

**Periodic and Stochastic Cellular Solids – Design, Manufacturing and
Mechanical Characterization**

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Resumo

Sólidos celulares incluindo espumas metálicas, cerâmicas e poliméricas, estruturas ninho de abelha e de micro-treliças são frequentemente utilizados como núcleos de painéis do tipo sandwich. O núcleo celular oferece um aumento do momento de inércia com pouca penalização em termos de peso. Veículos aéreos, terrestres e marinhos podem todos beneficiar do uso de painéis sandwich em termos de redução do consumo de combustível e emissões poluentes, bem como do maior alcance permitido e a capacidade de transportar cargas mais pesadas.

Este estudo apresenta o design e processos de fabrico de três sólidos celulares distintos: um núcleo periódico tridimensional composto por unidades de ABS obtidas por prototipagem rápida, um núcleo periódico bidimensional composto por tubos de fibra de carbono obtidos por pultrusão e um núcleo estocástico baseado em pedra-pomes. O comportamento mecânico em compressão e flexão em três pontos de geometrias de diversas densidades relativas será apresentado e analisado.

Foi determinado que o colapso dos núcleos de ABS obtidos a partir de prototipagem rápida sob compressão fora do plano é um equilíbrio entre material a deformar plasticamente e por encurvadura das pernas das estruturas. As suas propriedades mecânicas não apresentam variações significativas quando fabricados a escalas diferentes desde que a geometria das pernas e o seu ângulo se mantenha constante. No entanto verificou-se que a rigidez e resistência mecânica, entre outras propriedades mecânicas, se alteram significativamente com a variação da densidade relativa.

Os núcleos compostos por tubos de fibra de carbono apresentaram comportamentos semelhantes mesmo com uma variação da densidade relativa. Existe a necessidade de melhorar o processo de deposição dos tubos de carbono uma vez que o colapso se deu ao nível da interface entre os tubos e as faces de alumínio, bem como entre os próprios tubos.

Algoritmos de mapeamento de deformação foram usados para compreender os mecanismos de colapso do núcleo à base de pedra-pomes e diferentes modos de colapso foram identificados em ensaios de flexão em três pontos. Um mecanismo de colapso sob tensão foi identificado que não foi documentado em estudos anteriores. Um mapa experimental dos modos de colapso foi também criado para o design deste tipo de estruturas.

Gráficos de selecção de geometrias foram também criados e apresentam-se como ferramentas de integração destas novas estruturas em novos sistemas de veículos.

Abstract

Cellular solids including metallic, ceramic and polymer foams, honeycombs and microtruss structures are all commonly used for core materials within sandwich panels. The cellular core offers an increase in the moment of area with a very little increase in weight. Advanced air, land and sea vehicles can all benefit from using sandwich panels such as reduced fuel consumption and emissions, as well as the extended range it allows and the ability to carry heavier payloads.

This study presents the design and manufacturing of three distinct cellular solids used as sandwich panel cores: rapid-prototyped ABS three-dimensional periodic core, two-dimensional periodic carbon fiber lattice core and low-cost naturally occurring pumice based stochastic cellular solid core. Mechanical performance under compression loading and three-point bending at various relative densities and geometries will be presented and analyzed.

The out-of-plane compression failure mode of the rapid-prototyped ABS cores was determined to be a balance between material plastically deforming and strut buckling. Their core properties do not show significant changes when scaled up or down as long as strut geometry, topology angle, are not changed. However it was measured that stiffness, strength and other mechanical properties do change with relative density.

The carbon fiber lattice cores exhibited similar responses when relative density was changed. Optimization of the lay-up process used to manufacture these cores is needed, as the failure observed occurred on the interface between the core and the face sheets as well as between the tubes themselves.

Strain mapping is used to understand the active failure mechanisms of the pumice-based core and different failure modes were identified under three-point bending. A tensile failure mechanism is identified, which has not been reported in the past. An experimental failure mode map has also been created for design use.

Geometry selection or trade-off charts are created to provide designers with tools for the insertion of these novel lightweight materials into new vehicle systems.

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1 Introduction

1.1 Motivation and foundations

The automotive industry and vehicle systems in general have been evolving throughout the decades, seeking to increase performance and improve passenger comfort and most importantly safety. However, escalating oil prices and the rising of environmental awareness have led to an increased focus on the reduction of fuel consumption as well as CO₂ and other polluting emissions.

There are several ways to improve the fuel efficiency of vehicle systems, such as optimizing engine components to increase energy efficiency or implementing control systems that shut down unnecessary components when not utilized. All of these measures help improve fuel efficiency and reduce gas emissions.

Aside from the propulsion system itself, there is one parameter which plays a crucial role in fuel consumption: weight. For any given powertrain weight reduction of structural, static and moving parts enables improved performance, i.e. faster acceleration and more responsive handling, while reducing fuel consumption and consequently lowering emissions [1]. Another way to view the same concept is that, by reducing weight, a vehicle can achieve the same acceleration and range performance with a less powerful motor when compared to vehicles built with conventional material systems. By downsizing the vehicle's powerplant, fuel consumption and emissions are reduced as well, assuming efficiency remains the same.

Over the years, vehicles have become increasingly heavier to incorporate the latest safety technologies, increase rigidity in a quest to better protect the occupants as well as aesthetic and passenger comfort demands. The vast majority of the vehicles currently in production use steel as the material of choice when it comes to build the chassis and other structural components [2]. Aluminum is also a fairly common choice for some of those components, but usually only in higher end vehicles where cost premium does not out surpass performance improvements. Review of the specific stiffness of commonly used structural materials (Steel and Aluminum) explains this rational. Table 1.1 shows the specific modulus for steel and Aluminum and shows that for a stiffness limited design application the performance metric for both materials is very similar thus making it harder to justify increased production costs.

Table 1.1 - Typical values of rigidity and density of steel and aluminum. Specific rigidity is similar for both.

	Young's Modulus, E (GPa)	Density, ρ (kg/m ³)	E/ρ (GPa.m ³ /kg)
Steel	210	7700	0.0273
Aluminum	72	2700	0.0267

Composite materials benefit from a higher E/ρ ratio but its use is not widespread, if we exclude motorsport vehicles, predominantly for economic reasons. For most passenger vehicles, including higher end luxury motors such as the one on Figure 1.1, steel is still the material of choice for the majority of structural or chassis components.

It is also important to note that, while strength is obviously an important parameter, vehicle design is stiffness-limited and therefore stiffness is the critical constraint.

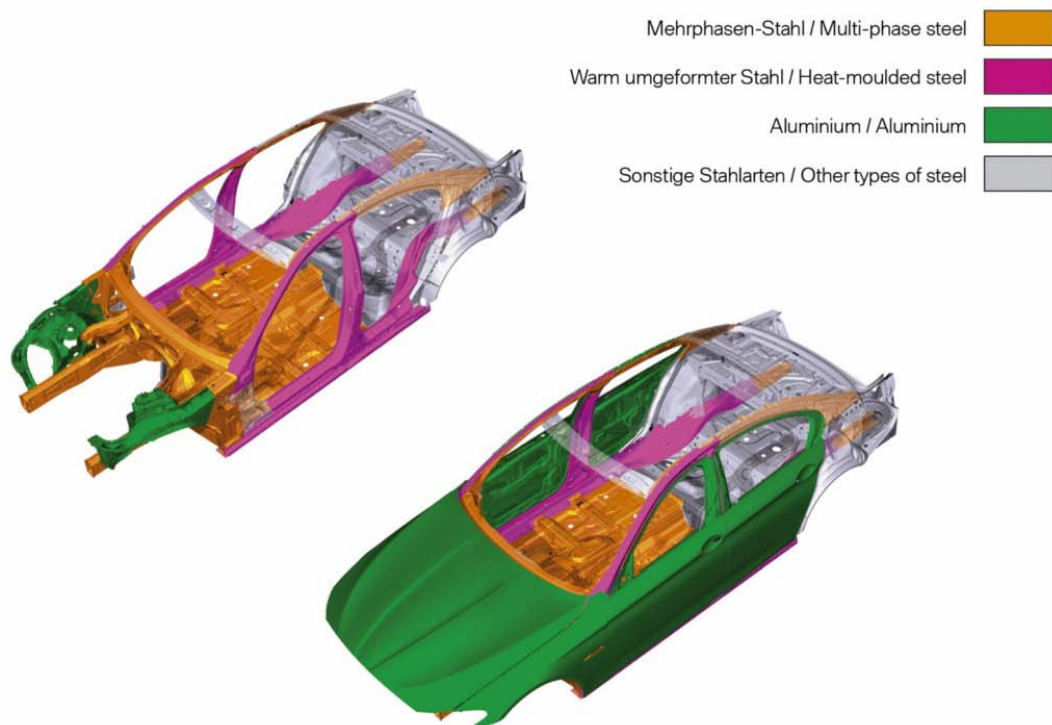


Figure 1.1 - 2010 BMW 5-Series (F10) chassis materials. This illustration shows the majority of the chassis components are made out of steel, especially structural parts, with some of the front and side body panels made out of aluminum in an attempt to offset the increased weight of the engine and achieve a better weight distribution and therefore better handling.

The ideal material for passenger vehicle application should be as light as possible, which is to say its density should be low, but structural components should possess a high stiffness. In addition, high energy absorption during the material collapse or deformation is needed to ensure the vehicle's occupants safety in case of collision, i.e. crashworthiness [3]. Bodywork components on

the other hand should also be lightweight but they must be able to absorb high amounts of energy through plastic deformation.

This conventional design of separating bodywork components from structural ones is required when using traditional materials. Composite structures enable a multifunctional design where the same component can perform both functions and dramatically reduce overall weight in the process while retaining the required mechanical properties i.e. the structural (load bearing) and body work component are a single piece eliminating the need for two components.

Figure 1.2 presents a material selection chart showing Stiffness on the vertical axis and Density on the horizontal axis. When material properties are plotted this way the chart is essentially presenting the specific stiffness for all of the materials in the world, with higher specific stiffness being in the upper left corner of the chart. By looking at this chart it is clear there is much to be gained by transitioning from traditional materials, such as steel and aluminum, to combinations of disparate phase materials (moving to the left and up on the chart) to achieve improved performance while keeping costs reasonable.

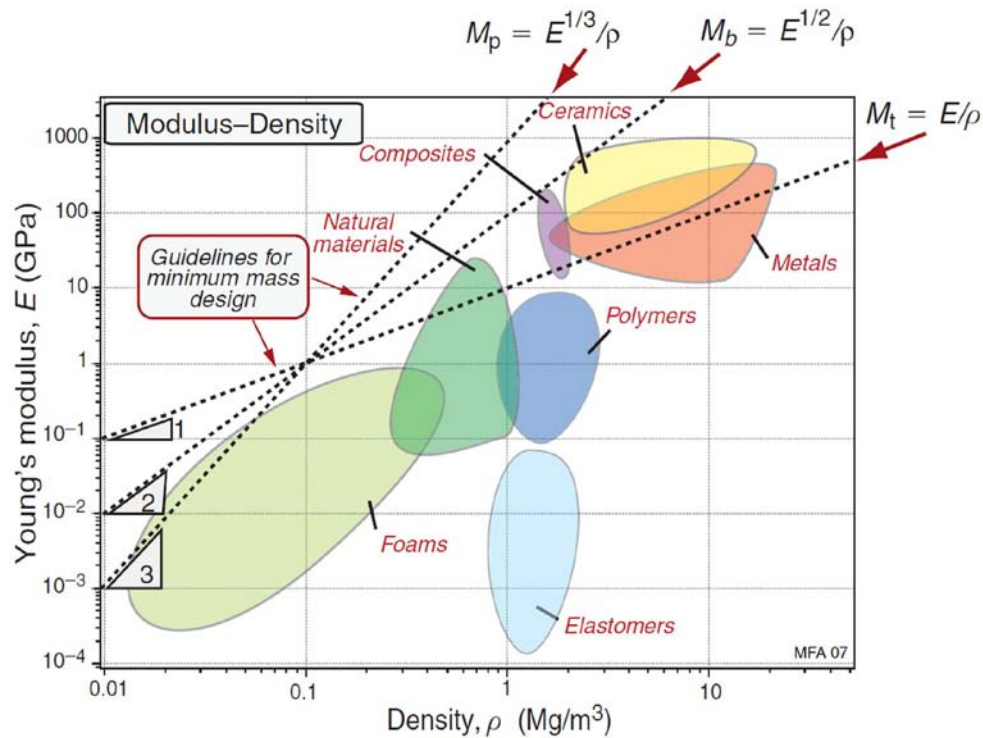


Figure 1.2 - A schematic E/ρ chart showing guidelines for three material indices for stiff, lightweight structures [4]. When designing a light stiff panel, the $E^{1/3}/\rho$ index should be used while $E^{1/2}/\rho$ is the index to maximize when designing a light stiff beam. The index E/ρ is used to design a light, stiff tie-rod.

The ability to tailor composites to fill gaps in the material space, namely the highest stiffness / lowest density region which currently is empty of materials, is a great advantage over traditional monolithic materials. Composites can be specifically engineered to meet design requirements that no single material can fulfill [4].

With the price of metals increasing, as well as the minerals used as the alloying agents in advanced monolithic materials to improve their performance, due to extremely high demand from countries whose economies are enjoying a rapid expansion, alternate materials are also becoming a more viable option. As such, composite hybridization can be more cost-efficient than the alternative of developing new monolithic materials. In the case of composite materials and cellular solids in general, as manufacturing costs go down, the improvement they offer against regular metal alloys in terms of mechanical properties make the transition seem all the more appealing.

1.2 Composites: conventional definition

A composite is defined as a combination of at least two different phases in a macroscopic scale. In most composites one phase is continuous, the matrix, and the reinforcement is discontinuous [5].

The matrix is typically metallic, ceramic or plastic, the latter being the most widespread and its function is to ensure the connection between the different phases and often protect the more fragile secondary reinforcement phase. The reinforcement is the phase which actually provides strength and stiffness to the composite whilst the matrix allows for load transfer between the reinforcement. Some of the most common reinforcements are fibers and led to the engineering of GFRP, KFRP and CFRP with the reinforcements being glass, Kevlar and carbon respectively.

While composites are sometimes perceived as new materials, they have been around in one form or another for millennia, mostly in construction. It is known that ancient Egyptians used straw and mud to create bricks which they would then use to build housing, see Figure 1.3.



Figure 1.3 - Mud bricks built by ancient Egyptians. The basic building material consisted of chopped straw mixed with mud from the Nile. The bricks were then shaped in a wooden mold and left to dry in the sun. Courtesy of Brooklyn Museum.

Over the past decades the high manufacturing costs of advanced composites and the broad spectrum of mechanical properties achieved by combining different phases and respective proportions have limited its use to high end applications where the budget is not such a limiting factor and performance is a premium, as is often the case in the aerospace and aeronautic industries.

Motorsport has also quickly understood the benefits of using composite materials as the quest for improved performance is deemed worth the higher cost they imply. Only in recent decades has its use been filtering down to higher volume applications, one of those being the automotive industry. Within the industry itself, the use of composites is quite common in the upper echelons, i.e. in the so called supercars, but the limited production and high retail cost of such vehicles means they represent a very small part of total automotive production. Potential for application in large scale production vehicles exists and is a matter of finding the balance between increased performance and elevated costs.

1.3 Sandwich panels

Composite sandwich panels, comprising of strong and stiff facing sheets adhered to a thick, weaker and low relative density core $\bar{\rho}$, (relative density is defined as the ratio between the density of the core and the density of a monolithic plate of the same material), provide a good design solution for weight-critical applications due to the specific stiffness and strength these panels achieve.

Sandwich panels are based on the assumptions that the face sheets are much thinner and stiffer than the core and perfectly bonded to each other, see Figure 1.4.

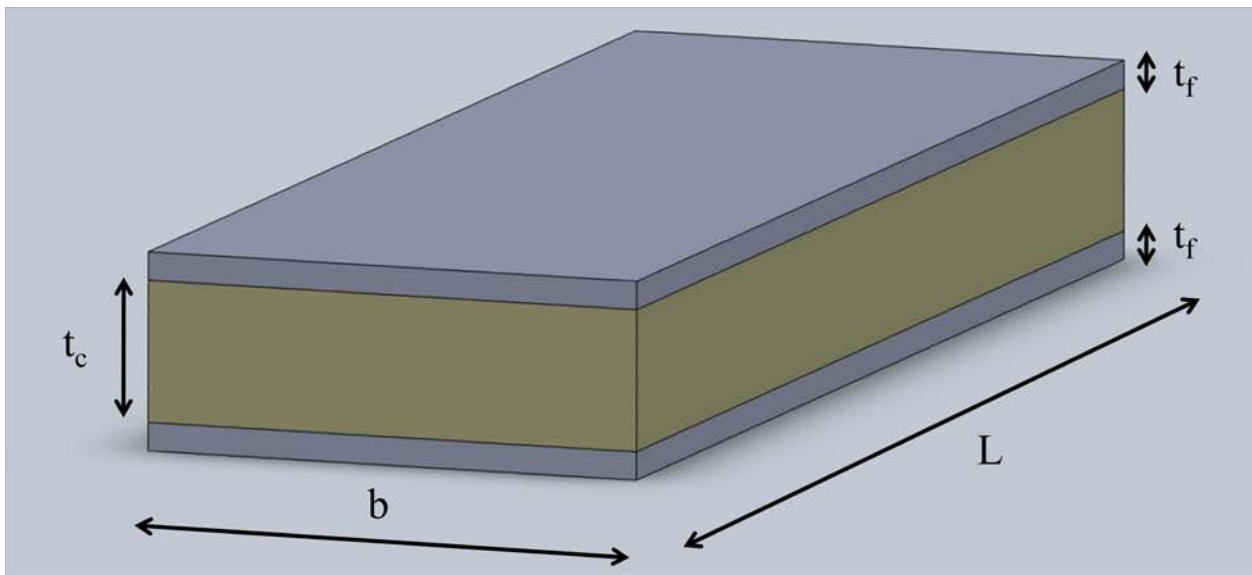


Figure 1.4 - Illustration of a sandwich panel comprised of a lightweight core and two identical face sheets substantially thinner.

The separation of the core increases the moment of area with a very little increase in weight. Flexural rigidity is achieved with the face sheets carrying the bending moment as longitudinal tensile and compressive stresses and the core the transverse shear force [6]. For symmetrical sandwich panels, meaning the faces are of the same material and of equal thickness, flexural rigidity is calculated according to the Parallel Axis Theorem and is defined as:

$$(EI)_{eq} = \frac{E_f b t_f^3}{6} + \frac{E_f b t_f d^2}{2} + \frac{E_c b t_c^3}{12} \quad (1.1)$$

where E_f is the Young's Modulus of the face sheet, E_c is the Young's Modulus of the core, b is the width of the panel, t_f is the thickness of the face sheets, t_c is the thickness of the core and d is the distance between the centroids of the faces, i.e., $d = t_f + t_c$.

This expression can be simplified for typical sandwich panels, where the thickness of the face sheets is very thin compared to that of the core, $d/t_c \approx 1$, and the core's stiffness much lower than the stiffness of the face sheets, $E_c/E_f \approx 0.001$. Thus, flexural rigidity can be approximated by:

$$(EI)_{eq} = \frac{E_f b t_f d^2}{2} \quad (1.2)$$

Advanced air, land and sea vehicles can all benefit from using sandwich panels such as reduced fuel consumption and the extended range it allows, to the ability to carry heavier payloads.

Face sheets are usually made of traditional monolithic materials such as steel and aluminum or fiber composites, namely carbon or glass, and will not be the focus of this research as they are often set for us. The core, on the other hand, offers a large possibility in terms of design optimization. As such, this thesis will focus on three distinct sandwich core materials. The next section is therefore broken into three parts, each presenting a different sandwich core:

- An engineered, completely design optimized core
- Low cost pumice
- An engineered, two dimensional periodic core

1.3.1 Rapid Prototyped ABS three-dimensional periodic core

Rapid prototyping has quickly gained popularity within the design and manufacturing community due to its ability to produce complex geometries much quicker and effectively than using traditional machining techniques. All that is necessary is to build a CAD model and send it to the 3D printer which prints an ABS prototype, see Figure 1.5. While the rapid prototyping machine provides ease of design and topological optimization, the realization of this process is limited by the available materials that can actually be used machine. This means, however, that the cores suffer from the limited properties of ABS. This material is often used to make light, rigid, molded products due to its impact resistance and toughness, but its strength and stiffness are too low to be used in structural applications.

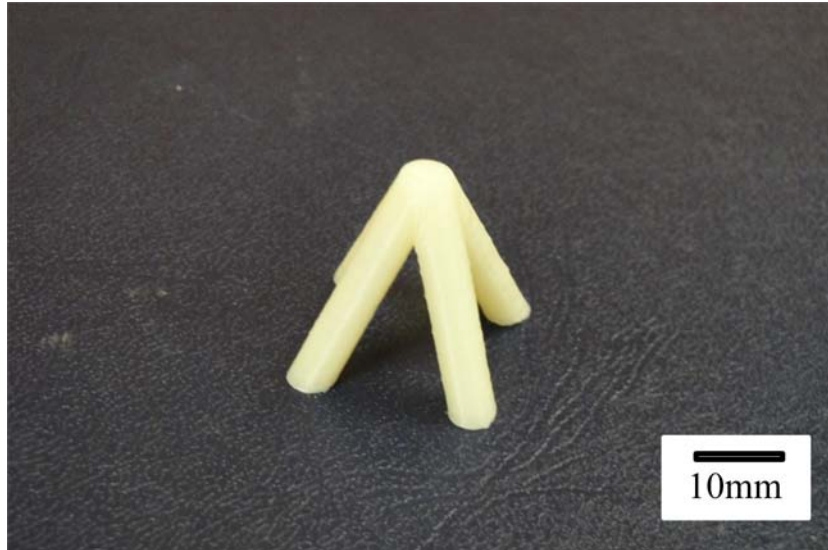


Figure 1.5 - ABS pyramidal core geometry manufactured using rapid prototyping techniques.

There are ways to improve the properties of the ABS cores, such as electroforming. Just like rapid prototyping, electroforming can also be applied on complex geometries. Previous work by Burns et al [7] suggests that electroforming ABS materials with copper and nickel may increase the yield strength four-fold and the elastic modulus by up to fifteen times.

This kind of mechanical improvement combined with topological optimization to enhance derived properties, such as E/ρ and σ/ρ , is enough to make the disparate phase hybrid mechanically competitive with structural materials such as aluminum honeycomb and foam-based cores and, in some instances, a better material selection than these.

1.3.2 Two-dimensional periodic carbon fiber lattice core

Carbon fiber consists of extremely small fibers, 5 to 10 μm in diameter, and comprised mostly of carbon atoms bonded in microscopic crystals aligned parallel to the long axis of the fiber. They can be manufactured from two different types of precursors, pitch and textile, the most common of which being PAN [8]. It was only a few decades ago that these fibers were successfully manufactured in large enough quantities with statistically repeatable properties and the aerospace industry has since led the development, optimization and insertion of this material into vehicle system structural components.



Figure 1.6 - Carbon fiber shafts. The manufacturing process is computerized and tightly controlled to meet strict tolerances in order to achieve properties consistency from shaft to shaft.

Carbon fibers present exceptionally high tensile strength and modulus to weight ratios as well as a very low coefficient of thermal expansion. They also possess high fatigue strength and high thermal conductivity [8]. These properties make them popular reinforcements for plastics and engineering high strength lightweight composites.

In this study the performance of pultruded carbon fiber reinforced polymer hollow struts, such as the ones on Figure 1.6, arranged in a two dimensional periodic lattice is analyzed (similar to what Wadley suggests on [9] and presented on Figure 1.7), experimentally evaluated and compared to other possible core topology solutions for composite sandwich panels.

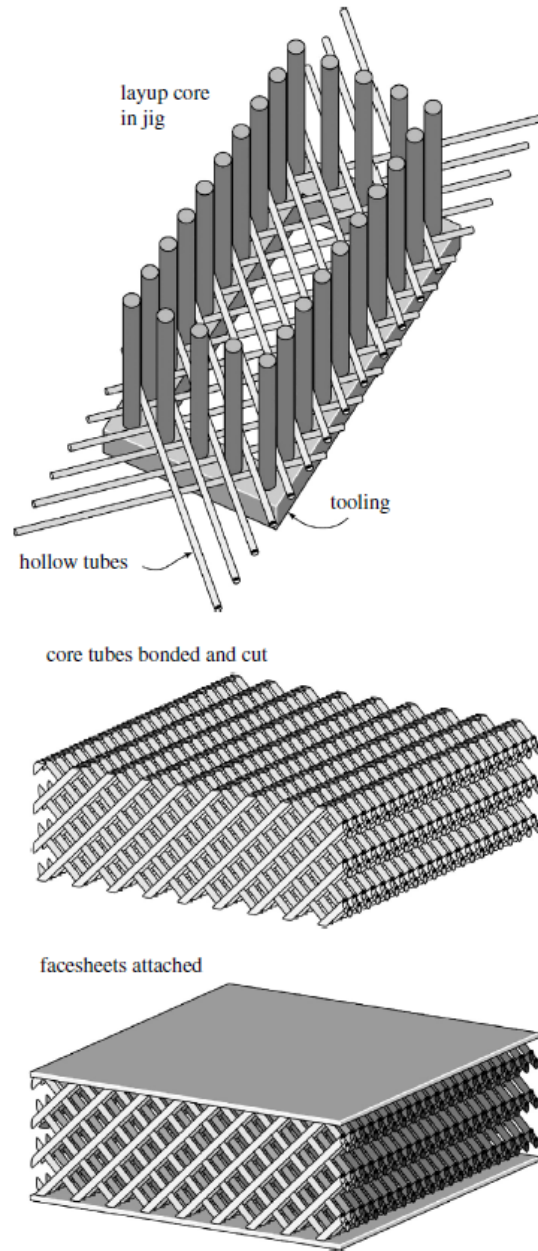


Figure 1.7 - Lattice truss structure comprised of layers of hollow tubes bonded to each other [9].

1.3.3 Naturally occurring pumice based stochastic cellular solid core

Pumice is the name given to a volcanic rock comprised mainly of Silica (SiO_2) and Alumina (Al_2O_3), which make up 63-67% and 17-19% by mass respectively, see Figure 1.8. It is formed when highly pressurized and molten rock is ejected during volcanic eruptions and suffers a rapid cooling and depressurization. The latter creates air bubbles within the rock and the simultaneous cooling converts them in vesicles, endowing pumice with a high porosity and a density approximately equal to that of water's 1000 kg/m^3 . On a microscopic level, the structure is similar to an engineered closed cell ceramic foam [10].



Figure 1.8 - Naturally occurring pumice are low cost, lightweight pyroclastic igneous rocks formed during volcanic eruptions.

This structure means the pumice has a high strength to weight ratio and can successfully be used to make lightweight concrete which is also less conductive and more resistant to adverse weather conditions. The Roman Empire made use of pumice and it is one of the main reasons its ancient architecture, from about two thousand years ago, is still mostly well preserved [11]. These characteristics are all the more attractive due to its abundance and consequent low cost, making it an appealing proposition to the civil engineering industry today.

As far as advanced vehicles development is concerned, and to the author's knowledge, the application of pumice derived composites is sparse at best. Besides exhibiting a high stiffness over density ratio, it is also an interesting material from an energy absorption standpoint. The frictional interference, or friction grinding, of pumice or any other granular materials, during flow provides energy absorption per unit mass additional to the value achieved from plasticity [12]. This effectively makes pumice a mechanical and chemical or physical absorber.

For these reasons its performance as a core in a sandwich panel will be included in this study.

1.4 Thesis Overview

This thesis presents the study of three cellular solid cores.

Chapter 2 presents literature salient to the fabrication and understanding of panel performance, including the understanding of stretching versus bending dominated architectures and a deeper insight into cellular solids.

Chapter 3 describes the manufacturing techniques developed to produce the different panels. The necessary level of detail is presented so that the manufacturing process can be readily repeated for future studies.

In Chapter 4 the experimental results of mechanical testing are presented, including compression and three-point bending tests.

The experimental results are then analyzed on Chapter 5 and the performance of different structures compared.

Finally, Chapter 6 encompasses the closing remarks, conclusions and possible suggestions for future work.

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2 Current understanding of Cellular Solids

2.1 Introduction to Cellular Solids

A cellular solid consists of an interconnected network of solid struts or plates which form the edges and faces of cells. Cellular solids can be naturally occurring such as pumice or the honeycomb of a bee's nest, Figure 2.1, and can also be manufactured and engineered such as two-dimensional metallic honeycombs, or polyhedra which pack in three-dimensions to fill space, i.e. both open and closed celled foams such as the ones on Figure 2.2 and Figure 2.3.



Figure 2.1 - Picture of a bee's nest honeycomb structure [1].

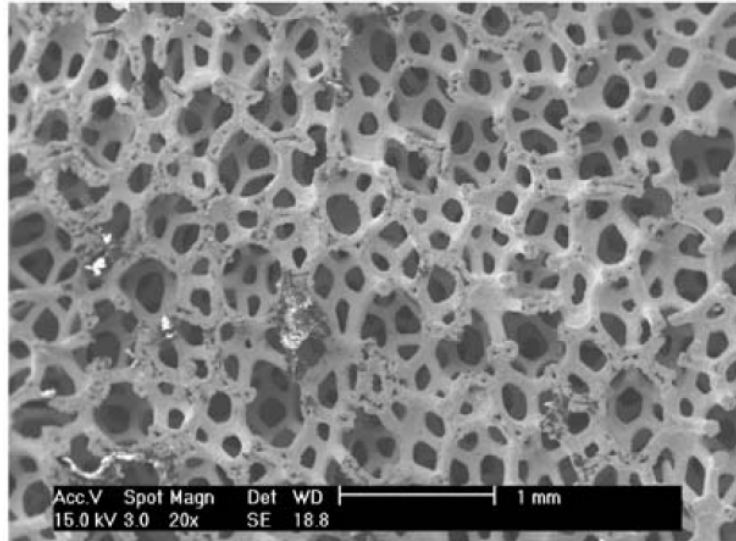


Figure 2.2 - Recemat Metal Foam, an open-cell polyurethane foam manufactured by Recemat International BV, The Netherlands [2].

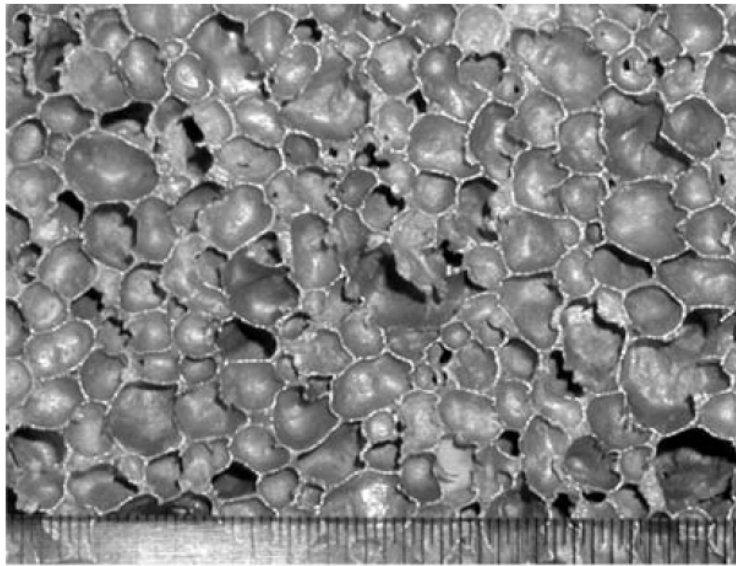


Figure 2.3 - Alporas closed-cell aluminum foam, manufactured by Shinko Wire Company Ltd, Japan [2].

There are several types of polyhedra, the most relevant for this study being the regular convex polyhedral presented on Table 2.1.

Table 2.1 - The regular convex polyhedra, where n is the number of faces meeting at a vertex and V , E and F are the numbers of vertices, edges and faces [3].

faces	n	name	symbol	V	E	F	symmetry
triangles	3	tetrahedron	3^3	4	6	4	$\bar{4} 3 m$
triangles	4	octahedron	3^4	6	12	8	$m \bar{3} m$
triangles	5	icosahedron	3^5	12	30	20	$m \bar{3} \bar{5}$
squares	3	cube	4^3	8	12	6	$m \bar{3} m$
pentagons	3	dodecahedron	5^3	20	30	12	$m \bar{3} \bar{5}$

When studying cellular solids the most relevant feature, identified by Gibson and Ashby [4] is defined as relative density, $\bar{\rho}$, which is the density of the cellular material, $\rho_{cellular}$, divided by the density of the solids from which the cell walls are made, ρ_{solid} . Foams have a wide range of relative densities, with the upper limit generally regarded as roughly 30%. Cork, whose microstructure can be seen on Figure 2.4 is a naturally occurring cellular solid which possesses a fairly low relative density, around 14%. However, special ultra low density foams can be made with a relative density as low as 0.1%. Changes in relative density are accomplished through thickening or thinning of the cell walls and consequent shrinking of the pore space between them. As such, for higher values than 30%, the architecture is no longer considered a cellular structure but a solid containing isolated pores [4].

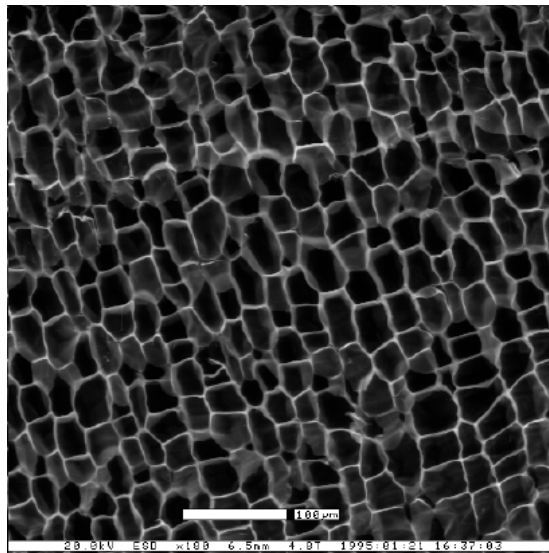


Figure 2.4 – Image of the microstructure of cork, taken with an environmental scanning electron microscope (ESEM). It is an open cell naturally occurring cellular solid. Courtesy of The Museum of Paleontology of The University of California at Berkeley and the Regents of the University of California.

Several materials can be used as foams, from polymers and metals to ceramics and glasses, which should be selected according to the intended application. The largest application for cellular solids and polymeric foams in particular, is thermal insulation. Packaging is also a very common application for these structures as they can provide low density lightweight structures and energy absorption.

On a microscopic level the structures of periodic architectures, such as the one on Figure 2.5, include micro-truss assemblies, commonly known as lattice materials, which can be arranged or engineered in topologies which exhibit design required specific properties vastly superior to those of their stochastic, or randomly oriented, counterparts [5], an example of which can be seen on Figure 2.6.

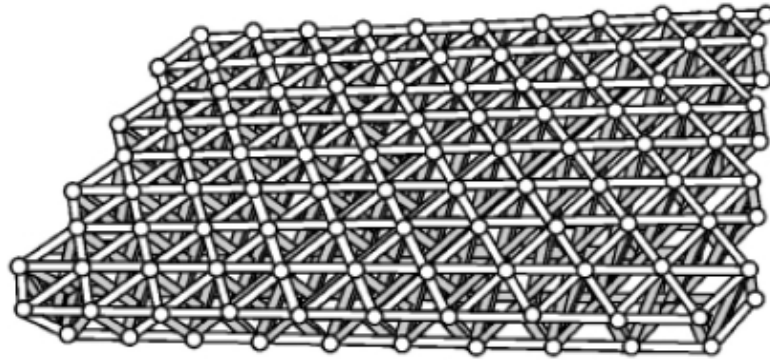


Figure 2.5 - Illustration of a periodic topology [5].

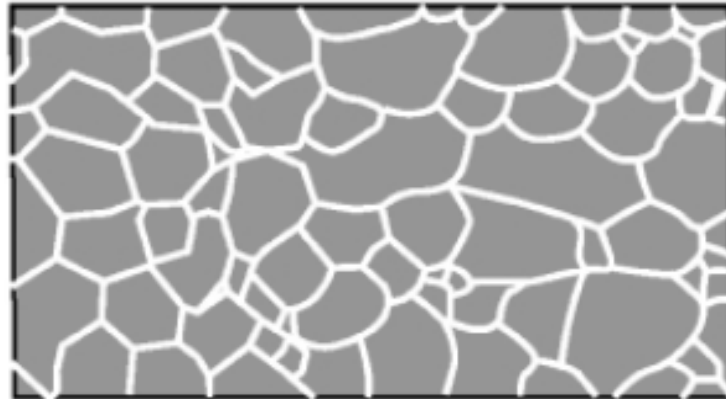


Figure 2.6 - Illustration of a stochastic topology [5].

Among periodic structures, the egg-box panel is a weight-efficient structure particularly interesting for its energy absorption properties. Zupan et al [6] have shown cold formed aluminum egg-box panels, Figure 2.7, to be competitive with commercially available metallic foams both from an energy absorption and cost standpoint.



Figure 2.7 - Photograph of a cold formed aluminum egg-box used by Zupan et al [6].

Cellular solids can also be naturally occurring, such as wood, which is still the most widely used structural material despite significant advances in metallurgy and material technology [7], and cancellous bone.

Bones are often perceived as being solid but in reality, and as shown on Figure 2.8, most bones are comprised of an outer shell of dense compact bone enclosing a core of porous cellular bone, also known as cancellous or trabecular bone.

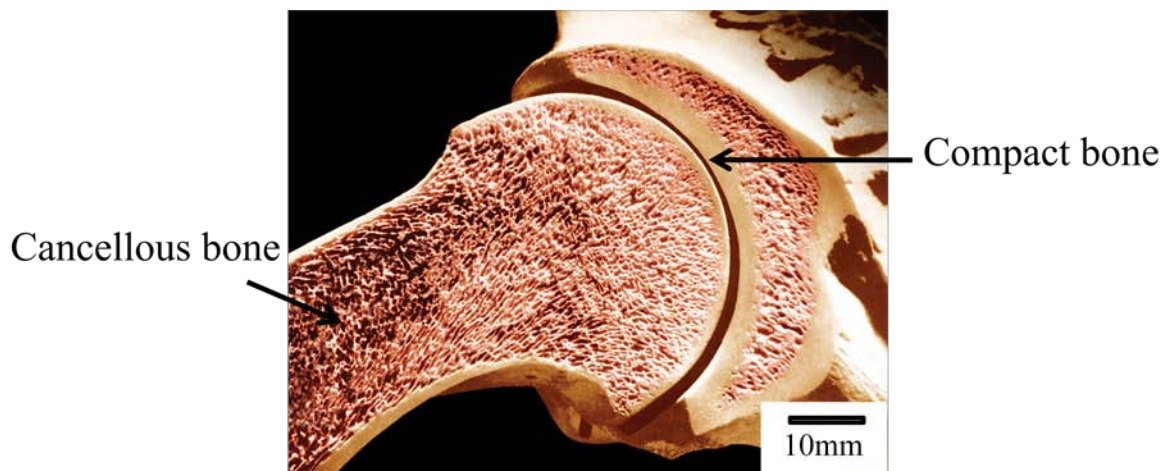


Figure 2.8 - Longitudinal section of the humerus (upper arm bone), showing outer compact bone and inner cancellous bone. Courtesy of Dr. Don Fawcett—Visuals Unlimited/Getty Images.

This consists of an interconnected network of rods or plates. The former produces low-density open-cells while the latter provides higher-density virtually closed-cells, highlighted in Figure 2.8. This configuration minimizes the weight of the bone itself, while still providing the stiffness and strength required by its primary mechanical function [4].

Osteoporosis consists of a reduction of bone mass in the body over time, in which the cellular struts in the cancellous bones become increasingly thinner and therefore more susceptible to failure. The effects of this condition are illustrated on Figure 2.9 and Figure 2.10, the first depicting the vertebral body of a woman without osteoporosis and the second of a woman suffering from that condition [8].

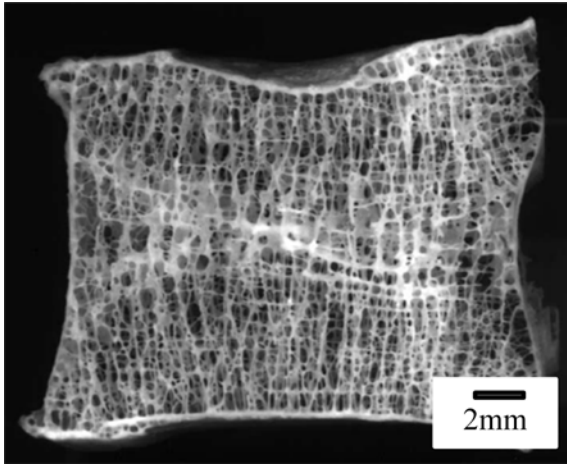


Figure 2.9 - Vertebral body from a 67 year old woman without osteoporosis. The network of cells is well organized [8].

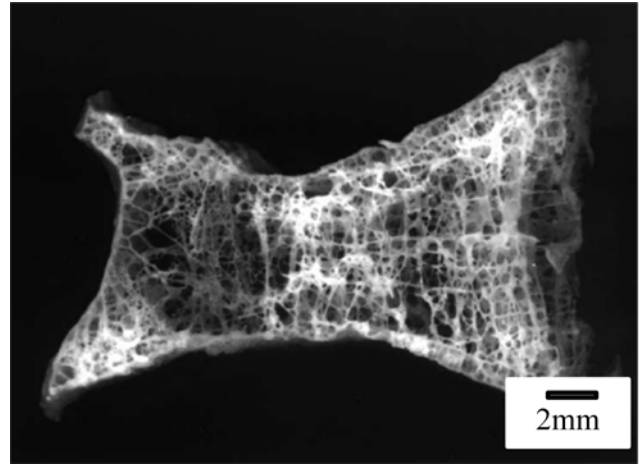


Figure 2.10 - Vertebral body from a 79 year old woman, with an osteoporotic fracture. The network is deteriorated [8].

Another way of looking at the same situation is that, as relative density changes, the mechanical properties also scale. The scaling ultimately results in a change in bones' relative density as a function of time. Gibson and Ashby [4] have provided models, further detailed in the next section, describing the scaling laws of strength and stiffness of foams with their relative density which can be expanded to include all cellular solids manufactured and naturally occurring. These scaling laws have been successfully applied to studying the effects of osteoporosis and its effect on bone strength and stiffness [9-12].

Overall, the most attractive properties of cellular solids are those that govern their use as cores for panels, having lower weight or density than most competing materials. This is a key advantage for lightweight sandwich panel constructions, which are the focus of this research. In such applications the most relevant mechanical properties, namely the shear modulus and strength, are sensitive to the micro-architecture of the cells, i.e. topology has a great effect on the performance of the structure.

2.2 Bending versus Stretching dominated architectures

Over the past decades several studies on open-cell foams have shown that the cell wall bending, under whichever loading conditions, governs both the stiffness and strength of foams.

The majority of closed-cell foams also follow these scaling laws, as the cell edges carry most of the load and therefore provide stiffness and strength to the foam. The cell faces, on the other hand, carry membrane stresses and add little more to the material performance because they rupture or buckle at very low stresses [13].

Gibson and Ashby [4] describe the mechanical performance and relative density of rigid foams by deriving the force balance equation of individual cell. Figure 2.11 shows schematics of individual cellular solid units, where a global force is applied to the back.

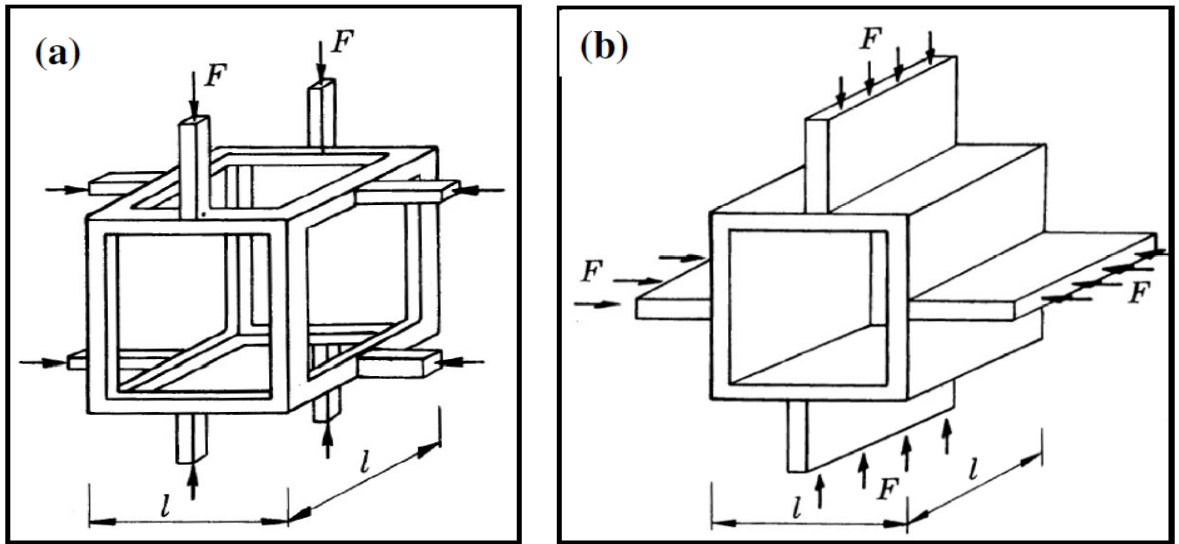


Figure 2.11 - Simplified unit cells that Gibson and Ashby modeled for rigid foam using work balance equations [4].

The results of these cell models on Figure 2.11 provided scaling laws which describe the mechanical properties of rigid foams scaling in relation to relative density. For a complete treatment the reader is directed to [4]. The scaling laws provided describe the Young's Modulus, E_{foam} , and strength of the foam, σ_{foam} , as:

$$\bar{E}_{foam} = C_1(\bar{\rho})^2 \quad (\text{open cells}) \quad (2.1)$$

$$\bar{E}_{foam} = C_2(\bar{\rho})^3 \quad (\text{closed cells}) \quad (2.2)$$

$$\bar{\sigma}_{foam} = C_3(\bar{\rho})^{3/2} \quad (\text{open cells}) \quad (2.3)$$

$$\bar{\sigma}_{foam} = C_4(\bar{\rho})^2 \quad (\text{closed cells}) \quad (2.4)$$

Where C_1 through C_4 are unique constants dependent on the parent material, cell size and other geometrical configurations and $\bar{\rho}$ is the relative density of the foam. The results from the Gibson and Ashby [4] model illustrate the scaling laws of open and closed cell foams and the relationship between the mechanical properties and relative density. The strength versus relative density models described in (2.3) and (2.4) can be expanded to include all cellular solids:

$$\bar{\sigma}_{foam} \propto A(\bar{\rho})^n \quad (2.5)$$

where A is a unique constant and n is an exponent that can be determined experimentally or through modeling.

Ideally two distinct deformation processes can take place in cellular solids: bending dominated deformation and stretching dominated deformation.

To understand these processes it helps to look at open-cell foams as a connected set of pin-jointed struts as presented by Deshpande et al [14] and shown in Figure 2.12 and Figure 2.13.

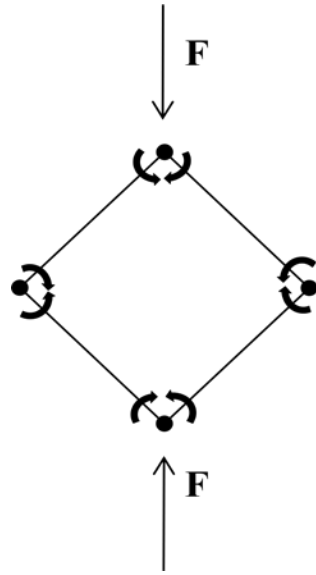


Figure 2.12 - A mechanism. The deformation is bending dominated.

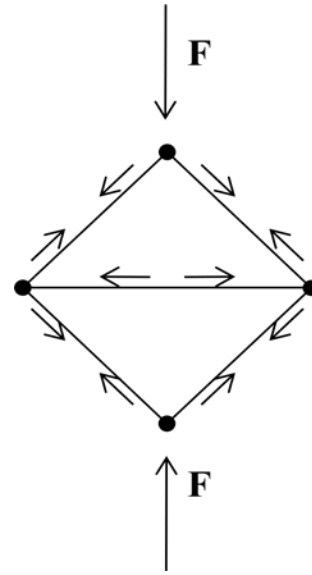


Figure 2.13 - A structure. The deformation is stretching dominated.

Assuming the struts are connected by frictionless joints, when a frame shown in Figure 2.12, i.e. a mechanism, is loaded, the struts rotate about the joints and the frame simply collapses. It has neither stiffness nor strength. However, if the joints are locked, so as to prevent free rotation of the struts, the same applied load as before induces bending moments at the joints, which cause the struts to bend given the structure a finite stiffness and strength. This is why it is described as a bending dominated architecture.

The frame in Figure 2.13, however, is a structure and its deformation behavior quite different. When this frame is loaded, the struts support axial loads, tensile in some and compressive in others. This loading results regardless of the frame joint configuration, be it free to rotate or locked. This means the frame accommodates deformation due to stretching of the individual

struts and is designated as a stretching dominated architecture. Even if the joints are locked, both stiffness and strength of the frame remain virtually the same, despite some bending of the struts. The collapse load is still mostly governed by the axial strength of the struts and much higher than the collapse load of a mechanism, i.e. a bend governed structure.

Foams that are stretching-dominated are much more weight efficient and expected to be about ten times as stiff and three times as strong as a bending-dominated foam for a relative density $\bar{\rho}$ of 0.1 [14].

It should also be realized that minimal stretch-domination offers only marginal gain over bending dominated architectures. In order for the full gain to be achieved, the structure must be predominantly stretch-dominated [14]. This understanding is of the utmost relevance for sandwich panel design, where weight efficiency and stiffness are the main focus of the concept of a sandwich structure, as stretching-dominated architectures can maximize its potential.

2.3 Lattice truss mechanical properties

As previously discussed, periodic cellular structures with high connectivity are stretching dominated and, as such, their elastic properties are predicted to scale linearly with the relative density.

Lattice truss structures possess inclined trusses which introduce factors that depend upon the topology of the truss structure and the direction of the applied load.

For a single layer tetrahedral lattice truss, such as one of the hybrid rapid prototyped – metallic engineered cores presented on this study and depicted on Figure 2.14, there are two independent stiffness constants of utmost relevance to assess the mechanical performance of a sandwich panel.

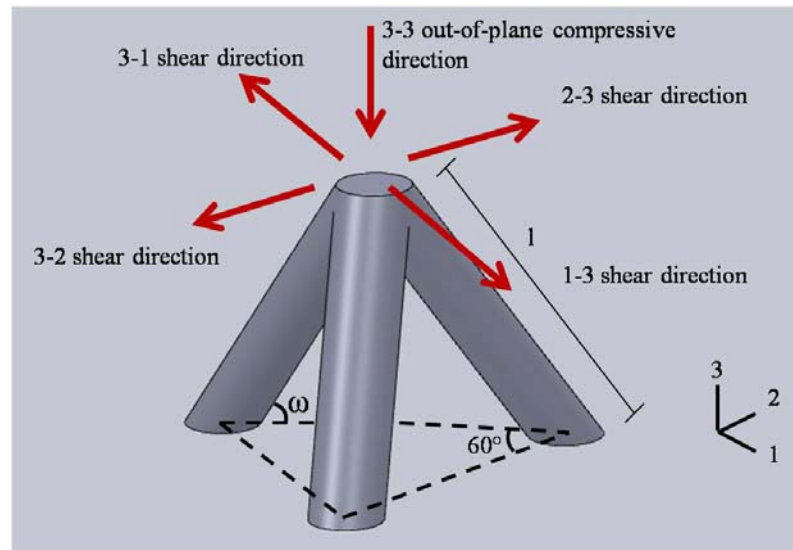


Figure 2.14 - Tetrahedral lattice unit cell showing coordinate system and loading directions.

The first is out-of-plane compressive stiffness, E_{33} , and Deshpande and Fleck [15] have defined it as:

$$E_{33} = E_s (\sin \omega \bar{\rho})^4 \quad (2.6)$$

where E_s is the Young's Modulus of the parent alloy, ω is the included angle and $\bar{\rho}$ is the relative density, as previously defined.

The second is the out-of-plane shear stiffness, G_{13} or G_{23} as they are identical for the tetrahedral lattice core. Deshpande and Fleck [15] define it as:

$$G_{13} = G_{23} = \frac{E_s}{8} (\sin 2\omega \bar{\rho})^4 \quad (2.7)$$

When comparing the out-of plane modulus of elasticity divided by relative density of different periodic cellular materials, honeycombs display the best performance and that is why they are usually preferred for stiffness limited designs under an out-of-plane loading. However, when loading is shear or non-axial to the honeycomb walls, their performance drops off precipitously. Nevertheless, the performance of other topologies in this regard is not much lower, they can provide a more isotropic response and their advantage in other mechanical properties may allow for a more interesting proposition than honeycombs [16].

Returning to the example of the tetrahedral lattice truss and considering it to be made from a metal exhibiting a rigid perfectly plastic behavior with a tensile yield strength σ_y . In this case, yielding of the lattice coincident with the peak strength of the lattice and must scale linearly with relative density and the yield strength of the parent material. Deshpande and Fleck [15] have shown that the peak strength, σ_{33}^{pk} , is given by:

$$\sigma_{33}^{pk} = \sigma_y (\sin \omega \bar{\rho})^2 \quad (2.8)$$

For lower relative densities, the trusses become increasingly slender and under some conditions the peak strength can be governed by elastic buckling rather than yield.

2.4 Simply supported transversely loaded three-point bending failure mechanisms

Different failure or collapse mechanisms can be developed on sandwich panels depending on the properties of the individual phases and panel geometry [17]. The phase with the lowest properties relevant to a particular mode is the first to fail, as it requires less energy for that given failure mode to occur [18].

Minimum weight designs are thus found by identifying the failure modes at a given stiffness or load capacity and varying the thickness of both core and face sheets to determine the lowest weight for a particular failure mode for the material combinations under three-point bend loading, such as depicted on Figure 2.15.

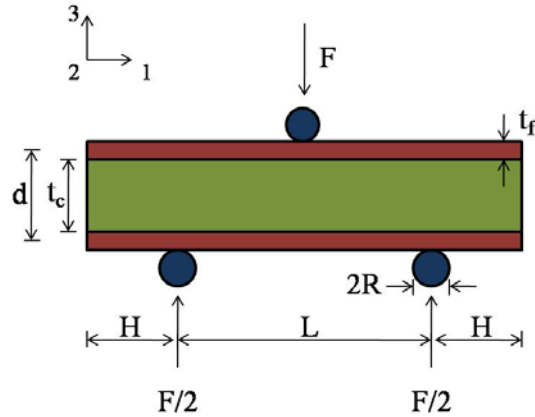


Figure 2.15 - Illustration of a sandwich panel in three-point bend loading. The facing sheets are identical and have a thickness t_f , the core has a thickness t_c and d is the distance between the centroids, i.e. $d = t_c + t_f$. The displacement of the central roller, or indenter, translates into a vertical force F on the structure. The supports are identical and have the same radius R as the indenter and the applied load is shared equally between them; the span between the outer supports is L and the overhang distance beyond the outer roller is H [15].

For foam core sandwich panels the most prevalent failure modes have been identified as indentation, core shear and face sheet failure [19-20] and will be further explained in the next pages. Face wrinkling and bond failure are also two possible failure modes for this type of configuration but are deemed to be of less relevance.

Failure mode maps can be constructed to predict the failure of a given sandwich panel. It is important to note that these are specific to each type of sandwich panel. Despite that, it is possible to plot a geometrically driven map indicating which specific failure mode is dominant as the dimensions of the sandwich panel are modified, as in Figure 2.16.

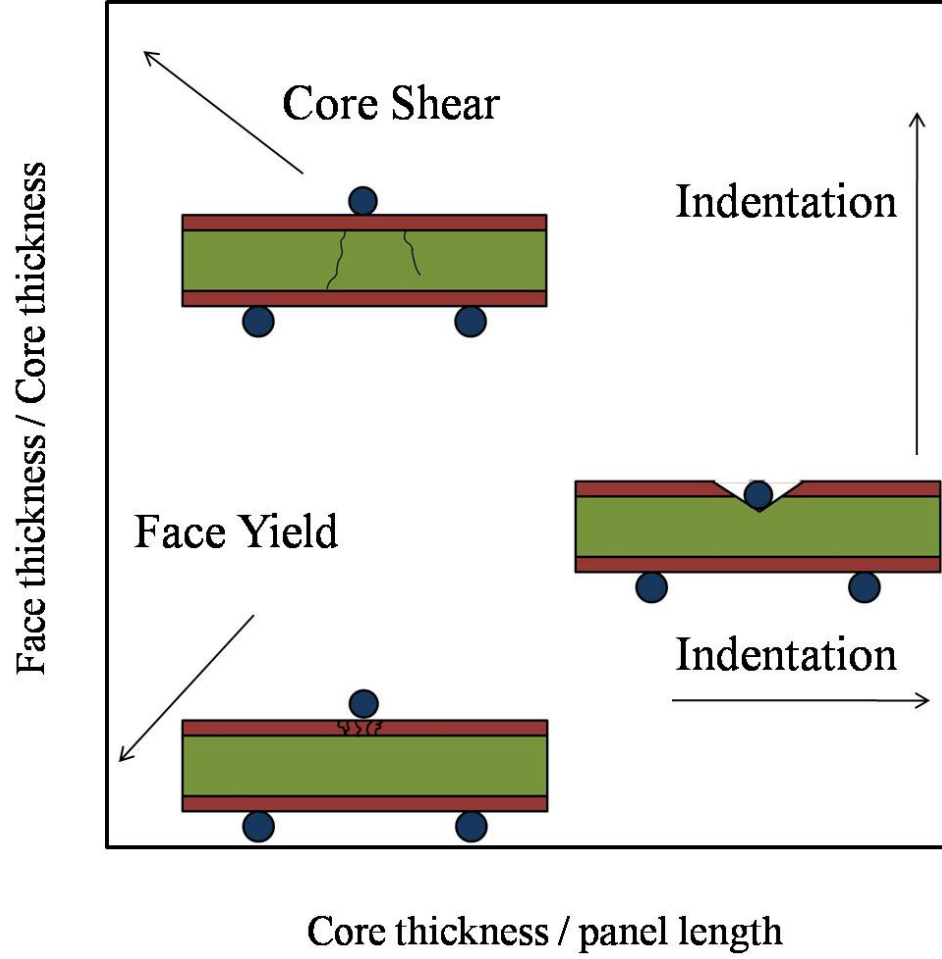


Figure 2.16 - Map illustrating the dominance of different failure modes as function of face thickness / core thickness core thickness / panel length ratios.

When constructing sandwich panels, the thickness of the facing sheets is minimized as they are often regarded as parasitic weight to the structure. Looking at the map it is evident that a decrease in the thickness of the facing sheets while retaining core thickness increases the likelihood of face yield dominated failure. It occurs when the axial stress within the compressive face sheet reaches the face sheet microbuckling strength [21].

This mode also becomes more dominant when the core thickness is increased while retaining face sheet thickness. The same is true if core thickness diminishes in relation to the panel length or the latter increases when compared to the former and this is also valid for core shear failure.

Two different modes of core shear can occur: mode A, where the facing sheets develop plastic hinges beneath the inner rollers or mode B, where the face sheets continue to bend elastically at collapse of the sandwich beam. Mode A is more likely to happen in beams with short overhangs. Chen et al [22] have demonstrated the transition length of overhang H to be given by:

$$H = \frac{t_f^2 \sigma_f}{2 t_c \tau_c} \quad (2.9)$$

where τ_c has been showed to be $\tau_c \approx 2\sigma_c/3$.

The distinction between these two collapse modes is only applicable for simply supported beams, as the only possible collapse mode for a clamped beam is mode B [20].

For weak face sheets it is accepted that the plastic bending strength of the faces elevates the collapse load of the structure by a contribution which scales with the plastic bending moment for the face sheets. This approach, however, is inadequate for strong face sheets such as metallic ones. This being the case, plastic shear of the core is accompanied by elastic bending of the face sheets [23].

This failure mode also becomes more dominant when increasing core thickness and retaining or reducing face sheet thickness.

Indentation becomes the dominant mode as the core thickness increases when compared to the panel length and is more dependent on this ratio rather than the one between core and face sheet thicknesses. It occurs when the local load at the central roller, which is twice that of the end supports, overcomes the compressive strength of the core.

For the majority of sandwich panels the indentation load is determined by plastic yield of the core, with the facing sheets deforming either elastically or plastically and previous studies by Ashby et al. [13] have shown that these provide significant strengthening by a beam-bending action. Different indentation models have been presented by Steeves and Fleck [24], Schuaeib and Soden [25], Deshpande and Fleck [15], among others.

Ideally all failure modes should occur at the same time, which means that the necessary energy to induce each mode is the same and thus the mechanical properties of the panel are optimized.

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3 Design and Manufacturing

3.1 Rapid Prototyped ABS three-dimensional periodic core

3.1.1 Slenderness Ratio

The optimization of any structure requires an understanding of the material properties and geometrically driven failure mechanisms pertinent to the design in question [1].

For the geometries considered in this study it has been suggested the individual legs, or struts, can be viewed as Euler columns and a work balance between the extensional deformation and the internal energy dissipated by the core as it deforms can be applied to identify the onset of collapse [2].

An end loaded column in compression fails by elastic buckling at a critical load below the material yield strength, Figure 3.1, provided the slenderness ratio, i.e. length over radius or L/R , is high enough [3]. In order to maximize weight efficiency, i.e. to maximize the effectiveness of the material elements within the struts, these are targeted to be as slender as possible. Thus, a designer chooses column designs that reside at the yielding – buckling transition.

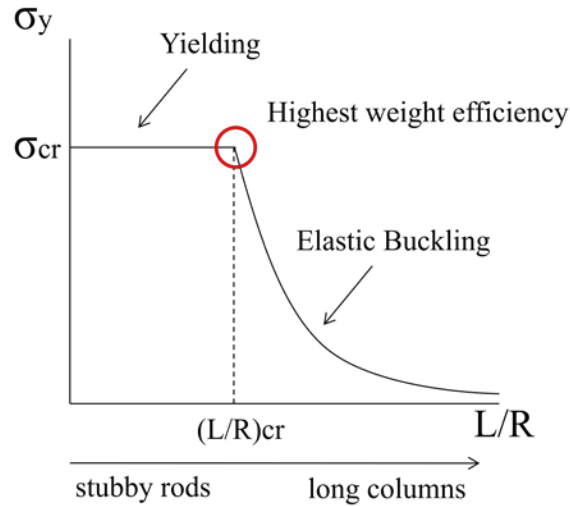


Figure 3.1 - Plot showing idealized column response as a function of slenderness ratio. The point of highest efficiency is reached at the critical slenderness ratio value, on the onset of buckling.

The transition between yielding and buckling is set by strut geometry and mechanical properties of the strut material. Thus, for a particular pair of material properties – σ_y and E – there is a unique optimized strut geometry.

For rapid prototyped ABS polymers S. Markkula et al [1] suggest an ideal slenderness ratio, i.e. the ratio which yields the highest weight efficiency, below 10 at approximately 8.5. Optimization of this ratio then ensued through modification of both length and radius of individual legs.

3.1.2 Design and optimization

As presented, three different topologies were considered in this work: pyramidal, tetrahedral and strut-reinforced tetrahedral (SRT), see Figure 3.2. Two different approaches were followed to characterize the performance of these topologies, one to evaluate the effect of scalability on the performance of these cores and the other to study the impact of relative density.

The first consists of manufacturing the cores with different scaling while maintaining the aspect ratio constant, i.e. the slenderness ratio of the struts L/R . This approach will enable an understanding of the effect of scalability on the performance of these cores. The individual units were designed to have the same material volume and height. While the first parameter is kept constant just to enable an easier comparison between geometries, the height of the cores is deemed to actively influence the composite stiffness and moment of inertia of a sandwich panel [1].

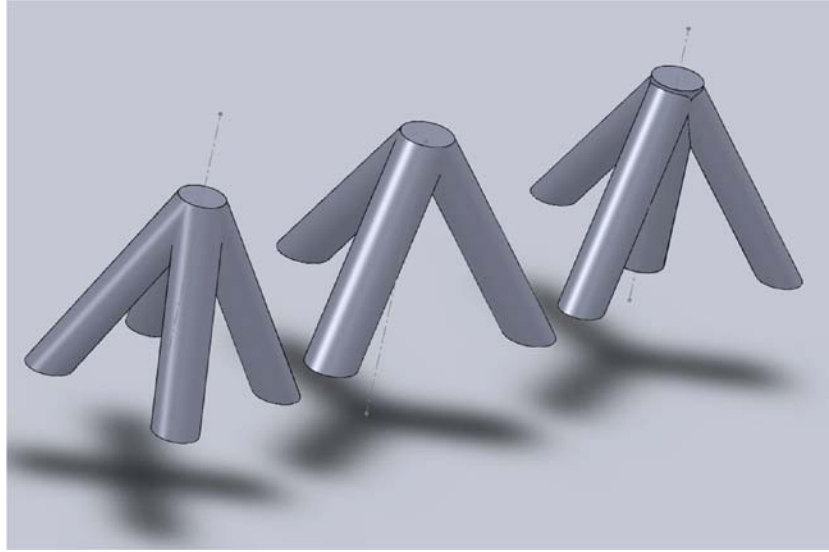


Figure 3.2 - CAD models for the three different geometries designed to evaluate scalability. From left to right: Pyramidal, Tetrahedral and SRT. The height is the same for the three geometries and they were designed to have approximately the same material volume, hence weight.

The pyramidal core was considered in this study as it represents a state-of-the-art core geometry which can be constructed using conventional deformation manufacturing techniques [4-6]. It consists of four legs of equal dimensions and spacing, each absorbing the same load, with a projected area defined by a square.

The tetrahedral core consists of three legs of equal dimensions and spacing, arranged in a way that each face defines an equilateral triangle. In this geometry all the legs carry the load evenly.

The SRT core presents a very similar geometry to the tetrahedral, the difference being the addition of a vertical center strut. Through matrix structural analysis, Sacks found the center strut to absorb the majority of the load applied to the structure compared to the legs [7]. For this reason, special attention was given to the design of this strut.

Taking that into consideration, the final dimensions of the cores and other relevant geometric parameters are shown in Table 3.1.

Table 3.1 - Optimized dimensions of the different ABS units for scaling analysis

Topology	Height [mm]	Length leg/strut [mm]	Radius leg/strut [mm]	SR leg/strut [mm]	Proj. Area [mm ²]	Proj. Volume [mm ³]
Pyramidal	25.40	29.15/-	3.04/-	9.59/-	408.85	10384.79
Tetrahedral	25.40	30.98/-	3.40/-	9.11/-	817.73	20770.34
SRT	25.40	30.98/25.40	2.94/3.28	10.54/7.74	817.73	20770.34

In order to calculate the projected area it is necessary to define the unit cell of each core topology. The volume of material presented is calculated for each strut and multiplied by the number of them in each topology. However, as the struts merge on the top, the real volume of material is bound to be inferior to the values listed on Table 3.1. Also the projected areas, and consequently projected volumes, are not affected by the radii of the struts as will be made clear with the definition of unit cells.

In crystallography, a unit cell is the smallest arrangement of atoms and interatomic bonds which can be repeated to form a pattern. The unit chosen would be designated a parallelogram in two dimensions or a unit cell in three dimensions [8].

There are rules which must be considered when choosing a unit cell [9] and, upon analysis of our lattice, the unit cells for the different topologies were chosen and are illustrated on Figure 3.3.

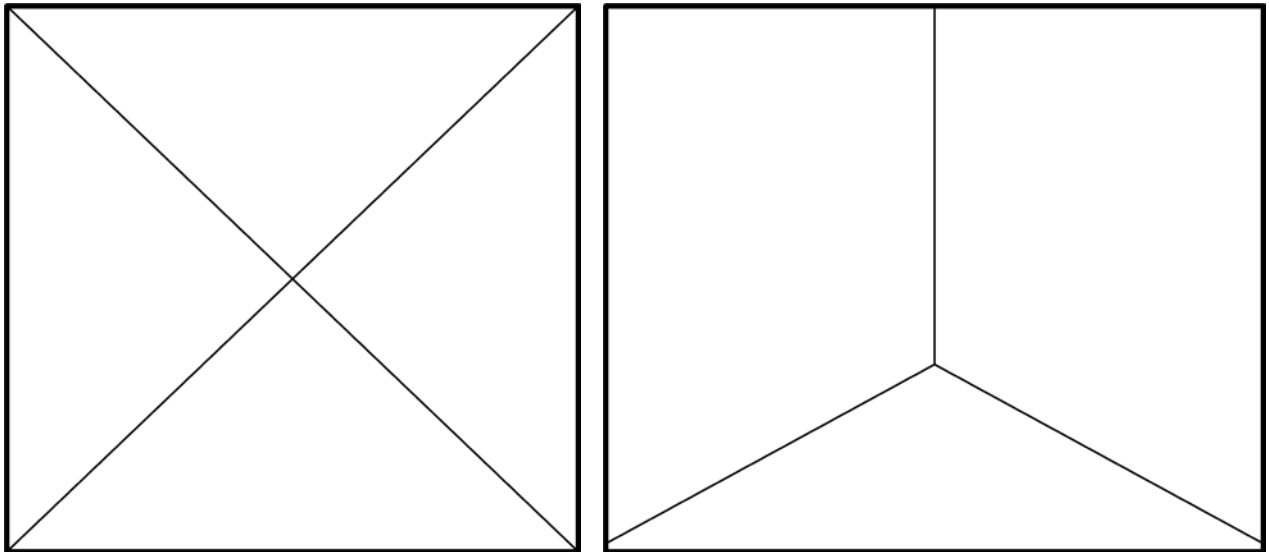


Figure 3.3 – Projected areas of the Pyramidal unit (left) and Tetrahedral and SRT units (both have the same projected area, on the right).

The projected area of the unit cores is the area defined by the very same unit cell. As for the projected volume it is calculated based on the projected area and the height of the single geometry unit.

For the second approach, in order to understand the effect of relative density on the performance of these topologies, the slenderness ratio of each strut was modified effectively leading to a change in relative density even within the same topology. To achieve this, the radii of the struts were modified and the other dimensions were kept constant to attain set values for the slenderness ratio. These modified dimensions are summarized on Table 3.2 where height and both projected areas and volumes are replaced by density and relative density as they are the same as presented on Table 3.1.

Table 3.2 – Dimensions of the ABS CAD models with varying slenderness ratios

Topology	Height [mm]	Length leg/strut [mm]	Radius leg/strut [mm]	SR leg/strut [mm]	Proj. Area [mm²]	Proj. Volume [mm³]
Pyramidal	25.40	29.15/-	5.83/-	5/-	408.85	10384.79
Pyramidal	25.40	29.15/-	3.64/-	8/-	408.85	10384.79
Pyramidal	25.40	29.15/-	2.65/-	11/-	408.85	10384.79
Tetrahedral	25.40	30.98/-	6.20/-	5/-	817.73	20770.34
Tetrahedral	25.40	30.98/-	3.87/-	8/-	817.73	20770.34
Tetrahedral	25.40	30.98/-	2.82/-	11/-	817.73	20770.34
SRT	25.40	30.98/25.40	6.20/3.28	5/4	817.73	20770.34
SRT	25.40	30.98/25.40	3.87/3.87	8/7	817.73	20770.34
SRT	25.40	30.98/25.40	2.82/2.82	11/9	817.73	20770.34

As before, volume is calculated based on the volume of each individual strut and projected volume is not affected by their radii, which explain why material volume is superior to the projected value in the case of the pyramidal with the lowest slenderness ratio.

3.1.3 Manufacturing

Having concluded the preliminary design work, all three individual geometries were modeled in SolidWorks 2009 SP3.0 with the dimensions listed previously in Table 3.1 and saved as STL files. These files were then loaded into the Catalyst EX software and sent to a Stratasys Dimension 1200 SST machine for printing, see Figure 3.4 and a representation on Figure 3.5.



Figure 3.4 – Rapid prototyping machine to manufacture the ABS topologies.

This is achieved through a fused deposition modeling (FDM) process where P430 ABS is incrementally built in layers. The properties of this material can be found on Appendix A. Once the first cross section is completed the build platform is lowered one layer thickness, 0.330mm for this study, and the next cross section is printed. This process is continued until the part is completed. Once complete, the part can be taken out of the machine and the support structures easily popped off from the struts by hand. If support material is used in locations harder to reach, and where this removal process is inadequate, the unit can be submersed in acetone and the support material would dissolve leaving the model material intact.

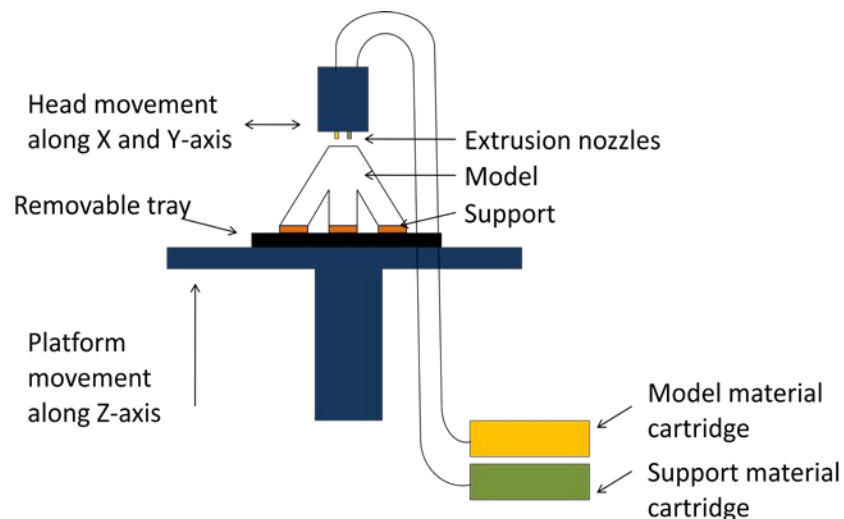


Figure 3.5 - Illustration of the rapid prototyping machine. Two cartridges located on the lower section of the machine, one for the model and the other for the support material, feed the head. The extrusion nozzles are heated up and displace liquefied ABS. The head moves along the X and Y-axis in order to create the desired cross section and, as the build progresses, the platform lowers the distance equivalent to a single layer's thickness at a time. When the build is complete, the tray is removed and the prototype detached from it.

When all the support material is successfully removed, the base of every leg and strut of the structure is then coated with an epoxy binder and bonded to aluminum plates. The binder used is a room temperature curable epoxy matrix. The physical properties are listed on Table 3.3 as given by the manufacturer.

Table 3.3 - Physical properties of binder as provided by the manufacturer

Property	105 resin + 205 fast hardener
Mix Ratio by weight	5.07:1
Mix Viscosity @ 72°F (cPs)	975
Pot Life of 100 g @ 72°F (min.)	12
Specific Gravity of Cured Resin	1.18
Hardness @ 1 day (Shore D)	80
Hardness @ 2 weeks (Shore D)	83
Compression Yield @ 1 day (PSI)	10120
Compression Yield @ 2 weeks (PSI)	11418
Tensile Strength (PSI)	7846
Tensile Elongation (%)	3.4
Tensile Modulus (PSI)	4.08E+05
Flexural Strength (PSI)	14112
Flexural Modulus (PSI)	4.61E+05
Heat Deflection Temperature (°F)	118
Onset of Tg by DSC (°F)	129
Ultimate Tg by DSC (°F)	142
Annular Shear Fatigue (lbs @ 100,000 cycles)	10629
Izod Impact, notched (ft-lbs/in)	0.93

In order to modify the core size and relative density, while retaining topologies, scaled versions were also manufactured, 20% smaller and 20% larger than the models. This allows for an understanding of how stress and relative density are related and find the optimum interval for each topology and how sensitive it is to changes in relative density.

Figure 3.6 and Figure 3.7 display the family of core topologies, sizes, strut ratios and relative densities explored in this study.

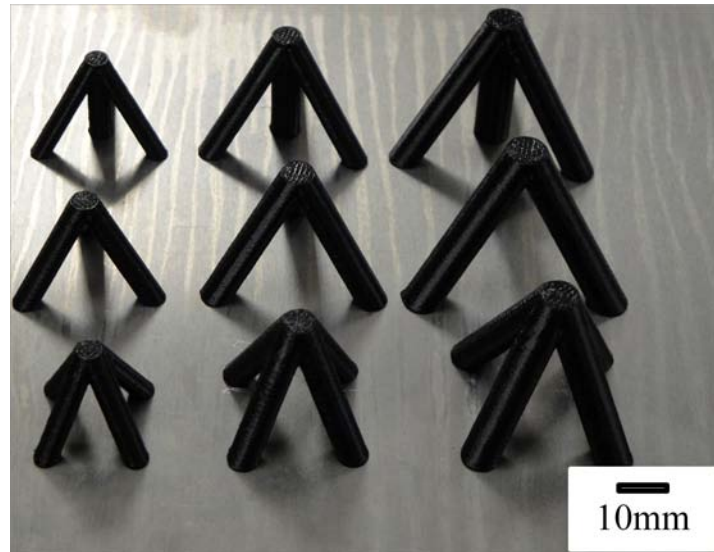


Figure 3.6 - Rapid prototyped ABS cores of different topologies and different scaling. From bottom to top: pyramidal, tetrahedral and SRT geometries. From left to right: $h=20.32\text{mm}$, $h=25.40\text{mm}$ and $h=30.48\text{mm}$.

The projected areas of the different unit cells also become evident when looking at the cores from a top view, such as in Figure 3.7.

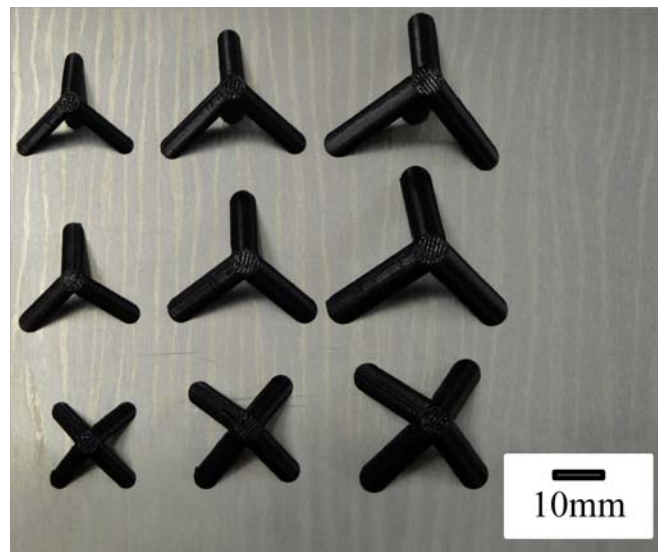


Figure 3.7 - Top view of the different ABS cores manufactured, such that the projected area of each unit becomes evident. From bottom to top: pyramidal, tetrahedral and SRT. From left to right: 20% smaller than model dimensions, 1:1 scale model, 20% larger than model dimensions.

Each unit was weighed and each one's density was calculated. Given the density of the P430 ABS, $\rho_s = 1040 \text{ kg/m}^3$, the relative density of each individual unit was calculated and are presented on Table 3.4.

Table 3.4 - Mass properties of rapid prototyped units.

Topology	Height (mm)	Weight (g)	Density (kg/m ³)	Relative Density
Pyramidal	20.32	1.26	227.9	0.219
Pyramidal	25.4	2.57	247.5	0.238
Pyramidal	30.48	4.43	237.4	0.228
Tetrahedral	20.32	1.28	115.7	0.111
Tetrahedral	25.4	2.50	120.4	0.116
Tetrahedral	30.48	4.29	114.9	0.111
SRT	20.32	1.23	111.2	0.107
SRT	25.4	2.46	118.4	0.114
SRT	30.48	4.26	114.1	0.110

The bases of these individual units of each topology were then coated with epoxy and bonded to metallic plates to ensure the struts were properly constrained and would not slip during compression testing, see Figure 3.8.

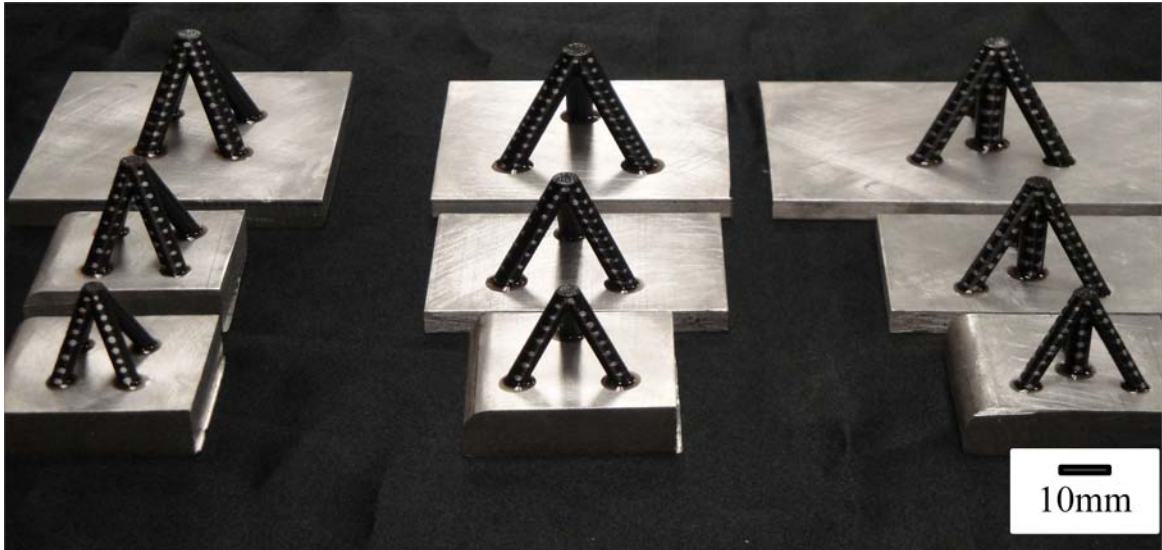


Figure 3.8 – Rapid prototyped ABS cores bonded to metallic plates so as to constrain the trusses and ensure proper load distribution during compression testing. From left to right: pyramidal, tetrahedral and SRT geometries. From bottom to top: $h=20.32\text{mm}$, $h=25.40\text{mm}$ and $h=30.48\text{mm}$.

The topologies with varying slenderness ratios were then manufactured in the same way as the other ABS rapid prototyped units and their mass properties are summarized in Table 3.5. The specimens are illustrated on Figure 3.9 through 3.11.

Table 3.5 - Mass properties of rapid-prototyped units manufactured with varying slenderness ratios to enable changes in densities.

Topology	Slenderness struts	Weight (g)	Density (kg/m ³)	Relative Density
Pyramidal	5	7.10	683.7	0.657
Pyramidal	8	3.54	340.9	0.328
Pyramidal	11	1.93	185.8	0.179
Tetrahedral	5	6.54	314.9	0.303
Tetrahedral	8	3.19	153.6	0.148
Tetrahedral	11	1.69	81.4	0.078
SRT	5	7.75	373.1	0.359
SRT	8	3.87	186.3	0.179
SRT	11	2.16	104.0	0.100



Figure 3.9 - Rapid prototyped Pyramidal topology manufactured with different L/R ratios. From left to right: slenderness ratio of 5, 8 and 11 respectively.



Figure 3.10 - Rapid prototyped Tetrahedral topology manufactured with different L/R ratios. From left to right: slenderness ratio of 5, 8 and 11 respectively.



Figure 3.11 - Rapid prototyped SRT topology manufactured with different L/R ratios. From left to right: slenderness ratio of 5, 8 and 11 respectively.

As with the other units, the struts are bonded to roughened aluminum plates with an epoxy binder. The curing process is identical to the other rapid-prototyped cores and when it is complete the specimens are ready for testing.

3.2 Two-dimensional periodic carbon fiber lattice core

It has been suggested by Wadley [11] that hollow tubes enable very low density lattices to be achieved and truss compressive buckling strengths to be increased by increasing the truss moment of inertia.

Wadley was successful in creating two-dimensional hollow tube cores using stainless steel tubes and liquid transient braze bonding. A similar manufacturing process was used for the carbon fiber lattice core.

To manufacture this core several carbon fiber pultruded tubes with different diameters and wall thicknesses were procured from the carbon composites manufacturer DragonPlate. Two different sets of dimensions were chosen in order to determine their effect in the mechanical properties of the tubes on the core response; Table 3.6 summarizes the tube geometries.

Table 3.6 - Dimensions of carbon fiber pultruded tubes, as provided by the manufacturer.

External diameter	Internal diameter	Wall thickness	Length
0.254" (6.45mm)	0.158" (4.01mm)	0.048" (1.22mm)	48" (1219.20mm)
0.375" (9.53mm)	0.290" (7.37mm)	0.043" (1.09mm)	48" (1219.20mm)

Extruded aluminum rails were used to create a layup jig for the carbon tubes, Figure 3.12. In order to ensure even spacing between the carbon fiber tubes, holes were drilled in the aluminum rails and wooden dowels fitted to act as layup guiding pins, see Figure 3.13.

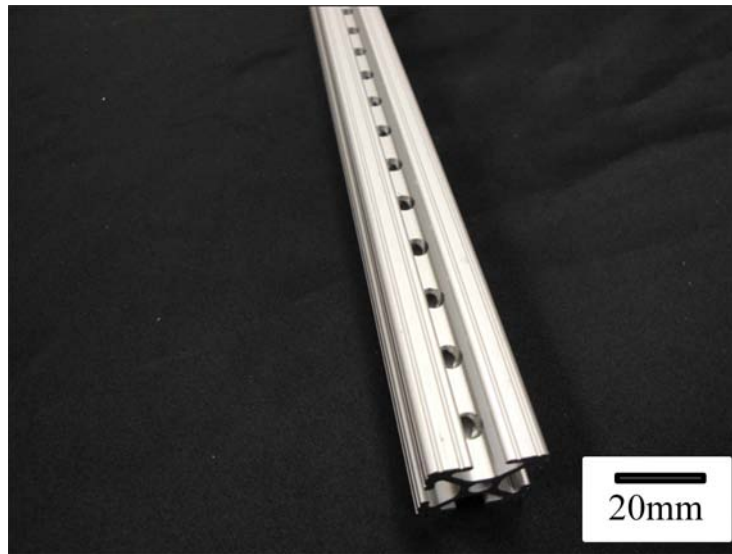


Figure 3.12 - Extruded aluminum rail with holes drilled, with even spacing between them.

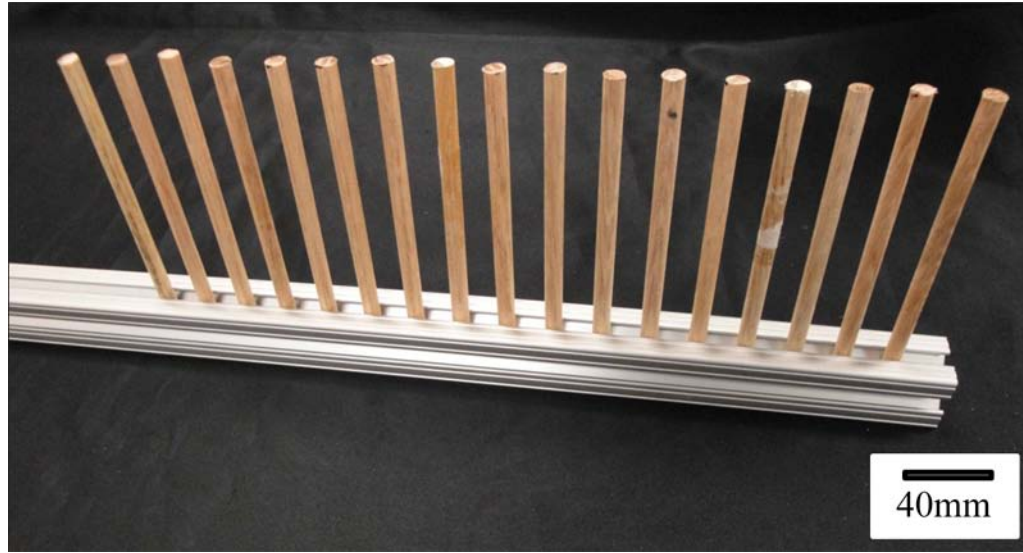


Figure 3.13 - Wooden dowels fitted in the holes drilled in the aluminum rails. They serve as guiding pins for the layup of the carbon fiber tubes.

The chosen spacings were one and two diameters, projected at 45 degrees, for each of the sets. An illustration of this layout can be seen on Figure 3.14 showing the local geometry of the support rods and the core struts. This results in a core geometry with tubes, or struts, located at 45° from the vertical.

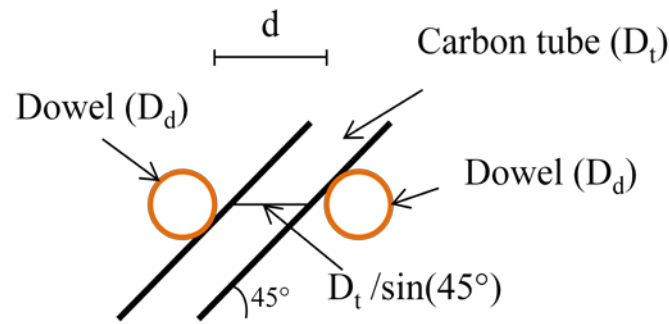


Figure 3.14 - Illustration of carbon fiber tube held in place between two identical dowels. In order to achieve a 45 degree angle, the spacing between the dowels actually needs to be larger than the diameter of the carbon for it to fit snugly.

To find the actual footprint of the tube between the dowels, d , the horizontal distance between the two edges of the tube laid at a 45 degree angle is calculated and the horizontal distance to each of the contact points on the dowels is added, as given by:

$$d = \frac{D_t}{\sin 45^\circ} + 2 \times \frac{D_d}{2} (1 - \cos 45^\circ) \quad (3.1)$$

where D_t is defined as the diameter of the carbon tube and D_d as the diameter of each wooden dowel. This distance d was then calculated for the different setups and the actual spacing chosen was slightly higher than that to account for machining tolerances and summarized in Table 3.7.

Table 3.7 - Spacings selected for the layup of the carbon fiber lattice cores.

	Spacing
$D_t=6.45\text{mm}$	11.33mm
$D_t=9.53\text{mm}$	16.64mm

Before the layup, the dowels are covered with adhesive tape and Frekote to prevent adhesion of the tubes to the layup rig. The bulk pultruded rods are cut into 50mm long carbon tubes, which are then coated with epoxy and laid upon the rails. Figure 3.15 shows a representative core layup. The carbon tubes are laid in an alternating pattern creating two-dimensional structural areas.



Figure 3.15 - Carbon tubes bonded with epoxy and displaced between the dowels at a 45 degree angle. A coat of epoxy is applied between each layer of tubes to ensure proper bonding in the contact points.

After curing, the jig and the layup are separated from the rails, resulting in a cellular core presented on Figure 3.16.



Figure 3.16 - Carbon tubes bonded together forming a two-dimensional lattice core.

These bulk cores are subsequently cut, using a low speed diamond coated water cooled saw, to meet the desired specimen dimensions, which are listed on Table 3.8 and the mass properties summarized in Table 3.9.

The importance of the length to height ratio of the cellular solid core has been discussed in Chapter 2. Zupan et al [12] explore the effect of length to height ratio upon compressive strength on woven-core sandwich plates and a value of $L/H=5$ appears to endow the sandwich panels with compressive strength that is representative of a bulk material, i.e. size dependence is removed for samples with $L/H > 5$. Taking this into consideration, the lattice cores were manufactured with an L/H ratio close to 5, as the dimensions on Table 3.8 indicate.

Table 3.8 - Dimensions for the different carbon fiber lattice sandwich panels.

Diameter of carbon tubes (mm)	Spacing between tubes (mm)	Length (mm)	Width (mm)	Height (mm)	Thickness face sheets(mm)
6.45	11.33	140	50	30	0.35
6.45	11.33	140	50	30	1.60
9.53	16.64	140	50	30	0.35
9.53	16.64	140	50	30	1.60

Table 3.9 - Mass properties of the carbon fiber lattice cores, including relative density calculated based on the density of the stochastic solid which the core is based on, $\rho_s=1490 \text{ kg/m}^3$.

Diameter of carbon tubes (mm)	Weight (g)	Density (kg/m^3)	Relative Density
6.45	70.41	335.2	0.225
9.53	54.43	259.2	0.174

A specimen for compression was also manufactured which is identical to the specimen with the lowest relative density and bonded to the thicker face sheets, with a shortened length of 125mm. The carbon fiber lattice cores are then bonded to 6061 T6 aluminum face sheets with two different thicknesses which were previously roughened and cleaned with acetone for a better adhesion to the binder. Figure 3.17 and Figure 3.18 illustrate two of the specimens manufactured, the former with larger diameter tubes and the thicker face sheets and the latter with the small diameter tubes and thinner face sheets. After the curing process is complete, the sandwich panels are ready for testing.

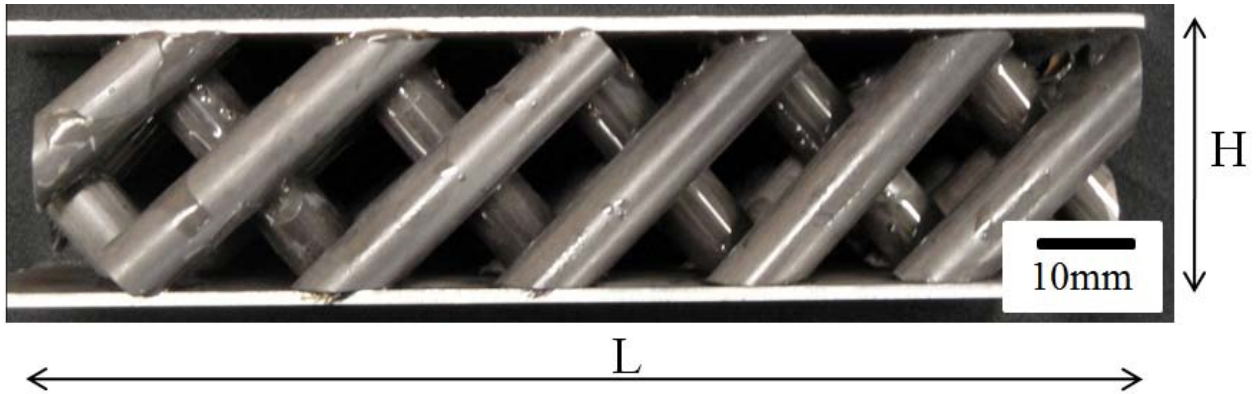


Figure 3.17 – Carbon fiber lattice core with the lower relative density, 0.174, bonded to 1.6mm thick aluminum face sheets with an epoxy binder.

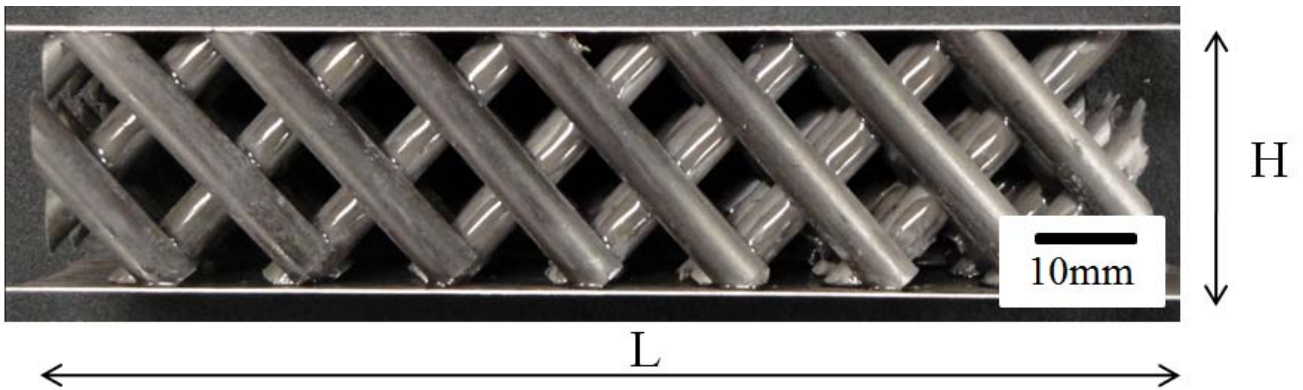


Figure 3.18 - Carbon fiber lattice core with the higher relative density, 0.225, bonded to 0.35mm thick aluminum face sheets with an epoxy binder.

3.3 Naturally occurring pumice based stochastic cellular solid core

For this research the pumice panels were made using level frames fabricated from wood, following the manufacturing techniques used by Fleischer [13]. The frames were then disassembled and the pumice/epoxy combination cut in smaller specimens with the dimensions listed on Table 3.10. A flow chart of this manufacturing process can be seen on Figure 3.19.



Figure 3.19 - Flow chart of pumice/epoxy specimen preparation. Pumice is provided in its naturally occurring state. A wooden frame is assembled with a bottom perforated plate to enable excess binder to flow out of the panel. The frame is then filled with pumice and binder is poured evenly on the panel. When the binder sets a diamond saw is used to cut specimens with the desired dimensions.

Table 3.10 - Dimensions of the pumice/epoxy based sandwich panels

Length (mm)	Width (mm)	Height (mm)	Thickness face sheets (mm)
100	50	25	0.35
100	50	25	1.60
150	50	25	0.35
150	50	25	1.60
250	50	25	0.35
250	50	25	1.60

Fleischer [13] has found the average relative density of these pumice/epoxy specimens with 4mm stones to be $\bar{\rho} \approx 0.700$.

6061 aluminum sheets of two different thicknesses are then cut to the dimensions of each pumice/epoxy core. These are then roughened using grit abrasive paper and the surface cleaned with acetone. This ensures a better contact surface for the binder, which is the same combination used for the ABS cores; see Table 3.3 for the binder properties. When the epoxy is cured, the sandwich panels are ready for testing, see Figure 3.20 and Figure 3.21 for representative sandwich plates.



Figure 3.20 - 250mm long pumice/epoxy core bonded to 0.35mm thick aluminum facing sheets.



Figure 3.21 - 100mm long pumice/epoxy core bonded to 1.60mm thick aluminum facing sheets.

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4 Experimental Results

4.1 Rapid Prototyped ABS three dimensional periodic core

4.1.1 Compression of ABS cells with different scaling and constant aspect ratio

A 50kN screw driven load frame and a set of circular compression platens with a diameter of 150mm were used to load the cores in compression under quasi-static load conditions, see Figure 4.1. The specifications of the machine used can be found in Appendix B. Total load carried by the cores was measured using an inline load cell and total displacement across the core height was measured using an LVDT.

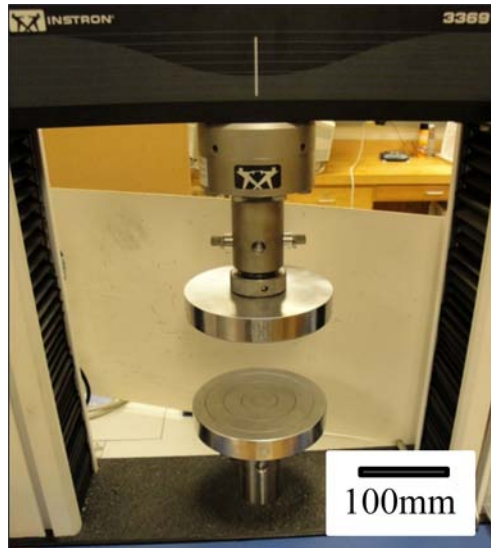


Figure 4.1 - 50kN screw driven load frame fitted with compression platens to perform out-of-plane compression tests.

The upper platen was then displaced at a constant strain rate of 6×10^{-4} /s to ensure deformation occurred in quasi-static regime.

Figure 4.2, Figure 4.4 and Figure 4.6 display representative load-displacement curves for each of the three core scales (heights) evaluated and plotted on the same axis limits allowing direct comparison between the different data sets. In this instance the relative density, $\bar{\rho}$, of the cores is held constant:

$$\bar{\rho}_{pyr} = 0.228 \quad (4.1)$$

$$\bar{\rho}_{tet} = 0.113 \quad (4.2)$$

$$\bar{\rho}_{SRT} = 0.110 \quad (4.3)$$

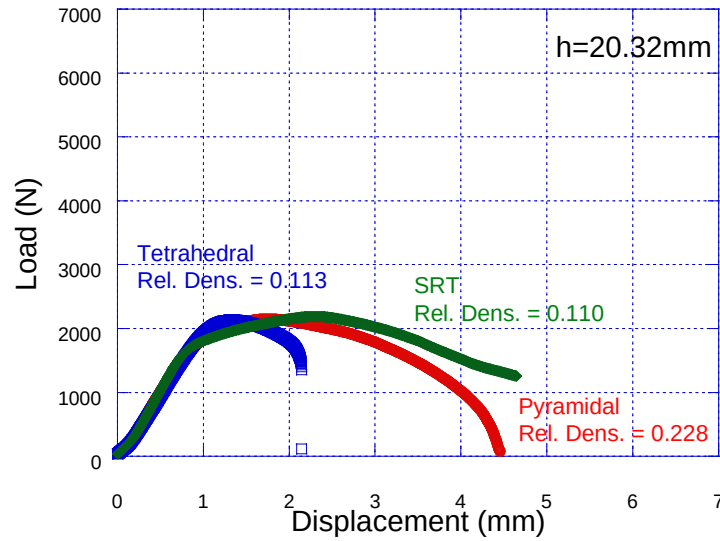


Figure 4.2 - Load versus displacement plots of the smallest topologies manufactured, with a height of 20.32mm. The curve that fails catastrophically after 2mm of displacement (blue) represents the tetrahedral topology; the curve which ends at about 4.5mm of displacement (red) represents the pyramidal; the curve which is still carrying significant load at the end of testing (green) represents the SRT.

Upon observation of Figure 4.2, the smallest height topologies show a linear loading region up to a similar peak load, at 2.15kN, 2.13kN and 2.19kN for the pyramidal, tetrahedral and strut-reinforced tetrahedral topologies respectively, setting the onset of collapse marking permanent deformation. The mechanical behavior of the pyramidal and SRT topologies is similar, but the strut-reinforced tetrahedral presents a slower decrease in load capacity beyond the peak of the three cores. The pyramidal topology loses load carrying capacity most precipitously after the peak load.

The tetrahedral unit failed quite early as one of the struts quickly buckled and broke off from the structure, which can be seen on Figure 4.3, along with the other two failed specimens.



Figure 4.3 - Failed specimens after testing. From left to right: pyramidal, tetrahedral and SRT smallest topologies manufactured, with a height of 20.32mm.

Figure 4.3 displays representative examples of each core topology after plastic collapse. Inspection of the photos shows that the individual struts of SRT and pyramidal cores show not only buckling but also provide indications of plastic deformation of the strut's parent material. The intermediate topologies, with a height of 25.40mm, were then compression tested and the resulting load versus displacement data plotted on Figure 4.4.

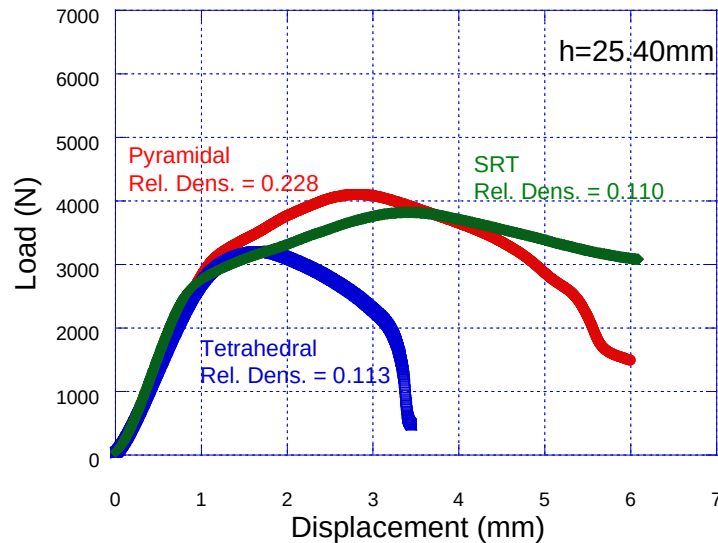


Figure 4.4 - Load versus displacement plots of the three intermediate topologies manufactured with a height of 25.40mm. When looking at a displacement of 3mm, the tallest curve (red) represents the pyramidal topology, the lowest curve (blue) represents the tetrahedral and the middle (green) represents the strut-reinforced tetrahedral topology.

All three topologies present a similar elastic response and the pyramidal and SRT curves are once again fairly similar, with the pyramidal reaching a slightly higher peak load of 4.11kN but losing load carrying capacity much more quickly than the SRT topology, which seems to hold a higher

load for a larger displacement. The extended post peak load carry capacity of the SRT and pyramidal cores is attributed to the plastic buckling behavior of the individual core struts.

Conversely a different failure mode is exhibited by the tetrahedral core where a shearing of the strut cross-section appears to set. The peak load of this topology and this separation of the struts would not enable post peak load strength and structural capacity. The experimental results in Figure 4.4 show that the absolute load value scales with larger core geometries. There is also a measurable difference between the peak loads of the three cores for this height.

The tetrahedral reaches peak load shortly after transitioning to a plastic regime although almost 1kN lower than the other topologies, at 3.20kN. Collapse ensued at about 3.5mm of displacement, where it loses its capability to carry any significant load. The deformed specimens, illustrated on Figure 4.5, appear to have deformed in a similar collapse mechanism to their 20.32mm tall counterparts. However, the differences in the load-displacement curves at this height imply a rebalance of the plastic buckling mechanism within the core struts, i.e. the ratio of material elements deforming and amount of plastic deformation compared to elements that are buckling.



Figure 4.5 - Failed specimens after testing. From left to right: pyramidal, tetrahedral and SRT intermediate topologies, with a height of 25.40mm.

The largest geometries were tested next and the results, once again plotted in terms of load versus displacement, are illustrated on Figure 4.6.

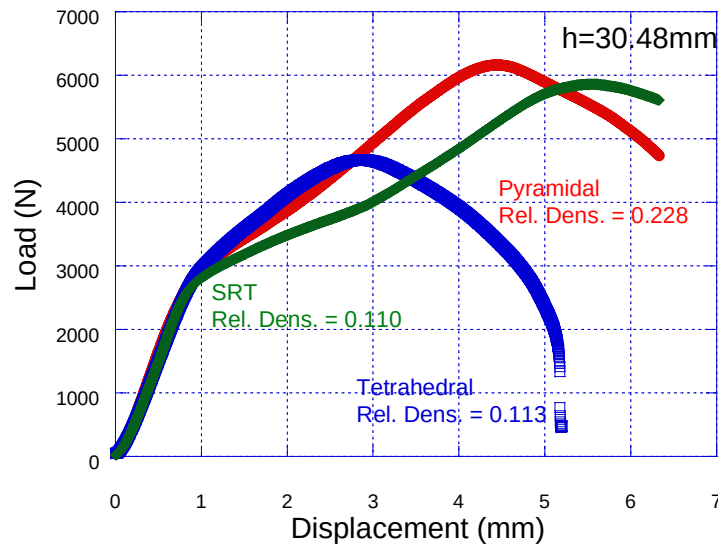


Figure 4.6 - Load versus displacement plots of the largest geometry topologies manufactured with a height of 30.48mm. When looking at a displacement of 4mm, the tallest curve (red) represents the pyramidal topology, the lowest curve (blue) represents the tetrahedral and the middle (green) represents the strut-reinforced tetrahedral topology.

Initial elastic load up is similar for the three topologies. In this instance each of the load-displacement curves show a deviation from elastic regime at approximately 3kN followed by an increase in the load carrying capacity of the cores. This deformation implies that the individual struts are yielding first and continuing to deform axially. The cores continue to harden up to peak loads of 6.17kN for the pyramidal and 5.86kN for the SRT topologies and 4.67kN for the tetrahedral. After plastic deformation at the peak load, collapse occurs and the load capacity of the core topology drops with continued deformation. Where the tetrahedral reaches peak load, at 2.9mm of displacement, the pyramidal unit keeps loading up almost linearly until reaching its own peak load. Soon after that it decreases quickly. The SRT topology appears to suffer a larger displacement until reaching its peak load, which is close to the one of the pyramidal, but it then manages to hold higher values of load for a longer displacement.

As before, the failed specimens look quite similar to the other geometries manufactured, see Figure 4.7.



Figure 4.7 - Failed specimens after testing. From left to right: pyramidal, tetrahedral and SRT largest topologies, with a height of 30.48mm.

4.1.2 Compression of ABS cells with different slenderness ratios

Figures 4.8, 4.10 and 4.12 display representative load-displacement curves for each of the three topologies evaluated and different geometries plotted on the same axis limits allowing direct comparison between the different data sets. In this instance the height of the cores is held constant at 25.40mm. The radii of the struts is then varied to modify their slenderness ratio and, consequently, relative density.

Plotted on Figure 4.8 are the results obtained from the different geometries of the pyramidal topology.

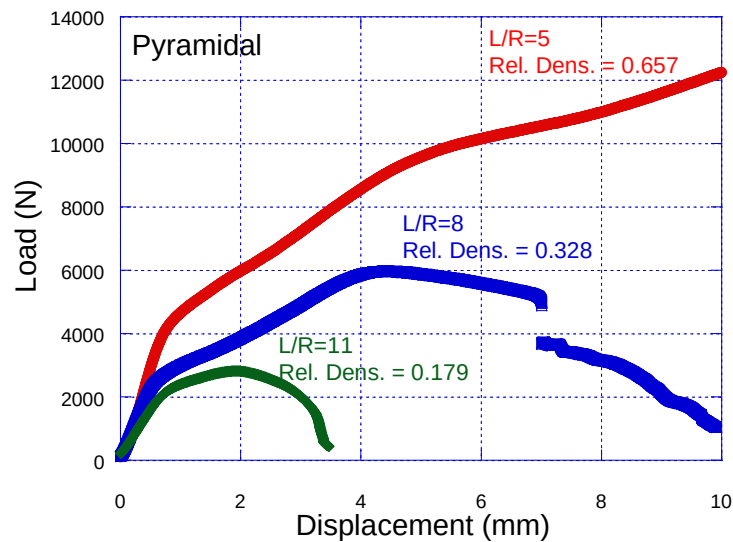


Figure 4.8 - Load versus displacement plots of the pyramidal topology geometries. When looking at a displacement of 2mm, the tallest curve (red) represents a slenderness ratio of 5 ($\bar{\rho} = 0.657$); the curve in the middle (blue) represents a slenderness ratio of 8 ($\bar{\rho} = 0.328$) and the lowest curve (green) represents a slenderness ratio of 11 ($\bar{\rho} = 0.179$).

The three geometries exhibit different mechanical behaviors. The specimen with the highest relative density loads up continuously, resembling the behavior of bulk material rather than a cellular solid. The high relative density, of 0.657, far exceeds what is considered to be the limit of 0.300 for a cellular solid [2]. The specimen with the lowest relative density appears to suffer from plastic buckling in the transition from elastic to plastic. It then reaches a peak load of 2.71kN and load capacity drops with continued deformation. The core with $\bar{\rho} = 0.328$ exhibits a behavior in between the other two geometries suggesting the core is in the boundary between cellular solid and bulk material in terms of mechanical behavior. The struts appear to suffer from plastic buckling and yielding soon after until the peak load of 5.91kN is reached. As deformation continues load capacity decreases and the sudden drop in load is attributed to one of the struts detaching from the metallic plate.

Upon observation of Figure 4.9 the signs of buckling in the core with $\bar{\rho} = 0.179$ are evident, whereas the heaviest core looks like a solid block of material. The core with $\bar{\rho} = 0.328$ shows evidence of both buckling and yielding.

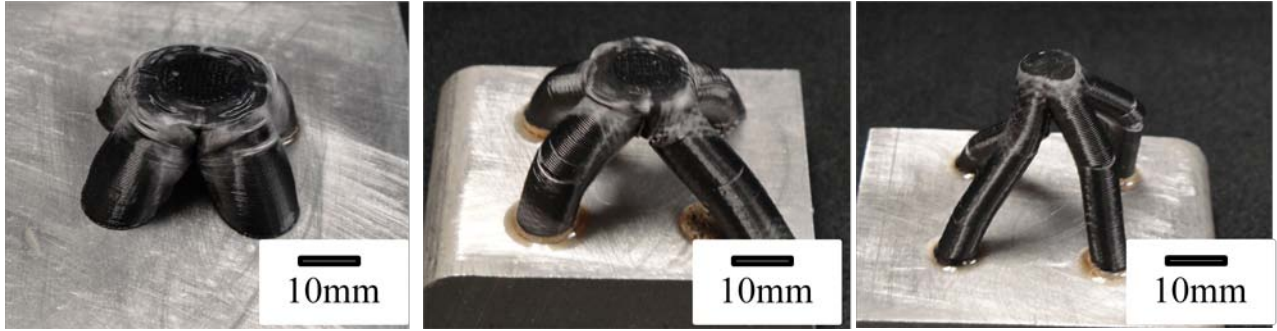


Figure 4.9 - Failed pyramidal specimens after testing. From left to right the slenderness ratio of the struts: $L/R=5$ ($\bar{\rho} = 0.657$), $L/R=8$ ($\bar{\rho} = 0.328$) and $L/R=11$ ($\bar{\rho} = 0.179$).

The tetrahedral geometries were tested next and the results are plotted on Figure 4.10 in terms of load versus displacement.

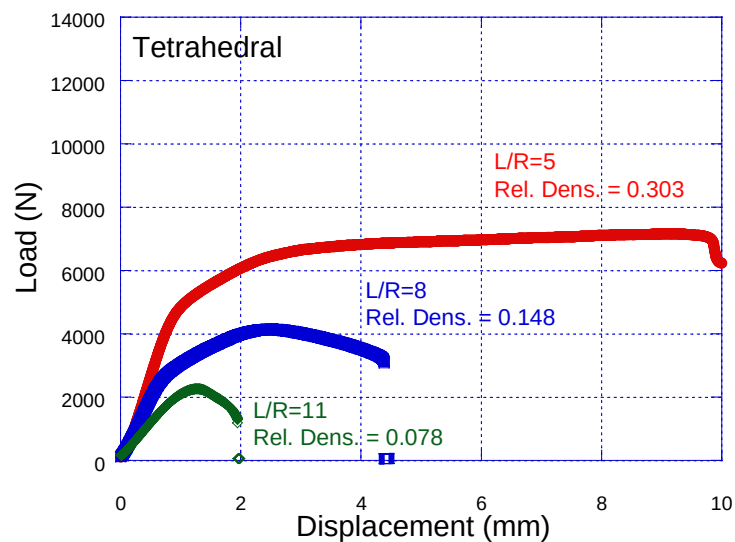


Figure 4.10 - Load versus displacement plots of the tetrahedral topology geometries. When looking at a displacement of 2mm, the tallest curve (red) represents a slenderness ratio of 5 ($\bar{\rho} = 0.303$); the curve in the middle (blue) represents a slenderness ratio of 8 ($\bar{\rho} = 0.148$) and the lowest curve (green) represents a slenderness ratio of 11 ($\bar{\rho} = 0.079$).

Looking at Figure 4.10, the core with the highest relative density displays a different behavior than the other two geometries. As with the pyramidal topology, the relative density of this specimen places it closer to a bulk material than to a cellular solid in terms of material behavior. Load capacity keeps increasing as the core begins to suffer densification through its crushing. The other two geometries exhibit similar behavior, appearing to suffer plastic buckling at the elastic-plastic transition, reaching a peak load of 4.10kN and 2.21kN for the cores with densities

of 0.148 and 0.078 respectively. As deformation continues, load capacity drops quickly until one of the struts breaks off from each of the cores.

This is evident in Figure 4.11 where the struts of the geometries with $\bar{\rho} = 0.148$ and $\bar{\rho} = 0.078$ display signs of buckling and one of them broke off from the rest of the core. The heaviest core again looks like a solid block of material.

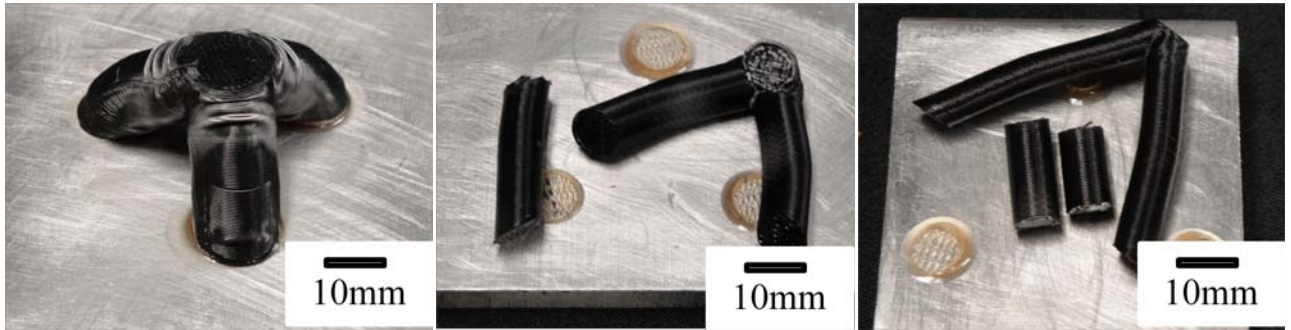


Figure 4.11 - Failed tetrahedral specimens after testing. From left to right the slenderness ratio of the struts: $L/R=5$ ($\bar{\rho} = 0.303$), $L/R=8$ ($\bar{\rho} = 0.148$) and $L/R=11$ ($\bar{\rho} = 0.078$).

The remaining geometries, of the strut-reinforced tetrahedral topology, were tested and the results plotted on Figure 4.12.

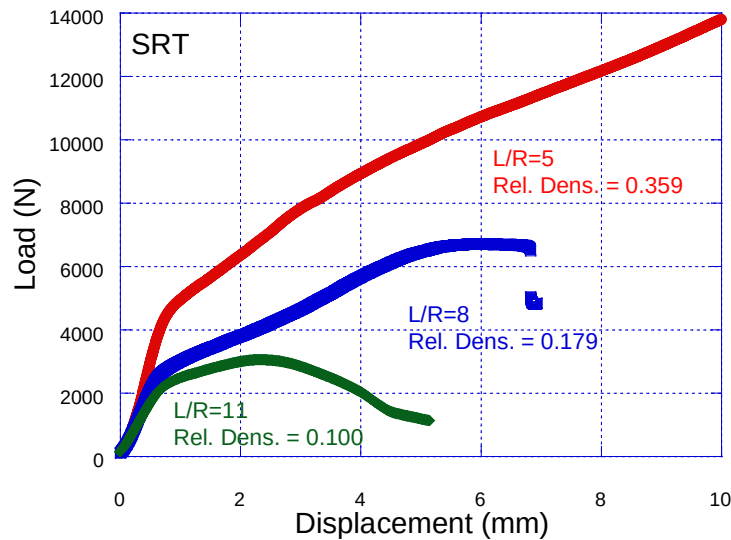


Figure 4.12 - Load versus displacement plots of the strut-reinforced topology geometries. When looking at a displacement of 2mm, the tallest curve (red) represents a slenderness ratio of 5 ($\bar{\rho} = 0.359$); the curve in the middle (blue) represents a slenderness ratio of 8 ($\bar{\rho} = 0.179$) and the lowest curve (green) represents a slenderness ratio of 11 ($\bar{\rho} = 0.100$).

Upon observation of Figure 4.12, the core with the highest relative density once again displays a different behavior than the other two geometries. As previously discussed with the pyramidal and tetrahedral topologies, the relative density of this specimen places it closer to a bulk material than to a cellular solid in terms of material behavior. For this reason load capacity keeps increasing as the core begins to suffer densification through its crushing. The other two geometries exhibit similar behavior, appearing to suffer plastic buckling at the elastic-plastic transition. The lightest specimen reaches a peak load of 3.02kN and loses load carrying capacity quickly until a load of about 1kN which it manages to hold. The core with $\bar{\rho} = 0.179$ reaches a higher peak load of 6.68kN and shortly after one of the struts broke off catastrophically.

This can be seen in Figure 4.13, where one of the struts of the geometry with $\bar{\rho} = 0.179$ got separated from the core. The remaining struts display signs of buckling as do the struts of the core with the lowest relative density. The heaviest core once again looks like a solid block of material.

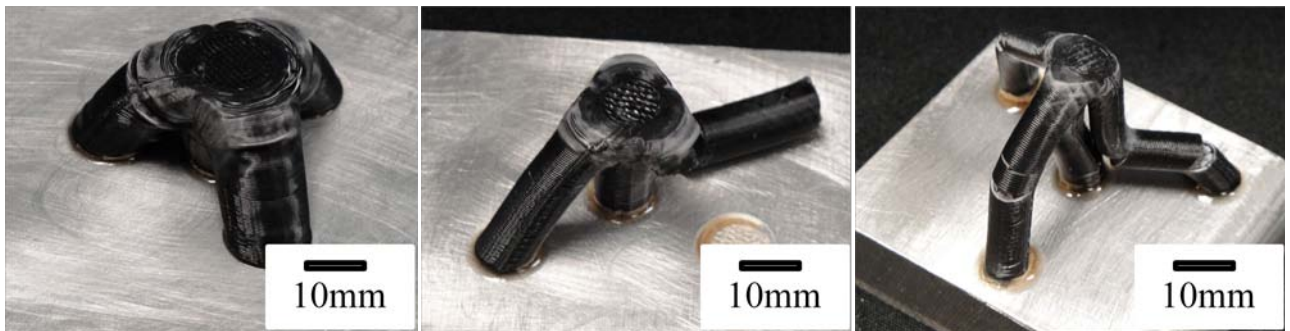


Figure 4.13 - Failed SRT specimens after testing. From left to right the slenderness ratio of the struts: $L/R=5$ ($\bar{\rho} = 0.359$), $L/R=8$ ($\bar{\rho} = 0.179$) and $L/R=11$ ($\bar{\rho} = 0.100$).

4.2 Two dimensional periodic carbon fiber lattice core

4.2.1 Compression

The 50kN screw driven load frame and set of circular compression platens were used to load the specimen in compression under quasi-static load conditions. Total load carried by the cores was measured using an inline load cell and total displacement across the core height was measured using an LVDT. The results were then plotted in Figure 4.14 in terms of load versus displacement.

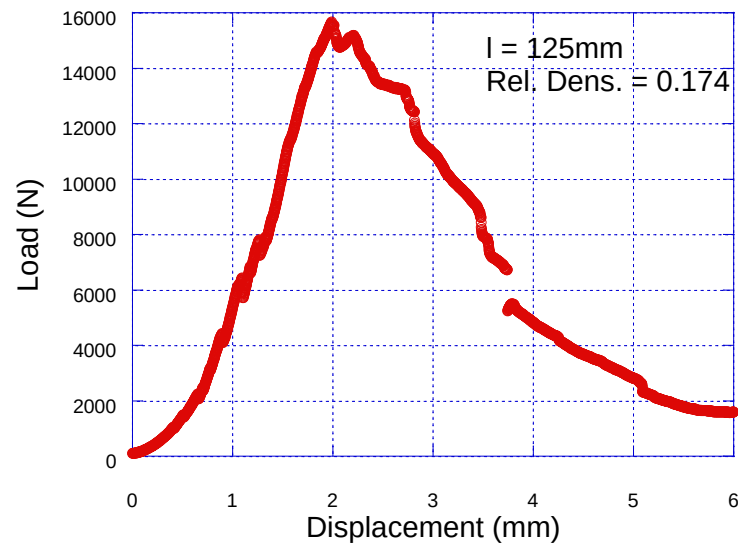


Figure 4.14 - Load versus displacement plot of a two-dimensional carbon fiber tube lattice core with $\bar{\rho} = 0.174$.

Figure 4.14 shows a quick load up in the elastic regime with little signs of plastic deformation right until the panel reaches its peak load of 15.67kN. The decrease in load capacity which ensues is erratic as the tubes are rearranged within the core during the course of the compression test.

This rearrangement can be seen on Figure 4.15.

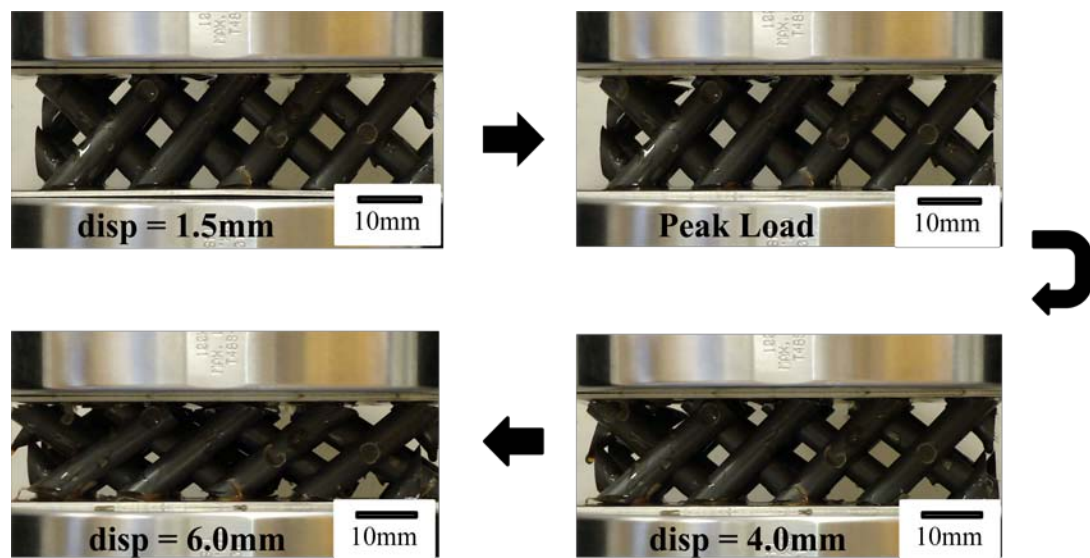


Figure 4.15 - Sandwich panel with a two-dimensional carbon fiber lattice core at different stages under uniaxial compression loading.

4.2.2 Three-point Bending

For these experiments the same load frame and instrumentation were used for the compression tests, albeit with a three-point simply supported bending rig within the loading environment, see Figure 4.12.

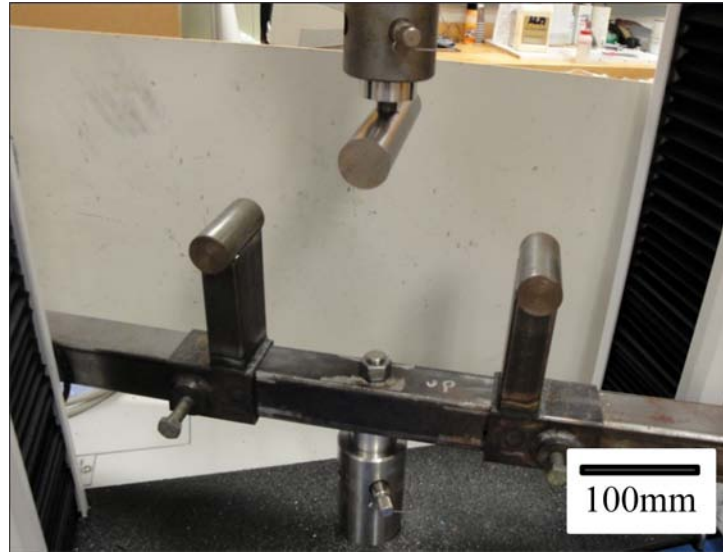


Figure 4.16 - 50kN screw driven machine fitted with a three-point bending rig.

The support rollers and the indenter have the same dimensions, with a diameter of 25.4mm and a length of 60mm which is superior to the width of the sandwich beams tested. The central roller is fixed whilst the outer supports can be adjusted to accommodate different spans. The span of each specimen was chosen so as to ensure identical overhangs measuring about 10% of the total beam length. Studies [1] have shown that this overhang was sufficient to eliminate any end effect interactions between the beam and the loading rollers. The indenter was then displaced at a constant speed of 1mm/min to ensure deformation occurred in quasi-static regime. The data collected was the displacement of the indenter and transverse load across the beam. Two charts were then plotted on the same axis limits, allowing direct comparison between the different data sets, one for each diameter of the tubes, i.e. for each relative density to compare the influence of the face sheet thickness on each pair. Figure 4.13 shows the mechanical response of the lower density array (comprised of the larger carbon tubes) with both face sheet thicknesses.

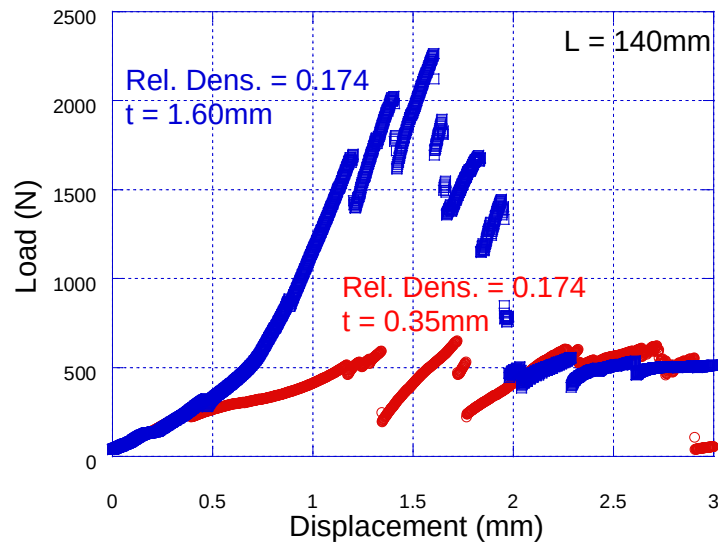


Figure 4.17 - Load versus displacement plots of the carbon fiber based sandwich panels with the lower relative density, 0.174, comprised of the larger carbon tubes.

Upon observation of Figure 4.13, the two specimens show a different initial response but after about 2mm of indenter displacement the curves are identical and flat at about 500N. The specimen with the thin face sheets displays a gentle slope until peak load, which is 650N. The sandwich panel with the thicker face sheets presents a much steeper slope and reaches a higher peak load, at 2.27kN and 1.6mm of displacement and then drops abruptly and remains constant at about 500N. Until the peak is achieved this curve is characterized by serrated load drops and reloads which are also present, to a lesser extent, in the specimen with the thinner face sheets. Illustrations of both specimens in the beginning and ending of the tests can be observed on Figure 4.14 Figure 4.15.

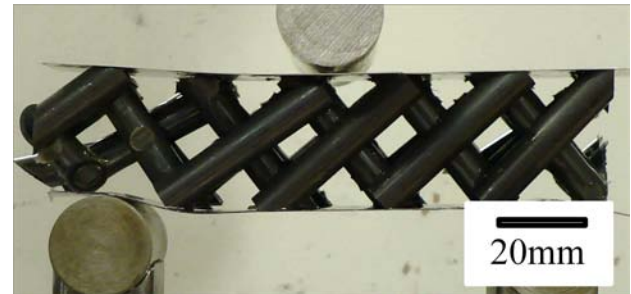
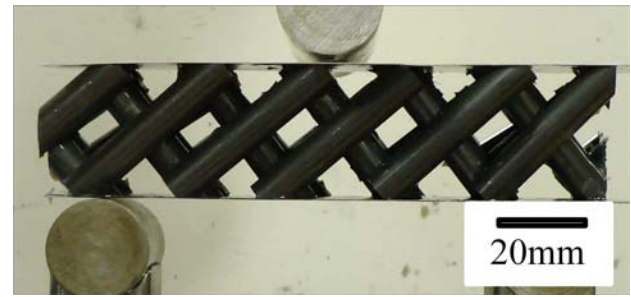
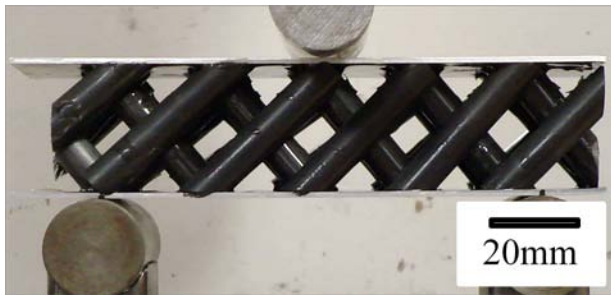


Figure 4.18 - Images of the specimen with a relative density of 0.174 with the thicker face sheets in the beginning of the test (top) and ending (bottom).

Figure 4.19 - Images of the specimen with a relative density of 0.174 with the thinner face sheets in the beginning of the test (top) and ending (bottom).

Plotted on Figure 4.16 are the mechanical performances of the panels with the higher relative density.

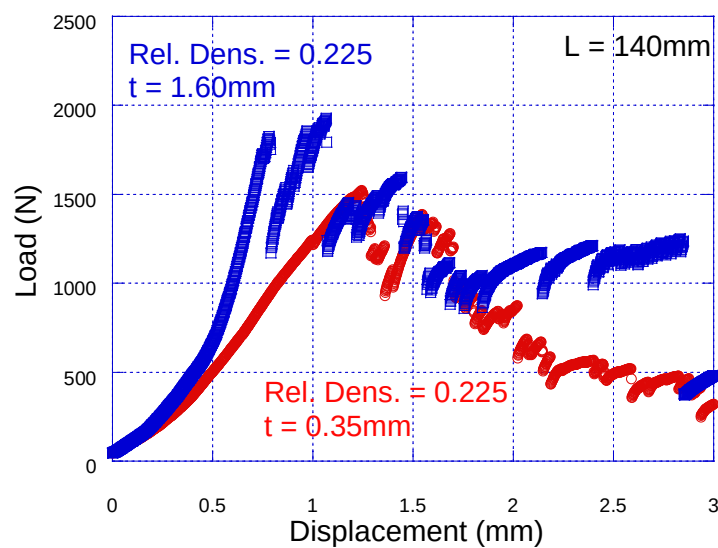


Figure 4.20 - Load versus displacement plots of the carbon fiber based sandwich panels with the higher relative density, 0.225, comprised of the smaller tubes.

Both curves exhibit a steep elastic response, particularly the panel with the thicker face sheets. There is a difference in peak load between these two sandwich panels, but the difference is not as accentuated as in the previous test. In terms of maximum load, the specimen with the thicker face sheets peaks at 1.93kN whereas the other one reaches 1.52kN. This specimen also gradually loses load carrying capacity, whereas the specimen with the thicker face sheets manages to hold a constant load of about 1.2kN. Figure 4.17 and Figure 4.18 illustrate the specimens in the beginning and ending of the tests.

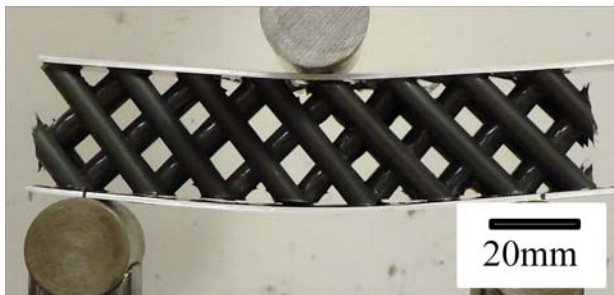
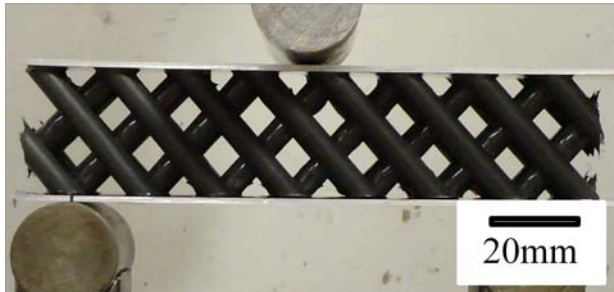


Figure 4.21 - Images of the specimen with a relative density of 0.225 with the thicker face sheets in the beginning of the test (top) and ending (bottom).

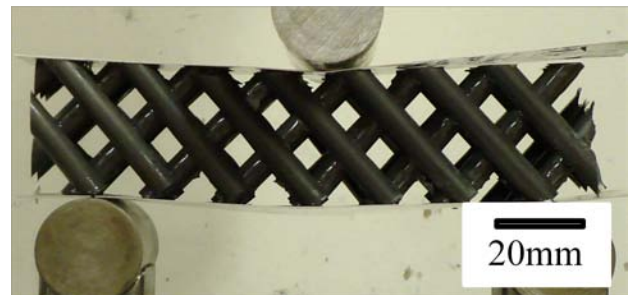
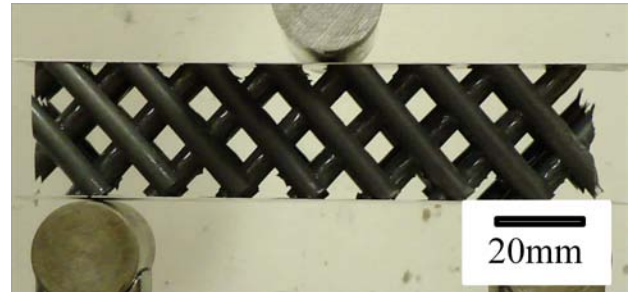


Figure 4.22 - Images of the specimen with a relative density of 0.225 with the thinner face sheets in the beginning of the test (top) and ending (bottom).

4.3 Naturally occurring pumice based stochastic cellular solid core

4.3.1 Three-point Bending

The three-point flexural tests of the pumice based sandwich panels were carried out similarly to the testing of the two-dimensional carbon tubes arrays, using the same machine and under all the same loading and instrumentation parameters. The span chosen for these also specimens also allowed for identical overhangs representing 10% of the beam length on each side. Beyond the loading rollers the results have been plotted in three different charts, one for each beam length, see Figure 4.19 through Figure 4.21. It is noted that all of the data is plotted on the same axis limits allowing direct comparison between the different data sets.

In Figure 4.19 the mechanical response of the 100mm long specimens with the different face sheets is plotted.

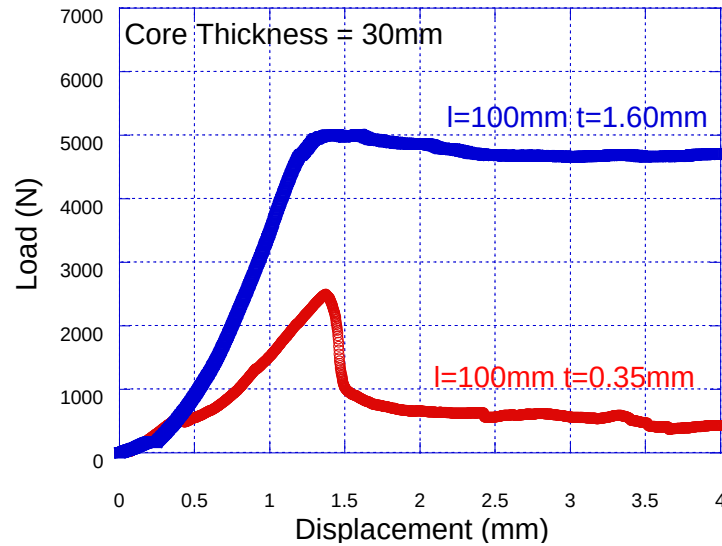


Figure 4.23 - Load versus displacement plots of the three-point bend tests performed on the 100mm long sandwich beams. The curve with the lower peak load (red) corresponds to the panel with the 0.35mm thick aluminum face sheets, while the curve with the higher peak load (blue) corresponds to the panel with the 1.60mm thick face sheets.

Looking at the chart, the specimen with the thicker facing sheets exhibits a nearly linear response until it reaches peak load is reached. Load then decreases slightly and presents a plateau at 4.8kN. The specimen with the thin face sheets also exhibits an initial linear response, but with a lower structural stiffness. After reaching peak load, at 2.5kN, there is a rapid drop in load carrying capacity and the specimen is no longer considered to be able to carry any load.

The medium sized sandwich panels, at 150mm long, with the different thickness facing sheets are plotted on Figure 4.20.

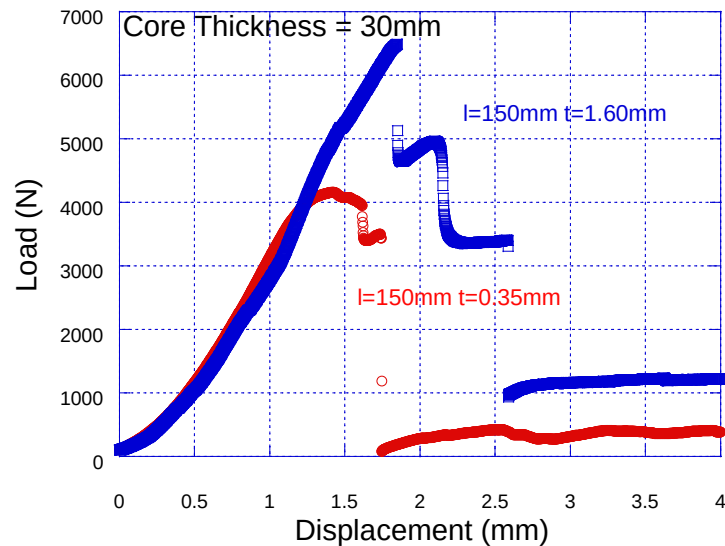


Figure 4.24 - Load versus displacement plots of the three-point bend tests performed on the 150mm long sandwich beams. The curve with the lower peak load (red) corresponds to the panel with the 0.35mm thick aluminum face sheets, while the curve with the higher peak load (blue) corresponds to the panel with the 1.60mm thick face sheets.

The specimen with the thinner face sheets, 0.35mm, exhibits an initial linear response almost until peak load, at 4.16kN, where it abruptly drops and is no longer able to carry any load. The specimen with the thicker face sheets presents a similar initial behavior, although reaching a higher peak load of 6.49kN. At that point there is a drop in load carrying capacity to about 4.6kN where it manages to recover or reload slightly before dropping to about 3.3kN. It holds that capacity for about 0.5mm of displacement until it is no longer able to carry any load.

The 250mm long pumice based panels are plotted on Figure 4.21.

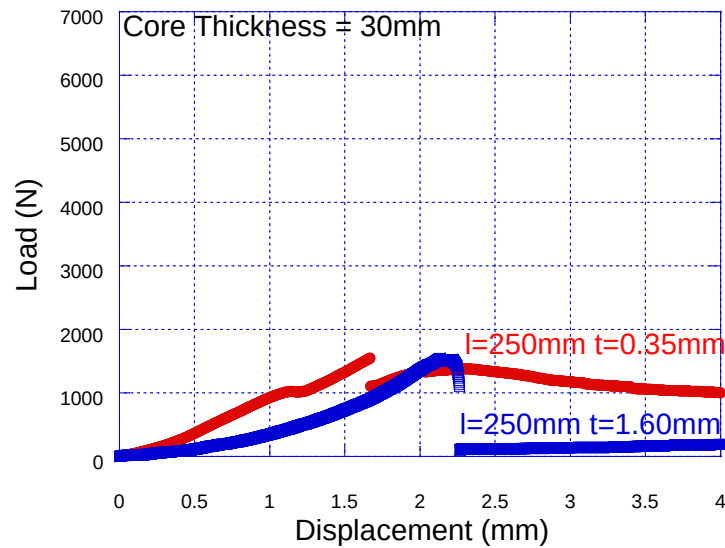


Figure 4.25 - Load versus displacement plots of the three-point bend tests performed on the 250mm long sandwich beams. The curve with the lower peak load (red) corresponds to the panel with the 0.35mm thick aluminum face sheets, while the curve with the higher peak load (blue) corresponds to the panel with the 1.60mm thick face sheets.

Both specimens exhibit a very similar mechanical behavior with a low stiffness, much lower than any of the other panels tested. The two plates show similar peak loads at 1.54kN and 1.55kN for the specimen with the 1.6mm thick face sheets and 0.35mm respectively. It is noted that after the peak load is reached their behavior diverges and the panel with the thicker face sheets, 1.6mm, it loses load carrying capacity shortly after peak load whereas the other plate decreases slowly.

References for Chapter 4

1. Zenkert, D., *The Handbook of Sandwich Construction*. 1997: EMAS Publishing.
2. Gibson, L. and M. Ashby, *Cellular solids - Structure and properties*. 2nd ed. 1997: Cambridge University Press.

5 Performance analysis

5.1 Rapid Prototyped ABS three dimensional periodic core

5.1.1 Compression of ABS cells with different scaling and constant aspect ratio

From the data collected through experimental procedures, load and displacement, it was also possible to plot nominal stress versus strain charts as

$$\sigma = \frac{P}{A} \quad (5.1)$$

$$\varepsilon = \frac{\Delta l}{l} \quad (5.2)$$

where we define σ as the nominal stress, P as the load, A as the projected area of the unit cell, ε as the nominal strain, Δl as the displacement across the entire height and l as the initial height of the core.

These definitions treat the entire core as a bulk material and allow macro scale behaviors required for design to be determined. It is noted that these definitions are independent of the core's parent material and local deformation mechanisms.

By plotting these charts it is possible to observe how each topology's mechanical response is affected by manufacturing scaling.

The performance of the pyramidal cores was analyzed first and the three curves plotted on the same chart, on the same axis limits allowing direct comparison between the different data sets, see Figure 5.1.

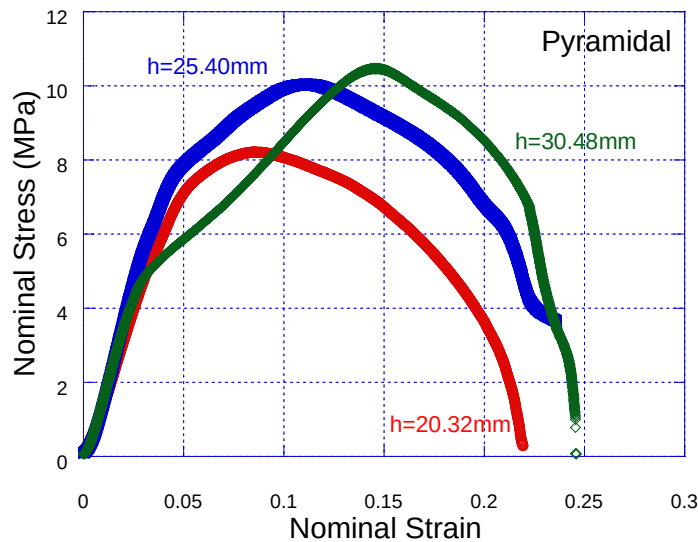


Figure 5.1 - Stress-strain curves of the pyramidal cores manufactured at different scaling. When looking at the middle of the chart, at a strain of 0.15, the lowest curve (red) represents the pyramidal core manufactured with a height of 20.32mm; the curve in the middle (blue) represents the mechanical response of the pyramidal core with a height of 25.40mm; the tallest curve (green) represents the unit with a height of 30.48mm.

Looking at Figure 5.1, peak stress is observed to be slightly reduced as the units are scaled down, but stiffness and mechanical behavior are, for the most part, virtually identical between the three units. The difference in peak stress between the specimens with the heights of 20.32mm and 25.40mm is significantly higher than the difference between the specimens with the heights of 25.40mm and 30.48mm. This appears to suggest the reason lies in manufacturing. As units become smaller manufacturing flaws, which are inherent to the minimum size limitations of the rapid prototyping system, are much more significant than in larger models and the impact on the mechanical performance of the unit that much more significant. The tallest unit also exhibits a slightly different behavior between 0.03 and 0.13 of strain as it seems to suffer plastic buckling when deviating from elastic behavior, as opposed to yielding observed in the other two cores. The results from the tetrahedral units' testing were also plotted in terms of nominal stress and nominal strain and the mechanical response of these units can be observed on Figure 5.2.

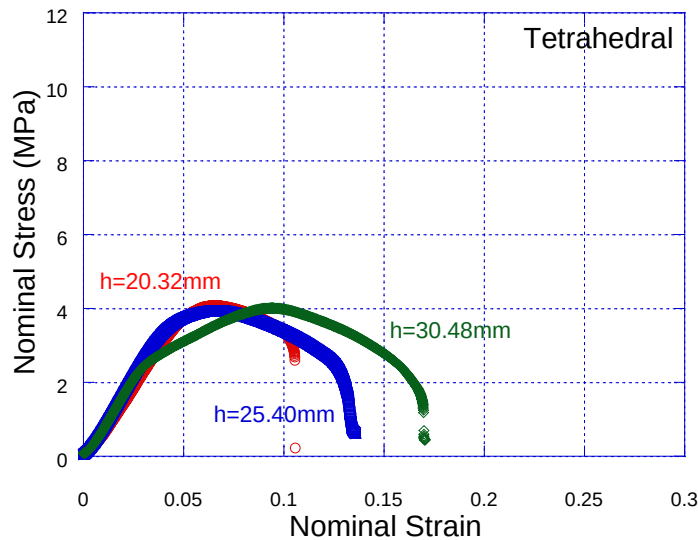


Figure 5.2 - Stress-strain curves of the tetrahedral cores manufactured at different scaling. The curve which reaches the least strain (red) represents the pyramidal core manufactured with a height of 20.32mm; the curve in the middle (blue) represents the mechanical response of the pyramidal core with a height of 25.40mm; the curve which reaches the highest strain (green) represents the unit with a height of 30.48mm.

Upon observation of the chart illustrated on Figure 5.2, all three units exhibit similar stiffness and peak stress. As with the pyramidal topology, the largest core deviates from the linear elastic behavior first at a nominal stress below both the other cores. This implies that the larger core undergoes the onset of buckling below the plastic yield point of the parent material. The stiffness of the core is then reduced as plastic-buckling accommodates the continued deformation.

Conversely the other two core geometries deviate from the linear at nearly the same level, implying the parent materials within the struts are plastically deforming to set the deviations from linear. The manufacturing issue suggested for the pyramidal cores might also be valid for this situation as the failure of the smallest unit was catastrophic whereas failure appeared to occur gradually in the other geometries.

The mechanical behavior of the strut-reinforced tetrahedral units was also plotted in one chart, see Figure 5.3.

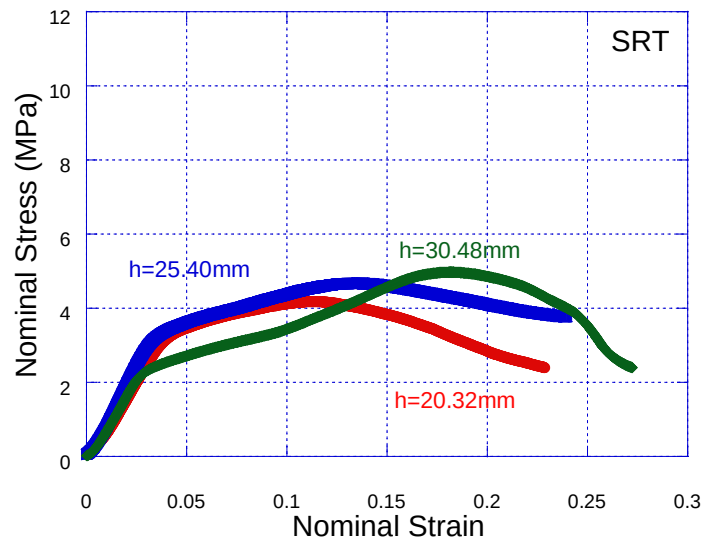


Figure 5.3 - Stress-strain curves of the SRT cores manufactured at different scaling. When looking at a strain of 0.2, the lowest curve (red) represents the pyramidal core manufactured with a height of 20.32mm; the curve in the middle (blue) represents the mechanical response of the pyramidal core with a height of 25.40mm; the tallest curve (green) represents the unit with a height of 30.48mm.

Observation of Figure 5.3 shows that the behavior of the three units falls in line with the results observed for the other topologies, exhibiting identical values for stiffness and peak stress, but the tallest unit appearing to undergo plastic buckling in the elastic-plastic transition and not yielding like the other two geometries. The curve of the larger unit is slightly different than the other two, but not enough to indicate a different mechanical response than the other geometries.

Analysis of these three charts suggests that the manufacturing scaling does not strongly affect the mechanical response of the rapid prototyped cores. Relative density remains constant across the cores of the same topology, i.e. the relative density of the scaled down pyramidal unit is the same as the over scaled unit and also the same as the unit with the CAD model dimensions and the same is true for the other topologies. This fact suggests that the mechanical response of these cores is dictated not by geometry, but by relative density.

As for the difference in performance between the three different topologies, the relative density of each topology is taken into account and on Figure 5.4 the mechanical response of each one is plotted in terms of specific stress and strain. Specific stress is obtained by dividing the stress by each unit's relative density. Since scaling does not appear to significantly affect the mechanical performance of the units, only the units with identical dimensions to the CAD models were plotted, i.e. with a height of 25.40mm.

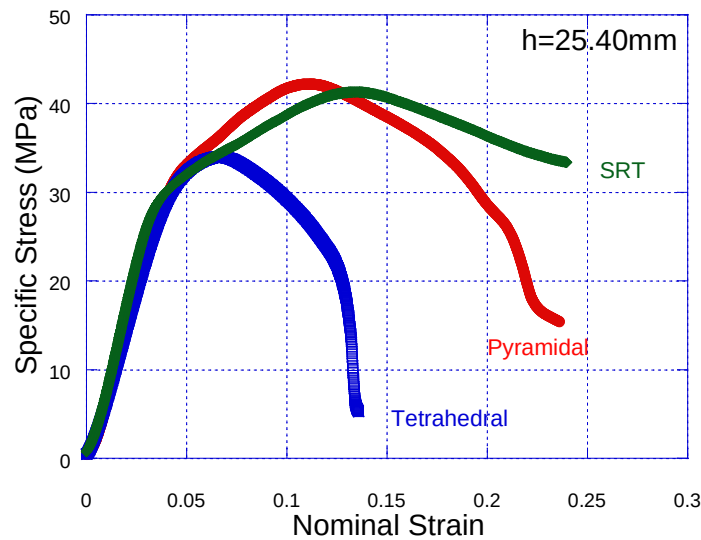


Figure 5.4 - Chart comparing the performance of the intermediate topologies, with a height of 25.40mm, in terms of specific stress and strain. When looking at a strain of 0.1, the tallest curve (red) represents the pyramidal topology, the lowest curve (blue) represents the tetrahedral and the middle (green) represents the strut-reinforced tetrahedral topology.

Observing Figure 5.4, the stiffness of the three topologies is similar. Peak stress reached by the pyramidal is the highest closely followed by the SRT, both peaking slightly above 40 MPa, at 42.19 MPa and 41.04 MPa respectively. The tetrahedral unit peaks much sooner and at 33.85 MPa, soon after it declines and quickly collapses. The stress of the pyramidal core decreases slower and can hold a much higher strain than the tetrahedral unit, but it still outperformed by the SRT which holds higher values of stress and for longer. The difference in the slopes of both topologies is evidence of this and suggests the SRT unit might hold the advantage in terms of energy absorption, or toughness, per unit of mass. In order to verify it, the areas under the nominal stress-strain curves were integrated, which provide the values of toughness per volume unit. Dividing these values by the density of the units provides the toughness per mass unit, which is the most relevant from a weight-efficiency standpoint. These properties are listed on Table 5.1.

Table 5.1 – Toughness and specific toughness values for the three distinct topologies. The pyramidal topology possesses the highest toughness value, but is edged out by the SRT when factoring in relative density.

	Energy absorbed per unit volume (KJ/m ³)	Energy absorbed per unit mass (KJ/Kg)
Pyramidal	17467.4	70.6
Tetrahedral	3826.5	31.8
SRT	9129.9	77.1

As predicted, even though the toughness values are the highest for the pyramidal unit, once relative density is taken into account the SRT topology surpasses the pyramidal by about 10%. The higher toughness value for the pyramidal can be explained by the fact that its projected area is much smaller than the other topologies, which increases its peak nominal stress and therefore toughness. However, when factoring in relative density of each unit cell, the smaller projected area is offset by its increased density, hence the difference observed.

5.1.2 Compression of ABS cells with different slenderness ratios

The results obtained from the compression testing were plotted in Figures 5.5, 5.6 and 5.7 in terms of nominal stress versus strain for ease of comparison with other cores.

As previously presented, the higher relative density geometry within each topology exhibits a mechanical response closely related to that of the bulk material with yield being the main deformation mechanism. The other geometries, provided their relative density is under 0.300, are considered to be cellular solids and present plastic buckling in the elastic-plastic transition until reaching peak load. At that point they begin losing their load-carrying capacity, in some cases faster than others.

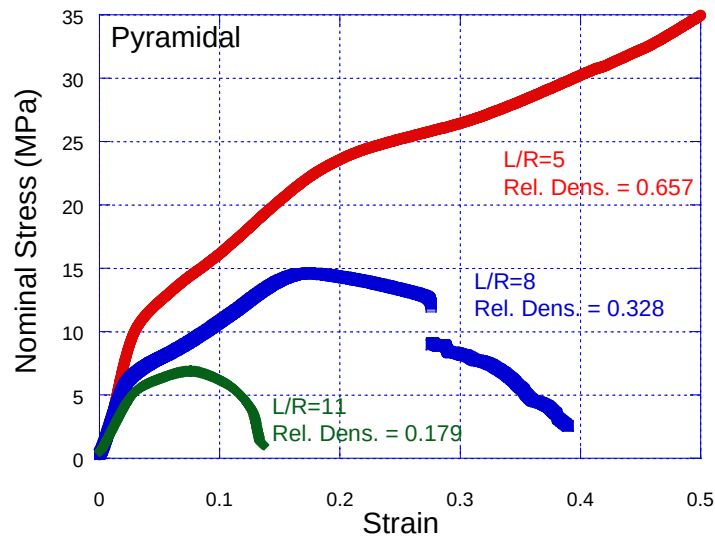


Figure 5.5 - Chart comparing the nominal stress versus strain performance of the pyramidal geometries with different relative densities. When looking at a strain of 0.1, the tallest curve (red) represents the geometry with $\bar{\rho} = 0.657$, the curve in the middle (blue) represents the core with $\bar{\rho} = 0.328$ and the lowest curve (green) represents the geometry with $\bar{\rho} = 0.179$.

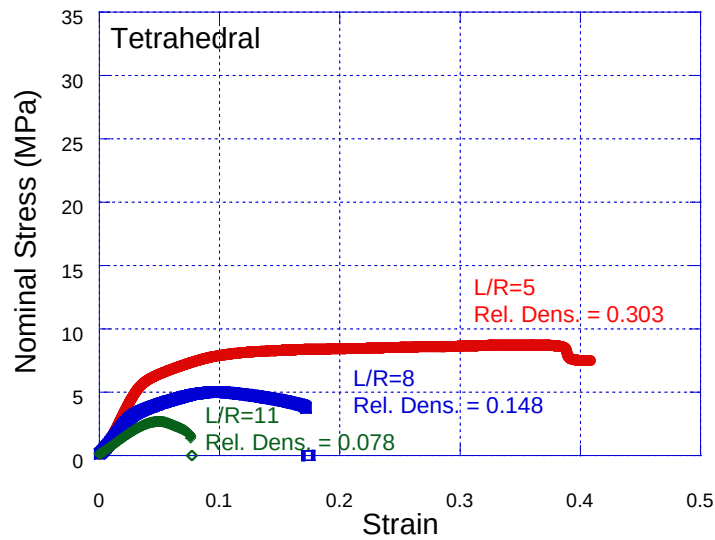


Figure 5.6 - Chart comparing the nominal stress versus strain performance of the tetrahedral geometries with different relative densities. When looking at a strain of 0.05, the tallest curve (red) represents the geometry with $\bar{\rho} = 0.303$, the curve in the middle (blue) represents the core with $\bar{\rho} = 0.148$ and the lowest curve (green) represents the geometry with $\bar{\rho} = 0.078$.

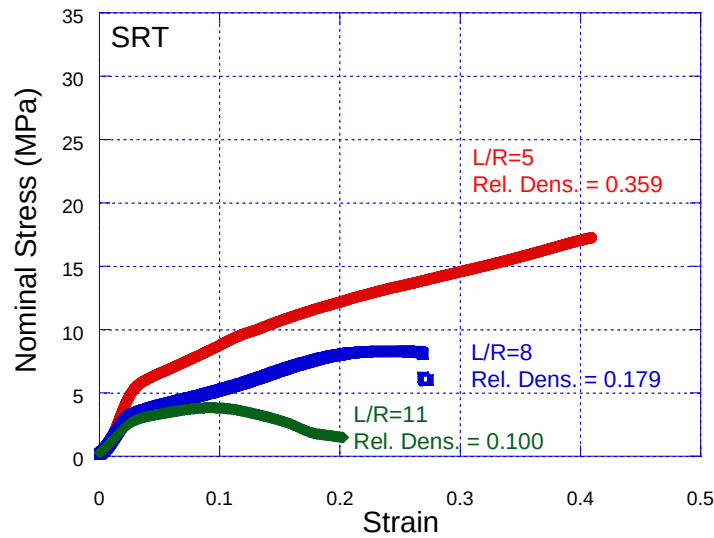


Figure 5.7 - Chart comparing the nominal stress versus strain performance of the strut-reinforced tetrahedral geometries with different relative densities. When looking at a strain of 0.1, the tallest curve (red) represents the geometry with $\bar{\rho} = 0.359$, the curve in the middle (blue) represents the core with $\bar{\rho} = 0.179$ and the lowest curve (green) represents the geometry with $\bar{\rho} = 0.100$.

Plotted on Figures 5.8 and 5.9 are column charts comparing the specific yield stress, $\bar{\sigma}_y$, of the different topologies and geometries.

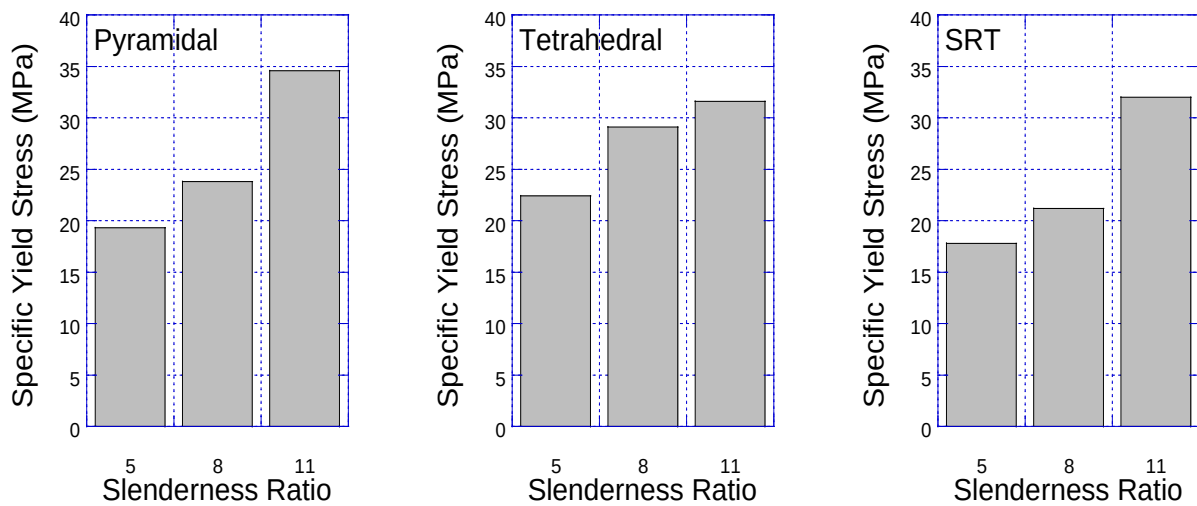


Figure 5.8 - Columns charts comparing the specific yield stress of the different topologies and geometries.



Figure 5.9 - Columns charts comparing the specific stiffness, $\bar{E}$, of the different topologies and geometries.

Looking at these charts it is clear that the cores with the highest relative density are the least weight-efficient in terms of strength and stiffness and the opposite can be said of the topologies with the lowest relative density. However, it is not as easy to define the best topology between the three. Firstly, these charts only look at the specific yield stress and stiffness. As such, the advantage of the SRT topology in terms of peak load and energy absorption against the other topologies cannot be seen here as it is outperformed in terms of specific yield stress by the other two topologies. As far as stiffness is concerned, it displays the highest value for the geometries with the highest slenderness ratio, but the lowest between the geometries with $L/R=8$. This variability shows that neither topology is perfect and each geometry must be optimized for a specific application.

Shown in Figures 5.10 and 5.11 are selection charts, similar to Ashby's [1], where stress and stiffness are plotted in terms of relative density and the different topologies and geometries plotted. The ideal topology and geometry combination should be as close as possible to the top left corner of the charts, which indicate the highest value for a given mechanical property and the lowest relative density, resulting in the most weight-efficient structure.

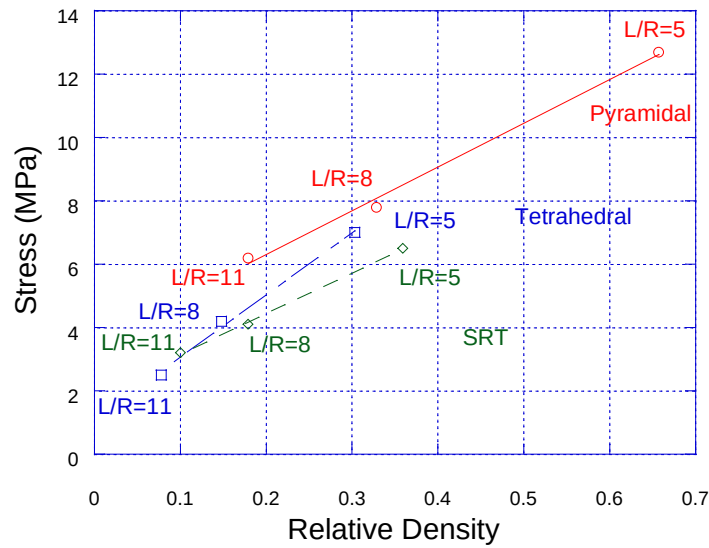


Figure 5.10 - Selection charts where the different rapid-prototyped ABS topologies and geometries are plotted in terms of stress and relative density.

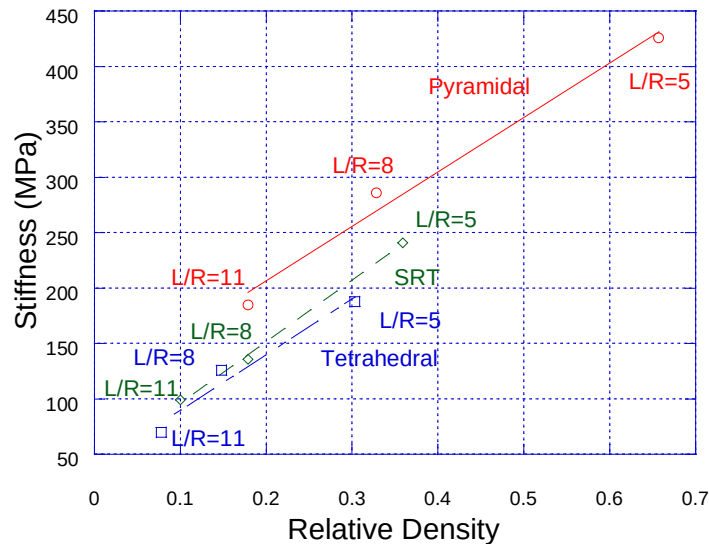


Figure 5.11 - Selection charts where the different rapid-prototyped ABS topologies and geometries are plotted in terms of stiffness and relative density.

From these selection charts it is possible to write the experimental scaling laws for these rapid-prototyped ABS topologies:

$$\bar{\sigma}_y = C_1 \bar{\rho}^{0.6} \quad (\text{Pyramidal}) \quad (5.3)$$

$$\bar{E} = C_2 \bar{\rho}^{0.7} \quad (\text{Pyramidal}) \quad (5.4)$$

$$\bar{\sigma}_y = C_3 \bar{\rho}^{0.7} \quad (\text{Tetrahedral}) \quad (5.5)$$

$$\bar{E} = C_4 \bar{\rho}^{0.7} \quad (\text{Tetrahedral}) \quad (5.6)$$

$$\bar{\sigma}_y = C_5 \bar{\rho}^{0.5} \quad (\text{SRT}) \quad (5.7)$$

$$\bar{E} = C_6 \bar{\rho}^{0.6} \quad (\text{SRT}) \quad (5.8)$$

5.2 Two dimensional periodic carbon fiber lattice core

The results obtained from the compression testing were then plotted in terms of specific stress versus strain and displayed on Figure 4.26. The axes chosen are identical to the ones chosen for the ABS cores to enable an easier comparison between the cores.

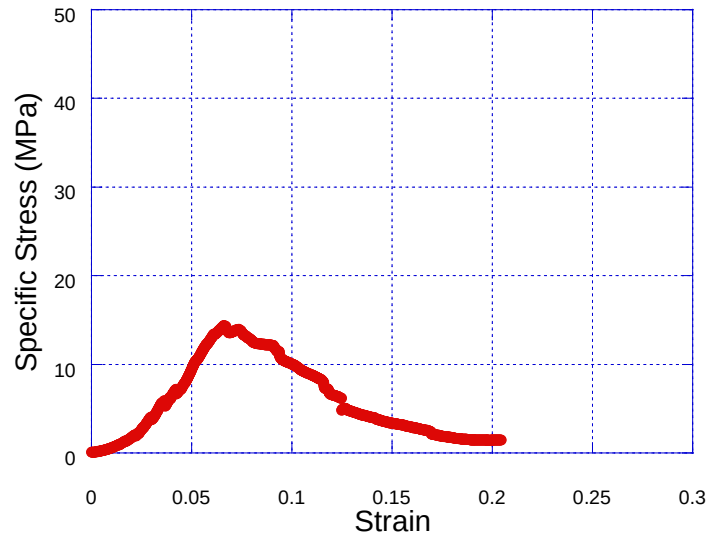


Figure 5.12 - Specific stress versus strain plot of the two-dimensional carbon fiber lattice core under uniaxial compression.

When compared to the results of the ABS individual topologies, the carbon tubes layup is clearly outperformed under compression loading. However, it might not be the case if compared against bigger arrays comprised of the same rapid-prototyped cores. The same can be said for flexural loading, as the ABS topologies were not tested under that type of loading.

5.3 Naturally occurring pumice based stochastic cellular solid core

5.3.1 Failure analysis and strain mapping

Prior to testing, several dots were painted on each of the specimens with a permanent marker and every quasi-static test was recorded with a high-definition video camera. Each frame was then individually saved as a separate image file to enable the use of Digital Image Correlation (DIC).

This technique was performed through Matlab files developed by Christopher Eberl, Robert Thompson and Daniel Gianola at Johns Hopkins University in Baltimore, Maryland [1].

The purpose of the markings is to increase the contrast in the face of the specimen and allow for more accurate tracking through DIC.

A rectangular grid with a resolution of 50x50 pixels is overlaid upon the digital test images, Figure 5.12.

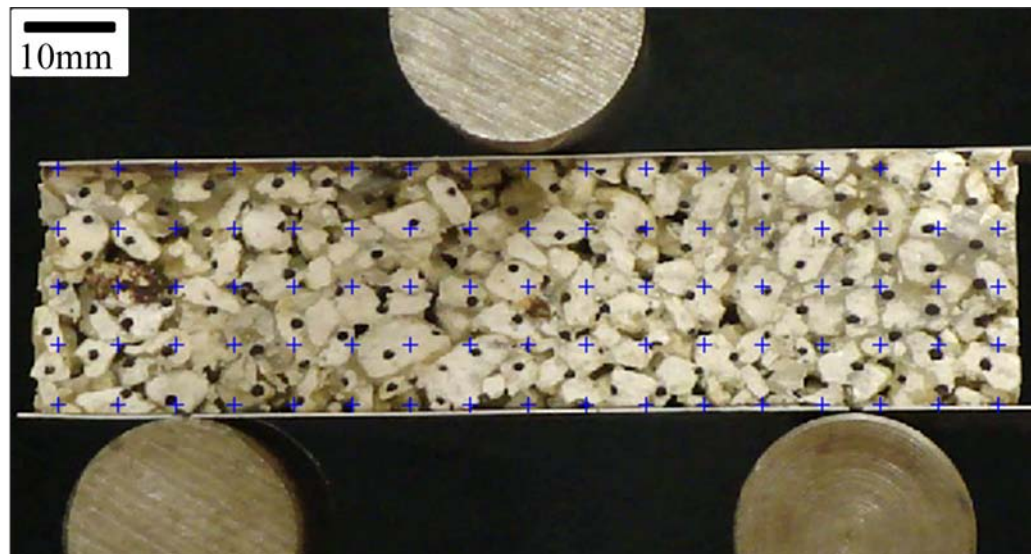


Figure 5.13 - A rectangular grid with a resolution of 50x50 pixels is overlaid on the first digital image of the sandwich panel being tested.

As deformation occurs, the tracking locations are displaced as well and a two dimensional trajectory of the local material unit can be evaluated, Figure 5.13.

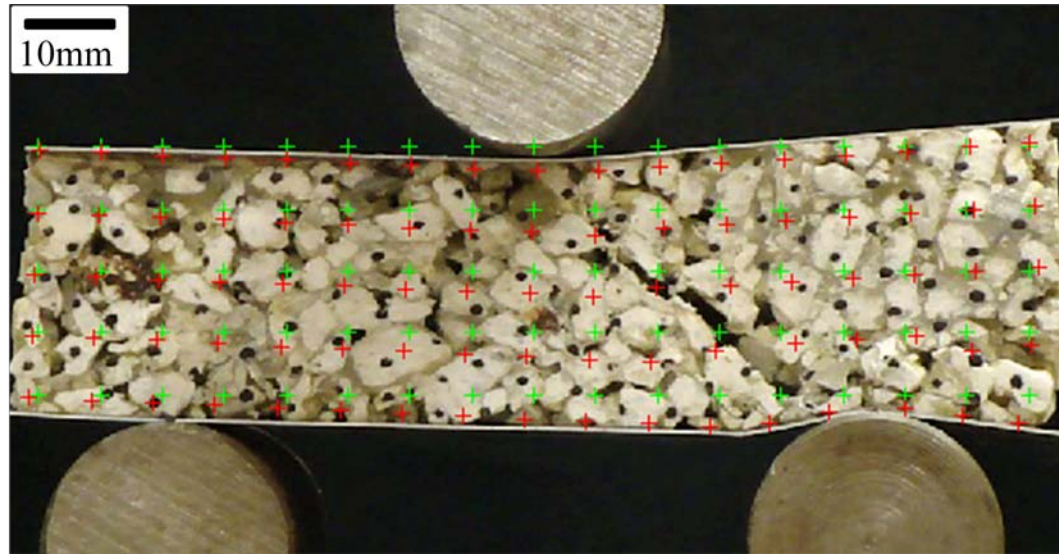


Figure 5.14 - As the test progresses, the tracking locations in the grid (green) displace with the local material units and compared to the initial grid (red) in order to evaluate the trajectory of each material unit.

The trajectories of each tracking point are then superimposed the initial image, where no deformation has occurred, and the structure failure is mapped by presenting the location of each material unit as a function of time.

This technique was applied to every pumice-based core sandwich panel to allow a better understanding of the failure mode dominating each panel and Figure 5.14 through Figure 5.19 illustrate three instances of each test, with pictures of the specimens themselves and matching strain mapping.

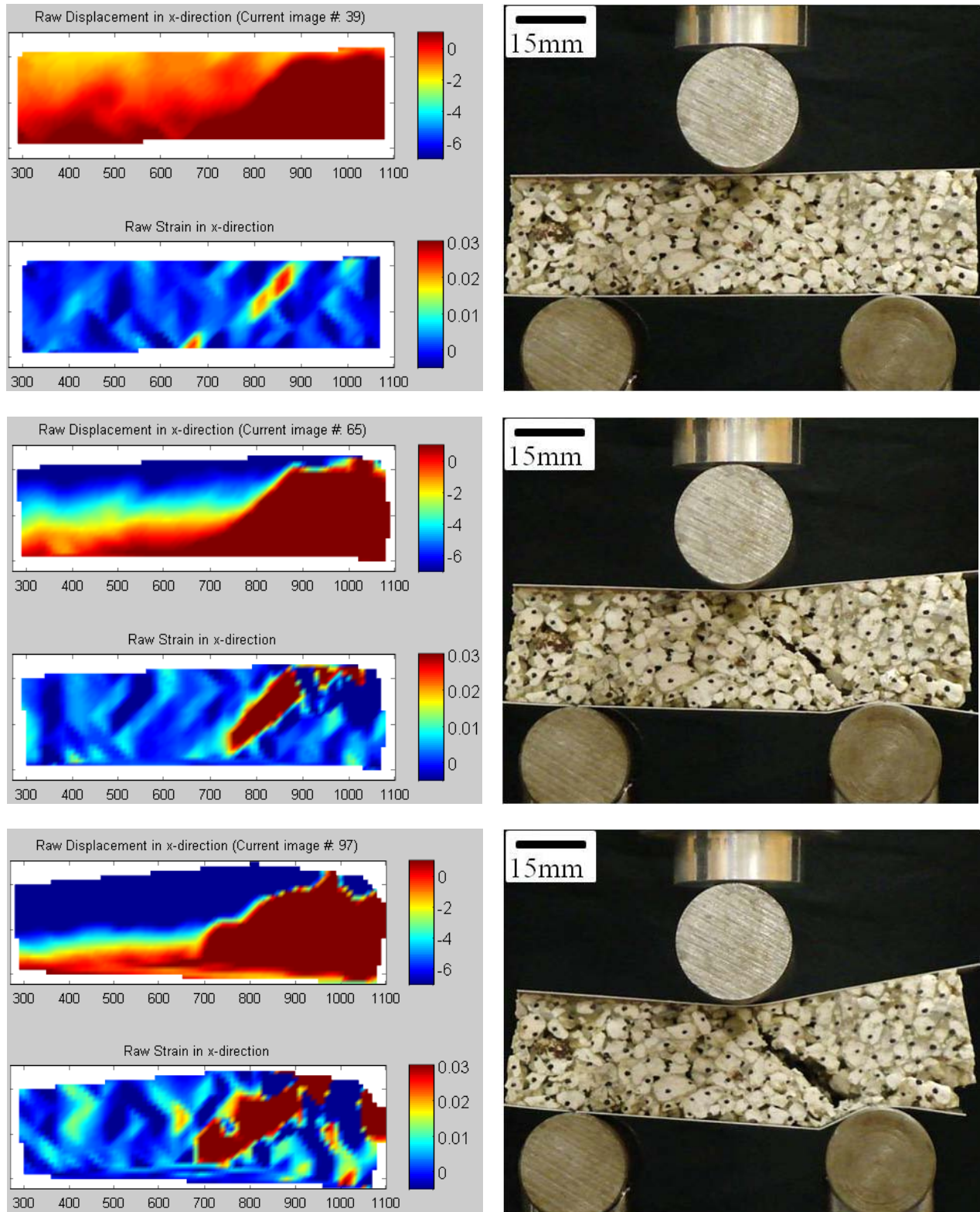


Figure 5.15 - Strain mapping of the 100mm long pumice-based core with 0.35mm aluminum face sheets. These three different stages of deformation illustrate how the crack propagates and how that translates in terms of local strain. For this particular specimen, the 100mm long beam with 0.35mm face sheets, it was observed a tensile failure. Strain mapping is in accordance, showing shear lines perpendicular to the crack in the specimen.

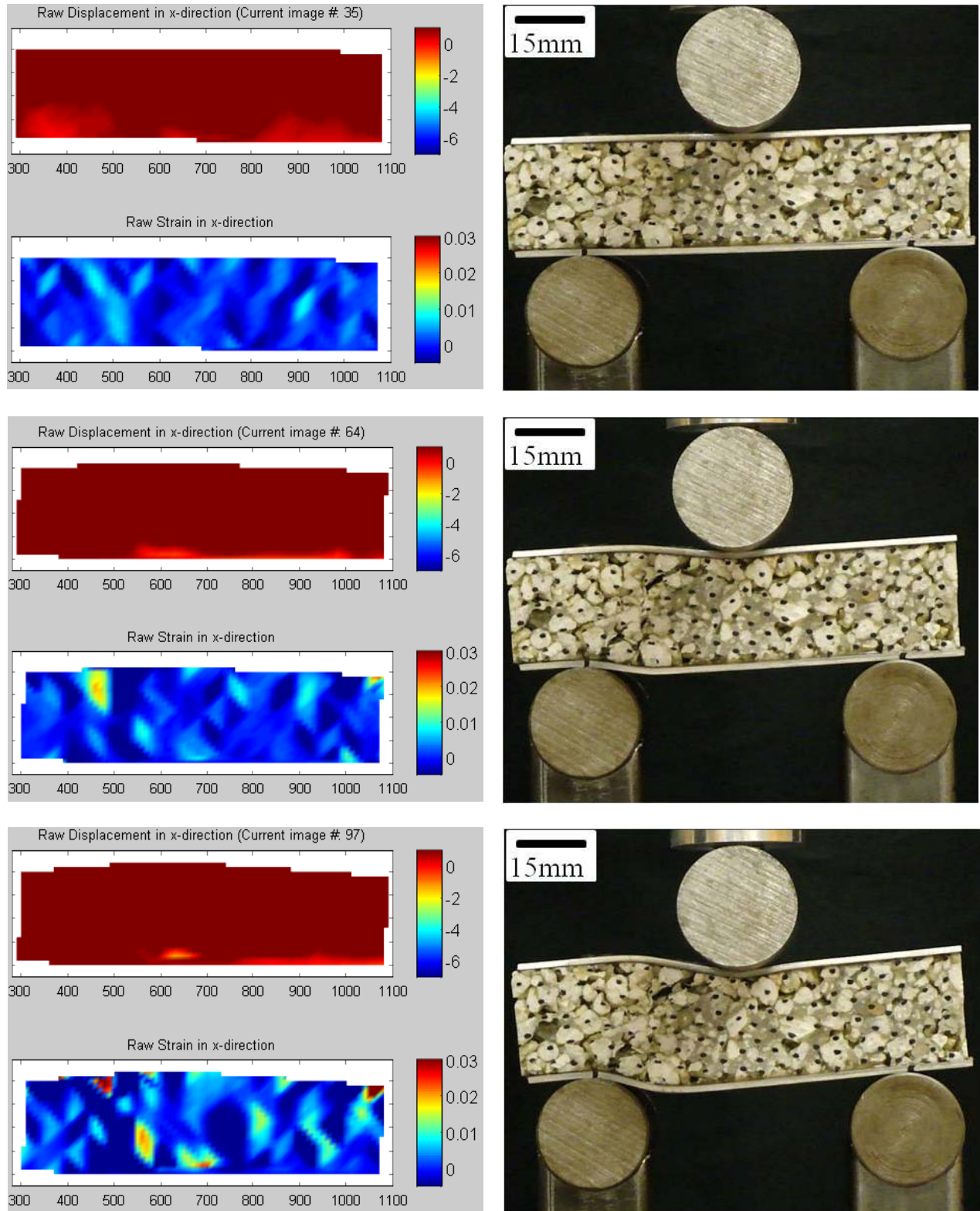


Figure 5.16 - Strain mapping of the 100mm long pumice-based core with 1.6mm aluminum face sheets. For this specimen a tensile failure was observed. Strain mapping is in accordance, showing shear lines perpendicular to the crack in the specimen.

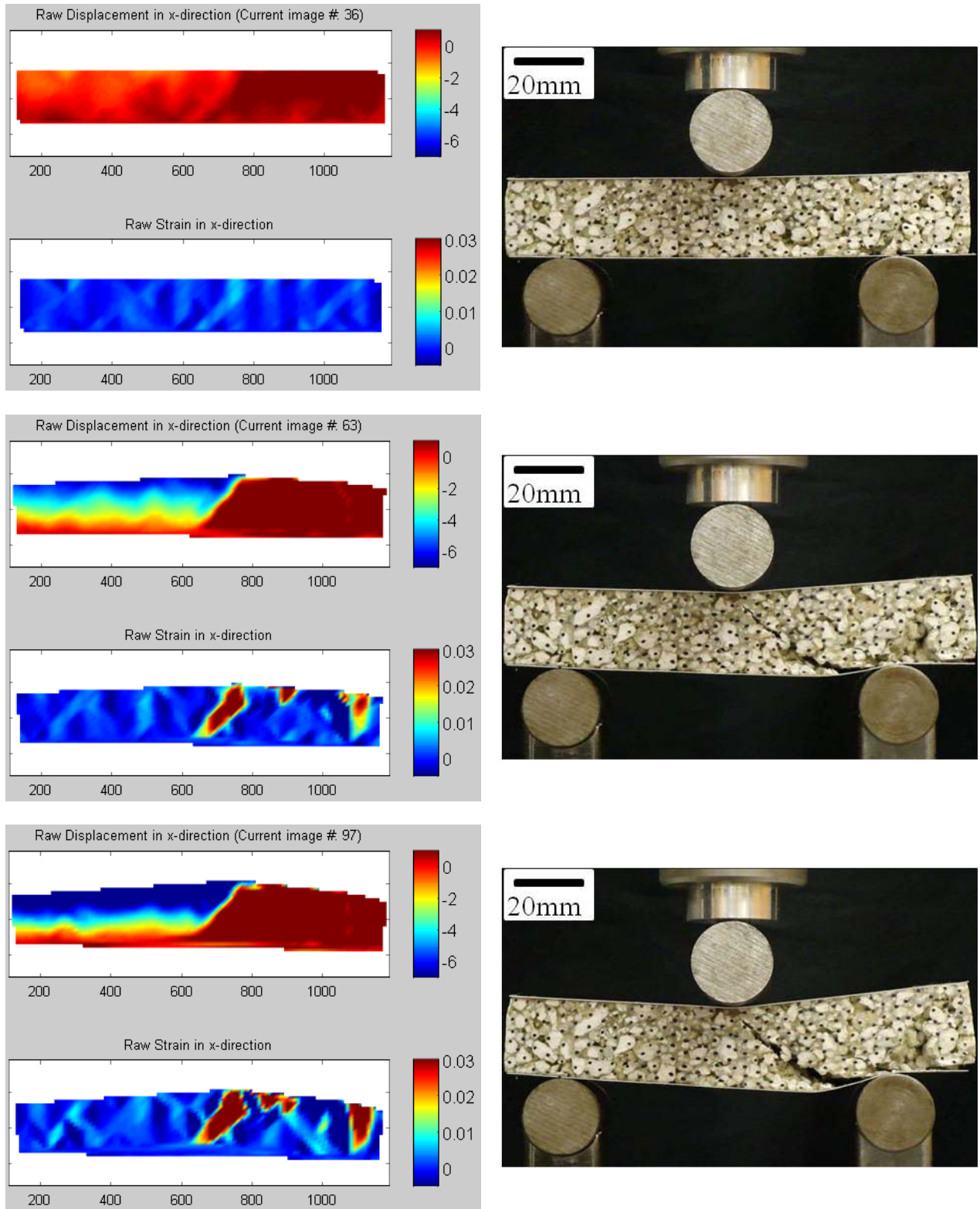


Figure 5.17 - Strain mapping of the 150mm long pumice-based core with 0.35mm aluminum face sheets. For this specimen a tensile failure was also observed. Strain mapping is in accordance, showing shear lines perpendicular to the crack in the specimen.

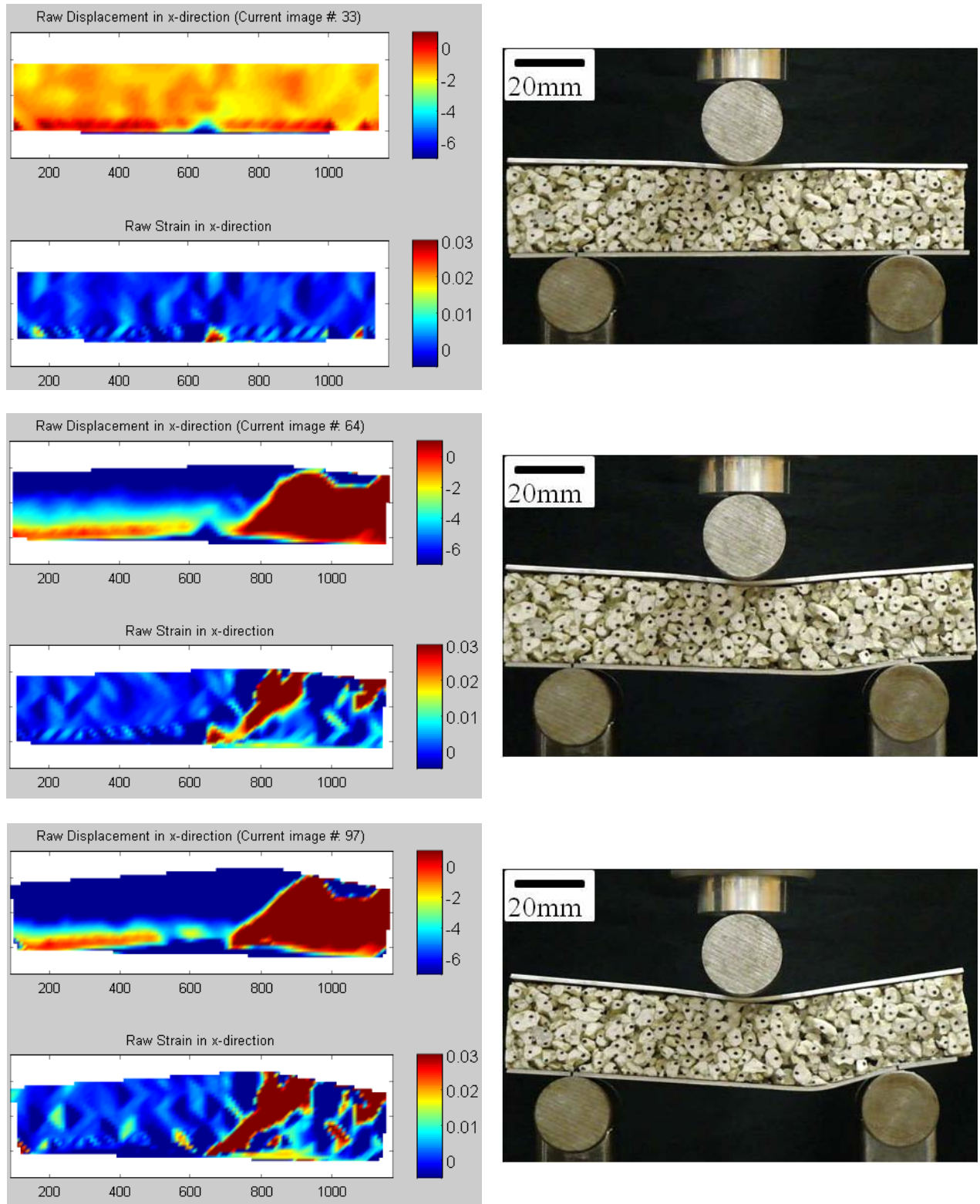


Figure 5.18 - Strain mapping of the 150mm long pumice-based core with 1.6mm aluminum face sheets. In this specimen the failure observed was core shear.

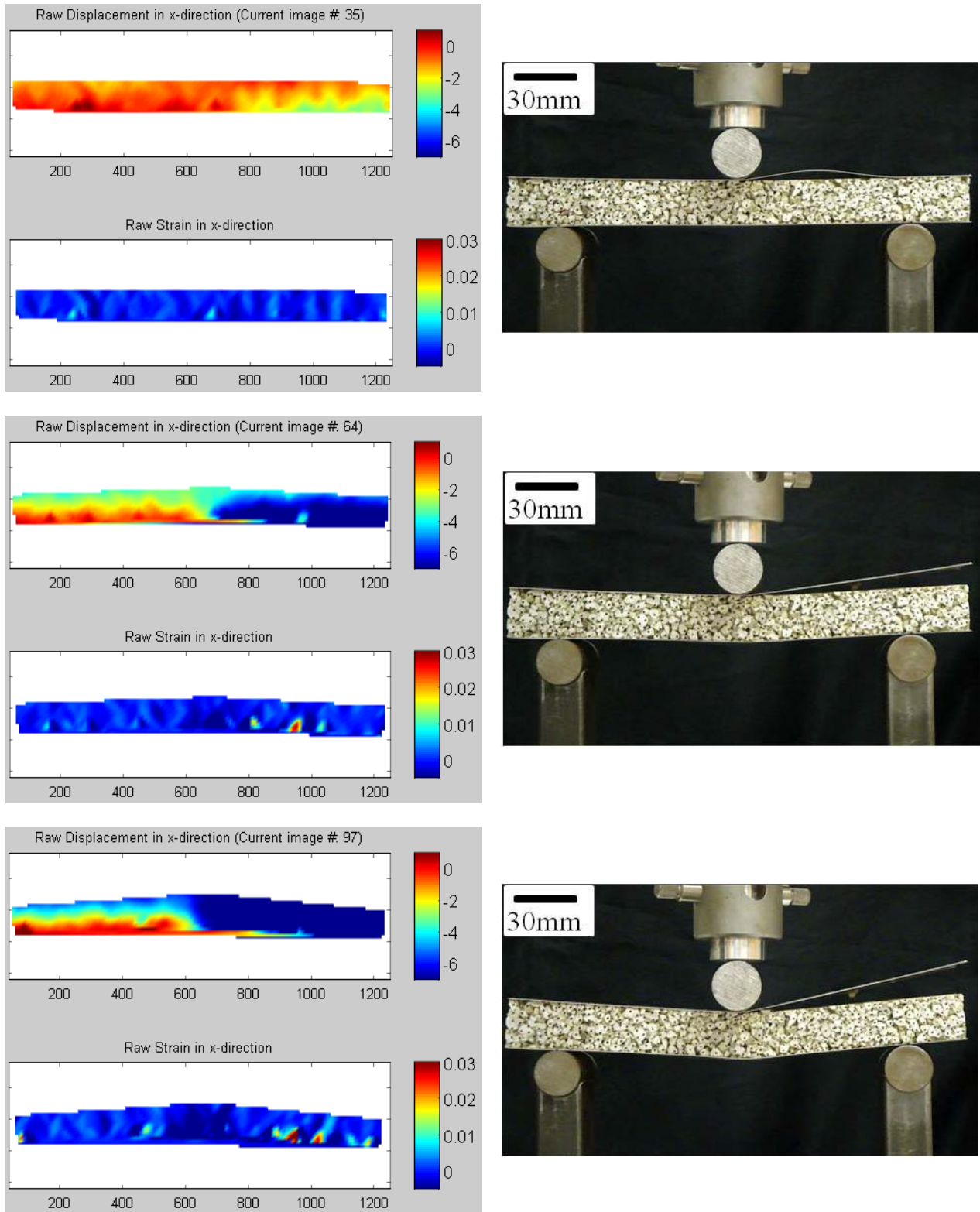


Figure 5.19 - Strain mapping of the 250mm long pumice-based core with 0.35mm aluminum face sheets. This specimen failed in the interface between the core and the face sheets.

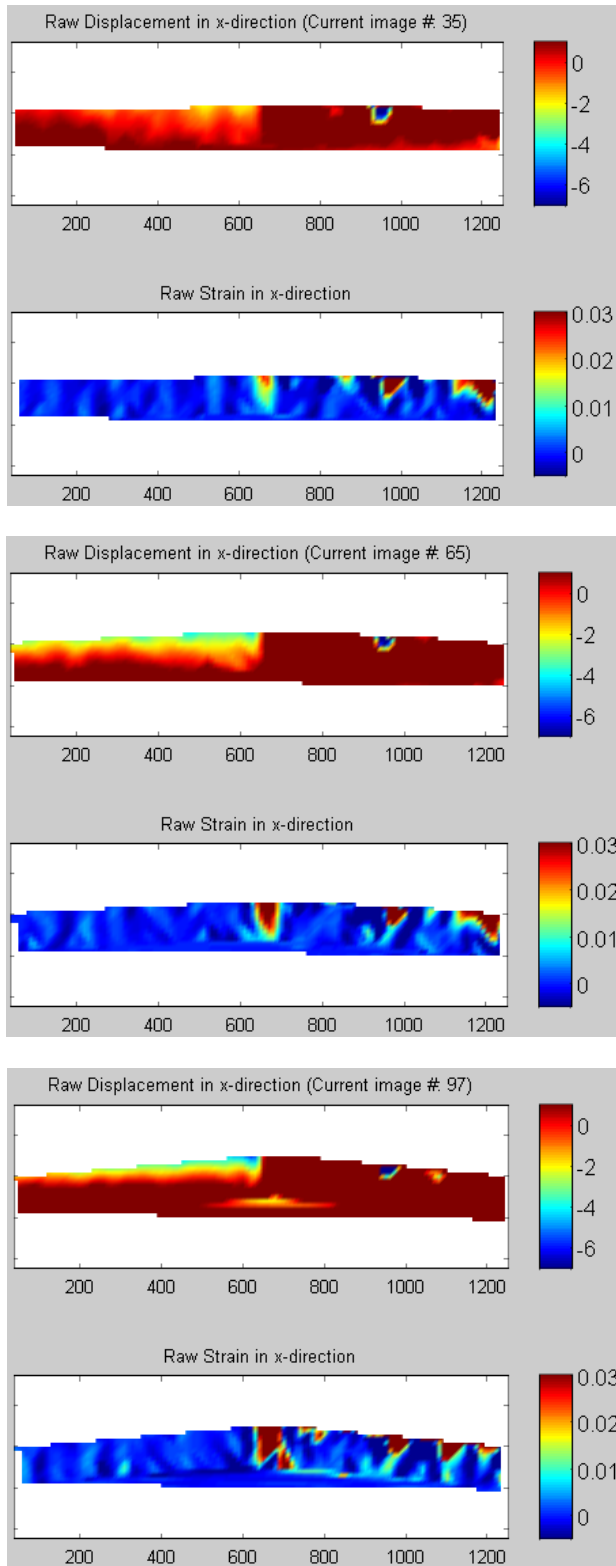


Figure 5.20 - Strain mapping of the 250mm long pumice-based core with 1.6mm aluminum face sheets. This specimen also failed in the interface between the core and the face sheets.

Upon analysis of each failed specimen, it was possible to plot a failure mode map for these sandwich panels, see Figure 5.20. The failure mode map takes axis of face thickness divided by core thickness versus core thickness divided by panel length. These non-dimensional axes allow all panel geometries, for a single core and face sheet type, to be compared. These maps are useful in indentifying the effect of geometry in a particular panel's collapse mechanism.

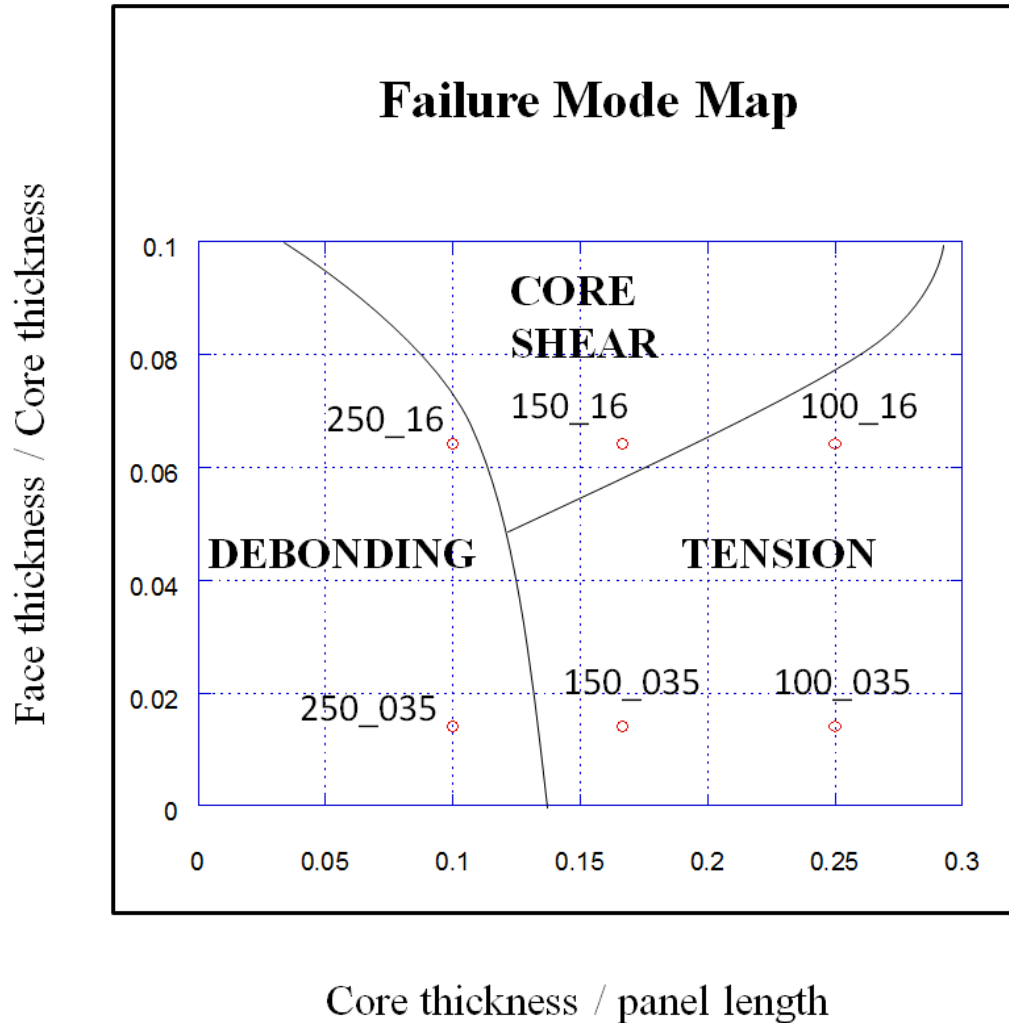


Figure 5.21 - Failure mode map for the sandwich panels comprised of a pumice-based stochastic core and aluminum facing sheets. The three failures observed were debonding, core shear and tension which divide the map in three regions where each failure mode is expected to be dominant. Both axes are adimensional and dependant on geometry only. The vertical axis is the ratio between face sheet thickness and core thickness and the horizontal axis is the ratio between core thickness and beam length. The red circles represent each of the sandwich beams tested and are designated by the length of the panel and the thickness of the facing sheets, i.e. 250_035 refers to the 250mm long panel with 0.35mm thick face sheets.

Inspection of the collapse mechanism and strain mapping allows the failure mechanism for the plates to be identified.

From the results it was observed that the shorter beams, both of them, and the 150mm long beam with the thicker face sheets suffered a tensile failure.

The 150mm long with thinner face sheets, on the other hand, was observed to collapse by core shear.

Both of the longer beams failed by face sheet debonding at a similar load level. The shear stress in the bond line is almost as high as in the middle of the core, which means that the adhesive joint had less strength than the core and therefore failed first. The main problem with this type of failure is that it occurs underneath the surface, which makes it harder to detect before the failure grows into critical size [2].

5.4 Limitations

Despite manufacturing techniques having substantially improved in the past years, some difficulties still exist in the manufacturing of the sandwich panels cores reviewed in this study.

The rapid prototyping machine used in the manufacturing of the ABS cores in this study often failed to manufacture larger arrays. This can be due to several different reasons, but it has been noted that full adhesion of support material to the removable plays a crucial role in the success of a build. This was the main source of failure in the longer arrays, where the strut count is high, as even one strut that failed to properly adhere to the tray was often enough to damage the build. This would not be properly constrained and allowed to move during the build. Layer deposition would not be achieved correctly and the array would inevitably be flawed. This was also an issue when trying to build multiple smaller units at the same time. In order to minimize failure rate each unit was built individually and thus overall manufacturing time increased. A change in support material could resolve this issue.

It has also been observed that the temperature of the tray also plays an important role in support material adhesion. The same build was more likely to fail if the tray had been used immediately before and was therefore still quite warm. This issue was solved by switching trays between build when possible and actively cooling the tray with a fan until it became cold before using it in a build.

The manufacturing of a periodic carbon fiber lattice core proved to be substantially harder than anticipated. The cutting process meant each carbon tube had to be cut individually from the pultruded rods which was time consuming but, more importantly, it had to be done carefully as it was easy to pull fibers from the tube which would decrease its performance considerably. Laying them between the dowels was challenging because the spacing between the wooden dowels was slightly different between each set of dowels, which was enough for some of the tubes to be loose while others were restrained in the same position. Coating the tubes with the binder proved harder for the same reason, as the loose tubes often moved from its intended position when coating. Some binder also flowed to the dowels and aluminum rails, complicating the removal of the layup. During this process some of the tubes would become unstuck from the layup and had to be bonded again. In order to minimize the problem with the binder, it was given a few minutes

to harden and become more viscous so it would be less likely to drip to the rails. Despite this, there is room for improvement in this manufacturing technique. Tee slots can be used with the aluminum rails, and it would make it easy to adjust their positions to accommodate tubes with different diameters. They were not used in this research due to lack of availability of tee slots compatible with the extruded aluminum rails used.

Pumice-based stochastic cores manufacturing also provided its fair share of challenges. The stochastic nature of this core means there is a high degree of variability inherent to the manufacturing of the specimens. Fleischer [3] encountered this issue and tackled it by averaging a number of different samples. It also proved difficult to ensure even spread of the epoxy binder across the pumice packed frame. The cutting of the specimens was also a bit challenging as, once again due to the stochastic nature of pumice, it was not easy cutting them into perfect rectangular shapes. For these reasons, once the specimens were cut, it was found they often contained large cavities which would hinder their performance.

References for Chapter 5

1. Ashby, M., H. Shercliff, and D. Cebon, *Materials Engineering, Science, Processing and Design*. 2007: Elsevier.
2. Christopher Eberl, R. Thompson, and R. Gianola. *Digital Image Correlation and Tracking*. 2006 11-Sep-2008; Available from: <http://www.mathworks.es/matlabcentral/fileexchange/12413-digital-image-correlation-and-tracking>.
3. Zenkert, D., *The Handbook of Sandwich Construction*. 1997: EMAS Publishing.
4. Fleischer, C., *Mechanical and Physical Characterization of Pumice/Epoxy Stochastic Cellular Solids*. 2007, University of Maryland, Baltimore County.

6 Concluding Remarks

6.1 Summary of this study

In this study, the performance of sandwich panels and specifically different cores of different cellular solids was investigated and their competitiveness and applicability in vehicle systems evaluated.

The design and properties of rapid prototyped ABS were explored in this study where the impact of scaling, whilst retaining the aspect ratio, was evaluated in three different topologies and a similar analysis was made with topologies where the slenderness ratios were varied to achieve different densities or relative densities.

Different configurations of two-dimensional periodic carbon fiber lattice cores were also manufactured based on a similar process as presented by Wadley [1] and their mechanical performance in three point bending evaluated.

This study also expands on the work of Fleischer [2] about the performance of naturally occurring weight and cost efficient pumice based stochastic cellular solid cores, exploring design variability and identification of corresponding failure modes in three-point bend flexural tests.

6.2 Conclusions and Key finds

This study has determined that the properties of the rapid-prototyped ABS cores do not show significant changes when scaled up or down as long as strut geometry and topology angle are not changed. Their mechanical properties as a function of relative density were measured. The effect of relative density on stiffness, peak stress, and energy absorption was measured. It was found that these properties scale with relative density in the following:

$$\bar{\sigma}_y = C_1 \bar{\rho}^{0.6} \quad (\text{Pyramidal})$$

$$\bar{E} = C_2 \bar{\rho}^{0.7} \quad (\text{Pyramidal})$$

$$\bar{\sigma}_y = C_3 \bar{\rho}^{0.7} \quad (\text{Tetrahedral})$$

$$\bar{E} = C_4 \bar{\rho}^{0.7} \quad (\text{Tetrahedral})$$

$$\bar{\sigma}_y = C_5 \bar{\rho}^{0.5} \quad (\text{SRT})$$

$$\bar{E} = C_6 \bar{\rho}^{0.6} \quad (\text{SRT})$$

The out-of-plane compression failure mode of these cores was determined to be a balance between material plastically deforming and strut buckling. The amount of each active deformation mechanism was not explicitly determined; however, the character of the core stress versus strain response provides insight into the switch between mechanisms.

The two-dimensional carbon fiber lattice cores exhibited identical load carrying capacity with different relative densities. Failure mode observed in three-point bending was face sheet debonding, resulting in a reorganization and reload of other tubes resulting in a serrated collapse. The simple lay-up technique used to manufacture these cores can be optimized to prevent or delay the onset of this failure mode.

Pumice cores were tested with different geometries, at 100mm, 150mm and 250mm long, in simply supported three-point bend. Strain mapping of the core was utilized to understand the active mechanisms whilst the beams accommodate deformation. The geometries tested resulted in three different failure modes being activated and identified. These modes are:

Core shear when beams are 150mm long and have 1.6mm thick face sheets.

Facesheet – core interface failure for beams 250mm long.

Pumice ceramic core tensile failure for beams 100mm long and the 150mm long beam with 0.35mm thick aluminum face sheets. This failure is novel as to the author's knowledge this is the first time this type of failure has been reported.

From the test observations an experimental failure mode map for pumice core sandwich plates has been created for design use.

6.3 Future Work

The performance of different cellular solids was studied in both compression and three-point bending scenarios. For the continuation of this research, further optimization should ensue regarding the ideal angle of the rapid prototyped ABS struts to endure flexural loading. The performance of electroformed topologies under three-point bending is also an interesting prospect. Another way to improve the properties of the ABS cores would be to reinforce them with carbon nanotubes.

The manufacturing and performance of naturally occurring pumice based cores with different face sheets should also be explored as their cost effectiveness makes them competitive with other, more advanced materials.

There is also room for an improved manufacturing process for the two-dimensional carbon fiber lattice core explored in this study.

Doubly-curved beams should be manufactured and analyzed, as this configuration is more interesting for the majority of vehicle system applications. This would require a modified core design for the sandwich panels and a study on the stiffness of such structures while varying parameters such as span of the beam divided by height of the core and other geometric configurations.

Finite element models could also be created as they would be easy to implement and further explore the failure modes of these cellular solids.

References for Chapter 6

1. Wadley, H., *Multifunctional periodic cellular metals*. Phil. Tras. R. Soc. A, 2005. **364**: p. 31-68.
2. Fleischer, C., *Mechanical and Physical Characterization of Pumice/Epoxy Stochastic Cellular Solids*. 2007, University of Maryland, Baltimore County.

Appendix A: P430 ABS Material Properties



P430 ABS Material Properties

A true industrial thermoplastic, ABS is widely used throughout industry. When combined with a Dimension Elite system, P430 ABS is ideal for 3D printing of models in the engineering office.

MECHANICAL PROPERTIES¹

	Test Method	Imperial	Metric
Tensile Strength, Type 1, 2 in/min (51 mm/min), 0.125	ASTM D638	5,295 psi	36 MPa
Tensile Modulus, Type 1, 2 in/min (51 mm/min), 0.125	ASTM D638	329,499 psi	2,272 MPa
Tensile Elongation, Type 1, 2 in/mm 51 mm/min, 0.125	ASTM D638	4%	4%
Flexural Delamination	Stratasys Standard	5,142 psi	35 MPa
Flexural Strength	ASTM D790	7,604 psi	52 MPa
Flexural Modulus	ASTM D790	319,737 psi	2,204 MPa
IZOD Impact, Notched, 73°F (23° C)	ASTM D 256	1.8 ft-lb/in	96 J/m

THERMAL PROPERTIES

Heat Deflection Temperature – unannealed ³	ASTM D648		
HDT, 66 psi (0.5 MPa)		204 °F	96 °C
HDT, 264 psi (1.8 MPa)		180 °F	82 °C
Melt Point		Not Applicable ²	Not Applicable

OTHER

Specific Gravity	1.04
Vertical Burning Test ³	HB, UL94
Coefficient of Thermal Expansion ³	4.9E-05

APPEARANCE

Natural

Stratasys, Inc.
14950 Martin Drive
Eden Prairie, MN USA 55344
Ph: 952.937.3000
Fax: 952.937.0070
www.dimensionprinting.com

The information presented are typical values intended for reference and comparison purposes only. They should not be used for design specifications or quality control purposes. End-use material performance can be impacted (+/-) by, but not limited to, part design, end-use conditions, test conditions, etc. Actual values will vary with build conditions.

Product specifications are subject to change without notice.

¹ Build orientation is on side edge

² Due to amorphous nature, material does not display a melting point

³ Injection molded properties

Appendix B: Instron 3369 Specifications

Specifications

		3365	3366	3367	3369
Load Capacity	kN kgf lbf	5 500 1,125	10 1,000 2,250	30 3,000 6,750	50 5,000 11,250
Maximum Speed	mm/min in/min	1,000 40	500 20	500 20	500 20
Minimum Speed	mm/min in/min	0.01 0.0004	0.005 0.0002	0.005 0.0002	0.005 0.0002
Maximum Force at Full Speed	kN lb	5 1,125	10 2,250	15 3,375	25 5,620
Maximum Speed at Full Load	mm/min in/min	1,000 40	500 20	250 10	250 10
Return Speed	mm/min in/min	1,200 48	600 24	600 24	500 20
Total Crosshead Travel*	mm in	1,122 44.2	1,122 44.2	1,122 44.2	1,122 44.2
Total Vertical Test Space	mm in	1,193 47	1,193 47	1,193 47	1,193 47
Space Between Columns	mm in	420 16.5	420 16.5	420 16.5	420 16.5
Height	mm in	1,582 62.3	1,582 62.3	1,582 62.3	1,582 62.3
Width	mm in	756 29.8	756 29.8	756 29.8	756 29.8
Depth	mm in	707 27.8	707 27.8	707 27.8	707 27.8
Weight with Typical Load Cell	kg lb	110 242	110 242	121 266	141 312
Maximum Power Requirement	VA	300	300	600	700

Notes:

1. All systems conform to all relevant European standards and carry a CE mark.
2. Total vertical test space on all systems is the distance from the top surface of the base platen to the bottom surface of the moving crosshead, excluding load cell grips and fixtures.

The above specifications were developed in accordance with Instron's standard procedures and are subject to change without notice.

Two Color Options

- Charcoal Gray
- Cobalt Blue

Common Specifications

Load Measurement Accuracy
±0.5% of reading down to 1/100 of load cell capacity. Meets or exceeds ASTM E4, BS 1610, DIN 51221, ISO 7500/1, EN 10002-2, JIS B7721, JIS B7733, and AFNOR A03-501 standards.

Strain Measurement Accuracy:
±0.5% of reading down to 1/50 of full scale with ASTM E83 class B or ISO 9513 class 0.5 extensometers. Meets or exceeds ASTM E83, BS 3846, ISO 9513, and EN 10002-4 standards.

Crosshead Speed Accuracy (Zero or constant load):
±0.2% of set speed

Power Supply
47 to 63 Hz. Must be free of spikes, surges, or sags exceeding 10% of the nominal voltage.

Operating Temperature:
+10 to +38°C (+50 to +100°F)

Storage Temperature:
-40 to +66°C (-40 to +150°F)

Humidity Range:
+10 to +90%, non-condensing

Atmosphere:
Designed for use under normal laboratory conditions. Protective measures may be required if excessive dust, corrosive fumes, electromagnetic fields, or hazardous conditions are encountered.

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