques, an accurate finite element model is generated. The compressive force-displacement response of APM foam elements is numerically evaluated for different diameters and strain rates. The results of the numerical analysis are compared with experimental data. Good agreement is found. Quasi-static and dynamic loading are both investigated by making use of numerical analysis and verified by comparison with experimental results.

1. Introduction

Cellular materials are known for their very high porosity, high specific stiffness, acoustic damping and the ability to absorb a relatively high amount of energy at a low stress level [1, 2]. Their versatile heat insulation property make them useful for heat exchangers or thermal insulation [3]. A major limitation of conventional cellular materials is their stochastic geometry which can result in unreliable mechanical properties. Another important challenge is the reduction of their high manufacturing cost. Control of the pore structure will allow the varying of the morphology and topology (pore size distribution, pore shape and cell wall geometry), which can be expected to allow a better definition of mechanical properties [4, 5]. Recently, a new concept of metal foam components production was patented by Stöbener *et al.* [6]. Carrying the name Advanced Pore Morphology (APM, see Figure 1) foam, this innovative cellular material has been developed on an improvement of the powder metallurgical FOAMINAL[®] process that was introduced earlier by Baumeister [7].

-Figure 1-

Several investigations have been conducted on either single or composite APM foam elements with both partial and syntactic morphology. Experiments have been carried out by Lehmhus *et al.* [8] to investigate the influence of APM foam density for both quasi-static and dynamic compressive loading as well as the effect of varying the bonding agent (an epoxy-based adhesive and polyamide). They reported that the dynamic initial strength of epoxy-bonded APM foam is slightly higher than the quasi-static initial strength. A notable increase

in the dynamic initial strength was observed for polyamide-bonded APM foam. Vesenjok *et al.* [9] investigated the behaviour of a single APM foam element and a composite APM foam with partial and syntactic morphology under compressive loading. Two APM foam element sizes with diameters $\varnothing=5$ mm and $\varnothing=10$ mm were tested experimentally. The results indicated that the larger APM spheres exhibit a higher energy-absorption capability due to a lower densification strain. They also investigated cylinder-shaped ($d = h = 30$ mm) epoxy samples with embedded APM foam elements. Experimental testing was conducted using free and confined radial boundaries. It was found that syntactic APM composites have energy absorption capacity approximately four times higher than non-bonded or partially bonded APM foam elements. Hohe *et al.* [10] conducted experimental and numerical tests on graded APM foams for multi-functional aerospace applications. The main focus of their investigation was perforation resistance against bird strike events. In a case study, a sandwich plate with graded APM foam core was compared with a sandwich plate with a conventional foam core. The results indicated that the use of a graded APM foam core increases the perforation resistance performance of the sandwich plate. This was achieved by dissipating the plastic energy over a larger volume. Vesenjok *et al.* [11] used an infrared thermal imaging camera to enhance the usual data acquisition during compressive experimental testing of APM foam elements. Infrared thermal imaging indicated that plastic yielding occurred predominantly in the outer region of the APM foam element and then propagated inwards in a shear band into the sphere. The present paper combines, for the first time, micro-computed tomography imaging and finite element analysis of APM foam elements. In contrast with earlier investigations, a highly accurate representation of the complex inner foam geometry is obtained and incorporated in the numerical analysis. As a result, detailed information on the internal deformation mechanisms is obtained. For verification purposes, numerical results are compared with experimental data published in the literature.

2. Manufacturing process of APM foam elements

The FOAMINAL[®] process is capable of successfully manufacturing near net-shaped parts and three-dimensional (3D) sandwich panels with a foamed core layer. In [10], an AlSi7 aluminum alloy was prepared in powder metallurgy precursor form with TiH₂ added as foaming agent. Foaming was activated by the heating of the precursor. This process usually takes place within a mold cavity. During the foaming process, furnace temperatures up to 800 °C are used depending on matrix alloys and the presence of stabilizing ceramic particles. As a result, the foaming mold has to bear high thermal loads in each foaming cycle [8]. A new process route proposed by Stöbener in APM foaming eliminates the need for expensive molds. The manufacturing procedure consists of powder compaction (by the CONFORM[®] process) and rolling of the AlSi7 alloy with TiH₂ foaming agent to obtain expandable precursor material. The wire-shaped precursor material (diameter $\varnothing = 3$ mm) is then cut into small granulates (length $l = 2$ mm) [12], which are expanded into sphere-like foam elements (see Figure 1) due to the thermal decomposition of the TiH₂ foaming agent in a continuous belt furnace. This is driven by internal gas pressure, surface tension and the formation of an oxide skin. So far, three sizes of APM foam elements have been manufactured with diameters 5, 10, and 15 mm and foam element densities varying from 0.5-1.0 kgm⁻³ [8, 13]. Structures assembled by APM foam elements exhibit two types of porosity: (i) the inner porosity in single APM foam elements and (ii) the outer porosity between many APM foam elements which depends on the size of the APM elements and their arrangement [14]. Detailed information on the automated production of APM foam elements can be found in the literature [12].

3. Model generation

Micro-computed tomography (μ CT) imaging is a non-destructive procedure that allows precise measurements on aluminum foams [15-17] with the advantage of repetitive 3D assessment and computation of micro-structural and micro-mechanical properties. The most outstanding feature of μ CT is the ability to image the sample's interior with high spatial and contrast resolution. A thorough review on μ CT can be found in the monograph [18]. In previous analyses, sintered metallic hollow sphere structure (MHSS), sintered metallic fibre structure (SMFS), lotus-type porous material, Alporas[®] and M-Pore[®] have been characterized using μ CT technology [2, 3, 15-17, 19, 20]. The companion study [21] first addressed μ CT of APM foam elements by analysing their geometrical micro- and meso-structure. By using the voxel data from the μ CT images, geometrical properties such as the number of pores and their size distribution in the cellular materials were characterised. This novel approach can be applied to any closed-cell morphology and will be expanded to open-cell cellular materials. Results show that the deviation of the porosity and the microstructure characteristics between specimens of the same size was moderate. In the present study, μ CT scanning of small ($\varnothing=5$ mm) and large ($\varnothing=10$ mm) spherical foam elements was performed. An Xradia MicroXCT-400 machine with a Hamamatsu L8121-03 X-ray source was used. Due to the size differences of the samples, the voxel resolutions were limited to $3.61\text{ }\mu\text{m}$ ($\varnothing=5$ mm sphere) and $6.28\text{ }\mu\text{m}$ ($\varnothing=10$ mm sphere), respectively. A total of 1800 absorption radiographs (exposure time 16 seconds) was captured with a 0.2° rotation for each projection. The selected acceleration voltage was 140 kV with a current of $70\text{ }\mu\text{A}$. The μ CT data was first segmented by gray-value thresholding. In this step, it must be ensured that the volume of the voxels representing the metallic phase matches the volume of metal in the APM foam element. To this end, the mass of the scanned APM foam elements was measured using a precision scale. Next, the metal volume was calculated using the AlSi7 material density $\rho = 2680\text{ kg.m}^{-3}$ [22]. The segmentation threshold was adjusted iteratively until the segmented voxel volume coincided with this calculated volume. The segmented voxels were then rendered to a 3D structure that was subsequently converted into a Stereolithography (STL) surface geometry mesh. Stereolithography surface geometry is widely used in 3D model rapid prototyping. Unlike the higher-level representation such as non-uniform rational B-spline (NURBS), the created STL mesh file is not very rich in information [23]. STL meshes only describe the surface geometry of a three dimensional object using triangulation. In order to avoid the loss of geometric detail during meshing, at least 750,000 triangles were used in the STL surface mesh. A volume mesh was then created within the bounds of the surface mesh by using the commercial automatic mesh generation software Sharc Harpoon. The small margin of error of the created model mesh volume is found for both APM foam element sizes. The small volumetric error percentages for $\varnothing=5$ mm and $\varnothing=10$ mm are 7% and 2% respectively. A Hex-dominant mesh that contains three types of elements namely linear hexahedral-, linear pentahedral- and tetrahedral- elements have shown superior performance in the numerical analysis of complex geometries [16]. Accordingly, mixed meshes were used in the present analyses.

3.1. Finite element simulation

The accurate representation of the complex internal foam geometry including the micro and macro porosity requires a high geometric resolution. As a result, a single APM foam element is too large to be meshed (and computed) on the available large memory computers (64 GB RAM). In this work, we made use of the symmetry of the roughly spherical-shaped APM foam elements to reduce the size of the calculation model. To this end, each spherical APM element was subdivided into eight segments (see Figure 2). For each diameter (i.e. 5 mm and 10 mm) four segments were converted into numerical calculation models.

-Figure 2-

The boundary conditions of the finite element analysis are shown in Figure 3. A rigid support was defined as a part of a contact boundary condition with the deformable elements of the APM volume meshes. Quasi-static and dynamic compressive loading was introduced using a time-dependent nodal displacement boundary condition at the upper symmetry plane of the foam element. For the dynamic loading case the rate of the displacement boundary condition was adjusted to achieve a macroscopic strain rate of 100 s^{-1} . Within the remaining two symmetry planes, the normal displacement was set to zero in order to simulate the remaining APM foam element. Such boundary conditions were introduced with the assumption that the deformation propagates in an identical way at the top and the bottom of the foam elements. Nevertheless, in the actual experiment the deformation progress can only be observed and confirmed at the top of the foam elements since the moving force platen is located at the top. The maximum deformation of the model was set to 10% (quasi-static) and 70% (dynamic) of the original APM sphere's height. The smaller deformation of the quasi-static model is caused by significantly longer calculation times. Material properties of AlSi7 used in this numerical model were: Young's modulus $E = 72400 \text{ MPa}$, Poisson's ratio $\nu = 0.3$, yield stress $\sigma_y = 120 \text{ MPa}$, density $\rho = 2680 \text{ kg.m}^{-3}$, and tangent modulus $T = 800 \text{ MPa}$ [22]. Within the dynamic simulations the base material inertia and its strain rate effect have been accounted for [20]. The dynamic response of cellular materials is mainly influenced by (i) the micro-inertial effect and (ii) the material strain-rate sensitivity [24-26]. The micro-inertia of the individual cell walls can affect the deformation of metal foams as discussed in [27, 28]. According to [29] the inertia effects associated with the dynamic localisation of crushing are responsible for the enhancement of the dynamic strength properties in high velocity regimes. The authors in [28] state that inertia effects contribute significantly to the rate effect, even when the strain rate sensitivity of material properties is ignored. The material rate-dependence is usually taken into account within the constitutive material model [30]. In addition, the strain-rate sensitivity of the cellular structure might be affected by the presence of a gaseous pore filler (e.g. air, H_2) [31, 32]. However, the strain rate sensitivity effect is usually more apparent for structures with higher initial pore pressures or higher relative densities [33, 34]. It should be noted that air compression within the cells was not considered in the scope of this work which might influence the response of the APM element subjected to dynamic loading (high strain rates). The base material strain rate sensitivity was introduced using the Cowper-Symonds constitutive model with the parameters $C = 6500 \text{ s}^{-1}$ and $p = 4$ [35-37]. All nodes of the aluminium foam belong to a single surface contact accounting also for friction with a coefficient of friction of 0.5 [38]. A user-defined subroutine was used to

extract force-displacement data. To this end, the sum of nodal reaction forces and the average displacement of these nodes selected on the upper plane were recorded. The computational models were analysed using the commercial finite element codes MSC.Marc for the quasi-static loading case and LS-DYNA for the dynamic loading case [37].

It should be mentioned here that the simulation of a complete APM foam element will serve better results. The simulation of a full sphere with an adequate geometric resolution that captures the internal pore structure requires extremely long computation times (> 4 months) and large random access memory (> 128 GB). This obstacle is overcome by considering only a segment (one-eighth of an APM foam element) for the numerical simulation. However, this simplification introduces a number of shortcomings that should be considered during the result interpretation. First, the size and shape of pores that intersect a symmetry plane are going to be altered. Second, the boundary conditions may affect local bending and buckling of the solid phase. However, this effect seems to be limited since the analysis of stress and strain distributions in vicinity and away from the boundary condition showed no significant deviation. Third, the boundary conditions affect the stress wave propagation through the foam structure and influence the dynamic response. However, considering the high porosity of the structure and moderate loading velocities the influence of the symmetric boundary is not significant. This has also been confirmed by validation of the computational results with experimental tests.

-Figure 3-

Prior to the mechanical characterisation of APM foam elements, the mesh independence of the solution was addressed. The results of the mesh refinement study are illustrated in Figure 4. The boundary conditions described above were used and the initial gradient dF/dy of the force-displacement curve was calculated. Figure 4 shows that 640,000 nodes ($\varnothing=5$ mm) and 550,000 nodes ($\varnothing=10$ mm) yielded satisfactory numerical convergence. The corresponding average element sizes were 0.014 mm for $\varnothing=5$ mm and 0.035 mm for $\varnothing=10$ mm APM foam elements. In addition, for the dynamic simulations, the time step sensitivity analysis had to be performed in order to satisfy the Courant–Friedrichs–Lewy condition for the explicit integration scheme. Based on the smallest finite element edge length it was confirmed that the time step of 0.39 μs provides stable convergence [36].

-Figure 4-

4. Results and discussion

Figure 5 shows the quasi-static force-displacement response of APM foam elements with $\varnothing=5$ mm and $\varnothing=10$ mm diameters. Numerical simulations of APM foam elements are denoted by thin continuous lines and their average value is represented by a thick continuous line. The experimental data taken from [9] and the corresponding average is denoted by the thin and thick dotted lines respectively. It can be observed that absolute values as well as the scattering of numerical and experimental results are consistent. In particular, good agreement is found in their averaged values. The comparison of large ($\varnothing=10$ mm) and small ($\varnothing=5$ mm) foam elements clearly indicates higher compressive force values for the large APM element.

This result is expected since (unlike stress-strain data) force-displacement data are not normalised by the sample size. Accordingly, the larger ($\varnothing=10$ mm) foam elements provide more resistance to compressive loading. To enable a direct comparison between the two foam element sizes, additional numerical simulations are conducted. To this end, two of the 3D segments from the $\varnothing=5$ mm APM elements are scaled in size by a factor of two (i.e. their diameter is increased to 10 mm). This scaling process does not change the geometry of the microstructure of the “small” APM spheres. It can be observed that the force-displacement curves from the “scaled $\varnothing=5$ mm” APM foam elements are different from the $\varnothing=10$ mm APM spheres. The “scaled $\varnothing=5$ mm” curves exhibit a reduction in structural stiffness between displacements of 0.2 mm to 1.0 mm. The most likely explanation for this deviation is differences in the internal microstructure and outer particle shape between “scaled $\varnothing=5$ mm” and 10mm APM foam elements.

-Figure 5-

The structural stiffness, k of $\varnothing=5$ mm and $\varnothing=10$ mm APM foam elements is shown in Table 1. It can be seen from Figure 5 that APM foam elements with different diameters exhibit different stiffnesses. The structural stiffness is the change in compression force divided by the difference in displacement, e.g. the slope of the dot-dashed line in Figures 5b. For the $\varnothing=10$ mm APM foam elements, the displacement range between 0.2 mm and 1.0 mm was considered. Low displacements are disregarded in order to eliminate initial effects due to the establishment of contact between the foam element and contact plane. In the case of the $\varnothing=5$ mm APM foam elements, the selected range is 0.15 mm to 0.5 mm. The average structural stiffness of $\varnothing=10$ mm APM foam elements is 3.3 times higher in comparison to $\varnothing=5$ mm APM foam elements. In addition, the relative variability value was calculated by dividing the standard deviation of the structural stiffness by the corresponding average value. Comparing the relative variability of both diameters, it can be seen that the structural stiffness of the larger foam elements is more consistent. The variability of the stiffnesses is probably linked to the relative size of the pores with respect to the diameter of the foam elements. A study has been conducted in [21] to investigate the number of pores in one $\varnothing=5$ mm and one $\varnothing=10$ mm APM element with respect to their pore radius. It has been found that the number of pores per APM element for $\varnothing=5$ mm and $\varnothing=10$ mm are 4363 and 13797 respectively. Furthermore, the study conducted in [21] also counted the number of large pores in $\varnothing=5$ mm and $\varnothing=10$ mm APM foam elements. These largest pores in the APM (with radius of about 20% or larger of the foam elements' diameter) are likely to strongly affect the mechanical properties of APM foam elements. Referring to the data reported in [21], there are more than 10 pores larger than 2 mm in radius for the $\varnothing=10$ mm APM foam element. Furthermore, there are more than 120 pores larger than 1 mm in radius distributed in the $\varnothing=10$ mm APM sphere. It should also be noted that the largest pores (radius $\geq 20\%$ of the foam elements' diameters) shown in Figures 1, 2, 6, 7 and 9 are non-homogenously distributed compared to the more evenly distributed pores of size 1 mm in radius. Investigation done in [21] also found more than 10 pores (with a radius about 20% or larger of the foam elements' diameter) in a $\varnothing=5$ mm APM sphere, but the number of pores with radius of about 10% of the foam elements' diameters is much lower (fewer than 20 pores). The higher number of more evenly distributed pores (pores with radius $\geq 10\%$ of the foam elements' diameters) in $\varnothing=10$ mm APM sphere results in more consistent results. On the other hand, a significant reduction of the number of pores with radius attaining more than 10% of the foam elements' diameters in

a $\varnothing=5$ mm APM foam element has some effect in representing an adequate RVE and this resulted in inhomogeneity of the stiffnesses.

The scatter of the structural stiffness for $\varnothing=5$ mm APM sphere was also possibly caused by the irregular outer shape of the simulated segments. Comparing all the segments from $\varnothing=5$ mm and $\varnothing=10$ mm APM foam elements, the outer shape of $\varnothing=10$ mm APM segments is closer to a perfect sphere. In contrast, the smaller APM foam elements exhibit a more irregular outer shape potentially causing scatter of their mechanical properties.

An additional numerical simulation was conducted to investigate the effect of the skin on the APM foam sample. To this end, the skin has been virtually removed from segment #2 of the $\varnothing=10$ mm APM foam sphere. This reduced the sphere volume by 13%. The structural stiffness of both APM foam elements with and without skin was then calculated. The results of 412.2 N/mm for the original sphere and 290 N/mm for the sphere without the skin reveal that a significant reduction of structural stiffness has occurred. The structural stiffness of the sphere without the skin is reduced by a factor of 1.4 compared to the original APM sphere elements. The skin thickness is thicker for diameter 5 mm APM foam elements compared to the diameter 10 mm APM foam element.

Table 1. Structural stiffness of $\varnothing=5$ mm and $\varnothing=10$ mm APM foam elements determined by the slope of their respective graphs

APM Sphere size	Effective Stiffness, k (N/mm)				Simulations	
	Segment #1	Segment #2	Segment #3	Segment #4	Average	Relative Variability
$\varnothing=5$ mm	107.4	166.6	76.6	77.6	107.0	0.39
$\varnothing=10$ mm	370.0	412.2	328.7	280.9	348.0	0.16

Figure 6 shows the distribution of equivalent plastic strain for quasi-static loading for segment #1 of $\varnothing=5$ mm and $\varnothing=10$ mm diameter APM foam spheres. The maximum displacement applied is limited to 10% of the sample height. This displacement was chosen in order to achieve an adequate calculation time. Thus, for the APM foam element with $\varnothing=5$ mm and $\varnothing=10$ mm, the applied displacement is 0.25 mm and 0.5mm respectively. It can be observed that the upper part of the foam element is flattened by the simulated compressive plate. This is more likely due to minimum cross section. A similar observation has been reported by Stöbener *et al.* [39] who conducted an experimental compression test of $\varnothing=10$ mm APM foam elements. Figure 6 further shows that plastic deformation is not uniformly distributed over the complete foam element but occurs predominantly in proximity of the contact area. Vesenjāk *et al.* [11] studied the propagation of the plastic yielding within the APM foam element using infrared measurements. They too observed that the yielding originates from the contact area between the APM foam and the rigid support and spreads in a shear band with an angle 45° towards the lower part of the foam element. Figure 6 clearly supports this observation and demonstrates that plasticisation is not limited to the immediate

surface area. A line with a distance of 2.5 mm from the initial contact point is drawn in Figures 6a and b. It can be seen that independent of the foam element size a similar depth is affected by high levels of plastic deformation at the same macroscopic deformation $u = 0.25$ mm. However, in the case of the larger foam elements the affected volume is larger.

-Figure 6-

Internal deformation analysis The internal deformation characteristics of APM foam elements under quasi-static loading are elaborated here. Localised concentrations of equivalent plastic strain are shown in Figure 7. The distribution of plastic strain validates the shear band premise made earlier in this section. During compression, a shear cone with an angle of 45° (generated by revolving the 45° line about the vertical axis in Figure 6) with respect to the loading axis was formed. Whenever features like thin walls and thin struts are located within the shear cone, they will be among the first to experience high levels of plastic deformation. In addition, high levels of plasticity occur near the contact area of the external load. In quasi-static analysis, this phenomenon is caused by the high contact stresses (contact force divided by contact area) due to the small initial contact area of the sphere. However, in dynamic analysis the flattening of the top part of the model is (regardless to the loading velocity) a result of the distribution of cross sectional areas in sphere-like bodies. Such behaviour is different to the uni-axial compression observed in hexahedral shape cellular material (e.g. Alporas®), wherein the incremental deformation maps show collapse bands originating from neighbouring previous bands [40].

-Figure 7-

Next, the dynamic behaviour of APM foam elements is considered. The time step increment in these direct finite element simulations is based on the size of the shortest finite element edge, i.e. 0.0093 mm for $\varnothing=5$ mm foam and 0.0109 mm for $\varnothing=10$ mm foam. These small lengths put extreme demands on computational time. As a result, dynamic analyses were limited to $\varnothing=10$ mm foam elements. Figure 8 shows the dynamic force-displacement response of $\varnothing=10$ mm APM foam elements. Numerical simulations of APM foam elements were conducted at a macroscopic strain rate of 100 s^{-1} and are denoted by thin continuous lines. Their average value is represented by a thick continuous line. In addition, experimental data taken from [11] are shown. The thick dotted line shows the results of experimental testing with a macroscopic strain rate of 20 s^{-1} . For comparison, results of quasi-static testing are plotted as a dashed line. The compressive response of APM foam elements shows the typical behaviour of porous materials. Following the initial elastic response one can observe the onset of an elastic-plastic transition zone that is then manifested as a plateau followed by the final densification [41]. The averaged numerical results are in good agreement with the experimental measurements. The numerical results correspond to a compressive strain rate 100 s^{-1} . In contrast, experimental results were obtained at lower strain rates (i.e. 20 s^{-1}) and quasi-static conditions. Numerical tests had to be performed at the higher strain rate since a transition to 20 s^{-1} would have caused unreasonably long calculation times. As a result, the numerical results exhibit an increased plateau stress and slightly decreased densification strain. Furthermore, it can be observed that the stiffness of the structure increases at high loading rates.

-Figure 8-

Figure 9 shows the distribution of total equivalent plastic strain in the $\varnothing=10$ mm APM foam element at different displacement increments. As already observed in experiments and quasi-static numerical results, the local deformation originates at the contact between the APM foam element and the loading/support plate due to the lowest load bearing cross section of the spherical shaped object. Again we can note that the propagation of the plastic strain spreads in a shear band towards the centre of the foam element in agreement with previous observations [11]. The numerical investigations conducted within this paper only focus on a single APM sphere rather than a more complex structure made up of several APM spheres. Assuming that one APM sphere can be considered as a representative volumetric element (RVE) of a structure formed by these elements, the findings presented in this work can to some extent be used to predict the mechanical properties of this material.

-Figure 9-

5) Conclusions

This paper has addressed the compressive properties of spherical APM foam elements. Two different sphere sizes, i.e. $\varnothing=5$ mm and $\varnothing=10$ mm were investigated. Numerical finite element analyses were conducted for quasi-static and dynamic loading. To account for the complex interior foam geometry, calculation models were directly derived from micro-computed tomography data. Results were compared with experimental measurements conducted on similar samples. Good agreement was found. Single APM foam elements demonstrated typical cellular material behaviour, i.e. an extended stress plateau followed by densification at high macroscopic strains. Numerical analyses of the APM meso-structure showed that plastic deformation does not occur uniformly but is concentrated in a relatively small sub-volume. This deformation is not limited to the surface of the spherical element but continues within the interior foam structure. More specifically, plasticity originates from the contact area of pressure stamp and sphere and propagates in a 45° shear cone towards the interior of the samples. As expected, larger APM foam elements were able to support higher compressive loads, i.e. $\varnothing=10$ mm APM foam elements exhibit a 3.3 times higher structural stiffness. The investigation on the skin effect shows that the skin significantly contributes to the mechanical strength of APM foam elements. The single APM foam elements with removed skin have a reduction in structural stiffness by a factor of 1.4 from the original APM foam counterpart. Internal microstructure deformation analysis reveals that weak structures like thin walls and thin struts within the 45° shear cone are likely to experience high levels of plastic deformation. Finally, dynamic compression simulation indicates an increase of stiffness and plateau stress with increasing macroscopic strain rate.

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