Chapter 1  INTRODUCTION

Engineers are constantly endeavouring to create, combine or redesign to produce materials that are as suitable as possible for a particular application. In many fields, the desired material needs to be both light weight and strong for functionality, while economic considerations require characteristics of low cost and ease of manufacture. Ideal materials have a combination of properties that allow multi-functionality where the single component can perform a number of roles. Composite materials have been developed as part of this pursuit with the capacity to have enhanced properties when compared to the constituent materials. Hybrid materials and structural composites continue to be developed with significant potential in a wide range of applications.

Sandwich structures have been developed as a way to increase the flexural rigidity of a structure while minimising the associated weight. To achieve this, a sandwich structure consists of two thin stiff and strong faces separated by a thicker lightweight core. These structures are an efficient configuration for sustaining bending and buckling loads. Typical applications are those that require minimal weight, such as in aerospace, marine, sporting equipment and portable structures. Increasingly, other forms of transport are looking for alternative light weight construction materials to help improve fuel efficiency.

Traditionally, honeycomb structures and polymer foam cores have been widely used in sandwich structures for a variety of applications. These materials can have limited function in high temperature systems as the core materials can be sensitive to heat. This temperature sensitivity also limits the range of skin materials that can be used, restricting the use of those that need high processing temperatures. Polymer foam can display significant fracture under localised loading which is typical in many sandwich structure service applications. Polymer foams do not have particularly high energy absorption properties and can have quite brittle catastrophic failure behaviour particularly under impact loading.
Honeycomb cores have strong stiff behaviour under axial loading, but this drops considerably for any shear load component. The isotropic nature of foams provides much greater multidirectional behaviour, and the development of new varieties of cellular materials is increasing the range of areas where foam sandwich structures could be utilised.

Metal foams have potential as sandwich cores for a range of applications. Foaming of metals was first encountered when alloying a new combination of elements including a volatile metal (for example, mercury or magnesium) [1] and there are now a range of manufacturing methods that have reached commercial production levels. These manufacturing improvements have increased the material’s attractiveness for high volume markets. Metal foams have attractive properties for use as sandwich cores including good stiffness and strength to weight ratios, high impact energy absorption, good sound damping, electromagnetic wave absorption, thermal insulation and non combustibility. Metal foams may therefore be more appropriate where multi-functionality is valuable.

Bulk aluminium foam has been implemented in a number of applications. Rolled aluminium foam has been found to have a large sound absorbing coefficient, particularly for low frequencies, and can be equivalent to, or greater than, the same volume of glass wool [2]. It has been employed as a sound absorber in expressway constructions to reduce noise for neighbouring residential areas (see Figure 1.1). Metal foams have displayed considerable energy absorption properties through the progressive deformation of the cellular structure at constant stress. Much research has been conducted on the potential for metal foams as fillers within traditional crash box structures in automotive applications to further enhance energy absorption. Figure 1.2 shows a typical crash box arrangement with details of prototype foam filled crash boxes. In particular, the use of metal foam within vehicle crashboxes has been found to produce significant reductions in their weight and dimensions [3]. In addition, the foam greatly improves energy absorption in off-axis collisions, compared to the traditional energy absorption method of the plastic collapse of empty tubular structures [4]. Crash protection using metal foam has also been developed for rail-based vehicles [4].
Further applications of aluminium foam use its light weight structure to add stiffness to existing hollow components. The foam can be used as a core in a low-pressure die-casting process where a composite of light-weight inner foam core and cast outer surface is formed. These parts have increased stiffness and damping compared to equivalent hollow parts, while only having a slightly increased mass. A prototype BMW engine mounting bracket (see Figure 1.3) has been manufactured using this method [4]. Another method of combining the light weight foam with dense material is to use the foam within a sandwich structure. One particular product uses integral aluminium skins bonded as part of the foaming process [4]. These sandwich panels can be formed into quite complex shapes and combined with new construction principles, have great potential as alternative stamped steel parts in cars. German car maker Karmann and the Fraunhofer-Institute in Bremen have co-developed large aluminium skinned aluminium foam sandwich panels used in a concept car to demonstrate potential applications for the material [5].
There are further applications in other transportation industries, such as rail and ship building. A commercially produced aluminium foam, Alporas®, has been incorporated as panels in Japanese trains to improve crash energy absorption [6]. The combination of excellent damping behaviour in a light and stiff structure makes aluminium foam sandwich panels a potentially useful material in ships [6]. There are a range of applications for aluminium foam in the building industry including brackets for external facade panelling, elevator panels and lightweight firedoors [6].

Applications in the aerospace industry include replacing traditional honeycomb structures, with the potential benefits of reduced cost, use of more complex 3D shapes and increased performance in the form of enhanced isotropy, and improved behaviour in fire situations [6]. Test parts using aluminium foam sandwiches with integral skins have been produced for space applications [7]. Figure 1.4 shows a test cone segment for the Ariane 5 rocket making use of foam panels.
A further variation on the use of aluminium foam within sandwich structures is to use composite skins. This provides an alternative to integrally bonded metal skins, or the use of adhesive with metal skins. The thermal properties of the metal foam, in contrast with polymer foams, allow the use of tough thermoplastic skins. These can be bonded to the core in a single stamping process providing a quick and low cost manufacturing method [8]. These structures have been found to display excellent energy absorbing characteristics across a range of impact velocities and a high degree of adhesion between the composite skins and the aluminium foam core [9]. These energy absorbing properties, in addition to the low weight and flexural rigidity features of the sandwich panels are desirable in a range of applications.

The development of aluminium foam composite sandwich structures has great potential to provide an alternative to traditional sandwich materials, and to possibly widen the range of applications for which sandwich structures are appropriate. Further understanding of the mechanical behaviour of these structures is required to predict their response under various loading situations, and hence enable their suitable implementation.

Figure 1.4: Foam panels in the Ariane 5 rocket: cone segment showing details of flange and upper edge [7]
1.1 Scope and Objectives

The aim of the current research is to characterise the mechanical behaviour of aluminium foam when utilised in a thermoplastic composite sandwich structure. The study focuses on the quasi-static flexural loading behaviour and features the use of full field strain distributions produced using a 3D optical measurement technique during the experimental testing. This full-field strain information provides an insight into the flexural and deformation mechanisms of the structure. The project also explores the use of finite element modelling to replicate and predict the behaviour of the sandwich structure in flexural loading. The experimental strain contours provide verification of the performance of the model, and can be used to suggest areas for improvement. The future development of accurate FE models will then allow a range of loading situations corresponding to possible applications to be investigated, and hence enable improved utilisation of the structure in appropriate real world applications. The behaviour of the aluminium foam as a bulk material has already been investigated to some extent, but further studies are required on the behaviour within the constraints of a sandwich structure system using thermoplastic skins.

The study employed a number of steps towards this aim of flexural characterisation, beginning with an investigation directly comparing aluminium foam composite sandwich structure behaviour with the more traditionally used polymer foam composite structure. Subsequently, an existing constitutive model for metal foam that has previously been implemented as a material option within a finite element code was investigated for its ability to predict the behaviour of the sandwich in flexural loading. This material model has been utilised primarily for energy absorbing and compression dominated loading situations, and it would be very useful if it could also be successfully used in complex bending loading situations. In particular, the capacity of the model to capture the change in behaviour with varying sandwich component thicknesses was studied. The influence of the material model parameters on various aspects of the flexural response is investigated. Suggestions on possible improvements to the model are made; however details of implementing constitutive models are outside the scope of this project.

1.2 Thesis Structure

This thesis is structured into chapters following the development of the research project. It begins with experimental comparisons of the aluminium foam sandwich structure with a polymer foam sandwich, followed by more detailed studies of the strain development in a variety of core and skin thicknesses. The performance of a flexural finite element model
is investigated and a study on the effect of the material model parameters on the flexural behaviour of the FE structure is described.

Chapter 1 is followed by a literature review chapter which develops the concept of metal foam, its production methods and the current understanding of its mechanical behaviour. Chapter 2 also provides a background on the use of foams within sandwich structures and the existing characterisation methodology. A review of constitutive models and finite element modelling techniques for the foam and its use within sandwich structures is provided. A review of the use of the full field strain characterisation method is discussed. Chapter 3 presents details on the experimental methods used in this study, including the sample manufacturing method, the physical testing method of four-point bend and an explanation of the optical full-field strain characterisation process. An initial comparison study of the behaviour of both the aluminium foam composite sandwich structure and a traditional polymer thermoset composite sandwich structure is provided in Chapter 4. This study concentrates on flexural testing of the two structures. Chapter 5 presents experimental results from further flexural testing of the aluminium foam structure, including the effect of varying core or skin thicknesses. Both load-displacement curves and progressive full-field strain distributions are discussed.

The second half of the thesis describes the investigation into FE modelling of the sandwich structure. Chapter 6 investigates the experimental behaviour of the bulk foam in compression and tension. The results are analysed to produce input parameters for the finite element foam material model and FE compression results are compared with experimental strain contours. Chapter 7 explores the performance of the FE model as a full sandwich structure under flexural loading. The model behaviour is compared with the experimental results, investigating in detail the strain development throughout the test. This is achieved using load-displacement curves, energy calculations, full-field strain distributions and strain section line plots. The ability of the model to predict the behaviour of various core and skin thicknesses is investigated. Chapter 8 discusses a study into the effect of the material model parameters on the flexural response of the sandwich structure. The final chapter provides a summary of the findings and implications of the work, and provides suggestions for future studies in the area.
Chapter 2  BACKGROUND AND LITERATURE REVIEW

This thesis investigates the flexural behaviour of composite aluminium foam sandwich structures, using experimental strain contours and exploring the performance of an FE model. To be able to predict behaviour, it is important to understand the constituent materials used in this novel structural composite. This chapter provides a general background on these materials individually, as well as their use in sandwich structures. It provides an overview of cellular solids, and their properties. Traditional polymer foam structures and their use in sandwich structures are discussed. The development of metal foams is explained and a review of the literature shows the growing interest in them. The results of various mechanical characterisation studies of aluminium foams are explored. These foams are increasingly used in structural composites and their applicability to sandwich structures is discussed. The implementation of metal foam sandwich structures requires a thorough understanding of their deformation behaviour. A range of methods to characterise these structures are presented. Finally, the development of finite element methods appropriate for the complex metal foam material is discussed. This chapter provides an introduction to the general aim of this study: the development of the understanding of composite metal foam sandwich structures so as to fully enable their successful utilisation.

2.1 CELLULAR SOLIDS

A small enclosed or definable space can be described as a “cell”. Groups or collections of these packed together are called cellular solids. Each cell can be an entirely closed volume or can be partially or fully open. The cells can be made up of struts or faces and are coupled together such that the group forms a complete structure [10]. The unit cells can be repeated pattern or a random assortment of shapes and sizes. Two dimensional
patterning forms structures known as honeycomb – named for the hexagonal linear cells of a bee hive. There are numerous examples of naturally occurring cellular solids such as wood, cork and bone. Many cellular structures are able to retain many of the bulk material’s desirable properties at a low weight. This important property can be defined as the relative density $\rho^*/\rho_S$: the ratio of the density of the cellular material as a whole and the density of the material of the cell walls. Many of the cellular material properties have been found to be directly proportional to their relative density.

A number of synthetic cellular materials have been produced and are now growing in their variety and application. The 2D honeycomb is an easily manufactured structure that is used in a range of structural applications with a range of materials including cardboard, aramid, polymer and metal. These honeycomb materials are used in a range of applications such as vehicle crash barriers, aircraft wings, and floor panels; however have limited use where multidirectional loading is involved. The increased isotropy of 3D repeated cell structures compared to honeycombs makes them suitable for a wider range of applications. Cellular materials with a closed cell structure and a relative density less than about 0.3 are defined as foams. Porous structures with greater relative densities are commonly manmade but do not have the extreme low weight properties of foam and outside the scope of this work.

Common man-made cellular materials are the range of polymeric foams; including polystyrene foam packaging, soft polyurethane foam cushioning, and rigid structural polyvinyl chloride foam. Foamed materials are no longer limited to polymers as manufacturing techniques improve. Glasses, ceramics and even composites can be formed into cells [10]. Some metals are suitable for foaming and a variety of production methods have been developed for a number of alloys, in both open and closed cell configurations. Metal foams in general have a combination of properties that make them desirable for an array of engineering situations [11]. Properties include high strength and stiffness to weight ratios, energy absorption, sound damping, thermal stability, electromagnetic wave absorption and non-combustibility. The combination of properties makes the foams appropriate for multi-functional applications. They have a functional versatility that is a consequence of the ability to design the material to suit the application. This is achievable by selecting appropriate bulk material properties, controlling density and manipulating cell geometry [12]. One significant functional opportunity for metal foams is as the core material of a structural composite such as a sandwich structure.
2.2 **SANDWICH STRUCTURES**

Sandwich structures are a form of structural composite. This is a structure composed of a number of materials, each geometrically positioned to enhance the overall mechanical properties of the structure. Laminar composites are a common form of structural composite, such as plywood and multi-laminar glass fibre reinforced plastics. These use layers of high uniaxial strength sheets, each oriented to provide increased isotropic strength properties for the overall structure [13]. Sandwich structures generate greatly increased flexural rigidity compared to the constituent materials. They make use of two stiff, strong skin layers separated by a lightweight core. The skins are separated to increase the overall moment of inertia of the panel without greatly increasing the total weight. This results in a light weight stiff structure that will resist bending and buckling loads [10]. The skins will bear most of any in-plane loads or transverse bending stresses, while the core will provide some shear rigidity along planes that are perpendicular to the skins. A range of materials have been effectively implemented in sandwich structures, including metal, plywood and fibre reinforced plastic for skins and honeycombs, polymer foams, cements and balsa wood as core materials.

Sandwich structures occur naturally in a range of biological systems such as bone, plant stems and bird beaks. These natural sandwich structures have evolved to meet needs of strength, rigidity and low mass. These traits are also desirable in many artificial structures. Manmade sandwich structures are becoming more common in a range of applications. Historically aircraft design has made extensive use of sandwich structures starting with its first use in powered aircraft by E. Bishop, chief designer of De Havilland [14]. Other typical applications include aerospace, marine, land transport, and building industries. The range of materials being investigated and utilised as sandwich structure components is continually advancing, varying from simple balsa wood or paper-phenolic honeycomb cores to polymer foam and plastic skins. The improving technology in producing foam materials to meet design specifications has opened up the possibilities for new sandwich materials – specially designed for particular applications.

2.2.1 **THEORY**

Each element in a sandwich structure performs different functions in the mechanical response of the structure. The skins take the tensile and compressive stresses, especially under flexural loading. Under certain conditions the skins may come under point loading, and when this is expected, skin dimensions may need to be increased to sustain the shear
forces associated with localised pressure [15]. The core material is used to increase the flexural rigidity of the structure by separating the upper and lower skins to increase the moment of inertia about the neutral axis of the structure. The core must therefore be stiff enough to maintain the skins at a constant separation. It must also possess enough shear rigidity to prevent the skins from sliding over each other and acting as individual plates in bending. For effective sandwich structure behaviour, the bonding layer between the core and skins must be able to transfer the shear forces between the core and the skins. With each constituent performing its role, the sandwich arrangement as a whole can be very effective as a lightweight and rigid structure, especially under bending or buckling loads [15].

Sandwich structure mechanical properties can be predicted using the known material properties of the constituent materials and details of construction geometry. In particular, flexural properties can be calculated using beam bending theory adapted to sandwich structures [15].

Figure 2.1 shows the geometry of a sandwich beam. The flexural rigidity $D$ is calculated using the sum of the flexural rigidities of the constituent parts, about the centroidal axis of the sandwich beam, as shown in Equation 2.1.

$$D = E_f \frac{bf^3}{6} + E_f \frac{bdl^2}{2} + E_c \frac{bec^3}{12}$$  
(Eq 2.1)

where $E_f$ is the modulus of the skins in Newton per metres squared (N/m²), $E_c$ the modulus of the core, $b$ is the width of the sandwich beam, $f$ is the skin thickness, $d$ is the distance between the skin centroids and $c$ is the core thickness. The maximum core shear stress is given by Equation 2.2.

$$\tau_{max} = \frac{P_{max}}{D} \left( \frac{E_f f d}{2} + \frac{E_c c^2}{2} \right)$$  
(Eq 2.2)

where $P_{max}$ is the maximum load on the sample in Newtons (N), and $D$ is the flexural rigidity in Newtons metres squared (Nm²). The maximum stress in the facings and core are calculated using Equation 2.3 and 2.4 respectively where $M$ is the maximum bending moment and $h$ the total sandwich thickness.

$$\sigma_f = \frac{Mz}{D} E_f \quad \text{where} \quad z = \frac{c}{2} + \frac{1}{2} \left( \frac{h}{2} - \frac{c}{2} \right)$$  
(Eq 2.3)

$$\sigma_c = \frac{Mz}{D} E_c \quad \text{where} \quad z = \frac{c}{2}$$  
(Eq 2.4)
The maximum moment in four–point bending is

\[ M = P_{\text{max}} (l - s) \]  

(Eq 2.5)

where \( l \) is the support span, and \( s \) is the loading span.

2.2.2 FAILURE MODES

Sandwich beams loaded in bending display a range of failure mechanisms dependent on parameters such as material yield strengths and geometry. Idealised cases, assuming rigid, ideally plastic solids, can provide analytical solutions to determine limit loads for each failure mode. The typical failure modes are as follows [10, 12]:

**Indentation at loading point** – this failure mechanism is a consequence of localised point loading effects and should be avoidable if loading point area is larger than core thickness.

**Skin yield** – the skins may yield or fracture.

**Skin wrinkle** – the compression skin may buckle into the core.

**Core failure** – the core will usually fail in shear, though tensile or compressive failure is possible.

**Bond failure** – the bonding method is usually chosen to avoid failure, commonly resin adhesive are used so failure is by brittle fracture.

Each mode can be predicted using consideration of normal and shear stresses acting in the skins and core, with the mode associated with the lowest collapse load being most likely to occur. Collapse mechanism maps can be generated for individual sandwich structure circumstances showing likely failure modes for a range of sandwich design options. Geometry or material parameters can be used as map axes [10, 12].
2.3 POLYMER FOAM CORE SANDWICH STRUCTURES

Currently, one of the more common sandwich structures used in a number of industries is the combination of polymer foam cores with fibre reinforced composite skins. These structures have been successfully used for some decades in areas such as marine, building industries or sports equipment. Figure 2.2 shows some example applications. Many of these materials have limitations in their utilisation at raised temperatures or in some cases, have moisture dependent properties restricting their use [12].

![Figure 2.2: Example polymer foam/composite sandwich structure applications: LM 61.5 P Wind turbine[16], Mundal Båt AS Fishing Vessel [17]](image)

2.3.1 FOAM AND SKIN MATERIALS

Generally, polymer foams are manufactured from three types of polymer: thermoplastics, thermosets and elastomers [10]. Some of the more commonly used foams include polyethylene, polystyrene, polyvinylchloride and polyurethane. The mechanical properties of the foams are dependent, among other things, on their structure, such as any cross-linking, or crystallinity, and their density. As such there is a wide range of foams available with assorted Young’s modulus, yield strength, and fracture toughness. The more rigid foams are most suitable for use as sandwich structure cores. These foams can be combined with a range of composite skin materials. Both thermoset and thermoplastic resins can be used as matrix materials, however high processing temperatures can degrade many of the polymer foam cores. The choice of fibre materials is only limited by the suitability of the matrix. These structures can display high strength and stiffness to weight ratios and manufacturing methods have progressed to produce consistent high quality and reasonable cost sandwich panels.
While polymer foam sandwich structures are widely used in a variety of applications, there can be a range of associated weaknesses. Polymer foams can display brittle and catastrophic failure which can be highly undesirable in certain in-service situations. Similarly, barely visible impact damage can significantly reduce residual flexural strength and may be hazardous if not detected. These sandwich structures can be susceptible to localised loading and indentation which can also considerably reduce the structure’s effectiveness. These types of loading are typical in the areas of application where sandwich structures are utilised, and further understanding of, and improvements to the structures are continually pursued.

### 2.3.2 Current Research

Polymer foam/composite sandwich structures have been widely researched, with studies looking at a range of aspects including material selections, delamination, flexural testing, indentation and impact loading. Some typical studies are summarised here. Steeves and Fleck completed an extensive investigation into the analytical models of the collapse mechanisms of sandwich beams combined with experimental data from glass epoxy and pvc foam sandwich structures. They developed failure mechanism maps and found support for models of collapse, similar to those described above (see section 2.2.2), though with more emphasis on indentation. They also explored finite element calculations to predict structural response [18, 19]. The sensitivity of polymer foam to failure by the application of localized surface loads was examined by Rizov [20, 21] using a numerical approach to model static indentation behaviour. Indentation tests were examined by Shuaeib and Soden [22], finding an increase in skin thickness or core density was most effective at increasing the failure load while increasing the indentor diameter had no significant effect. Impact studies have included low impact response investigations looking at energy-balance models to model the elastic response [23], work on low velocity perforation and energy absorption [24], and studies on higher velocity impacts involving finite element analysis to create impact failure mode maps [25]. Much of the general understanding and methods for investigation of polymer foam/composite sandwich structures are applicable to metal foam sandwich structures.
2.4 **Metal Foam Core Sandwich Structures**

Metal foams have a number of advantages over polymer foams including higher operating temperatures, consistent properties over time and an absence of noxious fumes during decomposition. They are generally isotropic, can be recycled and can be cost effective [26]. Some metal foams can be up to an order of magnitude stiffer and stronger than polymer foams [27]. Other desirable characteristics include increased energy absorption, sound damping, electromagnetic wave absorption and non-combustibility. While metal foams are not currently widely utilized, commercial interest is growing quickly as manufacturing methods improve the quality and consistency of the foam. This, in combination with an increased understanding of their mechanical behaviour, could lead to more extensive use.

2.4.1 **Aluminium Foam**

Methods to foam various metals are constantly under development. Currently, aluminium and nickel are the most common metals foamed and are available commercially [12]. It is possible to foam a range of metals and alloys including magnesium, lead, zinc, copper, bronze, titanium and steel [12], though currently Al foam is attracting the most research attention. Aluminium is of particular interest for foam because of its inherent strength and stiffness to weight properties.

2.4.1.1 **Open Cell**

Open cell metal foams are those that consist of cells connectable to each other through open faces. The solid material is contained in cell edges consisting of struts and rods rather than in solid faces. This form of foam is open to fluids passing through it so it is useful as a filtering medium [28]. The connectivity of the voids along with the structure’s high thermal conductivity and high internal surface area are functional as part of a heat transfer system [11, 12]. There has also been research into using open cell metal foams as cores in sandwich structures [29]. Figure 2.3 shows a typical open cell structure. Open cell metal structures are often made with an investment casting process. An open cell polymer foam is coated with a heat-resistant material. The polymer is then removed by heating, leaving a mould into which molten metal is poured. The mould is then removed with a pressurised water jet [11].
2.4.1.2 CLOSED CELL

Closed cell metal foams contain non-interconnected cells with solid material faces. These foams have been investigated for potential uses where the structural properties are desired in combination with one or more of the foam’s other properties. For example, Al foams have uses as structural wall panels with additional functions as thermal barriers or for sound proofing. The variation in cell size, wall thickness, constituent wall materials, and defects will all affect the mechanical properties of the bulk structure. Controlling these characteristics is an important consideration in the manufacturing process.

There are a range of different processes used to manufacture closed cell structures, and a number of them have reached commercial production levels, though there is still much room for improvement. Each method works on a restricted set of metals and produces foam with a limited range of cell density, size and consistency. Typical cell structures for a range of commercial metal foams are shown in Figure 2.4. The two main manufacturing methods are melt processing, and powder processing techniques. The melt processing technique involves manipulating gas bubbles throughout the molten metal and controlling the cooling such that the gas remains trapped, thus forming the porous structure. Powder processing uses a solid particulate foaming agent mixed with the powdered metal which decomposes on heating to form the metal foam. This method is suitable for producing a range of shapes as the precursor mix can be pre-shaped or heated within a mould.
2.4.1.3 ALPORAS MANUFACTURE

One of several commercially available aluminium foams is “Alporas®”, known for its consistent structure. This is the aluminium foam that was in used in this research project, purchased from Gleich GmbH of Germany [33]. The manufacturing technique was developed by Shinko Wire of Amagasaki, Japan and was patented in 1987 [34]. The mass production of foamed aluminium has been considered difficult because of problems including low foamability of the molten metal, the varying size of the cells, and solidification shrinkage [2]. The Alporas process has been refined sufficiently to enable the manufacture of large consistent quality blocks using a batch casting method, with the cell size and density controllable to desired levels. A typical cell structure of Alporas aluminium foam is shown in Figure 2.5.

The Alporas manufacturing method involves stabilising bubbles in molten aluminium as shown in Figure 2.6. The viscosity of the melt is increased by adding 1.5 wt.-% Ca to prevent bubbles from floating. Once the appropriate viscosity has been reached, measured by monitoring the stirring resistance, the thickened alloy is poured into a mould. A blowing agent, 1.6 wt.-% TiH₂, is stirred in. This blowing agent reacts and produces gaseous hydrogen and foams the molten metal. The mix is allowed to expand and fill up the mould before being cooled with a powerful blower under controlled pressure. The large cast block
(450 × 2050 × 650 mm, 160kg) can then be cut into flat plates according to use [2, 34]. Alporas was chosen for this project because its cell consistency makes its behaviour more predictable [35] and hence more appropriate for structural applications.

![Figure 2.5: Typical Alporas cell structure](image1)

![Figure 2.6: Alporas production method using foaming agent [12]](image2)
2.4.2 MECHANICAL CHARACTERISATION OF BULK FOAM

The various manufacturing methods used to fabricate metal foams have produced a range of displayed mechanical properties. Many manufacturing process parameters will influence the mechanical behaviour such as additives, cooling rates, pressures and the collection method. These parameters affect characteristics including metal microstructure, cell size, wall thickness, uniformity and cell distribution which can greatly influence the bulk behaviour of the foam [12]. The general behaviour of metal foams is consistent, but each foam type may have individual characteristics and it is therefore important to investigate each thoroughly. This section will describe the current understanding of the general mechanical characteristics of aluminium foam particularly relevant to sandwich structure applications, with reference to studies conducted on specific types of foam.

2.4.2.1 COMPRESSION

The compression deformation behaviour of aluminium foam is one of the characteristics that make the material desirable in energy absorption applications. In particular, the ability of the foam to undergo large amounts of plastic deformation at nearly constant stress is advantageous. A typical compression stress-strain curve is shown in Figure 2.7. The initial behaviour for small strains is a constant increase in stress in an apparent elastic manner. However, a detailed investigation has shown that some irreversible plastic deformation of the cell structure generally occurs even at low strains [36]. Following this initial slope the plastic deformation increases up to a first peak in the stress strain curve. The foam then enters a region of continuous steady plastic deformation, shown by a very small slope. This region defines the plateau stress characteristic of the foam which is commonly used as a classifying property. After this plateau region, the cellular structure of the foam has almost completely crushed, with individual cells collapsing completely and cell walls starting to come into contact with each other. This is densification of the foam and is seen in the stress strain curve as a steep increase in slope. The details of the compression stress strain curve vary with each type of metal foam or density, with differing peak stress, plateau stress and densification strain values.
Bastawros et al. [38] have used a digital image correlation procedure to study the deformation mechanisms occurring during the initial plastic deformation in compression of aluminium foam. Three stages were identified involving cell wall distortion and the formation of deformation bands. Cell crushing and failure was observed to occur in progressive bands across the sample. Oscillations in the stress-strain curve after the peak load correspond to the formation of successive deformation bands.

The compressive behaviour of five different aluminium foams was investigated by Andrews et al. [39], comparing experimental observations with values calculated from theoretical models for cellular solids [10]. The measured properties of the closed cell foams were found to be below the theoretical predictions. The presence of defects such as cell wall curvature and corrugations, as well as density variations, are likely causes for the reduction below idealised values. The minimisation of such defects by process improvements could lead to much enhanced foam compressive properties. Ramamurty and Paul [35] looked at the variability of Alporas properties such as elastic modulus, plastic strength and energy absorption as a function of density, using uniaxial compression testing. A connection between the mechanical response and the cell size distribution was also examined. While the variability of the structure of Alporas is minimal compared to many other aluminium foams, it was observed that the variability in the measured properties is much greater than the parent metal Al. It was recommended that to obtain half the accuracy in test results that is achieved with three sample repetitions in ductile metal, at least seven repeat tests must be conducted on the foam material.
An understanding of indentation due to point loading behaviour is appropriate for many possible in-service loading situations. The indentation load and response have been studied for Alporas by Olurin et al. [40], using a range of indentator geometry. Ramamurty et al. [41] studied the use of indentation testing with deep canonical indentors as an alternative to uniaxial compression testing, to provide deformation and energy absorption information. It was found that properties such as shear strength could be elucidated from the testing, and that the presence of multiple deformation processes such as crushing, shearing and tearing in indentation behaviour suggest indentation could be a more appropriate test method for energy absorption measurements than simple uniaxial compression.

2.4.2.2 TENSION

The tensile stress-strain response of aluminium foams is different to the compression behaviour. The initial slope is less than the Young’s modulus, and is followed by a strain hardening up to a peak yield stress [12, 42]. This yield stress is generally the same order of magnitude as the compressive peak stress. The foam then fails by tearing and fracture. Motz et al. [43] tested two densities of Alporas foam in tension and found deformation mechanisms were quite different to those observed in compression. There were no plateau or plastic instabilities observed and no deformation bands visible. Four stages were identified in the tensile response: an initial linear-elastic behaviour, plastic deformation without crack initiation, formation of a fracture process zone, and finally, fracture as a main crack propagated. Further work included investigating standard fracture mechanics tests and the use of SEM images to identify fracture processes at both cell wall and multiple cell levels [44].

2.4.2.3 SIZE EFFECT

The inhomogeneous nature of cellular materials suggests the mechanical response may vary with the ratio of sample size to cell size. Bulk material properties will be observed in samples with a high ratio, however as the sample size is reduced localised cell mechanisms may begin to affect the material behaviour. The use of aluminium foam in sandwich structures will typically involve thicknesses that may experience a size effect. An understanding of this size effect is necessary to enable appropriate design decisions. Onck et al. [45] developed analytical models to investigate size effects in honeycombs under uniaxial and shear loading. These investigations were applied to foams by Andrews et al. [46] and compared with experimental results. They looked at the effect of specimen size relative to cell size in Alporas and found the models developed for honeycombs gave good predictions.
for the foam behaviour. The Young’s modulus and plastic strength were found to increase to a plateau level as the ratio ($\kappa$) of specimen size to cell size increased. The plateau level for the modulus was observed at a ratio ($\kappa$) of 6, while the compressive strength reached a plateau at a ratio ($\kappa$) of 8.

In contrast, the shear strength was found to decrease to a plateau level as the ratio of specimen to cell size increased to a thickness of more than twice the cell size. It was considered that the free surfaces of the sample influence each measured response. Chen et al. [47] conducted double lap shear testing on Alporas foam and also found the shear response was sensitive to the thickness of the specimen, with a stronger response displayed by samples of diminishing thickness. Within experimental scatter, the shear modulus was found to be independent of sample thickness. Rakow and Waas [48, 49] investigated the shear response of aluminium foam, in particular, looking for a relationship to specimen size, relative to the mean cell size. Using a digital image correlation technique to calculate shear strain, they found a minimum area of mean cell diameters below which the shear strain response became inconsistent, and was not represented by the bulk behaviour. As the dimensions decreased further, the shear response increased. Jeon [50] looked at effect of structural defects on compression as well as their relation to size effects. A significant reduction in modulus and strength was found with a reduction in size for samples with structural defects; a much smaller size effect was noted in samples with minimal structural defects.

These studies show the influence of a size effect is potentially very significant in predicting the behaviour of aluminium foam in real-life applications. The size effect generally results in increased compressive strength and modulus, but decreased shear strength, as the ratio of specimen to cell size increases. Thoroughly quantifying it is important in developing accurate analytical models.

### 2.4.3 Bonded Metal Skins

Metal foams have properties that are suitable for use in sandwich structures. In addition, many metal foams have additional desirable characteristics for specific applications such as energy absorption or sound damping. Most research into the use of metal foam as sandwich cores has involved ductile metal skins. The general behaviour of these structures was expected to be similar to traditional polymer foam based sandwich beams and initial studies have followed similar analytical methods.
Chen et al. [47] investigated collapse modes of metal sandwich structures under 4-point bend loading, observing three main mechanisms of face yield, indentation and core shear. Collapse mechanism maps were produced showing predictions of failure mechanism based on geometrical parameters. McCormack et al. [51] compared analytical predictions with experimental observations for aluminium skin sandwich beams under 3-point bend loading. For indentation failure and core shear failure, the peak failure load was calculated using limit load analysis and was found to match measured values reasonably well. Harte et al. developed and tested fatigue failure maps for Alporas foam with aluminium skins loaded in 4-point bending, observing the common modes of face sheet yield, core shearing and indentation. They found the core shear regime was particularly dominant in fatigue loading [52, 53]. A similar study was conducted by Bart-Smith et al. using 3-point bending to develop failure maps. Numerical simulations were also conducted and compared with experimental results, showing similar failure mechanisms [54]. Tagarielli et al. looked at the effect of clamped boundary conditions on the flexural behaviour, finding face sheet stretching was an important factor [55].

Investigations into the indentation failure modes of aluminium foam sandwich panels were conducted by Hou et al. [56]. Samples were tested under simply supported and fully fixed conditions; four failure modes were observed. Understanding behaviour under these loading conditions is important for anticipated applications. The perforation resistance of aluminium skinned sandwich structures was investigated by Zhao et al. [57], using a novel inverse technique allowing the measurement of piercing forces throughout the whole perforation process. They found an enhancement of the top skin peak loads at increased impact velocities. Hanssen et al. [58] studied the effect of bird strike impacts on aluminium foam sandwiches with aluminium skins. Full experiments were conducted with impact velocities of 140 and 190m/s and were compared with a numerical model generated with LS-DYNA. No penetration of the structure was observed.

2.4.4 INTEGRAL METAL SKINS

The method used to attach skins to metal foam cores can influence mechanical behaviour. The bond must be strong for the combination of materials to act as a sandwich structure. An alternative approach is to produce the sandwich structure in a single step as the metal is foamed. This approach provides a strong integral bond and allows the manufacture of non-flat panels. These integrally skinned materials are referred to as Aluminium Foam
Sandwich (AFS) and can be produced by laminating a precursor of Al and TiH₂ with Al sheet followed by foaming in a furnace. The pre-foamed laminated structure can be reshaped with many conventional manufacturing methods increasing the range of possible applications [59]. Salvo et al. looked at the microstructure of AFS structures using x-ray tomography and SEM analysis, investigating the cell wall failure behaviour under compression [60]. Crupi and Montanini [61] compared the flexural and impact structural response of sandwiches with bonded and integral aluminium skins. Different collapse modes were observed between the two sandwich types, as well as significant increased absorbed energy in the integral skin samples.

Open-cell foam sandwich beams are less widely investigated, however Pollien et al. have shown a method of producing open cell foams with integral metal skins. In particular, they looked at functionally graded cores, with a number of layers of different density foams joined together. The method involved infiltrating a layered core of NaCl powder sandwiched by dense Al skins with pure molten aluminium. Flexural testing found these structures may be of interest in load-limited design [29].

2.4.5 ALTERNATIVE SKIN MATERIALS

Non-traditional combinations of materials have been suggested as possibilities in achieving better design performance for a greater range of conditions [62]. One hybrid sandwich construction was investigated by Mohan et al. [63]: the combination of ceramic alumina face sheets with aluminium foam cores. The alumina skins display good stiffness, wear resistance and fire retardation when compared with aluminium skins. The beams were tested in flexure with three failure modes found. The indentation response of sandwich structures with various skin materials was investigated by Mohan et al. [64]. Skin materials were chosen to represent elastic-brittle and elastic-plastic behaviour, including aluminium, stainless steel, alumina and CFRP matrix composite sheets. Varying failure mechanisms and energy absorption levels were observed.

2.4.6 METAL FOAM WITH COMPOSITE SKINS

An alternative skin material choice for aluminium foam is fibre reinforced composite materials. Composite skins potentially have advantages over metal skin materials with alternative energy absorption and failure behaviours. In particular, fibre reinforced polypropylene composite systems have shown excellent toughness properties which are desirable in many sandwich structure applications [9]. This combination of materials
permits a straightforward manufacturing process in which the layers of thermoplastic composite and aluminium foam can be heated to the processing temperature of the composite and stamped in a cold press, consolidating the composite and bonding the skins to the core. This manufacturing cycle is potentially quicker and more cost effective than an adhesive bonding process. The high energy absorbing properties of the material combination has resulted in much research work concentrating on the impact behaviour of these structures. Further characterisation of the flexural behaviour is necessary. Potentially the flexural deformation process may be quite different to metal skinned aluminium foam sandwich structures as the composite skins will display more elastic-brittle characteristics compared to the more ductile metal skins [47].

Cantwell and Reyes Villanueva [8, 9] investigated the interfacial fracture properties of structures with Alporas cores and glass fibre polypropylene prepreg skins; observing a strong bond. They also conducted low velocity impact tests observing buckling and interlamination within the skin as well as fracture of the cells below the point of impact. This study was followed by an investigation into the high velocity impact of such structures as well as sandwiches with fibre-metal laminate (FML) skins [65]. High levels of dynamic energy absorption were observed resulting from a combination of failure mechanisms such as fibre-matrix delamination, longitudinal splitting and fibre fracture in the composite skins and the typical progressive collapse and densification of the foam core. Use of FML skins further improved specific perforation energies for similar composite volume fractions. Kiratisaevee and Cantwell [66, 67] found that the processing temperatures used on the thermoplastic composite to manufacture the sandwich structure did not degrade the fracture properties of the aluminium foam. In investigating the impact response, they found a simple energy-balance model which accounted for energy dissipation in bending/shear, and indentation effects gave good agreement with their experimental observations. McKown and Mines [68] looked at Alporas foam with skins of cross-ply laid continuous glass fibre reinforced polypropylene under static and dynamic 3-point bending. The deformation progression was similar in both cases with upper skin failure followed by progressive crushing and shear failure in the core. With increasing strain rate, the fraction of energy absorbed by the upper skin decreased, with an increasing contribution from the core crushing behaviour. Vaidya et al. [26] manufactured composite sandwich structures using a vacuum assisted resin transfer molding technique with a range of fibre materials including E-glass, carbon, aramid and S2-glass fabric. They investigated the impact response at low and intermediate velocities,
finding core utilization for energy absorption was maximised in the structures with S2-glass fabric.

These energy absorption characteristics have raised interest in the potential for composite skinned aluminium sandwich structures in blast loading situations [37]. Sriram et al. [69, 70] investigated the modelling of these structures subjected to blast loads using LS-DYNA, looking at the behaviour of the individual materials as well as their interaction within the sandwich structure.

There is great potential for composite skinned metal foam core sandwich structures to be of use in a range of industries, with many favourable characteristics such as ease of manufacture, light weight stiffness, thermal protection and a number of other traits contributing to multi-functionality. Further research is required to develop a deeper understanding of the mechanisms involved to produce these characteristics. An ability to control and enhance these mechanisms will lead to more appropriate materials designed for specific applications. In particular, an understanding of the flexural behaviour of these sandwich structures will help advance their implementation.

2.5 MODELLING

The increasing use of numerical finite element codes as part of the design process compels the development of appropriate mathematical material models for any new material system. The methods used to model the material must be suitable for the type of end application. Currently, metal foams are mainly used as filler materials within energy absorbers so constitutive models must be able to produce a stable and efficient solution for large strains [71]. There is significant potential for these structures in a range of structural applications, but further investigations to more fully understand and model their flexural behaviour are necessary.

There are some important considerations in modelling the cellular structure of aluminium foam. The structure is generally inhomogeneous, can be anisotropic and can have a large variation in density. The detailed topology and structure of the foam can be modelled specifically with repeated unit cells. An alternative that is perhaps less computationally intensive for more complex application loading situations is to model the foam as a continuum. The continuum model must allow the foam to change volume
extensively under load as cell walls can buckle or collapse into void spaces. The number of input parameters and their attainability are further important considerations for the model.

2.5.1 CONSTITUTIVE MODELS

A number of isotropic constitutive models have been developed for metal foams, based on experimental observations of a range of loading states such as uniaxial and hydrostatic compression. These models have been investigated on a variety of commercially available foams as each manufacturing method can greatly influence the mechanical behaviour of the structure.

Various studies have focused on cell structure aspects to model bulk foam behaviour. Gibson and Ashby [10] used a skeletal cubic unit-cell to model open-cell foams, relating the material properties of the unit cell to its relative density. This concept was developed to represent closed cell foams [72, 73]. Santosa and Wierzbicki [74] developed a new model of a truncated cube unit cell with a system of collapsing cruciform and pyramidal sections to obtain the crushing mechanism of the foam. Meguid et al. [75] used a modified representative unit cell model which included random density variations to study the crush behaviour, reproducing experimentally observed localised collapse behaviour. A multi-unit cell using interconnected ellipsoids model was developed by Czekanski et al. [76] suitable for oblique loading situations. Kim et al. [77] have developed a multiple lattice model that includes variation in geometrical parameters such as wall thickness to realise the inhomogeneity of the foam.

A review of constitutive continuum models applicable to aluminium foams was conducted by Hanssen et al. [71]. Most models have been validated experimentally using uniaxial compression loadings. A continuum model with a simple visco-elastic with softening material model was developed by Hučko et al. [78]. Miller [79] has proposed a constitutive model that describes the plastic flow behaviour, based on the Drucker-Prager model for soil [80]. Deshpande and Fleck [81] measured the initial yield surface of two metal foams and developed two constitutive models; one a simple geometrically self-similar yield surface, and a second more complex model including differential hardening.

Sridhar and Fleck [82] investigated the yield surface of Alulight foam using triaxial pressure loading and found it was closely matched the elliptical mean stress versus effective stress surface predicted by the Deshpande-Fleck model. Gioux et al. [83] studied the failure
of an open and a closed aluminium foam under multiaxial loading and found that both the Miller and Deshpande-Fleck constitutive models gave reasonable descriptions of the failure with consideration of local imperfections and variations in relative density. Uniaxial compression and tensile tests, along with triaxial compression tests of Cymat foam were used by Ruan et al. [84] to construct experimental yield surfaces. It was found the Gibson criterion [72] overestimated the yield stresses, while the experimental data was consistent with predictions from both the Miller and Deshpande-Fleck models when appropriate plastic Poisson’s ratios were utilised.

A number of these continuum models have been implemented as material model algorithms in finite element codes. Xue and Hutchinson [85] implemented a continuum constitutive model in the explicit finite element code ABAQUS, particularly focused on metal skinned sandwiches; an expansion and variation of the Deshpande-Fleck constitutive model. Chen et al. [47] used similar methods with good agreement between measure collapse strength and finite element calculations. In similar studies with clamped sandwich beams, Tagarielli et al. [55] found the model gave good predictions for the initial collapse load of the structures. Mohan et al. [63] conducted FE modelling of sandwich beams with alumina face sheets using the Deshpande-Fleck model for the aluminium foam cores and found good agreement with experimentally measured behaviour, further validating this constitutive model. Shahbeyk et al. [86] have also implemented the Deshpande and Fleck model using ABAQUS, and investigated metal foam-filled columns for crashworthiness. Bart-Smith et al. [54] used an ABAQUS implementation of the Deshpande-Fleck criterion to model thin Alporas foam sandwiches with metal skins and found the load response was underestimated until the material input shear parameters were found using test samples with the same thickness as the model geometry. The inability of the model to capture this size effect is a limitation of the constitutive model, however the literature widely supports its use. Many studies have focused on compression-type loading and further investigations on the applicability of these types of models in more complex loading situations are needed.

### 2.6 Summary

This thesis aims to develop the understanding of the flexural behaviour of a composite skin metal foam sandwich structure. Much previous work has concentrated on the behaviour of the bulk metal foam. Studies on sandwich structures have mainly focussed on the use of ductile metal skins, and have investigated their promising energy absorption and impact behaviours, with some studies looking at flexural behaviour. Work with composite skinned
metal foam sandwich structures has also focussed on energy absorption. The flexural behaviour requires further consideration, as the combination of materials appears to display contrasting behaviour to other sandwich structures. Additional investigations are necessary to characterise more fully the deformation mechanisms involved. In particular, this project studies the strain contours produced by a full-field optical strain measurement technique. These measurements are also used to explore the performance of an existing finite element material model for aluminium foam when used within a sandwich structure undergoing flexural loading. These studies aim to provide a greater understanding of the deformation and strain behaviour of these complex structures, facilitating an improvement in modelling methods and therefore helping to advance the implementation of these novel structures.
This research project used both experimental testing and finite element modelling to investigate the mechanical behaviour of aluminium foam sandwich structures. This chapter provides details on the experimental methods used in the study including the sandwich manufacturing method, the four-point bending physical testing method and the full field strain capture system. Details of experimental studies on comparison materials or concerning alternative physical tests are provided in later chapters.

3.1 MATERIALS

This study investigated a single type of commercially available aluminium foam. The foam was a closed cell structure, *Alporas* (Gleich GmbH [33]), of density 0.23 g/cm³. Three core thicknesses of 5, 10 and 20mm were used during the study. Figure 3.1 shows the three foam thicknesses, as supplied by the manufacturer, giving a qualitative comparison of some minor differences in cell size and structure between the thicknesses. A quantitative study of the average cell size was not undertaken though it is clear from Figure 3.1 there is a small increase in cell diameter as the foam thickness increases. This effect was not examined in this project; however, a consequence of this variance in cell structure has been noted in observations of the size effect [46]. Regions of panels with obvious defects and large voids were not used for sandwich manufacture; however the majority of each panel was of consistent structure and without defects.

The commingled glass-fibre/polypropylene prepreg Twintex® (Saint-Gobain Vetrotex [87]) was used for the skin material. This is a balanced weave fabric with areal mass of 745g/m². The glass content by weight is 65%, giving a fibre areal mass of approximately 484g/m². Figure 3.2 shows the prepreg before and after consolidation.
Figure 3.1: Typical through thickness cell structures for Alporas foam panels with thicknesses of (a) 5 (b) 10 and (c) 20mm

Figure 3.2: Sandwich component materials, before and after consolidation

3.2 MANUFACTURE

Materials were cut down to a size of 200 × 200 mm, with the aluminium foam cut using a bandsaw. The sandwich structures were made by placing a single ply of the glass-fibre/polypropylene prepreg on either side of the aluminium foam core in a picture frame mould. Two layers of a 50μm thick hot-melt polypropylene-based adhesive (Glucu Ltd., UK) were placed at each bi-material interface. This method has been found to provide good bonding between the foam and the thermoplastic skin [9]. The laminate structure is shown
in Figure 3.3. The mould was heated to 185°C in a heated platen press, using a thermocouple within the Twintex layer to monitor the thermoplastic temperature. The structure was then held at a pressure of 2.5 MPa while it was rapidly water cooled to consolidate the skin material. Variations in the process included altering the core thickness or using an increased number of plys of skin prepreg material. The consolidated sandwich panels with core thicknesses of 5, 10 and 20mm, and a single ply skin had average thicknesses of 5.16, 10.19 and 20.47mm respectively. The apparent increase in skin thickness for the single ply skin as the core thickness increases may be related to the increase in cell diameter. During the sandwich manufacturing process the thermoplastic matrix material may experience some flow while in the liquid state before consolidation. This may result in some matrix material moving into the cells of the aluminium foam, particularly in the core with the larger cell size, reducing the overall thickness of the skin. Samples for testing were cut to width from the panels using a diamond tipped saw.

![Figure 3.3: Sandwich Structure lay up](image)

### 3.3 Flexural Testing

Four-point bend testing was the main method used to investigate the flexural behaviour of the sandwich structure. The bend testing method followed ASTM Standard C393-63, Standard Test Method for Flexural Properties of Flat Sandwich Constructions [88]. The appropriate support span dimension $a_1$ was determined from Eq 3.1;

$$a_1 = \frac{2F}{S}$$  \hspace{1cm} (Eq 3.1)

which depends on the facing thickness $f$ (mm), the allowable facing stress $F$ (MPa) and the allowable core shear stress $S$ (MPa). The term “facing” is used in the ASTM Standards as an alternative term for “skin”. The allowable facing stress for the Twintex was determined using three-point bending testing following ASTM D790M [89]. A value of 200MPa was measured. The allowable core shear stress was taken from the manufacturer’s data sheets [33] with a value of 1.2MPa used in calculations.
The four-point testing was conducted with a cross-head speed of 10mm/min using an Instron Universal testing machine (model 4505). The sample and testing dimensions were kept constant, with the exception of the sample width. The sample width was 25mm for the 5 and 10mm thick sandwich structures, and 45mm for the 20mm structures, as per the test standard. The support span was 150mm, and the load span 50mm. Load and support rollers had a diameter of 14mm. The test geometry is shown in Figure 3.4. A load-displacement plot was recorded for each test.

![Figure 3.4: Four-point flexural testing geometry](image)

3.4 FULL-FIELD STRAIN MEASUREMENT

The use of strain measurement during physical testing can greatly enhance the understanding of the deformation mechanisms involved. In particular, a full-field strain contour can provide considerable information on the behaviour of a complex structure.

3.4.1 LITERATURE REVIEW OF STRAIN MAPPING

The understanding of the deformation characteristics of bulk aluminium foams can be enhanced with information on the strain behaviour throughout the structure as deformation progresses. A number of studies have used surface strain mapping techniques to provide indications of strain distribution under loading conditions. Bart-Smith et al. [90] used x-ray computed tomography and surface strain mapping to determine compression deformation modes and cell morphologies that control the onset of yielding in Alporas and ERG foams. Deformation was found to be localised in narrow bands with widths in the order of a cell diameter. Cells that experienced large permanent strains were predominantly elliptical, indicating a shape correlation rather than a cell size effect. The strain distribution clearly showed the damage progression process; displaying a deformation band of about 1 cell thick initiating and then propagating across the sample as the load increased. At peak load the band had extended across the entire specimen with local densification. Bastawros et al. [38,
91] also used a digital image correlation procedure, to study the deformation mechanisms occurring during the initial plastic deformation. Three stages were identified involving cell wall distortion and the formation of deformation bands. Rakow and Waas [48] used surface displacement analysis software to produce a discretized displacement field for the surface of samples tested in shear loading using a window frame device. This method was used to investigate a shear strain size effect by comparing average strain levels within various sized sub-regions.

Sha and Yip [92] have looked at 4-point bending of aluminium foam with stainless steel skins using in situ surface displacement analysis software (SDA, Instron, 1997). This software calculates a strain distribution over an area of interest using partial derivatives of displacement fields that are generated from optical images captured during the deformation. The study found two dominating failure modes: indentation caused by localised compressive deformation, and core shear. This work was continued to investigate cyclic bending in sandwiches with aluminium skins, finding similar deformation mechanisms of indentation and core shear in monolithic and fatigue loading [93]. The surface displacement analysis showed that for the indentation mode, strain was at a maximum adjacent to the load rollers; and for the core shear mode, the maximum strain was between the inner and outer rollers. Chen and Fleck [94] investigated the constrained deformation of aluminium foam sandwiched between steel substrates. This constraint restriction is very relevant to understanding the behaviour of aluminium foam when used within a sandwich structure. A distinct size effect was found, similar to that observed in non constrained foam testing. The yield strength was observed to increase as the foam thickness was decreased. In particular, for constrained compression, the strength increased with diminishing thickness of the foam layer. For constrained samples under various ratios of combined shear and tension loading, the shear and normal strengths were consistently greater for the thinner samples. The results were used to measure a collapse surface for the foam which compared well with analytical predictions of the extent of the size effect. In work continuing from the study by Chen et al. [47], a surface displacement analysis was conducted to observe the shear strain profile across the thickness of specimens tested in a double lap shear test. The strain response clearly showed a boundary layer exists adjacent to each of the steel adherends.

The use of strain distribution analysis to investigate sandwich structure behaviour with potentially complex material interactions appears to be of great value in understanding the deformation mechanisms. A deeper understanding of local and global behaviour of
aluminium foam including size effects will help to maximise effective implementation in a variety of applications.

3.4.2 OPTICAL STRAIN MEASUREMENT

The Aramis optical strain measurement system was used to capture the deformation of samples during physical testing. Aramis is a camera and software system produced by Gom GmbH of Germany [95]. It uses an advanced photogrammetry method involving 3D image correlation to produce full field strain measurements. Optical full-field displacement and strain measurement techniques have become more robust and affordable in recent years and are of great use in a variety of situations [96]. They are particularly useful as an optical alternative when gauges or extensometers are inappropriate. This might be important in an aggressive environment, on particularly fragile samples or where a single measurement is not suitable as an area of interest is not known a priori (e.g., damage and strain localisation, crack initiation and progression) [96]. The 3D image correlation method using photogrammetric principles has advantages over other full field imaging techniques such as electronic speckle pattern interferometry (ESPI), shearography and moiré. Advantages can include reduced vibration interference, fast data collection and a higher dynamic range of deformation measurement [97, 98]. The optical non-contact method is independent of the material and the loading conditions. This makes it a useful tool in a wide range of applications, including unusual non-homogenous or anisotropic materials. Amsterdam et al. [99] used scanning electron microscope images of tensile testing of Alporas aluminium foam as input for the Aramis system. The strain analysis showed regions of high strain in the cell wall between which a crack subsequently formed. The regions of high strain were compared to microstructural composition observations. A further advantage of the full-field measurement is the ability to directly compare results with finite element analysis results enabling direct verification of model simulations.

3.4.3 SAMPLE PREPARATION

The optical strain measurement method works on the principle of tracking individual correlation areas within stereo images. A pair of high resolution, CCD cameras record the deformation of the structure. This is described further in the next section. At each time step, the system attempts to match areas in the stereo images from the cameras. This requires the sample to have enough image variation in tone and contrast throughout, such that correlation areas are uniquely identifiable. This is generally achieved by applying a small-sized, random speckle pattern to the surface of the sample. For this study, all samples were treated with a
base coat of matt white paint. This was followed with a matt black speckle pattern, achieved using a half depressed spray can nozzle method. The pattern was distributed throughout the sample surface, with no large regions of un-speckled colour. Similarly, the size of the spots of paint was deliberately varied, however large black spots were minimised. The aim of this patterning process is to provide enough variation in the recorded images that each area can be uniquely identified and its relative displacement observed. The finer the pattern, the greater the resolution possible from the system. However, there is a limit on the minimum size of the pattern that can be resolved by the cameras. Figure 3.5 shows a typical speckle pattern on a sample of aluminium foam composite sandwich structure.

![Figure 3.5: Photo showing (a) patterned sample in 4-point bend test, and (b) higher magnification of typical patterned foam surface](image)

### 3.4.4 SYSTEM SPECIFICATION

The *Aramis* real-time strain measurement system uses a displacement gradient analysis of the random speckle pattern that deforms along with the surface of the sample. The two high resolution CCD cameras are configured to capture stereo images of the measurement surface. Image processing identifies correlation areas over each imaging area. These areas are tracked in the successive stereo images and are used in a photogrammetric algorithm to calculate 3D coordinates for the surface of the sample [100]. Figure 3.6 shows the cameras as used to monitor the four-point bend testing. The geometry of the camera arrangement determines the possible measurement volume. The base distance between the
cameras and the angle between them can be adjusted to vary the measurement volume from the order of \(10 \times 8 \times 8 \text{mm}^3\) to \(1700 \times 1360 \times 1360 \text{mm}^3\). For this study, a measuring volume of \(50 \times 40 \times 40 \text{ mm}^3\) was used. The full system specifications are provided in Table 3.1.

**Figure 3.6: Image showing stereo cameras capturing four-point bend test**

**Table 3.1: Aramis 1.3 M System specifications [95]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring Volume</td>
<td>(10 \times 8 \times 8 \text{ up to } 1700 \times 1360 \times 1360 \text{ mm}^3)</td>
</tr>
<tr>
<td>Camera resolution</td>
<td>(1280 \times 1024 \text{ pixels})</td>
</tr>
<tr>
<td>Camera chip</td>
<td>2/3 inch, CCD</td>
</tr>
<tr>
<td>Maximum frame rate</td>
<td>12 Hz</td>
</tr>
<tr>
<td>Shutter time</td>
<td>0.1ms up to 2s, computer-controlled, asynchronously triggerable</td>
</tr>
<tr>
<td>Strain measuring range</td>
<td>0.05% up to &gt; 100%</td>
</tr>
<tr>
<td>Strain accuracy</td>
<td>Up to 0.02%</td>
</tr>
</tbody>
</table>

For corresponding points in the images, with image coordinates \(p_1(x_1, y_1)\) and \(p_2(x_2, y_2)\), the corresponding object point \(P(X, Y, Z)\) can be found using geometry parameters in a procedure called space intersection [101]. A full description of the sample surface coordinates can be found by transforming image points to object points using the following relation [101]:

\[
\begin{bmatrix}
    x - x_0 - d_x \\
    y - y_0 - d_y \\
    c
\end{bmatrix} = s \cdot R \cdot \begin{bmatrix}
    X - X_0 \\
    Y - Y_0 \\
    Z - Z_0
\end{bmatrix}
\]

(Eq 3.2)

where \(x, y\) - image coordinates
\(x_0, y_0\) - principal point
\(d_x, d_y\) - lens distortion
\(c\) - camera constant
\(R\) - rotation matrix
\(X_0, Y_0, Z_0\) - projection centre
\(X, Y, Z\) - object point
These parameters are shown geometrically in Figure 3.7. Some of the parameters used in this transformation are dependent on setup specific variables such as camera lenses and spacing. For this reason, a thorough calibration procedure is required to acquire these variables before images are captured. The procedure uses a calibration plate with a precise known pattern of white dots on a black background. This plate is positioned at various angled orientations and distances to the cameras as images are captured. The captured images of the calibration pattern are compared with the expected pattern spacing variations within the calibration software for this particular set up geometry. This process uses a feature based algorithm based on an edge detection method [101]. This allows the photogrammetric method to use precise values for the camera angles, measuring volume and lens parameters.

Figure 3.7: Diagram of the geometry used to transform image coordinates from the stereo camera images to object points on the measurement surface [101]

Once the system has been calibrated, images can be taken of the progressive deformation during an experiment. When all images have been captured, the processing begins with the first stereo pair of images, representing the undeformed sample. One of the initial images is divided into square regions called facets. The user can define start points in the two images, defining matching facets in each image. Figure 3.8 shows start points defined on an Aramis image. With these start points the system then uses a shape recognition process to find corresponding facets throughout the two initial images.
Corresponding facets are then matched in each successive image during the test. These matching facets are used to calculate a displacement field for the deformed surface. The relative displacement of facet points is used to generate a strain field throughout the image.

The complex surface of the aluminium foam caused some difficulty in obtaining quality images for processing. A large number of start points were required to provide sufficient corresponding facets. The large variation in surface height from the cellular structure caused significant variation between the stereo images in the form of shadowing and pattern distortion. A range of methods for lighting of the samples were investigated to improve the image quality. The best results were found with diffuse lighting.

![Figure 3.8: A typical Aramis image showing user defined start points in red and computed facets in green](image)

### 3.4.5 DATA ANALYSIS

The calculated displacement fields were used to produce a range of strain information. Figure 3.9 shows a typical Aramis project file, with the calculated full-field strain distribution overlayed over a single camera image. An example strain contour with legend is shown in Figure 3.10.

![Figure 3.9: A typical calculated strain distribution overlayed on a camera image from an Aramis project](image)
A range of data post processing options are available. Filtering methods can be used to reduce possible noise or to emphasise local effects. Interpolation of 3D points was applied to fill any vacancies in the data where facets had not been calculated. In this project it was needed to fill spaces where parts of the speckled pattern were not matchable between the stereo images due to shadowing and high levels of surface variation. Results were evaluated statistically producing maximum, minimum, average, and standard deviation strain values for desired regions of the specimen. Planar sections were taken of the strain distribution to produce strain section line plots, providing an alternative perspective of the strain contours. The development of the strain distributions was elucidated by matching progressive images and associated calculated strain with the stages of the physical testing and increasing crosshead displacement. These various post processing options were used to explore the deformation behaviour of the samples, and enabled direct comparison with finite element modelling strain results.
Chapter 4  COMPARISON OF FLEXURAL BEHAVIOUR IN POLYMER AND METAL FOAM SANDWICH STRUCTURES

The possible application of aluminium foam composite sandwich structures in functions that are traditionally filled by polymer foam sandwich structures requires at least some initial direct comparison between the two material structures. This chapter describes a study investigating the performance of the two sandwich structures under typical loading conditions of flexure. The deformation behaviour of the structures was examined using the Aramis full field strain system to illuminate the strain and failure progression.

4.1 FLEXURAL BEHAVIOUR REVIEW

As discussed in previous chapters, polymer foam cores are widely used in sandwich structures for a variety of applications but have limited function in high temperature systems. Metal foams have attractive properties for use as sandwich cores, including good stiffness and strength to weight ratios, high impact energy absorption, good sound damping, electromagnetic wave absorption, thermal insulation and non combustibility [11]. Metal foams may therefore be more appropriate where multi-functionality is valuable [52].

The flexural behaviour of polymer foam sandwich structures has been widely investigated though often the emphasis has been placed on theoretical predictions rather than experimental studies. Generally, experimental observations of polymer foam structures have matched well with bending theory analysis. For example, Steeves and Fleck [18, 19] conducted a detailed study on sandwich beams with composite faces and a PVC foam core including analytical models, experimental work and numerical modelling aspects. They found three competing modes of failure: skin microbuckling, plastic shear of the core and skin indentation beneath the load rollers. Failure maps were constructed showing the
dependence of the collapse mode on the geometry of the beams. The relative strengths of the skins and core are also important in resolving the failure mode. This is of particular interest when using an alternative contrasting core material such as ductile metal foam.

Studies have been conducted on aluminium foam composite skin sandwich structures under 3-point bend loading, focusing on the failure modes produced by varying core thickness and span length [68]. The structures were found to fail mainly by either core shear or by upper skin compression failure. While prior work has made some initial investigations, further mechanical characterization of these metal foam structures is required to fully understand the structural behaviour. In particular, studying the different deformation mechanisms compared to polymer structures will develop this understanding.

4.2 EXPERIMENTAL METHOD

This study examines the flexural behaviour of a thin sandwich structure under 4 point bending loading, using Alporas aluminium foam and Twintex® skins. A polymer foam core sandwich structure with glass/polyester skins was also examined as a reference for the performance of the metal foam. The flexural tests followed the ASTM Standards which determine test geometry from the skin material properties and do not account for mass. The core materials have different densities (Aluminium foam 0.23 g/cm³, polymer foam 0.1 g/cm³) which may be significant for energy absorption. Real time strain analysis was incorporated using the 3D optical measuring technique (Aramis) to provide an indication of the strain distribution throughout the sandwich cores. This full field strain analysis provides a valuable insight into the localised deformation progression and therefore the overall mechanical behaviour properties of the foams under typical loading.

4.2.1 SAMPLE MANUFACTURE

Aluminium foam composite sandwich panels were constructed using the method described in Chapter 3, using cores of 10mm. A polymer foam core sandwich structure panel was manufactured using 10mm thick Divinycell H100 (a closed cell pvc polymer foam from Diab [102]) and 1 ply plain weave e-glass (630gsm, from Colan)/ UV curing polyester resin (Nuplex isophthalic polyester, 45% styrene content) as shown in Figure 4.1. Laminates were made by wet lay-up, with no vacuum bag. The UV curing resin has no gel time which allowed a long working time to lay-up carefully and ensure full wet out and void minimisation. The resin contained 0.5pph of photoinitiator (Irgacure 819) and each skin was cured through 10 minutes exposure to UV light (sunlight) with no further post curing.
required. The skins were manufactured with resin mass control so as to have an equivalent thickness and fibre:resin mass fraction to the Twintex skins used in the aluminium foam sandwich. Samples from both panels were cut to a width of 25mm using a diamond tipped saw. Figure 4.2 shows a micrograph of the two sandwich structures, detailing the different cell structures.

![Figure 4.1: Polymer foam sandwich lay up](image1)

![Figure 4.2: A comparison of the metal and polymer foam core cellular structures](image2)

### 4.2.2 Flexural Test Procedure

The sandwich structures were tested in a four-point bend test following ASTM Standard C393-63, as detailed in Chapter 3. The geometry of the testing rig was kept constant for both material structures, with a support span of 150mm and a load span of 50mm. The quasi-static test was conducted at 10mm/min. Full-field, real-time strain analysis was conducted during testing of each sandwich structure. The *Aramis* system was set up to capture a measuring volume of $50 \times 40 \times 40$ mm$^3$ which showed displacement information from the area of each sandwich structure between the load rollers as shown in Figure 4.3. Images were captured with a sampling time of 500ms, during the first 10mm of crosshead displacement. Load-displacement plots were also recorded for each structure.
Figure 4.3: Schematic of four-point bend test and Aramis measuring volume

4.3 FLEXURAL RESULTS

The flexural behaviour of both sandwich structures was compared using visual observations, load-displacement curves, and the recorded strain distributions from throughout the test progression. Movie files showing images from one of the Aramis cameras and the calculated von Mises strain distributions are provided in the appendix. Mechanical flexural properties including maximum core and facing stress, and maximum core shear stress were calculated using simple beam theory adapted for sandwich structures.

4.3.1 FAILURE BEHAVIOUR OF AL FOAM SANDWICH STRUCTURE

Figure 4.4 shows a typical load-displacement curve for the aluminium foam sandwich structure. There is an initial linear elastic behaviour followed by steady failure and damage progression. The structure was found to fail in compression with initial failure occurring in the top facing with fibre fracture and some skin wrinkling in the area between the loading rollers. Some core failure was visible in the centre of the span between the load rollers with the core deforming initially by cracking followed by crushing of the cells. There was no visible debonding between the core and skins, and no damage to the bottom facing. A micrograph of the final deformed structure is shown in Figure 4.5, displaying the central failure zone. The damage progression appeared to be steady and consistent and this can be seen in the smooth curve of the load-displacement plot. The load at yield (point (a) in Figure
4.4) was 0.353 kN with a yield displacement of 4.327 mm. The load curve then drops to a minimum of 0.22 kN before slowly rising to an apparent plateau of just above 0.3 kN. This plateau region has been widely observed in bulk aluminium foam as a result of progressive plastic collapse of the cells [10].

![Figure 4.4: Typical load-displacement curve for the aluminium foam structure, showing load a) at yield, b) at 6.5mm and c) at 10mm](image)

The strain distribution of the aluminium foam sandwich is shown in Figure 4.6. Figure 4.6(a), (b) and (c) show three frames corresponding to points (a), (b) and (c) on the load-displacement plot in Figure 4.4. The strain analysis initially showed dispersed regions of higher strain throughout the sample. This distribution continued during the elastic region of the loading. Figure 4.6(a) corresponds to the yield point (a) and shows these dispersed regions of higher strain. The areas of slightly higher strain appeared to correspond to the
larger cells visible on the surface of the foam. As the test went beyond the yield point, a region of high strain formed in the centre of the sample where cracking and deformation of the core was observed.

Figure 4.6: Typical 4pt bend Alporas strain maps at (a) 5mm, (b) 6.5 mm, (c) 10mm crosshead displacement, and (d) illustrating a side view of the surface strain contour in (c) showing out of plane deformation
This concentrated region of strain can be seen in Figure 4.6(b). The region of high strain continued to develop as the test continued, increasing in area and magnitude. Figure 4.6(c) shows the strain distribution corresponding to point (c) at the arrest of the load drop. The central high strain region reached maximum values in the order of 200% whereas the remainder of the sample had a maximum strain of 60% with an average of 4%. Figure 4.6(d) illustrates a side view of the surface strain contour shown in Figure 4.6(c). Notably, the surface had a significant deformation as the cells deformed out of the plane.

4.3.2 Failure behaviour of polymer foam sandwich structure

Figure 4.7 shows a typical load-displacement curve for the Divinycell polymer sandwich structure. Initial elastic behaviour was followed by a rapid load drop and catastrophic failure once the structure has passed the yield point. This contrasts with the steady drop in load seen in the aluminium foam structure. Similarly, the displacement over which the structure yields and drops to a plateau load is much smaller than in the aluminium foam. Figure 4.8 shows the deformed shape of the polymer structure. The structure was found to fail in compression with initial failure occurring in the top facing with fibre fracture underneath the loading rollers. Some minor core failure occurred toward the end of the test as the top of the core began to deform beneath the load rollers. There was no visible debonding between the core and skins, and no damage to the bottom facing. For the polymer foam structure, the load at yield (see point (b) in Figure 4.7) was 0.459 kN with a yield displacement of 3.5 mm. The load curve then drops sharply to 0.29kN at a displacement of 4.4mm before slowing to a plateau of about 0.2kN.

![Load vs Displacement Graph](image)

*Figure 4.7: Typical load-displacement curve for the polymer foam structure, showing load a) at 3mm, b) at yield, and c) at 4.5mm*
Figure 4.8: Typical damage observed in 10mm Divinycell polymer sandwich structure

Figure 4.9 shows three frames corresponding to points (a), (b) and (c) in Figure 4.7. The strain distribution of the Divinycell sandwich under bending loading was initially very uniform with no regions of high strain. As the load increased towards the yield load, the strain distribution remained fairly consistent with very little variation in value. At the yield load, regions of higher strain began to appear in areas corresponding to beneath the load rollers. This corresponds to the failure and deformation observed in the top skin and core under the load rollers. These regions of high strain continued to increase in magnitude and area as the test progressed. The remainder of the structure appears to maintain the initial low level strain throughout the test. The high strain regions reached values in the order of 45% whereas the remainder of the sample had a maximum strain of 15% with an average of 1%. These values are much smaller than those seen in the aluminium foam structure. Figure 4.9(d) illustrates a side view of the surface strain contour shown in Figure 4.9(c). This shows far less out of plane deformation than is seen in the aluminium foam deformation. Figure 4.10 shows the strain distribution of the polymer foam structure at a crosshead displacement of 10mm. This can be compared with the strain distribution of the aluminium foam structure in Figure 4.6(c), also at 10mm. The polymer distribution shows larger regions of concentrated strain beneath the load rollers. On the right hand side, there is some variation in the shape of the higher strain region visible. This suggests bands of high strain are starting to radiate out from the initial crush region.
Figure 4.9: Typical 4pt bend Divinycell strain maps at (a) 3 mm, (b) 3.5 mm, (c) 4.5 mm crosshead displacement, (d) illustrating a side view of the surface strain contour in (c) showing little out of plane deformation.
4.3.3 MECHANICAL PROPERTIES

The mechanical properties calculated from the 4-point bend results are given in Table 4.1. These values were calculated using equations 2.1 - 2.5 given in Section 2.2.1. Both sandwich structures were made with a similar core thickness and fibre:resin mass fractions in the skins to enable direct comparison. The maximum core stress was much greater for the aluminium foam, following the difference in compressive modulus between the cores; with Alporas having a modulus in the order of 1.10 GPa while the Divinycell H100 has a modulus of 0.125 GPa (Gleich, Diab product data sheets). Within scatter, the maximum core shear stress and maximum facing stress show no significant difference.

The energy absorption properties of the sandwich structures were considered by integrating the load-displacement curves. Figure 4.11 shows typical load-displacement curves from both structures for a visual comparison. The yield load for each structure was taken as the point at which the initial peak load was reached. The energy absorbed up to the yield load was significantly greater in the aluminium foam. Similarly, the energy absorbed up to point (c) in the load-displacement curves (Figures 4.4 and 4.7), where the drop in the load halted, was considerably higher in the aluminium foam. The polymer foam appears to absorb minimal energy after its initial yielding while the aluminium foam structure continues to absorb energy as it progressively deforms. This increased energy absorption is consistent with previous studies [9].
Table 4.1: Average mechanical properties for each structure (standard deviation in parentheses)

<table>
<thead>
<tr>
<th>Sandwich Structure</th>
<th>Max Core Stress (MPa)</th>
<th>Max Core Shear Stress (MPa)</th>
<th>Max Facing Stress (MPa)</th>
<th>Energy to yield load (J)</th>
<th>Energy to arrest of load drop (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alporas</td>
<td>13.64</td>
<td>1.90</td>
<td>126.44</td>
<td>1.30</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td>(1.61)</td>
<td>(0.23)</td>
<td>(15.03)</td>
<td>(0.20)</td>
<td>(0.48)</td>
</tr>
<tr>
<td>H100</td>
<td>1.61</td>
<td>1.58</td>
<td>145.55</td>
<td>1.04</td>
<td>1.25</td>
</tr>
<tr>
<td>Divinycell</td>
<td>(0.22)</td>
<td>(0.21)</td>
<td>(19.84)</td>
<td>(0.16)</td>
<td>(0.09)</td>
</tr>
</tbody>
</table>

Figure 4.11: Direct comparison of typical load-displacement curves for the two core materials

The deformation mechanism of the aluminium foam core/thermoplastic composite facing sandwich structure under 4-point bend loading was found to be significantly different to that of an equivalent polymer foam core sandwich structure. A full field strain analysis showed that the metal core had an irregular strain distribution consistent with the irregular cell distribution. A very high strain concentration was observed at a central deformation area where fracture occurred. The polymer foam had an even strain distribution with strain concentrations under the loading rollers. The energy absorbed up to yield was greater in the metal foam and continued to be greater as the structures deformed. This energy absorption characteristic of the aluminium foam structure, while displaying equivalent or enhanced mechanical properties compared to a polymer core, suggests such metal foam structures could be advantageous in a variety of structural situations.
4.4 SUMMARY

Initial investigations comparing the performance of the two sandwich structures in typical in-service loading conditions found aluminium foam sandwich structures may be a suitable alternative to the more traditional polymer sandwich materials. The four-point bend testing showed the aluminium foam structure to have equivalent or improved flexural properties such as maximum core stress before failure. Superior energy absorption properties during the flexural loading were also found in the metal structure. The deformation mechanisms displayed by each structure were considerably different, and were further depicted through contrasting developing strain distributions. The steady progressive core deformation shown by the aluminium foam generates the energy absorption characteristics and could be valuable in many structural application areas. The aluminium foam composite sandwich structure has been found to have suitable characteristics as an alternative to conventional structures. However, to fully utilise its superior properties, while minimising the effect of any unfavourable characteristics, further understanding of the deformation mechanisms is required.
Applications that utilise sandwich panels can typically involve complex loading situations including compression, tension, shear loads and localised indentation. It is important to be able to predict the response of new sandwich material combinations under these types of loading. Bend tests using three or four-point loads are commonly used to assess the flexural behaviour of sandwich structures, and material testing standards have been developed allowing for comparison between structures. The typical dimensions of cores used within sandwich structures are important to consider in the potential use of aluminium foam, since dimensions can approach magnitudes in the order of individual foam cells. In samples of this size, there is potential for the “size effect” to become significant, in which the foam can behave considerably differently compared to the bulk material. For this reason it is important to investigate the behaviour of the sandwich structure across a range of core and skin thicknesses.

5.1 INTRODUCTION

The bulk material behaviour of aluminium foam has been investigated and a distinct size effect has been observed [46, 48, 49]. The compressive and shear strength properties of the foam were found to reach a plateau level as the ratio of specimen size to cell size increased [46]. This size effect may influence the behaviour of the aluminium foam when used as a core in a sandwich structure. Studies have been conducted on aluminium foam composite structures under 3-point bend loading focussing on the failure modes produced by varying core thickness and span length [68]. The structures were found to fail mainly by core shear or by upper skin compression failure. Whilst these studies have made some initial investigations, further mechanical characterization of these structures is required to fully understand their structural behaviour and deformation mechanisms.
This chapter describes the experimental investigations into the effect of core and skin thickness on the deformation mechanisms of sandwich structures under 4-point bend loading. The focus of the study was to elucidate the deformation and failure behaviours. In particular, real time strain analysis (Aramis) was incorporated to provide an indication of the strain distribution development throughout the sandwich cores. This full field strain analysis provided a valuable insight into the localised deformation progression, the effect of core thickness and cell size, the influence of skin thickness and therefore the overall mechanical behaviour properties of the foams under typical flexural loading.

### 5.1.1 Materials and Manufacture

Sandwich structures were manufactured using the method detailed in Chapter 3, for three core thicknesses of 5, 10 and 20mm. These material thicknesses are available directly supplied by the manufacturer. The optical micrographs of the cores shown in Figure 3.1 of Chapter 3 give a qualitative comparison of the difference in cell structure within each thickness. It can be seen that the cell size tends to increase with an increase in thickness. Single ply skins were utilised for each core thickness, with additional samples prepared using 4 layers of skin material for the 20mm core. The three final aluminium foam sandwich panels with single ply skins and core thicknesses of 5, 10 and 20mm each had an average thickness of 5.16, 10.19 and 20.47mm respectively and the 20mm 4ply samples had an average thickness of 21.41mm.

### 5.1.2 Flexural Test Procedure

The sandwich structures were tested in a four-point bend test following ASTM Standard C393-63 [88] as described in Chapter 3. The sample and testing dimensions were kept constant across all core dimensions, with the exception of the sample width. The sample width was 25mm for the 5 and 10mm thick core structures, and 45mm for the 20mm structures, as per the test standard. At least four samples of each thickness were tested. Flexural properties were calculated using beam bending theory adapted to sandwich structures as described in Chapter 3. The average flexural rigidities for the 5, 10 and 20mm single ply samples are provided in Table 5.1. The Aramis system was used to capture the strain behaviour during the bending tests. A measuring volume of \( 40 \times 50 \times 50 \text{mm}^3 \) was used, focusing on the region between the load rollers of the four-point bend arrangement.
Table 5.1: Sandwich structure flexural rigidity for each sample core thickness

<table>
<thead>
<tr>
<th>Sample core thickness (mm)</th>
<th>Flexural Rigidity (Nmm²)</th>
<th>Standard Deviation (Nmm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.38</td>
<td>0.03</td>
</tr>
<tr>
<td>10</td>
<td>6.39</td>
<td>0.20</td>
</tr>
<tr>
<td>20</td>
<td>52.56</td>
<td>1.75</td>
</tr>
</tbody>
</table>

5.2 CORE THICKNESS

The effect of the core thickness on the failure behaviour and deformation progression was investigated using several methods: load-displacement data recorded during testing, visual observations, and full-field strain distributions generated by the Aramis optical strain measurement system. Movie files showing images from one of the Aramis cameras and the calculated von Mises strain distributions for each of the core thicknesses are provided in the appendix.

5.2.1 LOAD DISPLACEMENT CURVES

Figure 5.1 shows a typical load-displacement curve for each sandwich structure. Each structure showed an initial linear elastic behaviour followed by a decrease in slope up to a maximum load magnitude. As the thickness of the sample core and the flexural rigidity increased, the initial slope of the curve increased. Similarly, the magnitude of the maximum load increased with core thickness. The sample with the 20mm thick core had a significantly greater maximum load, as expected from the greater sample dimensions of thickness and width (45 mm).

Figure 5.1: Typical load-displacement plot for each core thickness
The curve progression after reaching the first peak load point varied between the samples. The sample with the 5mm thick core had a rapid decrease in load before plateauing. The sample with the 10mm thick core showed a steadier load decrease over a larger displacement before also reaching a plateau. The 20mm sample displayed a small drop in load after reaching the first peak load, followed by a slow increase in load to a plateau. A plateau has been described as an indication of cell densification [10].

5.2.2 ENERGY CURVES

The energy absorbed during flexural bending was examined using the area under the load displacement curves. Figure 5.2 shows the energy absorption progression for each core thickness. It can be seen in all of the thicknesses that the steady core deformation has produced consistent energy absorption throughout the bending test. The magnitude of the energy absorbed is consistent with the increase in geometry and flexural rigidity.

Figure 5.2: Energy absorbed calculated from area under load-displacement curves for each core thickness

5.2.3 MECHANICAL PROPERTIES

The flexural properties calculated from the 4-point bend results are given in Table 5.2. These values were calculated using equations 2.1 - 2.5 given in Section 2.2.1. The maximum core stress was found to decrease as the core thickness increased. This agrees with the decrease in compressive strength with respect to core thickness reported by Chen et al. [94]. The maximum core shear stress was, within scatter, comparable between the samples of different core thicknesses. This may suggest that the load and support roller spacing and geometry is more influential on the applied shear stress than a possible size effect similar to that reported by Chen et al. [47]. The maximum facing stress experienced
by the structures was found to decrease as the core thickness increased. It is possible that this is related to the occurrence of core failure in the thicker samples.

Table 5.2: Average mechanical properties for each core thickness (standard deviation in parentheses)

<table>
<thead>
<tr>
<th>Core thickness (mm)</th>
<th>Max Core Stress (MPa)</th>
<th>Max Core Shear Stress (MPa)</th>
<th>Max Facing Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.14 (0.13)</td>
<td>1.74 (0.04)</td>
<td>175.70 (4.23)</td>
</tr>
<tr>
<td>10</td>
<td>4.77 (0.43)</td>
<td>1.79 (0.16)</td>
<td>161.99 (14.53)</td>
</tr>
<tr>
<td>20</td>
<td>3.74 (0.48)</td>
<td>1.63 (0.22)</td>
<td>127.55 (16.62)</td>
</tr>
</tbody>
</table>

5.2.4 STRAIN BEHAVIOUR

Visual observations found each of the sandwich structures to fail by notably different failure mechanisms. Representative von Mises strain maps were recorded for each of the samples and also displayed three distinct strain distributions. Each strain distribution displayed the area between the loading rollers of the 4 point bend test.

5.2.4.1 FULL-FIELD STRAIN PROGRESSION

Figure 5.3(a) shows the typical damage seen in a sample with a 5mm thick core. This structure appeared to fail primarily in the skins through skin wrinkling and fibre fracture. There were two failure zones, each located just inside the loading rollers. There was some minor cracking in the core though no apparent crushing within the core structure. This agrees with the shape of the load displacement curve with the drop in load related to skin failure. Figure 5.3(b) shows the strain distribution in a sample with a 5mm thick core at a crosshead displacement of 8mm, when the peak load was reached. There are regions of slightly higher strain dispersed throughout the sample, with one region of increased strain starting to form in the area where some skin failure was observed. Figure 5.3(c) shows the strain distribution at displacement 10mm. There are prominent regions of higher strain that correspond to the regions of skin failure and core cracking observed as seen in Figure 5.3(a).
Figure 5.3: Typical deformation behaviour of sample with 5mm core; (a) Final deformed shape, (b) Strain distribution at peak load, displacement 8mm, (c) Strain distribution at 10mm displacement.

The typical damage observed in a sample with a 10mm thick core is shown in Figure 5.4(a). This sample was observed to fail in compression with initial failure occurring in the top facing as skin wrinkling and some minor fibre fracture. The failure in both the skin and the core occurred towards the centre of the load span with the core failing initially by cracking followed by some crushing of the cells. There was no visible debonding between the core and skins, and no failure of the bottom facing under tension. The damage progression appeared to be steady and consistent, with the dominant mechanism being core crushing. This is in contrast to the deformation observed in the sample with the 5mm thick core. The strain distribution of the sample with a 10mm thick core at maximum load is shown in Figure 5.4(b). Strain concentrations are dispersed throughout the sample; however there is no apparent region of high strain developing. Here, the strain pattern appears to somewhat reflect the morphology of the cell structure of the core. Figure 5.4(c) shows the...
strain distribution at a displacement of 10mm where there is a central region of increased strain which is consistent with the failure zone of core crushing that was visually observed.

Figure 5.4: Typical deformation behaviour of sample with 10mm core; (a) Final deformed shape (b) Strain distribution at peak load, displacement 4.5mm, (c) Strain distribution at 10mm displacement

Figure 5.5(a) shows the typical damage observed in a sample with a 20mm thick core. This structure displayed a contrasting third failure mechanism compared to those observed in the samples with thinner cores. The primary failure occurred as considerable indentation damage under the loading rollers. There was some skin failure observed with minor fracture and wrinkling. The main deformation occurred as core crushing and some associated core cracking. This core crushing was more significant than that observed in the sample with the
10mm thick core. The slow steady increase in load seen in Figure 5.1 can be attributed to the significant crushing of the core through the indentation of the load rollers. The strain distribution of the sample with the 20mm thick core at peak load at a displacement of 2.7mm is shown in Figure 5.5(b). The dispersed regions of strain are apparent, with a few areas of higher strain starting to form adjacent to the load rollers. Figure 5.5(c) shows the strain distribution in the 20mm thick core structure after the load has started to increase again. Significantly, the regions under the load rollers now exhibit concentrated high strain. These areas correspond to the indentation observed in the sample allowing the load to steadily increase as the core crushing continued. The strain pattern in this sample is also similar to the morphology of the aluminium foam cell structure indicating the thin cell walls are experiencing high strain.

![Figure 5.5: Typical deformation behaviour of sample with 20mm core and 1 ply skins; (a) Final deformed shape, (b) Strain distribution at peak load, displacement 2.7mm, (c) Strain distribution at 10mm displacement](image)
The strain analysis system provides a value for the strain throughout the captured image. The average value of the measured strain provides an indication of the extent of the distribution of strain throughout the image. There is a trend in the strain values recorded at the peak load for each core thickness. The average strain of the total area was found to increase slightly with an increase in core thickness, suggesting the high strain regions form an increasing proportion of the total area. The global average strain for the samples with 5, 10 and 20mm thick cores was 3.1%, 3.2% and 3.9% respectively. There were no clear trends in the strain measured for each sample at the displacement of 10mm.

5.2.4.2 STRAIN SECTION LINE PLOTS

The strain distribution was further investigated by taking section planes through the sample full-field strain images and producing line plots of the strain magnitude along the sections. For each sample, 5 sections were taken, evenly distributed through the thickness. Figure 5.6 shows an example image of the sections taken in the 20mm core sample strain contours. The data from the sections was used to generate line plots for comparison at points of interest during the deformation progression. These plots correspond to the displacement at which the peak load occurred, and to a displacement of 10mm, as shown previously in the full-field strain contours. Also, for each section, the line data from regular intervals of displacement were combined to provide a further representation of the strain distribution development. The strain data was filtered using a median filter method to remove any possible extreme strain values that resulted from miscalculations or noise in the image analysis. It is noted that for clarity of all of the section curves, the strain axes used are not constant across all of the section strain line plots.

Figure 5.6: Strain contour showing position of 5 section planes
Figure 5.7 shows the section line plots for the 5mm core structure. At the peak load displacement in Figure 5.7(a) the strain levels are reasonably uniform across all of the five sections in the central region of the x-position. There are some small variations throughout as seen in the non-uniform full-field strain contours, and corresponding to the cell morphology of the aluminium foam. At the left end there is slightly increased strain for most sections, while at the right end there are a few peaks of very high strain. These high peaks are in the sections towards the top of the sandwich beam and may correspond to large localised deformation in the region of individual weak cells. Figure 5.7(b) shows the section line plots at 10mm displacement. These curves show increased strain in similar regions to those seen in the peak load plot. These areas correspond to the regions of high strain seen in Figure 5.3(c).

![Figure 5.7: Section strain line plots showing the typical strain distribution of the 5mm structure at a) peak load, 8mm displacement (stage 93) and b) 10mm displacement (stage120)](image)

The section line plots for the 10mm core structure are shown in Figure 5.8. At the peak load there is no obvious clear pattern, with all 5 sections showing a similar range of variation in strain magnitude. Figure 5.8(b) shows a distinct pattern of strain deformation across the core thickness. Section 0 at the top surface of the beam shows high levels of strain in the central region. This peak is observed in all sections, with decreasing magnitude as the section moved away from the top surface. This corresponds to the visual observations of core crushing in the centre of the sandwich structure. The large magnitude of the peaks may be due to miscalculations in the image analysis where individual facets may have been misidentified.
Figure 5.8: Section strain line plots showing the typical strain distribution of the 10mm structure at a) peak load, 4.5mm displacement (stage 55) and b) 10mm displacement (stage 120)

Figure 5.9 shows the section line plots for the 20mm core structure. At the peak load in Figure 5.9(a) there are several high peaks visible in the section 1 and section 2 curves. The two highest peaks are at each end of the distribution, corresponding to the regions where core indentation was visually observed in the samples. However, the curve corresponding to section 0, at the top of the core thickness, does not have large strain peaks. This suggests the core deformation may not initiate at the top surface. At each end, the dominant curve corresponds to different sections. This may be a result of the inhomogeneity of the core material, with maximum strain occurring at the point in the thickness with the weakest cell structure. Figure 5.9(b) shows a similar pattern for the section line plot at 10mm displacement. The magnitudes of the curves have increased, with deformation spreading further through the thickness of the core.

Figure 5.9: Section strain line plots showing the typical strain distribution of the 20mm structure at a) peak load, 2.7mm displacement (stage 33) and b) 10mm displacement (stage 120)
The section line plots for each core thickness show a complicated strain evolution. The strain distributions do not follow standard pure bending theory in which maximum strain occurs at the maximum distance from the neutral axis. Instead, the strain distribution appears to be dominated by regions of failure or as a result of the inhomogeneous nature of the core structure. Peaks of high strain magnitude in all samples occur in regions of observed failure. There are no clear trends in the strain magnitude through the thickness as shown by the five sections. The experimental full-field strain measurements have revealed a very complex strain distribution.

Section line plots were produced to show the strain development during the flexural tests. Figure 5.10 shows the section line plots for 6 stages of the flexural test for section 2 in the centre of the sandwich beam. These stages correspond to the progression of the test machine crosshead displacement from 1.7mm to 10mm as follows:

- Stage 20 = 1.7mm
- Stage 40 = 3.3mm
- Stage 60 = 5.0mm
- Stage 80 = 6.7mm
- Stage 100 = 8.3mm
- Stage 120 = 10mm

Figure 5.10(a) shows the section 2 line plot for the 5mm structure. In the early stages, the curves have significant variation across the length of the beam. As the test progresses regions of increased strain form in the 8 to 16mm and 48 to 60mm regions of the x-position. The development of a concentrated strain in the central region of the 10mm structure is shown in Figure 5.10(b). This central strain magnitude is significantly greater than in other regions of the distribution. This is in contrast to the smaller range of variation seen in the 5mm structure. Figure 5.10(c) shows the section 2 line plot for the 20mm structure. Two regions of high strain develop at the edges of the beam corresponding to the observed core indentation. It is interesting to note that the maximum strain at the right side of the distribution does not correspond to the stage of maximum crosshead displacement. Instead, the strain magnitude seems to fluctuate, with both stage 20 and stage 100 having greater strain magnitudes than stage 120. This could be caused by miscalculations in the image analysis, particularly from the complex three dimensional nature of the surface structure.
Figure 5.10: Section strain line plots showing the typical progressive strain distribution of Section 2 (centre plane) across a displacement range of 1.7-10mm for a) 5mm structure, b) 10mm structure and c) 20mm structure

5.2.4.3 EPSILON X AND EPSILON Y STRAIN

The geometry of the bending test is configured such that the sandwich beam should experience bending loads in one direction only. Any out of plane loading may complicate the failure behaviour and may have contributed to the complex strain evolution observed. This was investigated by looking at the contours produced for strain in the bending direction, Epsilon X. The previous strain contours have shown the von Mises strain. In the case of pure bending, the von Mises strain contours should be dominated by the strain behaviour in the x direction. Figure 5.11 shows the distribution for Epsilon X strain at a displacement of 10mm for the sandwich with the 20mm core. This corresponds relatively closely to the von Mises strain distribution at the same displacement. The contour recorded for Epsilon Y strain is more uniform and shows less regions of high strain as illustrated in Figure 5.12. This suggests the configuration does approximate pure bending, with one strain direction (ε_x) being dominant.
It is clear that the thickness of the core affects the way in which the aluminium foam core, and the sandwich structure as a whole, deforms under 4 point bend loading. In the thinner structure, there is minimal damage in the core. This is reflected in the lower strain magnitudes shown in the full-field strain distributions and section strain line plots. Chen et al. [94] found that the compressive strength increased with the diminishing thickness of the foam layer when conducting constrained compression testing using steel face sheets and aluminium foam cores. They argued that the size effect may be due to the development of a boundary layer adjacent to the steel plates where the adhesive provides local reinforcement of the core cell walls. It is possible that this reinforcing effect may be influencing the damage behaviour observed in the aluminium foam composite skin structures, causing the thinner sample with a high proportion of “reinforced” core cells to be dominated by skin failure mechanisms. As the thickness of the core increases, the proportion of such cells decreases and the skin failure mechanisms become less prominent.
In the sample with the 10mm thick core there is both skin failure and core damage. When the core thickness is increased to 20mm, there is very little interaction between the thin skin and the core, causing the core to bear a larger load which results in major indentation damage. Andrews et al. [46] have reported that in bulk aluminium foam there is a reduction in shear strength with an increase in the thickness to cell diameter ratio down to a plateau level. Similarly, Chen et al. [47] also found a size effect in shear when investigating aluminium foam cores with aluminium skins, where the shear strength of the foam core is reduced for samples of increasing thickness. It is possible that a similar trend is occurring with this aluminium foam composite skin sandwich structure. The thicker samples have more significant core damage which may have been initiated by core shear failure. This agrees with one of the common damage mechanisms of core shear failure described by McKown et al. [68] in their investigation of aluminium core composite skin structures in three point bend loading.

5.3 SKIN THICKNESS

The indentation damage that was observed in the 20mm thick core structure suggested the load concentration under the load rollers was significant for this test geometry. The tests were repeated using rubber inserts below the load rollers in an attempt to minimise the effect of the load concentration, however, no change in behaviour was observed. It was considered that the thickness of the skin may influence the degree of indentation; therefore further testing was conducted on a sandwich structure with 20mm core and 4 ply skins. The sample thickness was 21.41mm and width 45mm. The sample was tested under the same conditions as used for the previous samples.

5.3.1 LOAD DISPLACEMENT CURVES

Figure 5.13 shows a typical load-displacement curve for each sample with a 20mm thick core. Each structure showed an initial linear elastic behaviour followed by a slowing of the curve to a maximum load point. The 4 ply sample sustains a maximum load twice that of the 1 ply sample. The shape of the curve up to and following the maximum load is quite different between the two structures. The single ply sample shows a small drop in load after reaching a peak load, followed by a slow increase in load to a plateau. The 4 ply sample demonstrates a high peak load at an increased displacement, then a significant load drop prior to reaching a plateau.
5.3.2 MECHANICAL PROPERTIES

The flexural properties for the 4 ply sandwich structure were calculated as before, using equations 2.1 - 2.5 given in Section 2.2.1. The flexural rigidity was calculated as 78.35 Nmm$^2$ which is greater than the 1 ply structure (52.56 Nmm$^2$) as expected from the increased geometry dimensions. The maximum core stress was 4.75 MPa which is greater than that calculated for the 1 ply 20mm sample (3.74MPa). The 4 ply structure was found to experience a significantly greater maximum core shear stress of 2.81MPa (1 ply: 1.63 MPa). The maximum facing stress was 165.55MPa which is greater than that calculated for the 1 ply structure (127.55MPa).

5.3.3 ENERGY CURVES

Figure 5.14 shows the energy absorbed during the flexural loading for the 20mm samples; found by integrating the load-displacement curves. The initial slope of the energy absorbed curve was greater for the thicker skinned sample. This corresponds to the early deformation mechanism of the shear crack initiation and growth. However, the slope of the energy curve decreases as the displacement progresses past 12mm, where the crack growth is arrested and the load-displacement curve begins to slow to a plateau. Here, the gradient of the slope is approximately the same as that of the single ply sample, where indentation dominates the deformation.
Figure 5.14: Energy absorbed calculated from area under load-displacement curves for each skin thickness

The increase in skin thickness was found to have a considerable affect on the failure mechanism experienced by the sandwich structure. Figure 5.15(a) shows the final deformed shape of the 4 ply sample which differs significantly to the shape of the single ply sample, shown in Figure 5.5(a). The 4 ply sample displayed reduced indentation damage beneath the load rollers. There was no observable damage to the core in the area between the load rollers, and the structure did not show any skin wrinkling or fibre fracture. The major damage occurred in the form of significant core shear cracks as highlighted in Figure 5.15(a). These cracks developed between the top load roller and the support roller. This different form of damage is consistent with the variation in the load-displacement curves of the two different skin thickness structures. The 1 ply structure experienced a sharper load drop which could be attributed to a sudden fibre failure, which was not observed in the 4 ply structure. The damage development of the 4 ply structure appears to be much steadier than the 1 ply structure as the cracking of the core is the dominant failure mechanism. The load drop after maximum load is likely to correspond to the crack initiation followed by steady crack growth, reaching a plateau as the crack grows completely through the thickness of the core and is arrested by the skin. In contrast, the failure of the 1 ply structure is dominated by core indentation which allows an increase in load as the core starts to crush and densify. The thicker skins appear to increase the shear stress in the core, with shear cracking in the core becoming the dominant failure mechanism.
5.3.4 Strain behaviour

The introduction of a thicker skin produced notably different deformation mechanisms in the 20mm core samples. Full-field strain contours were recorded for the 4 ply samples, displaying distributions corresponding well to the visually observed failure modes. The Aramis system was used on separate samples to capture strain distributions for both the area between the loading rollers and the area in which the shear crack occurred.

5.3.4.1 Full-field strain progression

Representative strain distributions for the 20mm core with 4 ply skin sandwich structure are shown in Figure 5.15. The strain distribution at the maximum load with a displacement of 4.5 mm is shown in Figure 5.15(b). The typical dispersed regions of higher strain are visible throughout the sample, again appearing to correspond to the core cell morphology. This is similar to the distribution seen in the 1 ply sample at peak load (see Figure 5.5(b)). On closer inspection, it can be seen that there is slightly increased strain in areas at the edge of the figure in the region of the load rollers. The average strain over the area captured by the strain measurement system was of 4.1%. This value is greater than that measured in the 1 ply structure at peak load. Figure 5.15(c) shows the strain distribution of the 4 ply structure at a displacement of 10mm. There are dispersed regions of higher strain throughout the sample, and definite regions of higher strain at the edges of the image, continuing down to the bottom of the image. This is in contrast to the concentrated regions at the top of the image under the load rollers that were observed in the 1 ply structure strain distribution (see Figure 5.5(c)). These high strain regions at the edges of the image suggest significant deformation may be occurring outside of the region captured by the strain analysis system. This corresponds to the shear cracks between the load and support rollers that were visually observed in the 4 ply sample.

The deformation mechanism of shear core cracking observed in the four ply sandwich structure was further investigated. Figure 5.16(a) shows an optical micrograph of a typical shear crack. These cracks most likely initiated in the region of a weak thin cell wall or localised defect and grew throughout the thickness and width of the structure, developing until it was arrested by the composite skins.
Chapter 5    Flexural behaviour of Al foam sandwich structure

Figure 5.15: Typical deformation behaviour of sample with 20mm thick Alporas core and 4 ply Twintex skins; (a) Final deformed shape, (b) Strain distribution at peak load, displacement 4.5mm, (c) Strain distribution at 10mm displacement

Figure 5.16 shows the strain distribution of the 4 ply sample with the image centred on the region between the left support and left load rollers. The strain distribution at the peak load for this sample at a displacement of 5.7mm is shown in Figure 5.16(b). The characteristic small dispersed regions of higher strain are visible throughout the sample, reflecting the cellular structure of the material. There is also the early development of another pattern: a region of higher strain extending through the centre of the core thickness and across the length of the image. This pattern is more obvious in Figure 5.16(c), which shows the strain distribution at a displacement of 10mm. This corresponds to the shear crack deformation. Figure 5.16(d) shows the strain distribution at a displacement of 20mm, where the crack has grown through the thickness of the core.
Figure 5.16: Typical deformation behaviour of sample with 20mm thick core and 4 ply skins focussing on the shear crack; (a) detail of crack, (b) Strain distribution at peak load, displacement 5.7mm, (c) Strain distribution at 10mm displacement, (d) Strain distribution at 20mm displacement
5.3.4.2 STRAIN SECTION LINE PLOTS

As before, additional investigations of the strain distribution were conducted using section planes through each of the 4 ply full-field strain distributions. Strain section line plots showing the strain distribution across the five sections were produced at the peak load and at 10mm displacement. The development of the strain in section 2 was characterized using strain line data at progressive displacement stages.

Figure 5.17 shows the strain section line plots of the 20mm core with 4 ply skin structure, for the strain distribution centred on the region between the load rollers. At the peak load, (Figure 5.17(a)), there are high peaks in the centre region for sections 1 and 3. These correspond to small spots of high strain seen in the full-field image, perhaps resulting from individual large core cells. Elsewhere, the strain magnitude is generally uniform below 10%, however there is a slight increase in magnitude for all sections at each end of the sample. This is in agreement with the visual observations of crack deformation occurring in the region outside the load rollers. Figure 5.17(b) shows the strain section line plot at 10mm displacement. At this stage in the deformation there is a definite increase in strain magnitude at each end of the sample, particularly for sections 0 and 1. The development of the strain across section 2 is shown with 6 stages in Figure 5.18. These stages correspond to the progression of the test machine crosshead displacement as follows: stage 20 = 1.7mm, stage 40 = 3.3mm, stage 60 = 5.0mm, stage 80 = 6.7mm, stage 100 = 8.3mm, and stage 120 = 10mm. In the early stages there are undulations in strain along the length of the sample. These grow in magnitude as the flexural test progresses. As noted in the previous figure, the strain appears to be increasing at each end of the sample, suggesting greater strains are occurring outside the area captured by the strain measurement system. It is likely the thicker skin has led to a greater load transfer to the core and an increase in strain in the region between the support and load rollers.
Chapter 5   Flexural behaviour of Al foam sandwich structure

Figure 5.17: Section strain line plots showing the typical strain distribution of the 20mm structure with 4ply skins for the region between the load rollers at a) peak load, 4.5mm displacement (stage 55) and b) 10mm displacement (stage 120)

Figure 5.18: Section strain line plot showing the typical progressive strain distribution of Section 2 (centre plane) across a displacement range of 1.7-10mm for the 20mm structure with 4ply skins, for the region between the load rollers

Strain section line plots were generated from the image capturing the region between the left support roller and load roller where the main deformation occurred. Figure 5.19(a) shows the line plot at the peak load, with a displacement of 5.7mm. For each section, the strain is distributed relatively uniformly along the length of the sample. Sections 1 and 2 have the greatest magnitude, corresponding to the middle section of the core thickness. Section 4 has a large peak at the right end of the sample length, which is consistent with the small concentrated region of strain visible in the full-field image. Figure 5.19(b) shows the section line plot at a displacement of 10mm. There has been a large increase in magnitude for all of the sections, throughout the sample length. Sections 1 and 2 continue to have the greatest strain values, corresponding to the large crack deformation. Figure 5.20 shows the progression of the strain along section 2 as the displacement increased. The stages
correspond to the test machine crosshead displacement as follows: stage 10 = 1.7mm, stage 20 = 3.3mm, stage 30 = 5.0mm, stage 40 = 6.7mm, stage 50 = 8.3mm, and stage 60 = 10mm. This shows the predominantly steady increase in strain magnitude along the section the flexural test progressed. This corresponds to the crack growth and deformation. There is some inconsistency in the magnitude of the strain at stage 50. This may be caused by a sudden localised failure or may be related to miscalculations in the 3D image analysis.

Figure 5.19: Section strain line plots showing the typical strain distribution of the 20mm structure with 4ply skins for the shear crack region at a) peak load, 5.7mm displacement (stage 35) and b) 10mm displacement (stage 60)

Figure 5.20: Section strain line plot showing the typical progressive strain distribution in the shear crack region of Section 2 (centre plane) across a displacement range of 1.7-10mm for the 20mm structure with 4ply skins

5.4 Summary

The failure behaviour of aluminium foam core/thermoplastic composite skin sandwich structures with varying core thicknesses was investigated under flexural loading to consider
the effect of the core thickness. Several contrasting deformation behaviours were observed and a full field strain analysis was conducted for each core thickness. The strain distributions supported the visual observations. Section strain line plots also provided an insight into the strain development within each structure. The thinner samples deformed through skin failure, with the occurrence of core deformation increasing with core thickness. The failure of the thicker samples was dominated by core deformation in the form of indentation.

The influence of skin thickness was investigated by increasing the skin from 1 to 4ply thickness. The increased skin thickness changed the bending behaviour of the structure. The samples with a single ply skin displayed indentation damage with plastic hinges forming on the upper skin either side of the load rollers. In contrast the thicker skin has produced plastic hinges forming on the lower skin at the support rollers, and significant core shear cracking in the structure. This is referred to as a ‘mode B’ type deformation [12]. This is similar to the behaviour reported by McKown et al. [68] when investigating the effect of reducing span size; where the smaller span size generated “mode B” type deformation. It appears the thicker skins have transferred more shear force to the core, resulting in the core shear plastic collapse.

The use of the optical full-field strain measurement system has shown the development of strain during the flexural testing differs greatly depending on the geometry of the sandwich structure. The strain distributions and section line plots have provided useful insight into the deformation behaviour of this composite structure. The system captured localised effects from the cellular structure as well as providing a quantitative representation of the observed failure behaviour. These results indicate a highly complex strain evolution in flexural loading, especially compared to theoretical pure plastic bending. These findings can be used to verify the performance of existing finite element modelling methods, and will be of use in driving the development of future FE models to capture more closely the complex flexural behaviour. The potential influence of a size effect in future applications of this structure can be more fully understood by further investigations with these measurement tools. Future work should include more wide-ranging geometry variations to enable a more complete understanding of the deformation and failure mechanisms.