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DESIGN, FABRICATION AND MECHANICAL CHARACTERIZATION OF PYRAMIDAL PERIODIC CELLULAR METAL/POLYURETHANE FOAM HYBRID MATERIALS

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ABSTRACT

A new type of hybrid material was designed and fabricated by reinforcing periodic cellular metals (PCMs) with rigid polyurethane (PU) foams. A pyramidal PCM geometry and various densities of two-phase rigid polyurethane foam were used to fabricate three different hybrid materials. These novel hybrid materials may find useful application as cores in sandwich structures. By increasing the density of the polyurethane foam used in the PCM/PU foam hybrids, the stiffness of the hybrid increased allowing the stiffness to be tailored for a specific application. Furthermore, the strength of the hybrids was greater than that of the PCM or foam alone, and in most configurations the strength was greater than the sum of the strength of the PCM and the polyurethane foam. Next, the resilience of the hybrids was greater than that of the PCM or foam alone and was also greater than the sum of the resilience of the PCM and foam. Finally, the impact energy at which surface failure would occur was greater in the hybrid samples than the foams or the PCM and was found to increase with increasing foam density.

KEY WORDS: periodic cellular metal (PCM), hybrid, sandwich structure, polyurethane foam

INTRODUCTION

There is an ongoing need for lightweight structural materials in the aerospace and automotive industries. Past trends have lead to the use of sandwich structures in which two high-strength skin layers are separated by a central core which provides stiffness against bending [1]. Less material is used in a sandwich structure than in its monolithic counterpart, which can allow for significant savings due to reduced material costs [2].

To select a core material for a sandwich structure, properties such as shear strength, shear modulus and compressive strength are all considered [3]. Sandwich cores have typically been made of honeycomb, metallic foam or polymer foam while the skin layers have been made of a lightweight metal such as aluminum, or a carbon fibre reinforced composite sheet [1,4]. Various studies have been performed on sandwich materials using three- and four-point bending tests in order to aid in the process of material selection for a given application [5,6].

An emerging trend focuses on multifunctional cores, or rather cores that offer something in addition to load carrying such as enhanced vibrational or acoustical damping, or heat transfer capabilities [7,8,11-14]. Periodic cellular metals (PCMs) have been identified as being potential core material since they offer this multifunctionality. They have superior load carrying capabilities and offer additional properties such as heat transfer and energy absorption [7,8].

PCMs are three-dimensional systems that use a truss-like geometry to reduce the overall amount of material used [9-11]. PCMs have been shown to have higher specific strength and stiffness compared to metallic foams. Other properties such as thermal management, dynamic load protection, acoustic damping and crush strength have made PCMs a more attractive alternative over traditional honeycomb or metallic foam cores [11-14].

Rigid polymer foams have also been commonly used as core materials. One of the most popular polymers for this application is polyurethane (PU) due to its ability to maintain high mechanical properties at high and low temperatures, its dimensional stability and low cost [15]. At lower densities, the damping capacity of polyurethane foam is greater [16]. Polyurethane is also preferred due to its thermal insulation capabilities and ability to bond with sandwich face sheets [1].

Another emerging trend in the materials venue has been the combining of two or more existing materials to create “hybrid” materials in order to access new regions of materials property space [17]. A few studies have examined the effects of adding fibres or fabrics to polyurethane foam [18, 19]. These studies found that at an optimum fibre content, the tensile strength, hardness and impact strength of the PU foam can be increased. In other studies, the effect of adding foam to partially or completely fill the open cells of honeycomb cores have had success in improving the impact resistance of the original honeycomb core [20-23]. In a similar study, the cells of PCMs were filled with hard ceramics and polymers to increase the impact resistance [24].

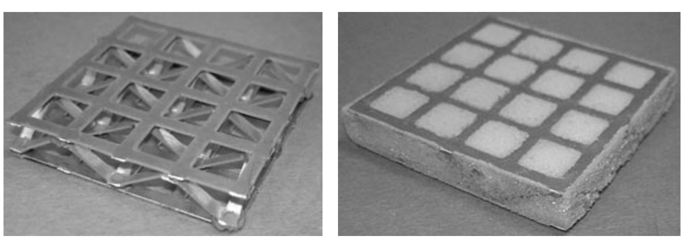
In this study, new PCM/polyurethane cellular hybrids are designed and fabricated. By reinforcing the PCMs with various densities of polyurethane foam we intend to create low-density hybrid materials with enhanced material properties.

MATERIALS AND METHODS

A pyramidal PCM architecture made of aluminum alloy 3003 (AA3003) was used in this study. The periodic cellular truss cores were manufactured using the method described in [11]. They were adhesively bonded to perforated face sheets in order to produce PCM sandwich panels as shown in Figure 1a. The pyramidal samples were approximately 56 mm by 56 mm with a thickness of 10 mm.

Three densities of commercially available two-phase rigid polyurethane foam produced by Smooth-On were used to create the hybrids: 113 +/- 2 kg/m^3, 232 +/- 12 kg/m^3 and 290 +/- 6 kg/m^3 (supplier reported nominal densities of 80 kg/m^3, 160 kg/m^3 and 240 kg/m^3, respectively).

The hybrid PCMs were fabricated by mixing the two components of the polyurethane mixture in equal volumes and pouring uncured foam into the open cells of the PCM. The expansion of the foam was restricted by clamping the uncured hybrid between two wooden frames. After two hours the foam was cured and the samples were released from the wooden frames. Excess foam was trimmed from the hybrids to create the sample shown in Figure 1b. Reference foam samples were made in a similar manner as above, excluding the PCM. These samples had comparable dimensions to the hybrids.



(a) (b)

Figure 1. (a) Aluminum alloy 3003 Pyramidal PCM, (b) Aluminum alloy 3003 Pyramidal PCM and Polyurethane Hybrid

The PCM and hybrid samples were loaded in uniaxial compression until truss core collapse occurred by inelastic buckling failure [11]. Foam samples were loaded in uniaxial compression until failure due to bending and crumpling of the cell walls [25]. Nominal strains were measured from the cross-head displacement [26-30].

Impact testing of the PCM, PU foams and PCM/PU foam hybrids was performed using a Gardner Impact tester (Qualitest IG-1142). The impact energy was measured by releasing a 0.227 kg mass from a 25.4 mm height above the sample. The test was repeated with the mass being released from increasing height increments of 25.4 mm until surface damage was observed. This method provided the impact energy at which the sample was damaged. In this case the impact energy was equivalent to the potential energy (PE)

$$PE = mgh$$

where m is the mass, g is the gravitational constant and h is the height at which the mass was dropped from. Frictional effects in the tube were considered to be negligible.

RESULTS AND DISCUSSION

Stress-strain curves for each sample were used to determine the strength, stiffness and resilience. Representative curves for each of the various densities of polyurethane foam are given in Figure 2, while representative stress-strain curves for the hybrids made from these foams are given in Figure 3.

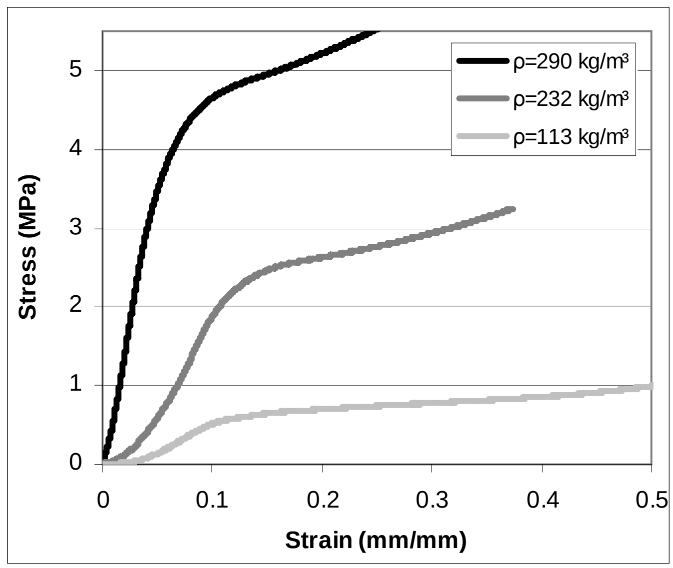


Figure 2. Representative stress-strain curves for the various densities of polyurethane foam.

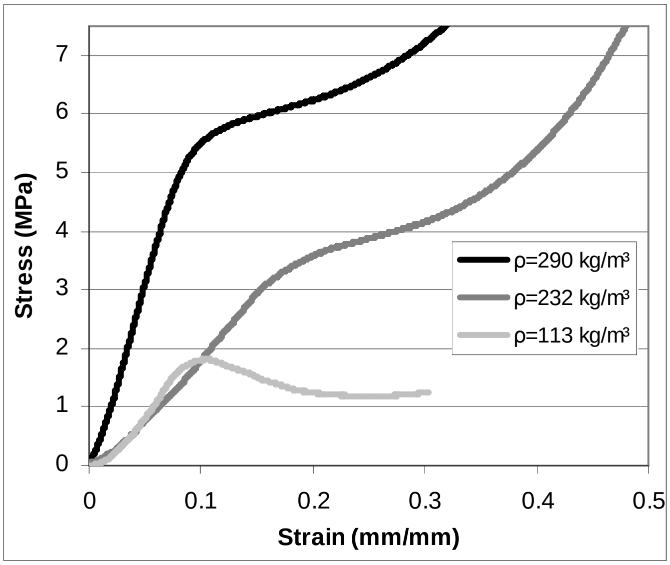


Figure 3. Representative stress-strain curves for the PCM-foam hybrids using various densities of polyurethane foam.

The stiffness was calculated from the maximum slope of the curve before the initial peak. The strength was calculated using the peak stress value. In the cases where there was no definitive peak, an intersection between the maximum slope before the first inflection point, and the minimum slope after the first inflection point was used to determine the strength. The resilience was calculated by integrating up to the peak (as defined by the strength).

The results from at least three samples were used to obtain an average result for each sample type. The error was calculated based on the standard deviation of these different sample results. Average results for density, strength, stiffness and resilience for each sample type are listed in Table 1.

Table 1. Average results of strength, stiffness and resilience from compression tests over at least three samples. Labels 113, 232, 290 indicate density of foam in kg/m^3, PU refers to the polyurethane foam samples and H refers to the hybrid samples.

Sample	Density (kg/m^3)	Stiffness (MPa)	Strength (MPa)	Resilience (kJ/m^3)
PCM	337 ± 1	34.4 ± 4.2	1.13 ± 0.02	37 ± 3
113PU	113 ± 0	7.7 ± 0.8	0.51 ± 0.05	21 ± 4
113H	395 ± 3	34.6 ± 6.2	1.80 ± 0.03	86 ± 9
232PU	232 ± 12	12.9 ± 1.1	2.56 ± 0.07	243 ± 33
232H	537 ± 17	24.9 ± 3.2	3.86 ± 0.53	309 ± 42
290PU	290 ± 6	80.9 ± 6.1	4.46 ± 0.02	117 ± 8
290H	650 ± 44	75.8 ± 6.9	5.33 ± 0.20	186 ± 32

Stiffness of PCM and PCM/PU Hybrids

The results for the average stiffness of the materials are represented by Figure 4. The foam samples, represented by the columns labeled with a 'PU' show increasing stiffness with increasing foam density. The stiffness of the hybrids is dominated by the component with the greatest stiffness. For example, in the case of the 113 and 232 kg/m^3 foams, the stiffness of the PCM was much greater than that of the foams and the overall stiffness of the hybrids was similar to that of the PCM alone. For the 290 kg/m^3 foam, the foam had a greater stiffness than the PCM and the stiffness of the corresponding hybrid was similar to that of the foam alone. These results show that the stiffness of the hybrids can be tailored for a specific application to be greater than or equal to the stiffness of the PCM alone, depending on the density of the polyurethane foam used to create the hybrid.

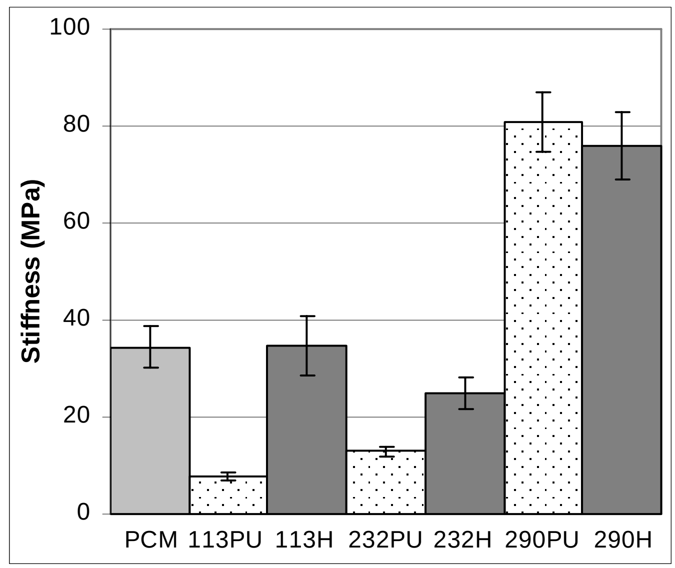


Figure 4. Comparison of stiffness for pyramidal PCM, polyurethane foam (PU) and hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3.

The relative density and stiffness of the PCM, foams and hybrids are illustrated in Figure 5. In this plot, the low density foams form a group at the left-hand side (the outlined symbols), while the hybrids form a group towards the right-hand side (the shaded-in symbols) due to their greater density caused by the addition of the PCM. When looking for a material with a stiffness in the range of 20 – 40 MPa, both the PCM, and lower density foam hybrids are viable options, whereas the higher stiffness options include the 290 kg/m^3 foam and hybrid. The stiffness property can be examined along with other material properties in order to optimize the material selection process.

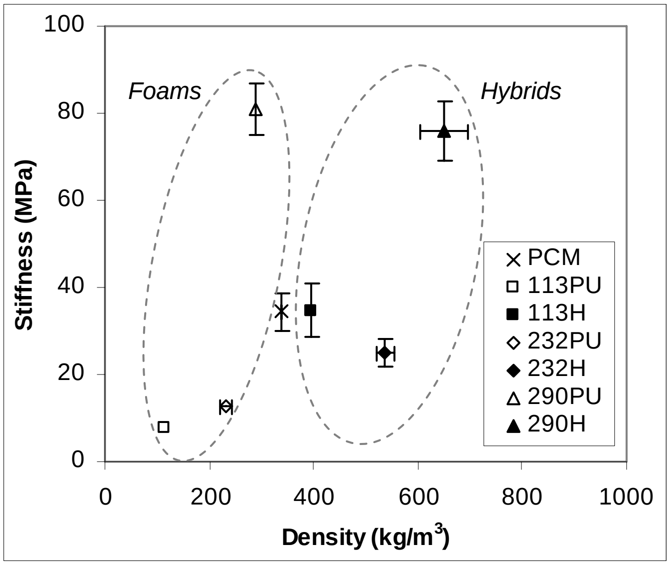


Figure 5. Comparison of stiffness and density for the PCM, foams (PU) and hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3. Error bars are omitted for standard deviations less than 2 MPa and 7 kg/m^3.

By comparing the stiffness of the hybrid samples and the stiffness of the polyurethane foam in Figure 6 the effect of the dominating PCM stiffness is more evident. Both the 113 and 232 kg/m^3 foam hybrids fall within the area bounded by the dashed lines which correspond to the stiffness of the PCM. Outside of the dashed lines, the stiffness of the foam will dominate, as is the case for the 290 kg/m^3 foam hybrid.

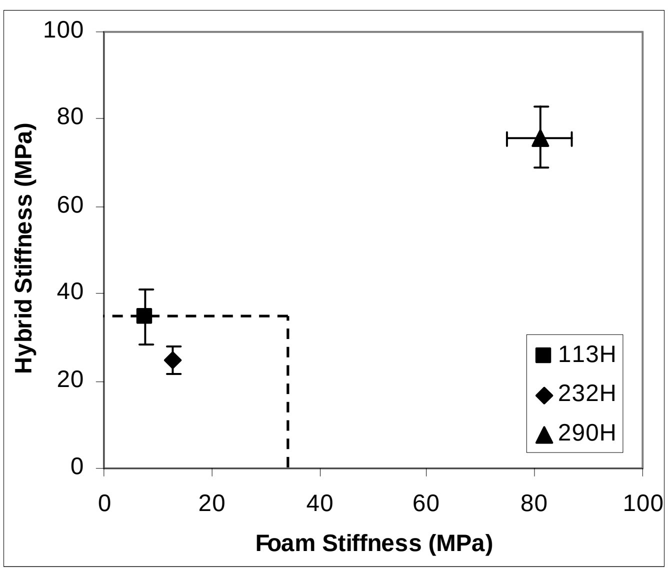


Figure 6. Comparison of hybrid stiffness and foam stiffness. Labels 113, 232, 290 indicate density of foam in kg/m^3. Error bars are omitted for standard deviations less than 2 MPa.

Strength of PCM and PCM/PU Hybrids

The results for the average absolute strength of the materials are represented by Figure 7. Both the foam samples (represented by columns labeled 'PU') and the hybrid samples (represented by the columns labeled 'H') show an increasing trend of strength with increasing foam density. Furthermore, the hybrid samples have a greater strength than either of the PCM or foam components. By examining the columns for the 113 kg/m^3 foam (113PU) and hybrid (113H), the increase in the 113 kg/m^3 foam/PCM hybrid is evident next to the 113 kg/m^3 foam. Not only is the strength of the hybrid greater than the foam and the PCM, but it is greater than the sum of the PCM and the 113 kg/m^3 foam strengths. This effect also occurs for the 232 kg/m^3 foam. By adding the foam to the PCM, the struts of the PCM have been reinforced against buckling, their first failure mode [11]. The foam supports the struts from every side and restricts their movement to provide greater overall strength. In developing a hybrid material, the strength of the new hybrid has become greater than the sum of its constituent parts.

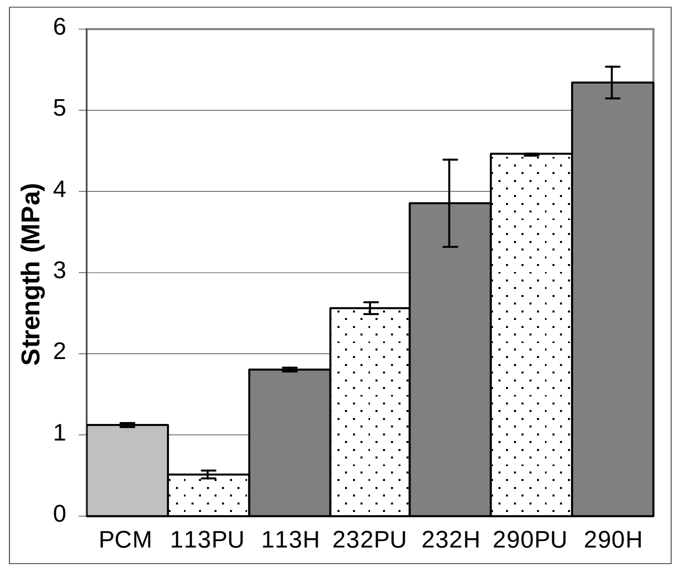


Figure 7. Comparison of strength for pyramidal PCM, polyurethane foam (PU) and hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3.

A comparison of the strength and density of the PCM, foams and hybrids is given in Figure 8. From this plot, the trend of the lower density foams on the left-hand side, and higher density hybrids on the right-hand side is again apparent. In this plot, the increasing trend of strength with density is also apparent for both the foams and the hybrids. Furthermore, it is evident that the hybrids have greater strength when compared to the foams.

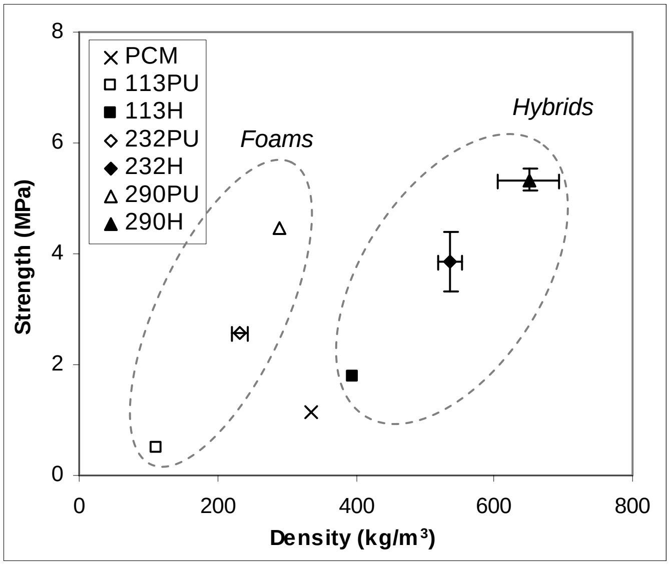


Figure 8. Comparison of strength and density for the PCM, foams (PU) and hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3. Error bars are omitted for standard deviations less than 10 MPa and 7 kg/m^3.

Resilience of PCM and PCM/PU Hybrids

The results for the average absolute resilience of the materials are represented in Figure 9. The addition of the foam to the PCM increased the resilience of the hybrids regardless of the foam density. Furthermore, the resilience of hybrids is greater than the sum of the resilience of both the PCM and the foam. This effect occurs for each of the foam densities.

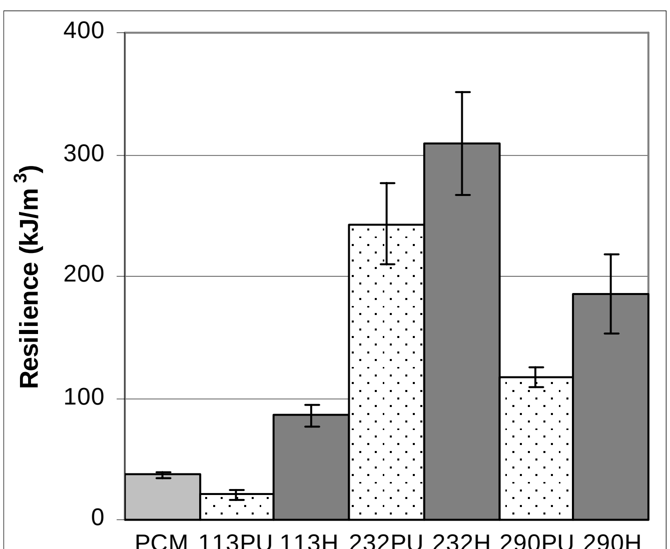


Figure 9. Comparison of resilience for pyramidal PCM, polyurethane foam (PU) and hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3.

Another interesting observation in Figure 9 is that of the peak resilience effect. Both the foam (PU) and hybrid (H) samples have a peak resilience with the 232 kg/m^3 foam. The resilience increases up to the 232 kg/m^3 foam and hybrid samples, but decreases with the greater density 290 kg/m^3 foam and hybrid samples. The comparatively lower modulus for the 232 kg/m^3 foam and hybrid resulted in larger elastic energy absorption. A comparison of the resilience and density of the PCM, foams and hybrids is given in Figure 10. This material selection chart can be used with those in Figures 5 and 8 to determine the ideal material for a given application in terms of its density, stiffness, strength and resilience.

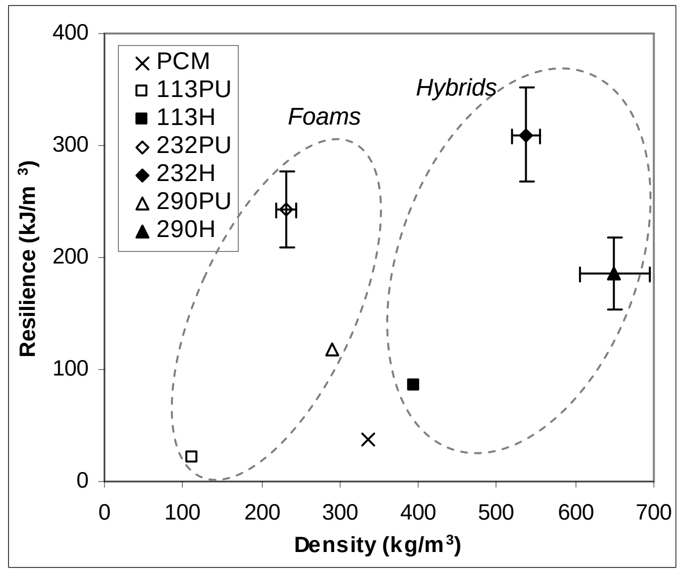


Figure 10. Comparison of resilience and density for the PCM, foams (PU) and hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3. Error bars are omitted for standard deviations less than 10 kJ/m^3 and 7 kg/m^3.

Impact Testing of PCM, PU and PCM/PU Hybrids

A Gardner impact test was performed and the surface damage of each sample was observed. The three distinct sample types: PCMs, PU foams and PCM/PU hybrids, were each found to have a different damage profile.

The PCMs were initially able to withstand any failure as shown in Figure 11a. Eventually they began to fail by the inelastic buckling of their struts at the point of impact as shown in Figure 11b. Next, a depression became visible on the top face sheet of the PCM as shown in Figure 11c. Finally, the base sheet began to deform due to the continuous buckling of the struts as shown in Figure 11d.

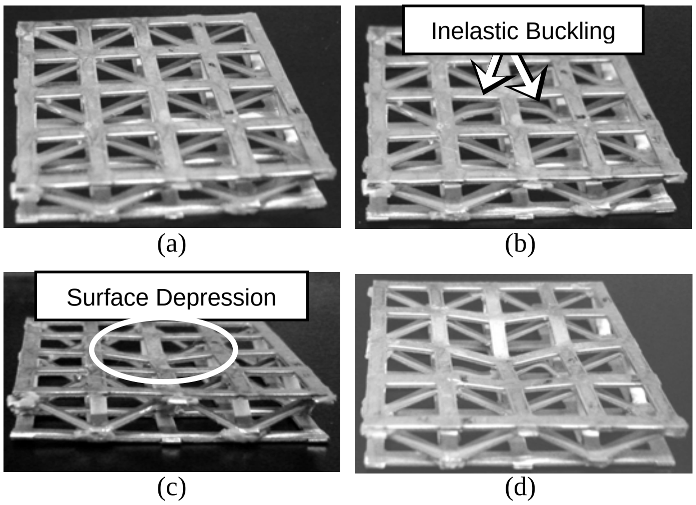


Figure 11. Damage profile for the pyramidal PCM includes (a) no damage, (b) inelastic buckling of the local struts, (c) top face sheet depression, and (d) base sheet deformation.

The damage profile for each of the PU foam densities contained the same failure modes. A foam sample before impact is shown in Figure 12a. Upon first impact, the foam displayed slight surface depression as shown in Figure 12b. As the impact energy increased, a crack would form in the depression as shown in Figure 12c. Finally, there would be complete penetration of the foam as shown in Figure 12d.

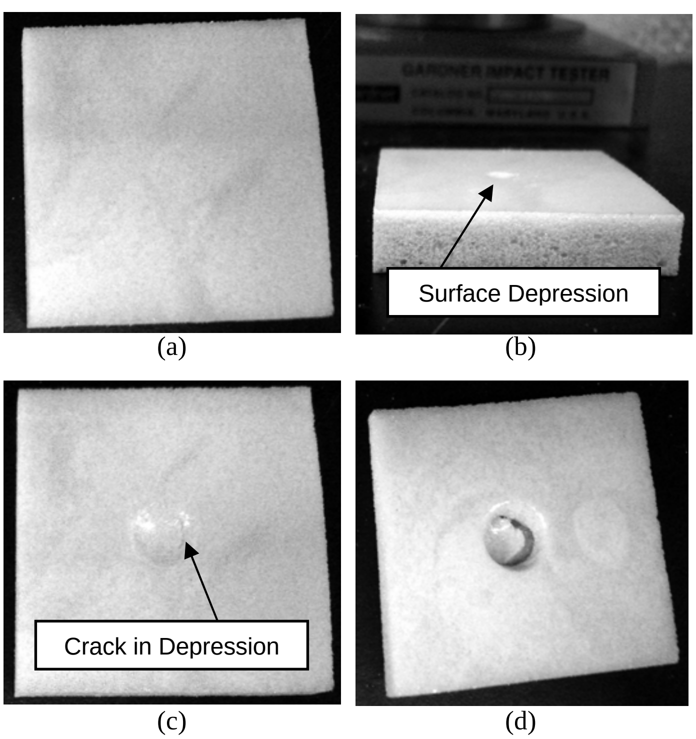
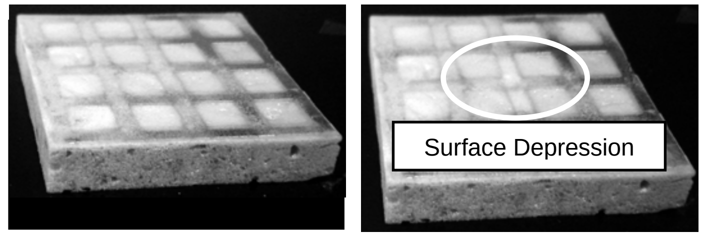


Figure 12. Damage profile for the PU foams includes (a) no damage, (b) surface depression, (c) crack in surface depression, and (d) complete penetration.

The hybrid samples had fewer visible failure modes. Initially they withstood the impact as shown in Figure 13a. Eventually, a depression would form on their surface as shown in Figure 13b. Finally, there would be shearing at the metal/foam interface.



(a) (b)

Figure 13. Damage profile for the PCM/PU foam hybrids includes (a) no damage, (b) surface depression and shearing at the metal/foam interface.

The impact energies required to reach the various failure modes for the PCM, PU foams and hybrids are summarized in Tables 2, 3 and 4, respectively. Figure 14 compares the failure modes of the samples. The only common failure mode was depression of the surface face. As mentioned above, the PCMs underwent inelastic buckling of the struts, surface depression and deformation of the base sheet. The PU foams underwent surface depression, cracking in the depression and complete penetration. Finally, the hybrids underwent surface depression and shearing at the metal/foam interface.

Table 2. Average results for the impact energy for given failure modes of the PCM.

	Impact Energy (mJ)		
	Inelastic Buckling	Depression	Base Sheet Deformation
PCM	283 ± 0	339 ± 0	640 ± 33

Table 3. Average results for the impact energy for given failure modes of the PU foams. Labels 113, 232, 290 indicate density of foam in kg/m^3.

	Impact Energy (mJ)		
	Depression	Crack	Penetration
113PU	57 ± 0	377 ± 0.033	697 ± 33
232PU	57 ± 0	640 ± 182	1187 ± 57
290PU	57 ± 0	867 ± 131	1488 ± 33

Table 4. Average results for the impact energy for given failure modes of the PCM/PU foam hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3.

	Impact Energy (mJ)	
	Depression	Shearing at Metal/Foam Interface
113H	414 ± 33	678 ± 0
232H	546 ± 33	867 ± 33
290H	697 ± 33	1130 ± 655

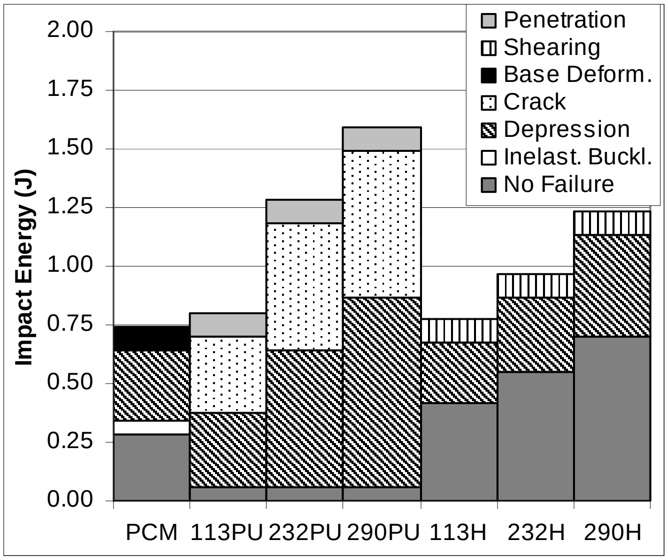


Figure 14. Comparison of impact failure modes for the PCM, foams (PU) and hybrids (H).

Each of the foam samples exhibited surface damage in the form of an indentation from the first impact test at a height of 25.4 mm. The PCM and hybrid samples continued to resist the impact beyond the first test, and up to a greater impact energy. These samples did not begin to show a surface depression until a height of at least 152.4 mm. Since the PU foams all exhibited damage from the first impact, smaller increments of impact energy are required in order to compare their initial damage. However, upon continuing the testing, the sample would eventually crack as the impact energy was increased. Figure 15 compares the impact energies of the foam for samples that have a visible crack in the depression that formed on their surface. This figure shows that there is an increasing trend of crack resistance with increasing foam density.

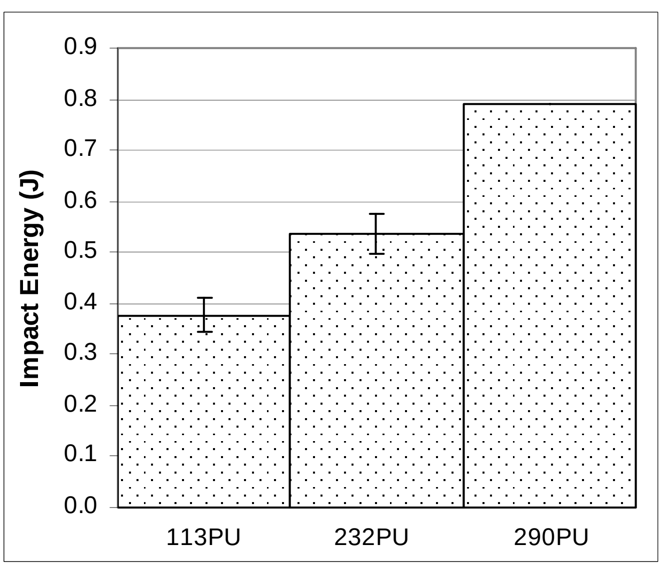


Figure 15. Comparison of impact resistance for crack formation in the PU foam samples.

In order to compare all of the different types of samples, the surface depression failure mode was used. Figure 16 compares the impact energy for surface depression of the PCM, the PU foams and the hybrids. Since the PU foams all exhibited surface damage upon first impact at an impact energy of 57 mJ, they are represented as one entry in Figure 16.

Figure 16 shows that the impact energies of the hybrids are greater than that of the PU foam or PCM alone. There is also a clear increasing trend in impact energy with the density of the foam used in the hybrid. So by increasing the density of the foam we can create a hybrid material with greater impact energy. Furthermore, with each of the foam densities the impact energy of the hybrid is greater than the sum of the impact energy of the PU foam and PCM.

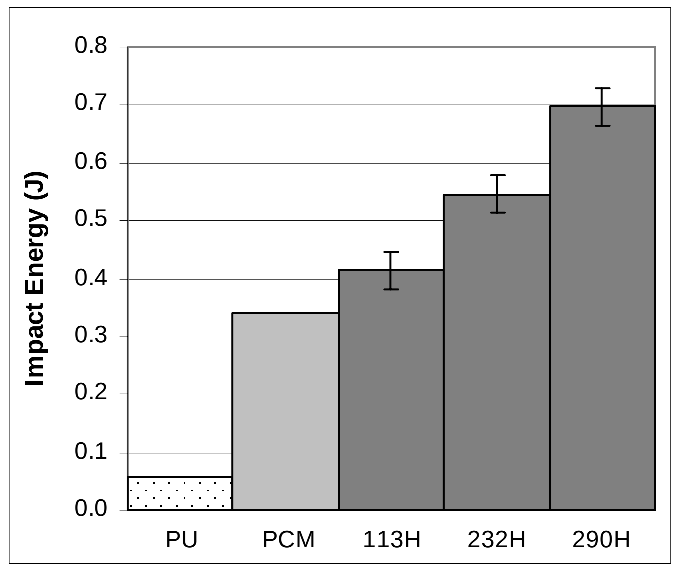


Figure 16. Comparison of impact resistance for pyramidal PCM and hybrids (H). Labels 113, 232, 290 indicate density of foam in kg/m^3.

A comparison of the impact energy and density of the PCM, foams and hybrids is given in Figure 17. The low density foams appear towards the left-hand side of the plot, however they offer little in terms of impact resistance as can be seen by the low impact energy at which they fail. The PCM performs relatively well, with an average density and impact energy, however the hybrid samples offer much more in terms of the impact energy which they can undergo before failure. Although there is a slight loss in terms of the density of the hybrids, the gain in impact resistance is substantial.

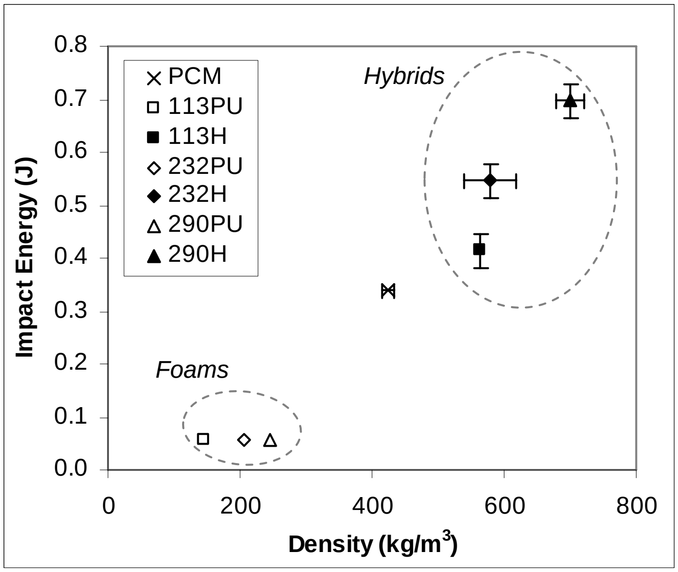


Figure 17. Comparison of impact energy and density. Labels 113, 232, 290 indicate density of foam in kg/m^3. Error bars are omitted for standard deviations less than 0.04 J and 2 kg/m^3.

CONCLUSIONS

A novel hybrid created from a pyramidal PCM architecture and rigid polyurethane foam has been designed, fabricated and tested in uniaxial compression and by the Gardner impact test. The hybrid materials exhibited a number of interesting properties including the ability to tailor the stiffness of the hybrid by using different densities of polyurethane foam. It was also found that the strength and resilience of the hybrid was greater than the sum of the strength and resilience of the PCM and the polyurethane foam components. Furthermore, it was observed that the impact energy required for surface deformation of the hybrids was greater than both the PU foam and the PCM, and by increasing the foam density, the impact energy also increased.

In developing a new material of PU foam and pyramidal PCM architecture, a hybrid material that offers greater strength, resilience and impact resistance than the sum of its parts has been created.

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