

**Continuous ultrahigh molecular weight
polyethylene fibre as through-thickness
reinforcement for sandwich-structured composites**

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Declaration of originality

I declare the work presented hereafter is based on research carried out by the author at the Department of Aeronautics of Imperial College London and it is all the author's own work except where otherwise acknowledged. No part of the present work has been submitted elsewhere for another degree or qualification.

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Abstract

This thesis describes the design and fabrication of continuous ultra-high molecular weight polyethylene (UHMWPE) fibre as through-thickness reinforcement for sandwich-structured composites consisting of mechanically frothed epoxy foam as the foam core material. It was found that the introduction of continuous UHMWPE fibres into an epoxy foam core increased its core shear, flatwise compressive, as well as edgewise tensile properties. More importantly, the failure of the continuous UHMWPE fibre-reinforced epoxy foam in tension was delayed. This thesis also discusses the properties of sandwich-structured composites with UHMWPE fibres weaved through both the facesheets and the epoxy foam core. It was found that sandwich-structured composites consisting of continuous UHMWPE fibres performed significantly better than their discontinuous fibre-reinforced counterparts in both core shear and flatwise tension. Charpy impact test further showed that continuous UHMWPE fibre-reinforced sandwich-structured composites improved the impact toughness of the resulting sandwich-structured composites. A set of strain energy based analytical equations was derived to estimate the upper bound mechanical properties of these reinforced epoxy foams and sandwich-structured composites and compared with experimentally measured values.

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List of publications

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Conference proceeding & oral presentation at international conference

Li D, Song, W, Tagarielli, V. L, Lee K-Y, UHMWPE fibre yarn established continuous wavy network construction reinforced epoxy foam composite, European Conference on Composite Materials, 25-28th June 2018, Athens, Greece.

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Chapter 1 - Introduction

As aeronautics components are often subjected to the threat of impact from birds, hail and runway debris, the aeronautics industry has fostered the development of reinforced foam cores; embedding pins of pultruded carbon fibre-reinforced epoxy rods (X-Cor® [1] and K-Cor® [2]), dry fibre yarns (STRUCTISO® [3]) or dry fibre rovings (Airbus tied foam core [3]) in regular foams. For X-Cor®, the reinforcing pins extend beyond the thickness of the polymer foam to enhance mechanical interlocking with the facesheet materials. For K-Cor®, the pins are uncured carbon fibre-reinforced epoxy prepreps that are punched through the structural foam core. The extended length of uncured carbon fibre-reinforced prepreg pins are folded back and co-cured with the facesheet materials. Reinforced structural foam cores offer superior compressive strength and better delamination resistance than that of their unreinforced counterparts. However, these reinforced foam cores still possess low shear strength (~2.2 MPa for X-Cor® [4] and 2.0 MPa for STRUCTISO® [5]). Furthermore, the reinforcing pins and yarns are inserted through foam cores prior to the fabrication of the sandwich-structured composites. This is driven by the fact the production of foam cores relies on first producing blocks of foam core prior to precisely machining the block to the desired shape, followed by insertion of the reinforcement.

A simple, scalable and waste-free manufacturing process of epoxy foams with density as low as 180 kg m^{-3} without the need of a blowing agent has recently been developed [6,7] (see Figure 1-1). This process is based on the principle of liquid-foam templating technique, whereby an uncured epoxy resin is first mechanically frothed to produce a liquid epoxy foam. This liquid foam, which does not undergo phase separation due to the high viscosity of the epoxy resin, can then be poured, shaped or moulded, followed by curing to produce an epoxy foam.

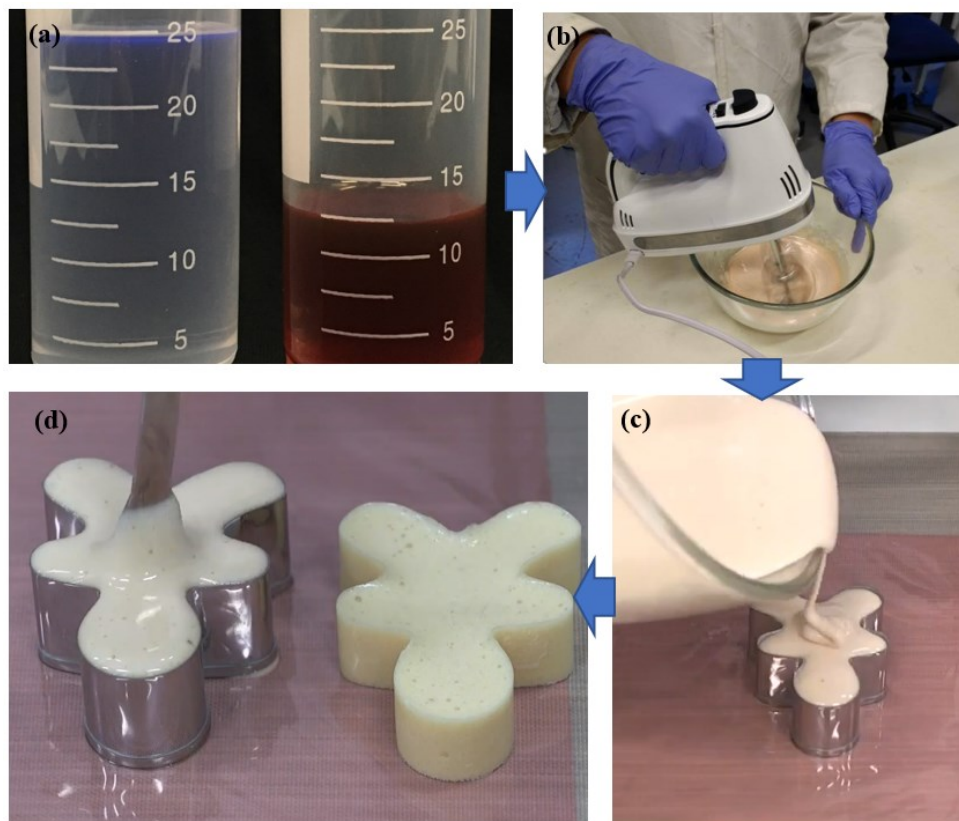


Figure 1-1 (a)-(c) The process of liquid epoxy foam templating; (d) Liquid-foam template on the left and cured epoxy foam on the right

The previously introduced air bubbles form the pores or cells of this epoxy foam. Unlike the production of conventional cellular materials, no expansion or

shrinkage occurred during curing. Thus, the final shape and geometry of the resulting epoxy foam is determined by mould used for liquid epoxy foam. The porosity of these mechanically frothed macroporous polymers could further be controlled by using heat [7]. This provides an exciting opportunity to produce through-thickness reinforced foams that does not require the insertion of through-thickness reinforcement through a block of polymeric foam.

1.1 Aim and objectives of this thesis

By combining liquid epoxy foam templating technique with a high-performance fibre as the continuous through-thickness reinforcement, it is envisaged that a novel sandwich-structured composite can be produced. The application of a continuous fibre reinforcement within the sandwich-structured composites is expected to improve the shear and tensile properties of the sandwich core structure by at least 50% to existing foams. A significant increase in the damage tolerance of this novel sandwich-structured composite is also anticipated. Therefore, the aim of the proposed research is to produce a novel integrated sandwich-core structure consisted of carbon fibre-reinforced polymer (CFRP) facesheets and high-performance mechanically frothed epoxy foam core reinforced with continuous ultra-high molecular weight polyethylene (UHMWPE) fibres weaved through both the CFRP facesheets and the epoxy foam core in a rapid and waste-free manner. The specific objectives are:

- To derive the optimum processing parameter to reinforce mechanically frothed epoxy foam core with continuous UHMWPE fibres;

- To develop and optimise a rapid and waste-free liquid foam moulding technology to fabricate the novel integrated structures consisting of continuous UHMWPE fibres weaved through CFRP facesheets and epoxy foam cores;
- To investigate the mechanical response of the reinforced foam cores in tension, compression, shear and Charpy impact.

1.2 Structure of this thesis

This thesis is divided into 7 chapters.

- Chapter 1 (current chapter) introduces the motivation and objectives of this thesis;
- Chapter 2 reviews the manufacturing methods of various polymeric foam, followed by the mechanics of cellular materials and sandwich-structured composites. In addition to this, the state-of-the-art of through-thickness reinforced sandwich-structured composites is also discussed;
- Chapter 3 demonstrates a simple strain energy-based analytical models to estimate the upper bound tensile, compressive and core shear properties of polymeric foam containing through thickness reinforcement are derived. These models are used in subsequent chapters to compare the experimentally obtained tensile, compressive and core shear properties of the reinforced epoxy foams;
- Chapter 4 describes the production and core shear properties of the through-thickness fibre-reinforced sandwich-structured composite containing

continuous UHMWPE fibre as reinforcement;

- Chapter 5 describes the properties of sandwich-structured composites consisting of epoxy-coated, continuous, UHMWPE fibre as through thickness reinforcement;
- Chapter 6 describes the fabrication of integrated structures consisting of continuous UHMWPE fibres weaved through CFRP facesheets and epoxy foam cores is discussed;
- Chapter 7 summarises the conclusion of this PhD thesis and recommendations for future work are provided.

Chapter 2 - Literature review

Cellular structure, or a foam, is a porous material consisting of a solid matrix and a gas phase. These materials are lightweight, possess good insulating and energy absorbing abilities, which makes them widely used in many applications. Foams can be classified as open- and closed-cell based on their pore geometries. In an open-cell foam, the pores are interconnected while in a closed-cell foam, the pores are not interconnected. Instead, the pores are completely enclosed by the surrounding matrix [8] (see Figure 2-1).

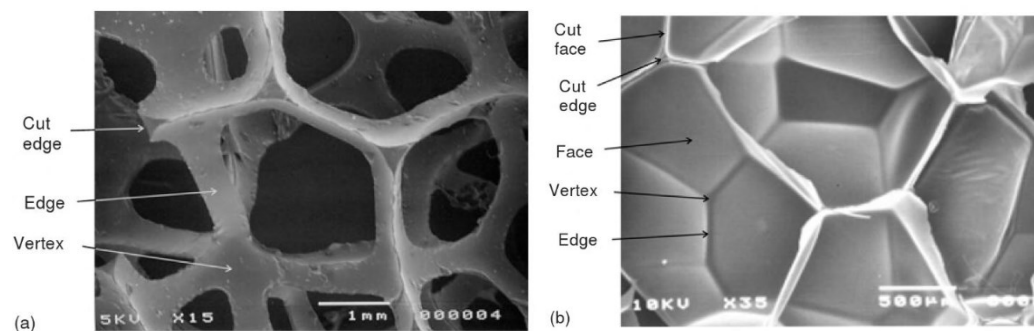


Figure 2-1 Scanning electron microscope (SEM) images of an (a) open-cell and a (b) closed-cell polyurethane (PU) foams. Obtained from ref. [8].

In addition to this, foams can also be classified based on their stiffness, e.g. rigid or flexible foams [9]. A rigid foam is typically made from a semi-crystalline polymer with a high glass transition temperature [10] or a polymer with a highly crosslinked network [11]. Rigid foams are often utilised as critical load bearing applications [12] due to their excellent impact resistance, high strength and stiffness to weight ratios [13]. A flexible

foam is made from a polymer with a low glass transition temperature [10] or a polymer with a moderate crosslinked network [11]. Flexible foams are used in applications like furniture cushions, mattresses, packaging and insulation materials [14]. In terms of materials of choice, commonly used polymeric foams are typically made from polyurethane (PU) [15], phenolic [16], epoxy [17], polyisocyanurate (PIR) [18]. Thermoplastic foams are typically made from polyvinyl chloride (PVC) [19], polystyrene (PS) [20], polycarbonate (PC) [21], polyethylene (PE) [22], polyolefin [23] and polymethacrylimide (PMI) [24]. Within these choices of material, epoxy-based foam is of particular interest which possesses good thermal and chemical stabilities and excellent dielectric properties [25]. Furthermore, epoxy foam is among the hardest and stiffest foams due to the highly crosslinked network [9].

This literature review chapter starts with a concise discussion of how commonly used polymeric foams are manufactured, followed by an in-depth discussion of mechanical frothing method (the foam manufacturing method used in this thesis) to produce polymeric foams. This is then followed by the literature review of the deformation mechanics of cellular structures, sandwich-structured composite and the development of reinforced sandwich-structured composites.

2.1 Manufacturing methods of polymeric foams

Various polymeric foams manufacturing methods have been developed throughout these years. Normally, the foaming process is conducted when the material is in its liquid state. For thermoplastics, the foaming process is conducted in the melt state. For

thermosets, the foaming process usually happens during the curing reaction. In both cases, the foamed system needs to be stabilised to ensure the final product retain the developed pore structures.

2.1.1 Chemical and physical foaming methods

The foaming processes are typically initiated chemically [26–28] and physically [29]. Chemical foaming is achieved by the decomposition of a chemical blowing agent through the application of heat or an exothermic reaction to generate gas. A high volume of gas is liberated and trapped within the polymer in its melt state (in the case of thermoplastics) or within its oligomer/partially crosslinked material in its liquid state (in the case of thermosets) to form the pores. The most commonly used chemical blowing agents are: azodicarbonamide (ADC) [30], 4,4-oxybis benzene sulfonyl hydrazide (OBSH) [31], p-toluene sulfonyl hydrazide (TSH) [32], 5-phenyltetrazole (5-PT) [33], p-toluene sulfonyl semicarbazide (PTSS) [34], dinitroso-pentamethylenetetramine (DNPT) [35], sodium bicarbonate (SBC) [36] and zinc carbonate (ZnCO_3) [37,38]. Physical foaming works by volatilising a low boiling liquid or expanding dissolved inert gas inside the melt state of a thermoplastic or the liquid state of a partially crosslinked system to grow the pores [39,40]. Commonly used physical blowing agents include low boiling point freons, halocarbon [41], n-pentane and methyl formate [42], nitrogen [43], helium [44]. Supercritical carbon dioxide [45] is also used due to their inert, non-inflammable nature. Figure 2-2 shows the pore structure of typical cellular structure of an ADC blown closed-cell polyethylene foam.

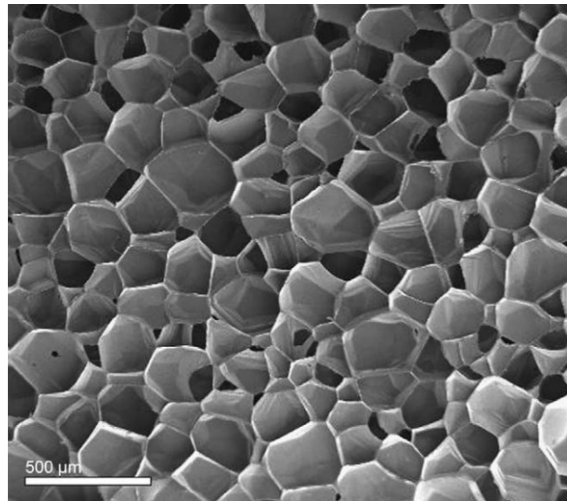


Figure 2-2 SEM image of closed-cell polyethylene foam (azodicarbonamide as the chemical blowing agent). Obtained from ref. [46]

2.1.2 Syntactic foam manufacturing method

Syntactic foam is a type of foam consists of a dispersion of hollow microspheres within a rigid polymer matrix [47]. The manufacturing method of syntactic foam differs from traditional polymeric foams as the porosity of the resulting syntactic foam is determined by the amount of hollow microspheres added [48], instead of generated through chemical or physical blowing agents. Microspheres are normally made from glass [49], carbon [50], phenolic [51] or polyvinylidene chloride (PVDC) [52]. The fabrication of a syntactic foam can be split into the powder resin approach [53–55] and the liquid resin approach [48,56]. The powder resin approach is achieved by mixing the microspheres and solid thermoplastic powders uniformly then followed by melting the thermoplastic powders with an application of heat. The formation is completed when the syntactic foam is solidified [55]. The liquid resin approach is achieved by adding microspheres into a liquid resin (can be either thermoset or thermoplastic) and gently mixed to avoid

gas bubbles generated. A vacuum is used to further ensure no unwanted voids. The syntactic foam is then produced by curing or solidifying the resin-microspheres mixture [57]. Figure 2-3 shows the pore structure of typical epoxy resin based syntactic foam filled with hollow glass microspheres.

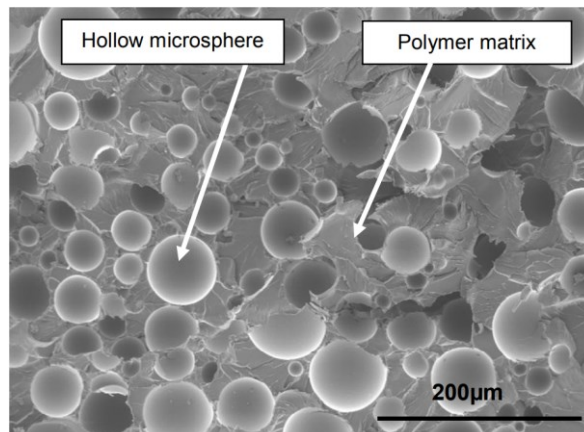


Figure 2-3 SEM image of epoxy resin based syntactic foam filled with hollow glass microspheres. Obtained from ref. [58]

2.1.3 Mechanical frothing as route to produce polymeric foams

Polymeric foams can be also produced using the mechanical frothing method. In this method, gas is entrained into a liquid, typically a monomer, by rapidly frothing. A stable liquid-foam template can then be formed if the liquid possesses suitable surface properties and viscosity. This liquid-foam template can be moulded into any shapes and polymerised to produce a polymer foam [59].

The mechanical frothing method was originally used to produce latex rubber foam [60]. Marlin et al. [61] firstly employed this mechanical frothing method to produce

polyurethane foam. This polyurethane foam was produced by using an industrial mixer to froth an isocyanate and polyol mixture to entrain air and generate a liquid-foam template. This was then followed by the curing of the liquid-foam template at 150 °C for 5 min. The mechanically frothed polyurethane foam was found to possess a density of 300 kg m⁻³ and a tensile strength of 0.68 MPa. In this specific study, the authors managed to produce a polyurethane foam with a maximum thickness of only ~6 mm as their targeted application was in man-made leather, carpet backing and gaskets.

Open-cell PVC flexible foams have also been produced using the mechanical frothing method [62]. The PVC foam was manufactured by mechanically frothing plastisol mixture using a hand mixer. The mechanically frothed plastisol mixture was poured into Teflon-lined baking pans and heat was applied to cure the mechanically frothed liquid foam. At a PVC foam density of 336 kg m⁻³, a tensile modulus of 0.18 MPa and a tensile strength of 0.06 MPa were obtained by the authors. The use of plasticizer was found to decrease the density of the foam but also the mechanical properties. The authors also observed that using higher mechanical frothing speed (128-220 rpm) could potentially shorten the required mechanical frothing time to only 5-7 min to produce same liquid foam. However, the density of the foam was difficult to control by using high speed.

More recently, Lee et al. [63] mechanically frothed acrylated epoxidised soybean oil (AESO) to produce AESO-in-air liquid-foam, followed by microwave-assisted polymerisation to produce polymerised AESO (polyAESO) foam. The resulting

polyAESO foam possessed a density of 440 kg m^{-3} , with a compressive modulus and a compressive strength of 111 MPa and 0.34 MPa, respectively. However, the pore structure of this polyAESO foam was found to be poor and irregular (see Figure 2-4). Even though the viscosity of AESO was high enough ($\sim 1000 \text{ mPa s}$) to be mechanically frothed successfully, the polymerisation process led to significant phase separation as the heat was applied when the AESO-in-air liquid-foam was exposed to microwave, which led to a decrease in the viscosity of AESO prior to gelation.

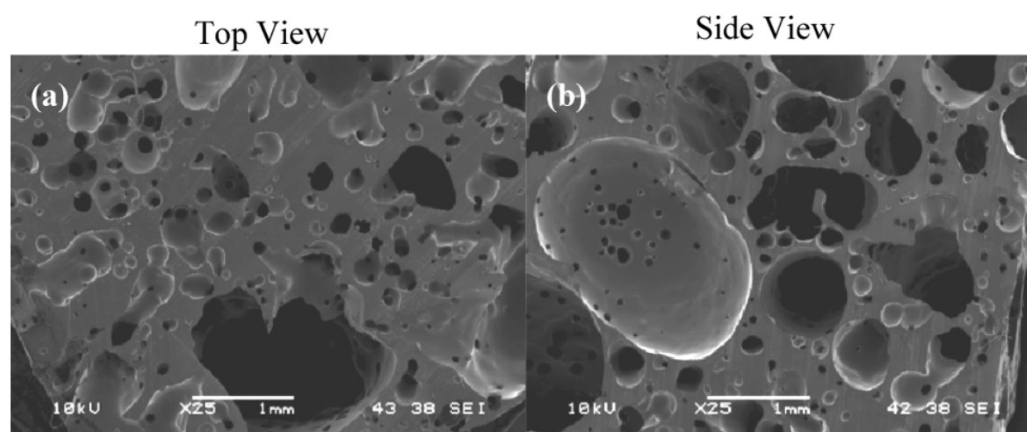


Figure 2-4 SEM images of mechanically frothed polyAESO foam. Obtained from ref. [63]

Nevertheless, the same group of authors circumvented this problem with the use of very viscous bio-based epoxy resin ($\sim 2500 \text{ mPa s}$) and a short gel time ($< 1 \text{ h}$) [6]. Once the highly viscous bio-based epoxy and hardener mixture were mechanically frothed, the resulting liquid epoxy foam template did not exhibit phase separation, even when stabilisers were not used. The liquid epoxy foam template was cured at room temperature. It was found that the cured mechanically frothed epoxy foam possessed a spherical closed-cell pore structure due to the surface tension tended to minimise the surface area and spherical shape has the minimum surface area with a given volume

[64] (see Figure 2-5) and densities of the cured mechanically frothed epoxy foams ranged from 224 to 293 kg m⁻³ (depending on the mechanical frothing time).

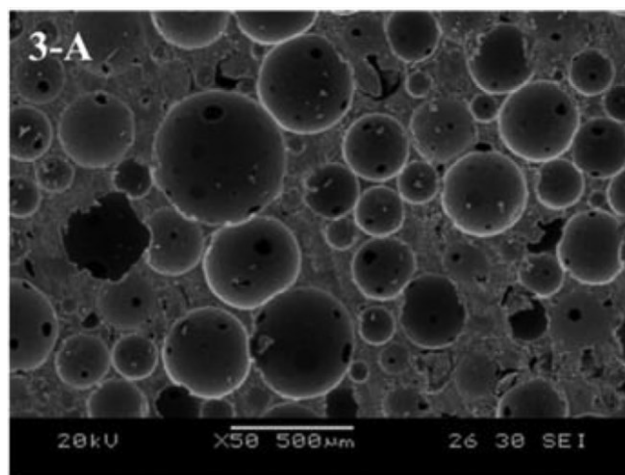
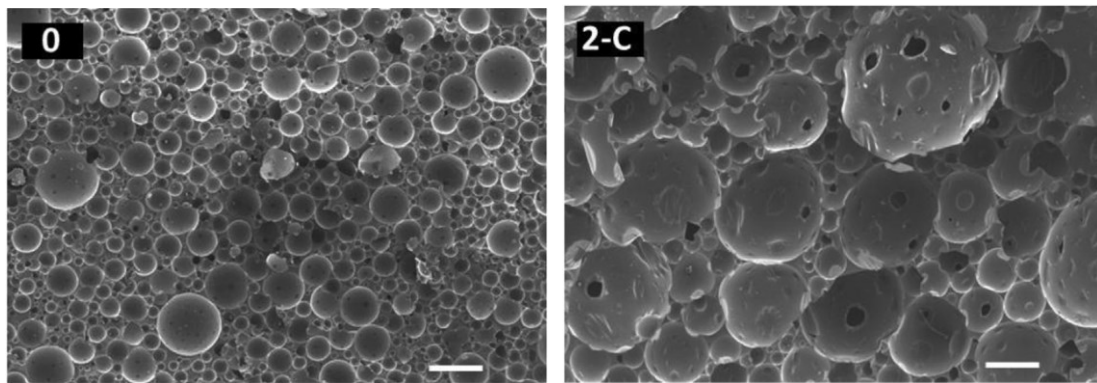


Figure 2-5 SEM images of mechanically frothed bio-based epoxy foam. Obtained from ref. [6]

The same group of authors further reported the use of heat to reduce the density of the mechanically frothed epoxy foams [7]. The application of heat increased the pressure inside the air bubbles trapped during the mechanical frothing of the epoxy resin. As a result, the bubble expanded further whilst the surrounding epoxy resin was undergoing a heat-induced curing reaction. This led to a reduction the porosity of the final heat-induced mechanically frothed epoxy foam. Neat mechanically frothed epoxy foams possessed a density of 350 kg m⁻³ whilst the heat-induced mechanically frothed epoxy foams decreased to 180 kg m⁻³ (see Figure 2-6). This was also accompanied by a decrease in the compressive modulus and strength of the epoxy foams from 231 MPa and 5.9 MPa, respectively, for unheated epoxy foams, to 58 MPa and 1.9 MPa, respectively for heat-induced mechanically frothed epoxy foams.



(a)

(b)

Figure 2-6 SEM images of mechanically frothed bio-based epoxy foam with a density of (a) 350 kg m^{-3} and (b) 180 kg m^{-3} . Obtained from ref. [7]

2.2 Mechanics of cellular materials – a brief overview

2.2.1 Introduction

As the deformation mechanics of mechanical frothed epoxy foams in this thesis will be important in subsequent chapters, this literature review chapter also includes a short description of the deformation mechanics of cellular materials and sandwich-structured composites.

2.2.2 Deformation of cellular materials

Gibson and Ashby [65] developed a simple 3D unit cell model (see Figure 2-7) to simplify the cellular microstructure into a single microscale cubic array unit cell. Open- and closed-cell foams were analysed for their different configuration. The open-cell cubic structure consists of beams representing for the cell walls. Closed-cell also has cell faces and gas is trapped inside.

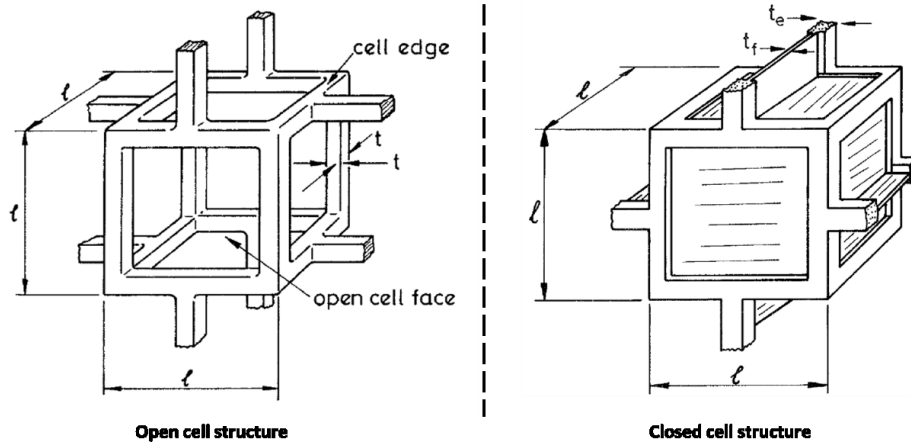


Figure 2-7 Schematic of Gibson and Ashby model for open and closed cell foam. Obtained from Ref. [65]

The elastic deformation of the open cell foam was mainly determined by the bending of cell walls. The stiffness of the foam has a relationship with its matrix material and their relative density. For the open-cell foam, the following simple expression is used for the prediction of the Young's modulus of a foam (E_f) [65]:

$$E_f \approx C_1 E_s \left(\frac{\rho_f}{\rho_s} \right)^2 \quad (2.1)$$

where E_s is the Young's modulus of the matrix material, ρ_f and ρ_s represent the density of foam and matrix material, respectively. C_1 is a geometric constant and based on the experimental data, which is approximately 1 [65]. The shear modulus of a foam G_f can be written as [65]:

$$G_f \approx C_2 E_s \left(\frac{\rho_f}{\rho_s} \right)^2 \quad (2.2)$$

where $C_2 \approx \frac{3}{8}$ based on experimental data [65].

For the closed-cell foam, the stretch of the cell faces and the compression of the internal gas are two extra factors considered. The equation is written as [65]:

$$E_f \approx \phi^2 E_s \left(\frac{\rho_f}{\rho_s} \right)^2 + (1 - \phi) E_s \left(\frac{\rho_f}{\rho_s} \right) + \frac{p_0(1 - 2\nu)}{\left(1 - \frac{\rho_f}{\rho_s} \right)} \quad (2.3)$$

where ϕ is the volume fraction of matrix material contains in cell walls and $(1 - \phi)$ is the rest in cell faces. p_0 is the internal gas pressure and ν is the Poisson's ratio of the foam. In pure shear, the pore volume does not change but could stretch the pore faces of closed cell foam. The shear modulus of a closed-cell foam could be written as [65]:

$$G_f \approx \frac{3}{8} E_s \left\{ \phi^2 \left(\frac{\rho_f}{\rho_s} \right)^2 + (1 - \phi) E_s \left(\frac{\rho_f}{\rho_s} \right) \right\} \quad (2.4)$$

The collapse mechanisms of a foam depends on the behaviour of the cell wall materials. For elastoplastic rigid foams, plastic yielding occurs when the stress increases beyond the linear-elastic regime. The strain is no longer recoverable when yielding starts. For the open-cell foam, this plastic collapse happens when the load applied on cell walls exceeding the plastic bending moment (see Figure 2-8).

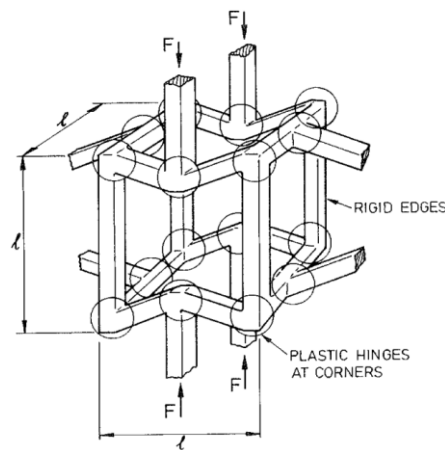


Figure 2-8 Schematic of Gibson and Ashby model for open cell foam in plastic yielding. Obtained from Ref. [65]

The plastic-collapse strength of the open-cell foam can be expressed as [65]:

$$\sigma_f \approx 0.3\sigma_{ys} \left(\frac{\rho_f}{\rho_s} \right)^{3/2} \quad (2.5)$$

where σ_{ys} is the yield strength of the matrix material.

The plastic-collapse of a closed cell foam is more complex as it includes the effects of cell faces and internal gas. The crumple or plastic-stretching of the cell faces contribute to the yield strength of the foam. The contribution of gas depends on its internal pressure. If the gas pressure (p_0) is at atmospheric pressure (p_{at}), then the influence of gas can be ignored during the calculation. The plastic-collapse strength of the closed-cell foam can be written as [65]:

$$\sigma_f \approx 0.3\sigma_{ys} \left(\phi \frac{\rho_f}{\rho_s} \right)^{\frac{3}{2}} + 0.4\sigma_{ys}(1 - \phi) \frac{\rho_f}{\rho_s} + p_0 - p_{at} \quad (2.6)$$

2.2.3 Deformation mechanics of sandwich-structured composites

When a foam core is bonded between two thin facesheets, a sandwich-structured composite is formed. The mechanical behaviour of a sandwich-structured composite is very different from the mechanical behaviour of the neat foam core. In flatwise compression and tension, the foam core bears the major stress and therefore the deformation mechanism of a sandwich-structured composite is dominated by the foam core. In bending, fatigue, impact, edgewise loading etc., the facesheets play an essential role in the sandwich-structured composite and the foam core is undergoing multiple

stresses. Beam theory can be used to analyse the mechanical properties of a sandwich-structured composite under three-point bending to elucidate the sandwich mechanism [66].

Figure 2-9 shows an idealised sandwich-structured composite with a thickness of facesheet (t), thickness of foam core (c) and width of sandwich-structured composite (b). The sandwich-structured composite is simply supported and loaded in three-point bending with an applied load of (P).

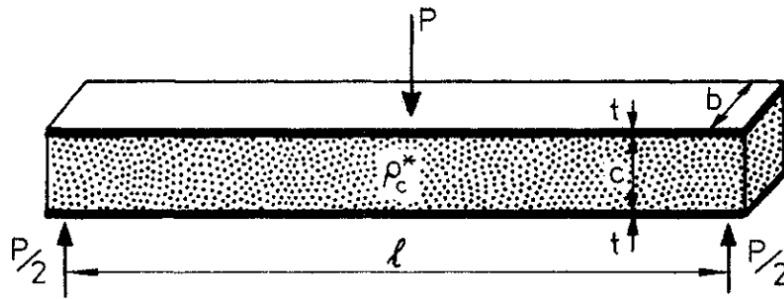


Figure 2-9 Schematic of foam core sandwich-structured composite under three-point bending loading. Obtained from Ref. [65]

The flexural stiffness (D) of the sandwich-structured composite can be expressed as [66]:

$$D = \frac{E_{fa}bt^3}{6} + \frac{E_{fa}btd^2}{2} + \frac{E_{co}bc^3}{12} \quad (2.7)$$

where E_{fa} , E_{co} are the Young's moduli of facesheet and core material, respectively, and $d = c + t$.

In equation 2.7, $\frac{E_{fa}bt^3}{6}$ and $\frac{E_{co}bc^3}{12}$ represent the flexural stiffness of the facesheet and core material, respectively. The term $\frac{E_{fa}btd^2}{2}$ is an associated term about the centroid axis bending of the whole sandwich-structured composite, which would not exist if there is no bonding between the facesheets and core.

The bending stresses in the facesheets (σ_{fa}) and foam core (σ_{co}) are [67]:

$$\sigma_{fa} = \frac{Mz}{D} E_f \quad (2.8)$$

$$\sigma_{co} = \frac{Mz}{D} E_c \quad (2.9)$$

where M is the bending moment at the cross-section of the sandwich-structured composite and z is the distance from centroid axis. The shear stress in the foam core can be written as [67]:

$$\tau_{co} = \frac{P_s}{2D} \left(\frac{E_{fa}td}{2} + \frac{E_{co}}{2} \left(\frac{c^2}{4} - z^2 \right) \right) \quad (2.10)$$

where P_s is the shear force at the cross-section. Foam core is normally much weaker than the facesheets and therefore are assumed to be $E_{co} = 0$. The equation can then be re-written as [67]:

$$\tau_{co} = \frac{P_s}{2D} \cdot \frac{E_{fa}td}{2} \quad (2.11)$$

In equation 2.7 (bending stiffness calculation), it should be noted that the magnitude of

$\frac{E_{fa} b t d^2}{2}$ is much larger than $\frac{E_{fa} b t^3}{6}$ and $\frac{E_{co} b c^3}{12}$, thus,

$$D \approx \frac{E_{fa} b t d^2}{2} \quad (2.12)$$

Hence, the simplest possible form of core shear stress can be written as:

$$\tau_{co} \approx \frac{P_s}{2 b d} \quad (2.13)$$

The deflection at the mid-span δ consists of two partial deflections, including bending deflection δ_D and shear deflection δ_S , which can be expressed as:

$$\delta = \delta_D + \delta_S = \frac{P l^3}{48 D} + \frac{P l}{4 S} \quad (2.14)$$

in which, the shear rigidity S is calculated as [67]:

$$S = \frac{b d^2}{c} G_{co} \quad (2.15)$$

where G_{co} is the shear modulus of the core.

In addition to this, the multiple stresses in a sandwich-structured composite loaded in three-point bending could result in different types of failure mechanisms. Possible failures including face micro-buckling, core shear, indentation (see Figure 2-10) and the critical forces to trigger each of the failure modes are summarised here [68].

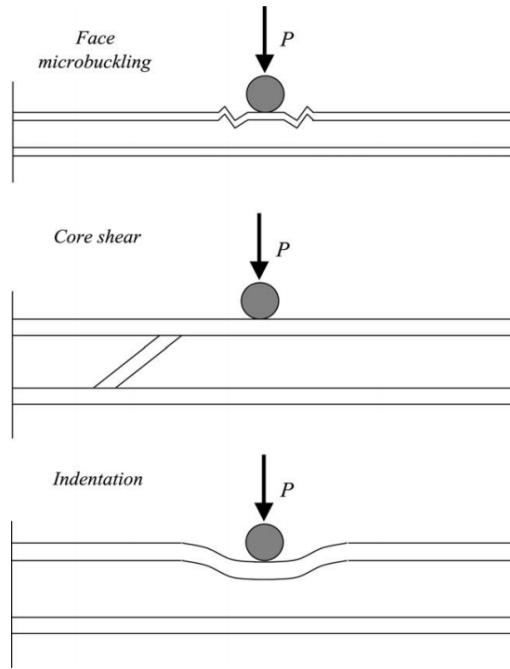


Figure 2-10 Failure modes of sandwich-structured composite subjected to three-point bending loading. Obtained from Ref. [68]

Face micro-buckling is a failure mode of sandwich-structured composite when the load reaches the micro-buckling strength (σ_{fm}) of the upper facesheet without the failure of foam core. The critical load (P_{fm}) to initiate microbuckling is [68]:

$$P_{fm} = \frac{4dbt\sigma_{fm}}{l} \quad (2.16)$$

If a uniform shear strength (τ_s^*) causes the shear failure in the foam core, the load (P_{cs}) to initiate this mechanism is [68]:

$$P_{cs} = 2bd\tau_s^* \quad (2.17)$$

Indentation happens is when the local compression causes yielding collapse of the foam core while the facesheets still remain the elasticity, the load (P_{in}) to initiate the mechanism is [68]:

$$P_{in} = bt \left(\frac{\pi^2 d E_{fa} \sigma_c^{*2}}{3l} \right)^{1/3} \quad (2.18)$$

where E_{fa} is the Young's modulus of the facesheet and σ_c^* is the compressive strength of the core. The failure mechanism of the sandwich structural composite under three-point bending loading condition is determined by the applied load first reaches the corresponding critical load.

2.3 Reinforced sandwich-structured composites

2.3.1 Introduction

Polymeric foam core-based sandwich-structured composites exhibit excellent mechanical performance under static compression and tension, as well as dynamic impact [69–73]. However, facesheet-core debonding issue has been a major concern in the application of polymeric foam core-based sandwich-structured composites for various engineering applications [73]. As a result, several technologies, including Z-pinning and stitching, have been introduced to enhance the out-of-plane properties and debonding resistance of polymeric foam core-based sandwich structure composite [74]. Z-pinning is achieved by using discrete solid pins [75] while stitching is by using continuous fibre yarns [76]. Commercial products of both types of reinforced sandwich-structured composites exist and used in the aerospace industry. This section discusses

the properties of Z-pinned sandwich-structured composites and stitched sandwich-structured composites.

2.3.2 Z-pinned sandwich-structured composites

A Z-directional pinning technology to reinforce foam core sandwich-structured composite has been developed over the last two decades [77,78]. The idea of Z-pinning was originally used to improve the delamination resistance of carbon fibre and glass fibre reinforced polymers (CFRPs and GFRPs) by inserting metal pins into the laminates in 1970s [79]. Similar to Z-pinned CFRP, Z-pinned sandwich-structured composites are created by punching discrete pins through the polymeric foam core at an orthogonal or inclined angle [80]. Pins are typically made of stiff and strong metal or carbon fibre reinforced polymers. Metallic pins are manufactured by extrusion. Composite pins are fabricated by pulling continuous fibre bundle through a resin bath, followed by curing of the resin. The diameter of the pins ranges from 0.2-1.0 mm [81]. Closed-cell PMI foam is the most commonly used foam core for Z-pinning as it possesses outstanding mechanical performance, as well as low density of 30 to 200 kg m⁻³ [82]. The insertion of Z-pins could be achieved by using an ultrasonic device to generate high frequency compressive waves to punch the pins into the foam core directly or the sandwich-structured composite when the composite facesheets are in uncured condition [80,83]. After autoclaving to cure the facesheets, the embedded ends of pins in the facesheets are fixed. The insertion can also be achieved by drilling [84]. The commercial name of this type of structure is also known as X-Cor[®] (see Figure 2-11)

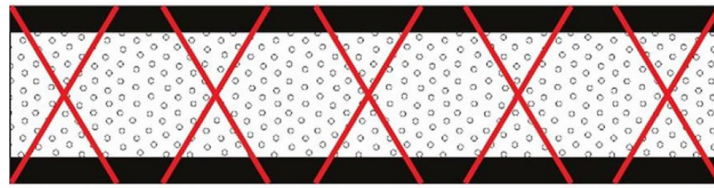


Figure 2-11 Schematic of X-Cor® Z-pinned sandwich-structured composite. Obtained from Ref. [73]

Numerous studies concerning the properties of Z-pinned sandwich-structured composites have been published [75,80,85–87]. Cartie and Fleck [83] compared both T300 carbon/bismaleimide (BA) pins and titanium alloy pins as the through thickness reinforcement for PMI foam core sandwich-structured composite. In this study, the authors studied sandwich-structured composites with different foam core thickness (5 - 20 mm) and densities (31 and 51 kg m⁻³). The inserting angle of the pins were 30° to the perpendicular direction with pyramidal arrangement and the diameter of pins was 0.5 mm. At 3.6 vol.-% of the pins, the compressive strength of the PMI foam increased from 0.4 MPa to more than 10 MPa. The buckling of pins was found to contribute to the increase in the compressive strength of the sandwich-structured composites (see Figure 2-12). However, the authors did not find significant differences between the reinforcing potential of using composite pins and metallic pins in this study.

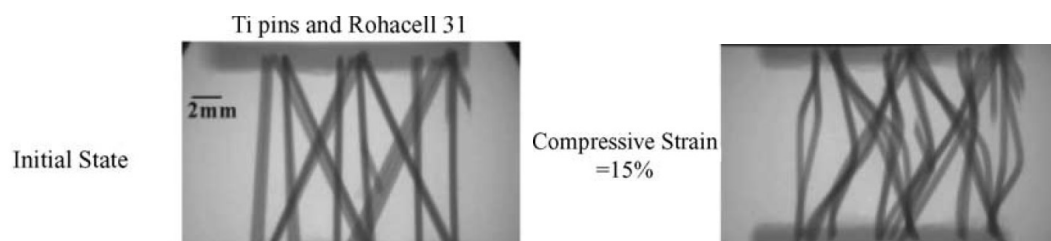


Figure 2-12 In situ X-ray images of pin buckling in Z-pinned sandwich-structured composite under compressive loading. Obtained from Ref. [88]

Thinner T300 carbon/BA pins with a diameter of 0.28 mm was also used to reinforce 75 kg m⁻³ PMI foam core sandwich-structured composite [80]. The inserting angle of the pins was 5-6° to the orthogonal direction. The compressive modulus of the Z-pinned sandwich-structured composite improved from 91 MPa (unreinforced sandwich-structured composites) to 253 MPa (2 vol.-% pin reinforced sandwich-structured composites). The compressive strength of the pin-reinforced sandwich-structured composite increased from 1.6 MPa (unreinforced) to 4.9 MPa (2 vol.-% of the pins). Drop weight impact testing (10-50 J energy levels) was conducted for these Z-pinned sandwich-structured composites. At low impact energy levels of up to 30 J, the foam was compressed elastically and the majority of the pins were undamaged, leading to no significant improvement in energy absorption (see Figure 2-13 (a) and (b)). However, a smaller debonding area was observed for Z-pinned sandwich-structured composite. At high impact energy levels between 30 J to 50 J, the energy absorption of the Z-pinned sandwich-structured composites increased slightly by about 10% compared to unreinforced sandwich-structured composites. This increase was attributed to pin-failure under the impact area (see Figure 2-13 (c) and (d)).

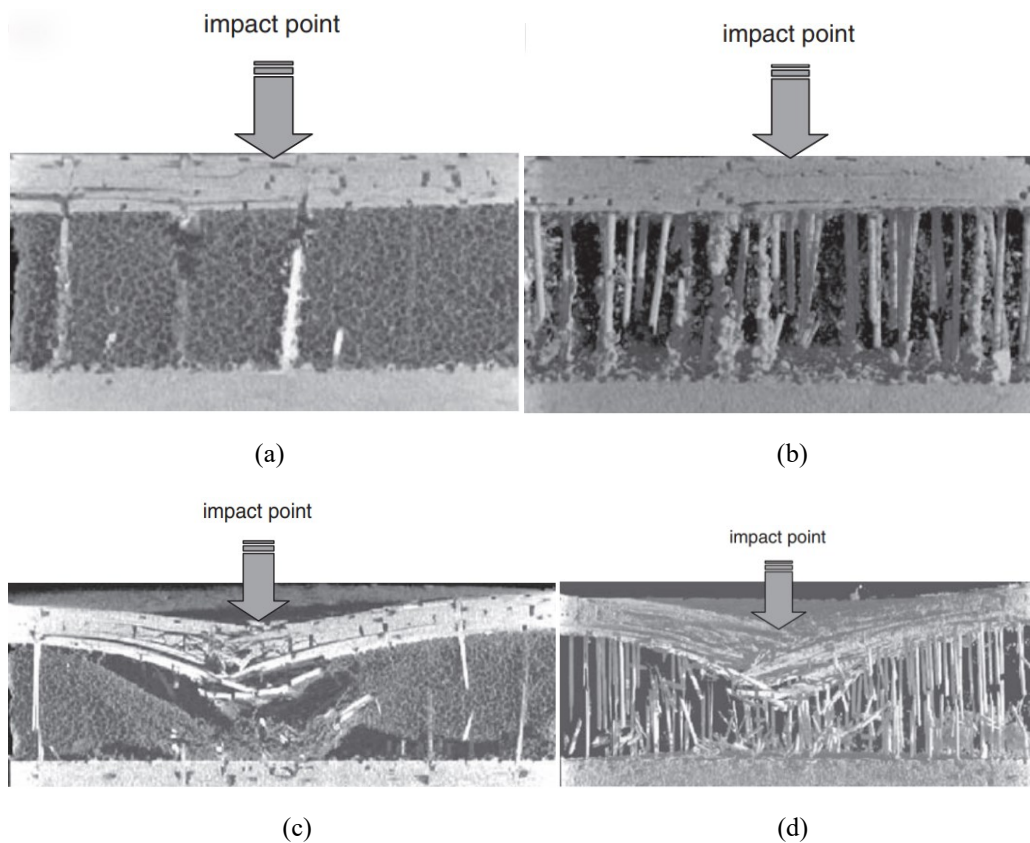


Figure 2-13 X-ray computed tomography images of the Z-pinned sandwich-structured composite after impact (a) and (b) were conducted at impact energy of 20J, (c) and (d) were conducted at impact energy of 40 J. In (b) and (d), the cores were digitally removed to reveal the Z-pins. Obtained from Ref. [80]

Vaidya et al. [89] studied the impact response of Z-pinned sandwich-structured composite reinforced with 0.5 vol.-% thick titanium alloy pins (with a diameter of 0.89 mm). A 75 kg m^{-3} PMI foam core and pins with an inserting angle of 10° to the orthogonal direction were used in this study. Drop-weight impacts (11-40 J energy levels) were conducted. The damage area was found to be confined by the pins nearby the impact zone without propagating through the bonding between the upper facesheet and foam core. However, the energy absorption ability of Z-pinned sandwich-structured composite was not quantified in this study.

The effect of pin volume fraction of Z-pinned sandwich-structured composite was studied in [86]. A PVC foam density of 90 kg m^{-3} was used in the sandwich-structured composites. The loading fraction of the pins was varied from 0.5 - 4 vol.-%. The authors found that the compressive modulus of the Z-pinned sandwich-structured composite increased from 43 MPa (0.5 vol.-% pin) to 111 MPa (4 vol.-% pin) and compressive strength increased from 3.5 MPa (0.5 vol.-% pin) to 12 MPa (4 vol.-% pin). The modulus and strength increased linearly with the pin volume fraction. The authors also investigated the influence of pin diameter on the compressive properties of their resulting Z-pinned sandwich-structured composite. It was found the use of thicker pins ($\varnothing = 0.51 \text{ mm}$) does not significantly improve the compressive properties of the Z-pinned sandwich-structured composite compared to thinner pins ($\varnothing = 0.28 \text{ mm}$) in this study at the same pin volume fraction (2 vol.-% pin).

In addition to an improvement in compressive performance, the core shear performance of sandwich-structured composite can also be improved with Z-pinning. Du et al. [84] studied the core shear performance of T300 carbon/BA pin reinforced sandwich-structured composite consisting of PMI foam core. Four different foam densities were used (ranging from 32 to 110 kg m^{-3}). The pinning angles in this study were $+15^\circ$, -15° and $\pm 15^\circ$ arranged as 'X' to the orthogonal direction. It was observed that foam core failure and pin pull-out were the main failure mechanisms in core shear. The same amount of stiffness was provided by pins in tension and compression directions. For 32 kg m^{-3} foam core, the core shear modulus and core shear strength of Z-pinned sandwich-structured composite with $\pm 15^\circ$ pins increased from 13 MPa (unreinforced) to 67.5 MPa

(32 kg m⁻³ foam) and 0.4 MPa (unreinforced) to 1.07 MPa (32 kg m⁻³ foam), respectively. For 75 kg m⁻³ foam, core shear modulus and strength of increased from 29 MPa (unreinforced) to 96.9 MPa (75 kg m⁻³ foam) and 1.3 MPa (unreinforced) to 1.75 MPa (75 kg m⁻³ foam), respectively. However, for 110 kg m⁻³ foam, the core shear strength decreased from 2.4 MPa (unreinforced) to 1.79 MPa (110 kg m⁻³ foam). However, the authors did not provide an explanation for this observed decrease at high foam density.

In addition to X-Cor[®] Z-pinned sandwich-structured composite, a structure with a commercial name K-Cor[®] (see Figure 2-14) was developed [2]. The aim of K-Cor[®] was to reduce the chances of pin pull-out in X-Cor[®]. In K-Cor[®], pins no longer penetrate the whole sandwich. Instead of using rigid cured pins, partially cured pins are inserted into foam core. The parts of pins beyond the foam core are folded back to the foam core by applied moderate heat and pressure. The pre-cured CFRP and metallic facesheets can be adhesively bonded onto the foam core to finish fabrication [90].

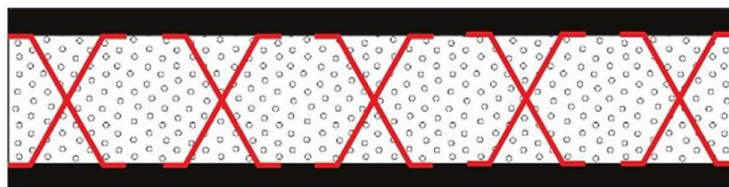


Figure 2-14 Schematic of K-Cor[®] Z-pinned sandwich-structured composite. Obtained from Ref. [73]

The mechanical performance of X-Cor[®] and K-Cor[®] has been compared in flatwise compression, flatwise tension and core shear [90]. T300 carbon/BA pins with a

diameter of 0.51 mm were used to reinforce the sandwich-structured composite consisting of PMI foam core. Two X-Cor[®] samples with 22° and 30° pinning angle to the orthogonal direction and K-Cor[®] sample with 30° pinning angle to the orthogonal direction were prepared in this study.

For X-Cor[®], the sample with 22° pinning angle exhibited better properties in compression and tension compared to the sample with 30° pinning angle. X-Cor[®] with 22° pinning angle possessed compressive modulus, tensile modulus, compressive strength and tensile strength of 508 MPa, 350 MPa, 5.0 MPa and 2.5 MPa, respectively. X-Cor[®] at 30° pinning angle was found to possess compressive modulus, tensile modulus, compressive strength and tensile strength of 428 MPa, 232 MPa, 4.8 MPa and 1.6 MPa, respectively. The authors found that the buckling of the pins contributed to the compressive properties of X-Cor[®] whilst pin pull-out contributed to the tensile properties of X-Cor[®]. For core shear, X-Cor[®] with a 30° pinning angle was found to possess better core shear properties than X-Cor[®] with a 22° pinning angle. X-Cor[®] with a 22° pinning angle possessed a shear modulus and a shear strength of 200 MPa and 0.8 MPa, respectively whilst X-Cor[®] with a 30° pinning angle possessed a shear modulus and a shear strength of 341 MPa and 1.0 MPa, respectively. The authors also observed that the dominant core shear failure mechanism in X-Cor[®] was pin pull-out.

The compressive properties of K-Cor[®] on the other hand did not show superiority over X-Cor[®]. K-Cor[®] at 30° pinning angle possessed a compressive modulus and strength of 441 MPa and 6.1 MPa, respectively, with the same failure mechanism (i.e. buckling of

pins) as X-Cor[®] in compression. However, the tensile properties of K-Cor[®] were found to be higher than X-Cor[®]. The tensile modulus and strength of K-Cor[®] were found to be 398 MPa and 2.9 MPa, respectively. For the structure of K-Cor[®] possessing folded pins onto the foam core, the debonding of facesheet-foam core and facesheet-pin dominated the failure. Compared to X-Cor[®], K-Cor[®] possessed a higher core shear strength but a lower core shear modulus. The core shear strength of K-Cor[®] is 1.4 MPa and the dominant core shear failure mode of K-Cor[®] was debonding of facesheet-core and pin-core. The smaller core shear modulus of K-Cor[®] (174 MPa) compared to X-Cor[®] was attributed to more significant rotation of pins changing the pinning angle.

2.3.3 Stitched sandwich-structured composites

In addition to Z-pinned sandwich-structured composites, stitched sandwich-structured composites, which used dry and continuous fibre yarn as the reinforcement [91], have also been developed. The concept of stitching originally was to reduce the face-core debonding issue under edgewise compressive loading, which will be improving the crushing load and energy absorption capacity of the resulting stitched sandwich-structured composite. Farley [92] reported the properties of Kevlar[®] yarn (with a linear density of 195 denier) stitched Nomex[®] honeycomb core sandwich-structured composite. A Nomex[®] honeycomb core was placed in between two carbon fibre/epoxy or two Kevlar[®] fibre/epoxy prepregs and a commercial drapery sewing machine was used to stitch the Kevlar[®] yarn in the sandwich structure (see Figure 2-15 (a)). The stitched sandwich structure was put into an autoclave to cure the prepregs to form the facesheets of resulting sandwich-structured composites. The author studied stitching

patterns of 0° , 90° , $\pm 90^\circ$ and $\pm 45^\circ$ relative to the edgewise compressive loading direction. The spacing between two adjacent stitched yarns was 25.4 mm in this study. Figure 2-15 (b) shows a stitched Nomex[®] honeycomb core sandwich-structured composite with $\pm 90^\circ$ pattern. It was observed that all samples failed due to the wrinkling of the facesheets in edgewise compression. However, the result also showed that there was no significant increase in the crushing load of the sandwich-structured composites. Nevertheless, the author suggested that a closer stitch spacing and a larger denier Kevlar[®] yarn could potentially improve the crushing load of stitched sandwich-structured composites.

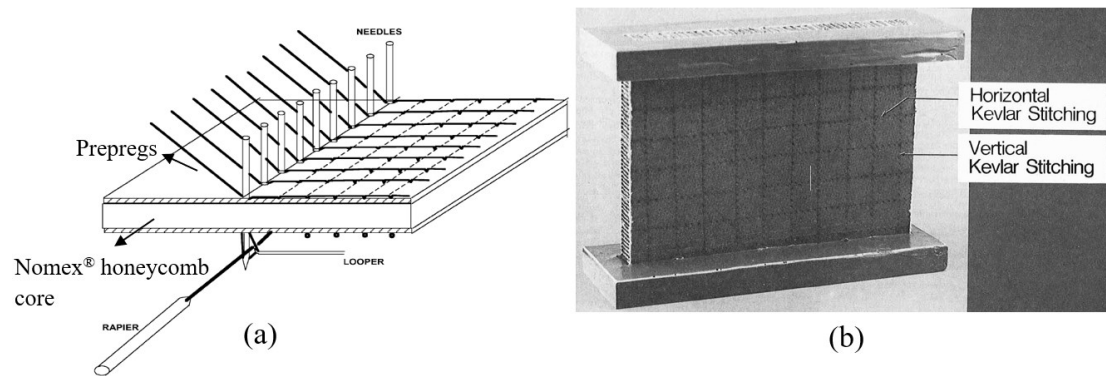


Figure 2-15 (a) Schematic of multiple-needle sewing machine for stitching sandwich-structured composite. Obtained from Ref. [93] (b) Stitched Nomex[®] honeycomb core sandwich-structured composite with $\pm 90^\circ$ pattern. Obtained from Ref. [92]

Instead of using a honeycomb core, Raju and Tomblin [94] used Divinycell[®] HT foam as the core material (density of 110 kg m^{-3}). Kevlar[®] yarn with a linear density of 1600 denier was used as the stitches and samples with a stitch spacing of 6.35 mm to 25.4 mm were studied. Glass fibre preforms were stitched with the foam core together and resin injection moulding (RTM) was used to infiltrate the preform with an epoxy resin, followed by curing. Both the maximum and average crushing load under edgewise

compression increased with decreasing the stitch spacing, consistent with the hypothesis by Farley [92]. The average crushing load of the tested sample increased from ~35 kN for unstitched sample to ~80 kN to stitched sample with a stitch spacing of 6.35 mm. It was verified by the authors using finite element analysis that the decrease in the wrinkling wavelength of the facesheets could result in the increase of wrinkling load. Therefore, the decrease in the stitch spacing reduced the wrinkling wavelength of the facesheets (see Figure 2-16), which in turn increased the crushing load of the resulting stitched sandwich-structured composites.

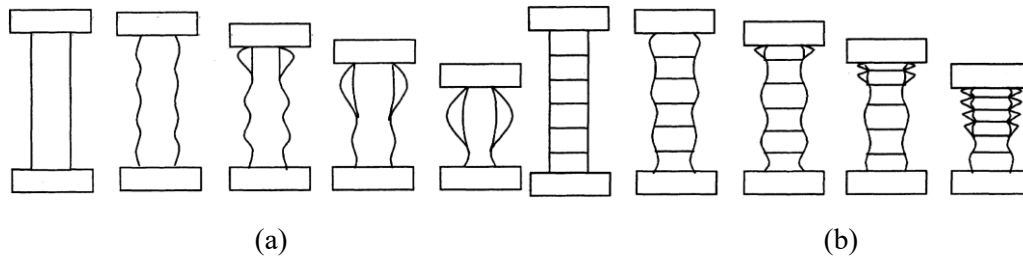


Figure 2-16 Schematic crushing process of (a) unstitched sandwich-structured composite and (b) stitched sandwich-structured composite under edgewise compression. Obtained from Ref. [94]

The out-of-plane properties of stitched sandwich-structured composite was studied by NASA's research centre [95]. Kevlar® yarn with a linear density of 1600 denier was used to stitch 31 kg m⁻³ PMI foam core (with a thickness of 12.7 mm) sandwich-structured composite (see Figure 2-17).

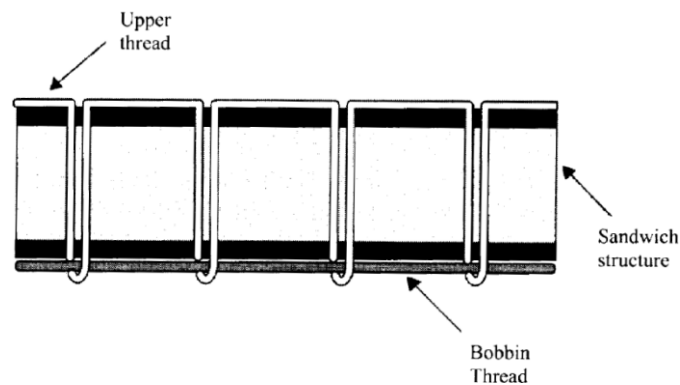


Figure 2-17 Schematic of NASA's stitched sandwich-structured composite. Obtained from Ref. [95]

Carbon fibre preforms and epoxy resin were used to produce the facesheets. The areal density increased from 0.96 g cm^{-2} for unstitched to 1.15 g cm^{-2} for the stitched sandwich-structured composite with a stitch spacing of 6.35 mm. Three-point bending test showed that the flexural stiffness of the sandwich-structured composite increased from 399 kN m^{-1} for unstitched sandwich-structured composite to 646 kN m^{-1} for stitched sandwich-structured composite. The initial failure mode of all samples was found to be core shear failure and there was no significant improvement in the initial failure load of the stitched sandwich-structured composite. However, the stitches in the sandwich-structured composite was found to prevent the propagation of the crack through the facesheet-foam core interface. The crack was contained in between adjacent stitches. As a result, the stitched sandwich-structured composite can continuously sustain structural load up to a maximum load of 3080 kN compared to unreinforced sandwich-structured composites of only 1120 kN.

In the same study, the authors also investigated the flatwise tensile and core shear properties of the stitched sandwich-structured composite. The tensile strength increased from 0.6 MPa for unstitched sandwich-structured composite to 10 MPa for stitched sandwich-structured composite. The unstitched sandwich-structured composite was found to possess a core shear strength of 0.2 MPa while the stitched sandwich-structured composite possessed a core shear strength of 0.92 MPa. The significant improvement in flatwise tension and core shear for stitched sandwich-structured composite was attributed to the tensile failures of the through-thickness Kevlar® stitches.

Instead of stitching the sandwich-structured composite in the perpendicular direction, Lascoup et al. [5,96] stitched the sandwich-structured composite at 45° to the facesheet (see Figure 2-18). Glass fibre yarn with a linear density of 2400 tex was used to stitch 35 kg m^{-3} polyurethane foam sandwiched between 2 plies of glass fibre woven plain preforms. The final sandwich-structured composite was formed using RTM with polyester resin. Stitch spacing was fixed as 25 mm and the stitch step ranged from 12.5 to 50 mm in this study (see Figure 2-18).

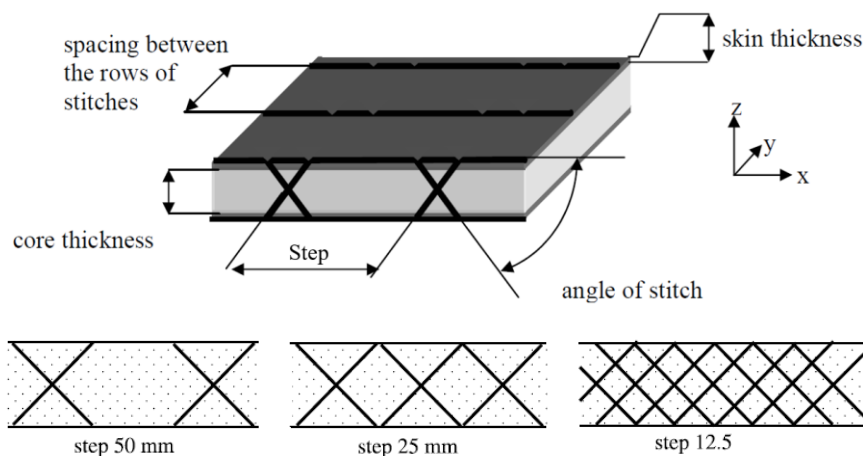


Figure 2-18 Schematic of stitching pattern of angled stitched sandwich-structured composite. Obtained from Ref. [96]

It was observed that the RTM process could cause resin-rich zone in between two adjacent stitches due to the stitching pattern (see Figure 2-19). The redundant resin increased the weight of the resulting sandwich-structured composites without providing significant reinforcement. The areal weight of sandwich-structured composite increased from 0.54 g cm^{-2} for unstitched sandwich-structured composite to 0.85 g cm^{-2} to stitched sandwich-structured composite at a stitch step of 12.5 mm.

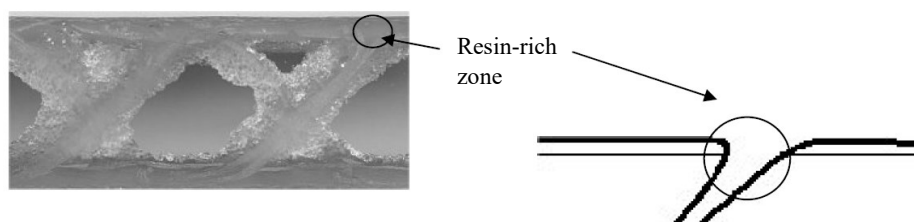


Figure 2-19 Resin-rich zone at the adjacent stitches. Obtained from Ref. [96]

Nevertheless, the largest improvement in the mechanical properties of the stitched sandwich-structured composites in this study was found to be for samples with a stitch step of 12.5 mm. Four-point-bending test was used to study the flexural performance of this stitched sandwich-structured composite. Unstitched sandwich-structured composite possessed a flexural modulus and a flexural strength of 1532 MPa and 7.6 MPa, respectively. The stitched sandwich-structured composite with a stitch step of 12.5 mm was found to possess a flexural modulus and flexural strength of 5791 MPa and 64.8 MPa, respectively. The unstitched sandwich-structured composite exhibited a local foam core indentation failure at the loading bar. Whilst the introduction of stitches increased the core stiffness, it also led to a more brittle core shear failure. The tensile failure of the glass fibre yarns under four-point-bending of the stitched sandwich-structured composite was observed by the authors.

The compressive modulus of the sandwich-structured composites was found to increase from 14.6 MPa for the unstitched sandwich-structured composite to 206.7 MPa for the stitched sandwich-structured composite with a stitch step of 12.5 mm. The compressive strength increased from 0.28 MPa for the unstitched sandwich-structured composite to 4.48 MPa for the stitched sandwich-structured composite with a stitch step of 12.5 mm. The compressive failure of the stitched sandwich-structured composite was dominated by the buckling of the glass yarn stitches.

The stitched sandwich-structured composite also has better core shear properties compared to the unreinforced counterpart. The core shear modulus of the sandwich-structured composites increased from 3.1 MPa for the unstitched sandwich-structured composite to 28 MPa for the stitched sandwich-structured composite. Similarly, the core shear strength increased from 0.2 MPa for the unstitched sandwich-structured composite to 2.02 MPa for the stitched sandwich-structured composite. The tensile failure of glass yarn stitches dominated the core shear failure of the stitched sandwich-structured composite. The glass yarn stitches break very quick when the failure occurred.

The same group of authors further studied the impact performance of the stitched sandwich-structured composites [97]. Drop-weight impact testing was conducted at the energy level of 130 J. It was found that stitched sandwich-structured composites possessed higher initial loads at damage compared to unreinforced sandwich-structured composites. The value increased from 3850 N for unreinforced sandwich-structured

composites to 10132 N for stitched sandwich-structured composite with a stitch step of 12.5 mm. The dynamic rigidity also improved by 50 % from 379 N mm⁻¹ for unstitched sandwich-structured composites to 717 N mm⁻¹ for the stitched sandwich-structured composites. Moreover, the penetration depth decreased from 14.2 mm for the unstitched sandwich-structured composite to 9.5 mm for the stitched sandwich-structured composite due to the energy absorption through the breakage of the stitches. The presence of stitches also prevented facesheet-foam core debonding from the unstitched sample.

Fan et al. [98] studied the impact performance of Kevlar[®] yarn stitched polyurethane foam core sandwich-structured composite at impact energies of 1-70 J. Kevlar[®] yarn with a linear density of 1600 denier was used to stitch 201 kg m⁻³ polyurethane foam sandwiched between 2 plies of glass fibre woven plain preforms. Vinyl ester resin was used to infiltrate the preforms by RTM to form the facesheets. At the low energy level of 25 J, the average damage angle of the stitched sandwich-structured composite increased by 48% compared to the unstitched sandwich-structured composite. The maximum cracking width and penetration depth of the stitched sandwich-structured composite decreased by 67% and 4%, respectively, compared to the unstitched sandwich-structured composite, respectively. At the high energy level of 70 J, the average damage angle and the maximum cracking width of the stitched sandwich-structured composite increased by 33% and decreased by 53%, respectively, compared to the unstitched sandwich-structured composite. This was due to the presence of perpendicularly oriented stitches inside the foam core which confined the damage

extension and delamination from the impact. Figure 2-20 shows the cross-section view of failed stitched sandwich-structured composite where the impact was at the stitches.

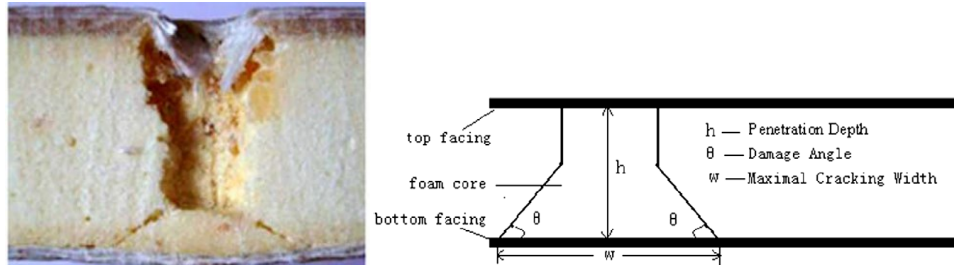


Figure 2-20 Cross-section view of failed stitched sandwich-structured composite. Obtained from Ref. [98]

Santhanakrishnan et al. [99] compared the effect of stitching angle on the impact properties of stitched sandwich-structured composite. Glass fibre yarn was used to stitch 80 kg m⁻³ Divinycell® H foam core in the 45°, 90° and 45°/90° to the facesheet. Drop-weight impact at 2 – 50 J was conducted. It was found that the 90° stitched sandwich-structured composite exhibited better impact performance than the 45° stitched sandwich-structured composite. At the energy level of 30 J, a non-destructive testing C-scan revealed that the length of surface crack of 90° stitched sandwich-structured composite is smaller than 45° stitched sandwich-structured composite (14.7 vs 22 mm). The 90° stitched sandwich-structured composite had smaller delamination area than the 45° stitched sandwich-structured composite (264.6 vs 451 mm²).

Quasi-static indentation test was conducted for Kevlar® yarn stitched Divinycell® H 130 kg m⁻³ foam core sandwich-structured composite [93]. Compared to unstitched sample, the loads to fail the top facesheet and the debonding at lower facesheet were

increased from 6.28 kN to 10.07 kN and 4.87 kN to 7.21 kN, respectively. The stitches enclosed with the resin increased the compressive properties and debonding resistance. The stitched sample with 5 mm stitch spacing exhibited best behaviours and the increase of the stitch spacing decreased the improvements, consistent with the initial hypothesis by Farley.

2.4 Summary

This literature review chapter discussed the manufacturing of polymeric foams, mechanics of the deformation of cellular materials and sandwich-structured composites. This chapter also discussed the various properties of through-thickness reinforced sandwich-structured composites. Table 2-1 summarises the mechanical properties of the reinforced sandwich-structured composites discussed in this chapter. All studies in reinforced sandwich-structured composites focussed on carbon, glass and Kevlar[®] fibres, as well as the stitching of the yarns or Z-pinning through an already made foam core, which added complexity to the reinforced sandwich-structured composite manufacturing process. In subsequent chapters in this thesis, the focus will be on the use of mechanical frothing to produce the foam core, which does not require the stitching of yarns or punching of pins through a solid block of foam.

Table 2-1 Summary of literature review for Z-pinned sandwich-structured composites and stitched sandwich-structured composites. E_c , σ_c^* , E_t , σ_t^* , G and τ^* denote compressive modulus and strength, tensile modulus and strength, shear modulus and strength, respectively

Z-pinned sandwich-structured composites						
Ref.	Core		Reinforcement			Main findings
	Material	ρ (kg m ⁻³)	Material	Ang.	Vol.-(%)	
[80]	PMI foam	75	CF/BA Pins	5-6°	2	Comp. Impact $E_c \uparrow$ 91 MPa $\rightarrow$ 253 MPa, $\sigma_c^* \uparrow$ 1.6 MPa $\rightarrow$ 4.9 MPa No improvement
[84]	PMI foam	32 52 75 110	CF/BA Pins	15°	0.48	Shear $G \uparrow$ 13 ^f MPa $\rightarrow$ 67.5 MPa, $\tau^* \uparrow$ 0.4 ^f MPa $\rightarrow$ 1.07 MPa $G \uparrow$ 19 ^f MPa $\rightarrow$ 81.5 MPa, $\tau^* \uparrow$ 0.8 ^f MPa $\rightarrow$ 1.35 MPa $G \uparrow$ 29 ^f MPa $\rightarrow$ 96.9 MPa, $\tau^* \uparrow$ 1.3 ^f MPa $\rightarrow$ 1.76 MPa $G \uparrow$ 50 ^f MPa $\rightarrow$ 111.6 MPa, $\tau \downarrow$ 2.4 ^f MPa $\rightarrow$ 1.79 MPa
[85]	PMI foam	75	Ti Pins	10°	0.5 ^s	Impact 8 % lower initial damage load
[86]	PVC foam	90	CF/BA Pins	4-22°	0.5 2 4	Comp. E_c 43 MPa, σ_c^* 3.5 MPa E_c 87 MPa, σ_c^* 7.5 MPa E_c 111 MPa, σ_c^* 12 MPa
[88]	PMI foam	31 51	CF/BA Ti Pins	30°	3.6	Comp. $\sigma_c^* \uparrow$ 0.4 MPa $\rightarrow$ 13 MPa $\sigma_c^* \uparrow$ 0.9 MPa $\rightarrow$ 15 MPa
[90]	PMI foam	32	X-Cor [®]	22°	2.86	Comp. $E_c \uparrow$ 21 MPa $\rightarrow$ 508 MPa, $\sigma_c^* \uparrow$ 0.4 MPa $\rightarrow$ 5.0 MPa
				30°		$E_c \uparrow$ 21 MPa $\rightarrow$ 428 MPa, $\sigma_c^* \uparrow$ 0.4 MPa $\rightarrow$ 4.8 MPa
			K-Cor [®]	30°	2 ^s	$E_c \uparrow$ 21 MPa $\rightarrow$ 441 MPa, $\sigma_c^* \uparrow$ 0.4 MPa $\rightarrow$ 6.1 MPa
			X-Cor [®]	22°	2.86	Tens. $E_t \uparrow$ 32 MPa $\rightarrow$ 350 MPa, $\sigma_t^* \uparrow$ 1.0 MPa $\rightarrow$ 2.5 MPa
				30°		$E_t \uparrow$ 32 MPa $\rightarrow$ 232 MPa, $\sigma_t^* \uparrow$ 1.0 MPa $\rightarrow$ 1.6 MPa
			K-Cor [®]	30°	2 ^s	$E_t \uparrow$ 32 MPa $\rightarrow$ 398 MPa, $\sigma_t^* \uparrow$ 1.0 MPa $\rightarrow$ 2.9 MPa
			X-Cor [®]	22°	2.86	Shear $G \uparrow$ 13 MPa $\rightarrow$ 200 MPa, $\tau^* \uparrow$ 0.4 MPa $\rightarrow$ 0.8 MPa
				30°		$G \uparrow$ 13 MPa $\rightarrow$ 341 MPa, $\tau^* \uparrow$ 0.4 MPa $\rightarrow$ 1.0 MPa
			K-Cor [®]	30°	2 ^s	$G \uparrow$ 13 MPa $\rightarrow$ 176 MPa, $\tau^* \uparrow$ 0.4 MPa $\rightarrow$ 1.4 MPa
[100]	PMI foam	75	CF Pin GF Pin	40°	0.75	Shear $G \uparrow$ 13.8 MPa $\rightarrow$ 19.9 MPa, $\tau^* \uparrow$ 1.04 MPa $\rightarrow$ 1.0 MPa $G \uparrow$ 13.8 MPa $\rightarrow$ 18.3 MPa, $\tau^* \uparrow$ 1.04 MPa $\rightarrow$ 1.1 MPa

Stitched sandwich-structured composites						
Ref.	Core		Reinforcement		Testing	Main findings
	Material	ρ kg m ⁻³	Material	Stitch pattern		
[92]	Nomex honeycomb	—	Kevlar 195 denier	0°, Spacing 25.4 mm	EW Comp.	No improvement
[94]	Diviny-cell HT foam	110	Kevlar 1600 denier	0°, Spacing 6.35 mm	EW Comp.	Average sustained stiffness↑ 35 kN m ⁻¹ → 75 kN m ⁻¹
[95]	PMI foam	31	Kevlar 1600 denier	0°, Spacing 6.35 mm	Bend.	Bending stiffness↑ 399 kN m ⁻¹ →646 kN m ⁻¹ Max load↑ 1098 kN →3018 kN
					Tens.	σ_t^* ↑ 0.6 MPa →10 MPa
					Shear	τ^* ↑ 0.2 MPa →0.92 MPa
[5,97]	PU foam	35	Glass 2400 tex	45°, Spacing 12.5 mm, Step 12.5 mm	Bend.	E_b ↑ 1532 MPa →5791 MPa, σ_b^* ↑ 7.6 MPa →64.8 MPa
					Comp.	E_c ↑ 15 MPa →207 MPa, σ_c^* ↑ 0.28 MPa →4.48 MPa
					Shear	G ↑ 3 MPa →28 MPa, τ^* ↑ 0.2 MPa →2.02 MPa
					Impact	Initial damage load↑ 3850 N→10132 N Dynamic stiffness↑ 379 kN m ⁻¹ →717 kN m ⁻¹ Max penetration↓ 14.2 mm→9.5 mm
[98]	PU foam	210	Kevlar 1600 denier	0°, Spacing 15 mm	Impact	Crack length ↓ 67 % at 25J Crack length ↓ 53 % at 70J
[99]	Diviny-cell H foam	80	Glass	0°/45° Spacing 10 mm	Impact	Crack length for 0° vs 45° (14.7 mm vs 22 mm) Delamination area for 0° vs 45° (264.6 mm ² vs 451 mm ²) at 30 J
[93]	Diviny-cell H foam	130	Kevlar 1600 denier	0°, Spacing 5 mm	Inden.	Load to fail top face↑ 6.28 kN →10.07 kN Load to fail lower face↑ 4.87 kN →7.21 kN

§ represents pin volume fraction that is calculated from areal pin numbers.

ƒ represents mechanical properties of Rohacell® PMI foams obtained from product technical data.

Chapter 3 - Derivation of a strain-energy based analytical model to predict the mechanical properties of through-thickness fibre-reinforced sandwich-structured composite

3.1 Introduction

A strain-energy based analytical model is derived and discussed in this chapter. It is used to estimate the upper bound mechanical properties of the fabricated reinforced sandwich-structured composite discussed in Chapters 4 to 6.

3.2 Moduli of the through-thickness reinforced sandwich-structured composite

3.2.1 Shear modulus

The through-thickness reinforced sandwich-structured composite with a cross pattern fibre reinforcement was simplified into a 2D unit cell model shown in Figure 3-1. The two fibre bundles in this model are considered as rods. The influence of facesheets is neglected in this model as they normally possess higher stiffness than the core. The bonding between rods and the foam is assumed to be perfect. The unit cell has a height of L and the angle of the rods to horizontal axis

θ . A steady increasing shear load F_s is applied to the unit cell. The small amount of deformation of the unit cell at the edge caused by the shear force is δ and the deformations of the rods in both tension and compression are ΔL .

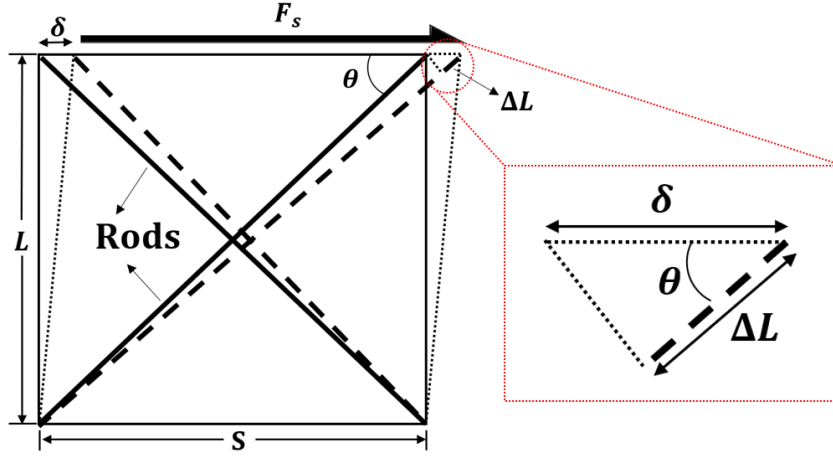


Figure 3-1 Diagram of the unit cell model under shear load.

The work done by F_s can be expressed as:

$$W = \int F_s \delta = \frac{1}{2} \tau_s S \delta \quad (3.1)$$

where S is the horizontal length of the unit cell. The unit cell also experiences an elastic deformation. In this context, the total work should be equal to the total strain energies stored in both epoxy foam and two rods. Therefore, the relationship can be written as:

$$W = U_f + U_r \quad (3.2)$$

whereby the strain energies stored in the foam and rods are:

$$U_f = \frac{1}{2} V_f G_f \gamma_f^2 \quad (3.3)$$

$$U_r = \frac{1}{2} V_r E_r \varepsilon_r^2 \quad (3.4)$$

where ε_r is the tensile or compressive strain of the rods, γ_f is the shear strain of the foam, V_f is the foam volume and V_r is rods volume. Due to the small amount of deformation of the unit cell, the change of fibre angle can be neglected. Thus,

$$\Delta L = \delta \cos \theta \quad (3.5)$$

$$\varepsilon_r = \frac{\Delta L}{L / \sin \theta} \quad (3.6)$$

$$\delta = \gamma_f L \quad (3.7)$$

From equation 3.2, the shear strain of the foam (γ_f) is approximate to the shear strain of the unit cell (γ_s). Thus, the core shear modulus (G_s) of the unit cell can be written as:

$$G_s = \varphi_f G_f + \varphi_r E_r \sin^2 \theta \cos^2 \theta \quad (3.8)$$

where φ_f is the foam volume fraction and φ_r is the rods volume fraction of the unit cell. Similarly, the elastic shear stress (τ_s) of the unit cell can be written as:

$$\tau_s = \gamma_s G_s \approx \varphi_f \gamma_f G_f + \varphi_r \varepsilon_r E_r \sin \theta \cos \theta \quad (3.9)$$

3.2.2 Compressive and tensile moduli

The tensile and compressive moduli (E_t and E_c) of the through-thickness reinforced sandwich-structured composite can also be derived using the strain-energy approach. Figure 3-2 shows the unit cell under a tensile or compressive load and its deformation δ .

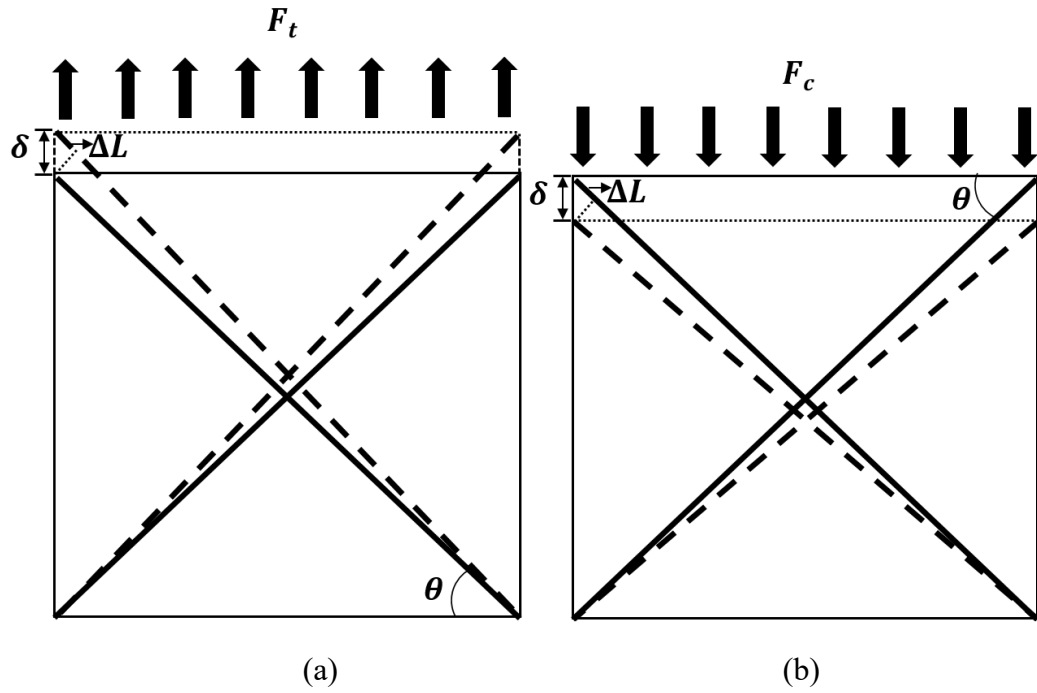


Figure 3-2 Diagrams of the unit cell model under (a) tensile load (b) compressive load.

When the rods are stretched by ΔL , the work done W is expressed as:

$$W = \frac{1}{2} \sigma S \delta \quad (3.10)$$

The strain energies stored in the foam and rods are:

$$U_f = \frac{1}{2} V_f E_f \varepsilon_f^2 \quad (3.11)$$

$$U_r = \frac{1}{2} V_r E_r \varepsilon_r^2 \quad (3.12)$$

Using the following relations:

$$\varepsilon_f = \frac{\delta}{L} \quad (3.13)$$

$$\varepsilon_r = \frac{\delta}{L} \sin^2 \theta \quad (3.14)$$

the compressive and tensile moduli (E_t and E_c) of the unit cell can be written as:

$$E_t = E_c = \varphi_f E_f + \varphi_r E_r \sin^4 \theta \quad (3.15)$$

The elastic compressive and tensile stresses (σ_t and σ_c) of the unit cell can be written as:

$$\sigma_t = \sigma_c = \varphi_f \varepsilon_f E_f + \varphi_r \varepsilon_r E_r \sin^2 \theta \quad (3.16)$$

3.3 Ultimate strengths of the through-thickness reinforced sandwich-structured composite

3.3.1 Ultimate shear strength

Prior to discussing the ultimate strengths of the through-thickness reinforced sandwich-structured composite, the failure criteria need to be considered first. There are four possible failure modes in the through-thickness reinforced sandwich-structured composite:

- (i) Failure of the foam core
- (ii) Compressive failure of the rods
- (iii) Tensile failure of the rods
- (iv) Debonding of the rods from the foam core

Specifically for the case of the unit cell loaded under shear, both rods in the unit cell have different failure modes. This is because one of the rods undergoes compression while the other undergoes tension. In this simple model, the compressive strength and tensile strength of the rod are assumed to be the same.

The ultimate shear strength of the unit cell can then be determined by identifying the dominant failure amongst all the possible failure mechanisms including the polymeric foam failure (which is commonly seen in Z-pinned sandwich-structured composites [84,90], although the pin pull-out failure is not considered in this chapter) and rod failure (which is commonly seen in stitched sandwich-structured composites. [5,95]).

The polymeric foam failure occurs when the polymeric foam reaches the shear strain-at-break (γ_f^*) before the rod tensile failure occurs. With the assumption that the rods are in elastic deformation, the rods have a strain (ϵ_r^{ff}) at this moment and which is

$$\epsilon_r^{ff} = \gamma_f^* \sin\theta \cos\theta \quad (3.17)$$

According to the equation 3.9, the ultimate shear strength of the unit cell can be expressed as

$$\tau_s^* = \varphi_f \tau_f^* + \varphi_r \epsilon_r^{ff} E_r \sin\theta \cos\theta = \varphi_f \tau_f^* + \varphi_r \gamma_f^* E_r \sin^2\theta \cos^2\theta \quad (3.18)$$

When the rods failure happens, the rods reach the strain at break (ϵ_r^*). According to the equation 3.9, the ultimate shear strength of the unit cell can be expressed as

$$\tau_s^* = \varphi_f \tau_f^* + \varphi_r \sigma_r^* \sin\theta \cos\theta \quad (3.19)$$

where σ_r^* is the ultimate strength of the rods. In addition to this, if the unit cell failed at the interface between fibres and foam core, the ultimate shear strength of the unit cell is

$$\tau_s^* = \tau_{Ifss} \quad (3.20)$$

3.3.2 Ultimate tensile and compressive strengths

When a tensile or a compressive load is applied to the unit cell, both the rods and the foam are loaded under tension or compression. If the dominant failure mode is foam core failure, the foam reaches its tensile strain-at-break or compressive yield strain (ε_f^*). At this moment, the tensile strain of both rods (ε_r^{ff}) is

$$\varepsilon_r^{ff} = \varepsilon_f^* \sin^2 \theta \quad (3.21)$$

According to the equation 3.16, the ultimate tensile or compressive strength of the unit cell (σ_t^*) can be expressed as

$$\sigma_t^* = \varphi_f \sigma_f^* + \varphi_r \varepsilon_r^{ff} E_r \sin^2 \theta = \varphi_f \sigma_f^* + \varphi_r \varepsilon_f^* E_r \sin^4 \theta \quad (3.22)$$

If the dominant failure mode is a rod tensile or compressive failure. According to the equation 3.16, the ultimate tensile or compressive strength of the unit cell (σ_t^*) can be expressed as

$$\sigma_t^* = \varphi_f \sigma_f^* + \varphi_r \sigma_r^* \sin^2 \theta \quad (3.23)$$

3.4 Verification of the analytical model

The model was verified by comparing with the published experimental data of Marasco et al. [4,90] (the PhD thesis and following published paper). Based on the information provided in both of the studies, the mechanical and physical properties of the foam core and Z-pins are summarised in Table 3-1.

Table 3-1 The mechanical and physical properties of the foam core and Z-pins used by X et al. [4]

	Core	Z-pin
Material	PMI	T300 / CYCOM 5250-4
Density (kg m^{-3})	32	
Compressive modulus (MPa)	21	115000
Compressive strength (MPa)	0.4	1100
Tensile modulus (MPa)	32	115000
Tensile strength (MPa)	1.0	1100
Shear modulus (MPa)	13	
Shear strength (MPa)	0.4	

Based on the data presented in Table 3-1, the predicted compressive and tensile moduli were calculated from equation 3.8 whilst equation 3.15 was used to predict the shear modulus of the Z-pinned sandwich-structured composites. The results are plotted in Figure 3-3.

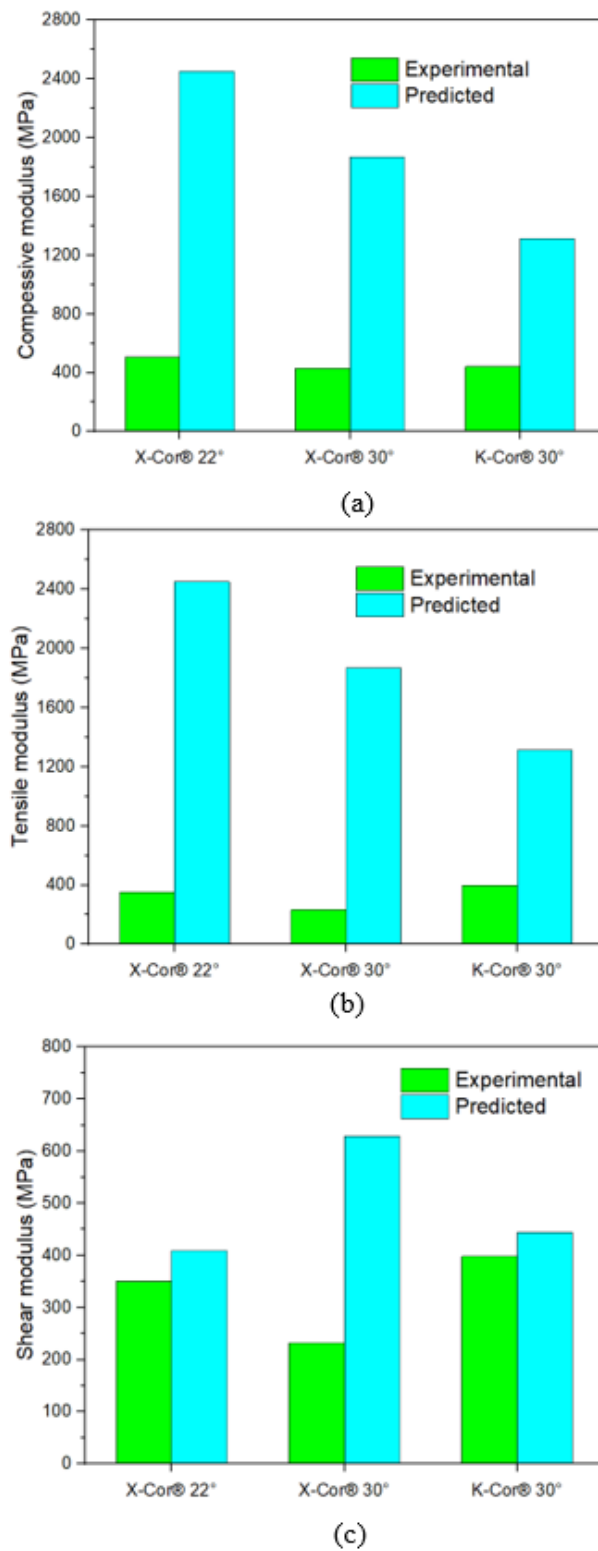


Figure 3-3 Comparison of experimental results and predicted values of X-Cor® and K-Cor® Z-pinned sandwich structural composites (a) compressive modulus (b) tensile modulus (c) shear modulus

From the Figure 3-3, it can be seen that the large discrepancy between the predicted and experimental compressive and tensile moduli of the Z-pinned sandwich structural composites. The overestimation of the compressive and tensile moduli could be attributed to the assumption of the model, whereby the Poisson's effect of the unit cell was neglected to replace the continuity of the reinforcement. This is due to the fact that the deformation of a material consists not only of longitudinal deformation of the reinforcements but also the rotation of the reinforcements. However, the lack of research about the Poisson's effect of fibre reinforced foam limited the development of the current model. Nevertheless, the simplicity of the model derived in this chapter allowed for the prediction of the *theoretical maximum mechanical properties* of the reinforced sandwich-structured composites. It should be noted that the predicted shear modulus agrees well with experimental data due to the lack of volume change in the unit cell during pure shear deformation.

3.5 Summary

In this chapter, strain energy-based models to describe the core shear, tensile and compressive properties of the reinforced sandwich-structured composites have been derived. The theoretical values obtained from these models will be used as a yardstick to evaluate the performance of the reinforced sandwich-structured composites manufactured in Chapters 4-6.

Chapter 4 - Continuous ultra-high molecular weight polyethylene (UHMWPE) fibre reinforced sandwich-structured composite consisting of mechanically frothed epoxy foam

4.1 Introduction

Mechanical frothing method provides an exciting opportunity to produce through-thickness reinforced foam core sandwich-structured composites that does not require the insertion of through-thickness reinforcement through a block of pre-fabricated or pre-made polymeric foam core, typical of Z-pinned or stitched sandwich-structured composites (see Chapter 2). This chapter discusses the design, fabrication and characterisation of continuous ultra-high molecular weight polyethylene (UHMWPE) fibre-reinforced sandwich-structured composites. UHMWPE fibres were chosen due to its tenacity and the possibility of forming a zero-radius curvature. Mechanical frothing was used to produce the epoxy foam core.

4.2 Experiment

4.2.1 Materials

Ultra-high molecular weight polyethylene (UHMWPE) yarn (Dyneema® SK-78) was kindly provided by DSM (Heerlen, Netherlands) and used as the continuous fibre reinforcement for the sandwich-structured composites. The physical and mechanical properties of the UHMWPE fibre are summarised in Table 4-1.

Table 4-1 The physical and mechanical properties of UHMWPE yarn, including D_F , N , ρ_F , σ_F , E_F and ε_F^* denote fibre diameter, number of fibres in the yarn, fibre density, tensile strength, Young's modulus and tensile failure strain, respectively. Data obtained by Ref. [101]

Name	D_F (μm)	N	ρ_F (kg m^{-3})	σ_F (GPa)	E_F (GPa)	ε_F^* (%)
Dyneema® SK-78	17-21	780	970-980	3.2-3.4	108-113	3.5

Epoxy resin with 56 % biomass content (Greenpoxy 56, $\rho = 1.20 \pm 0.01 \text{ g cm}^{-3}$, $\eta = 2500 \text{ mPa s}$ at 15°C) and amine-based hardener with 58 % biomass content (GP 505 v2, $\rho = 0.99 \pm 0.01 \text{ g cm}^{-3}$, $\eta = 1800 \text{ mPa s}$ at 15°C) were purchased from Matrix Composite Materials Company Ltd (Bristol, UK) and used as received. Carbon fibre-reinforced polymer composite laminates with a fibre volume fraction of 54% (1 mm thick, reinforced with 2/2 twill woven carbon fabric) was purchased from Easy Composites Ltd (Staffordshire, UK) were used as the facesheet

materials for the sandwich-structured composite. The physical and mechanical properties of the CFRP facesheet are summarised in Table 4-2.

Table 4-2 The physical and mechanical properties of CFRP facesheet, including t , ϕ_{cf} , W_{fa} , σ_f , E_f and ε_f denote thickness, fibre volume fraction, Areal weight, tensile strength, Young's modulus and tensile failure strain, respectively. Data provided by Easy Composites Ltd

Name	t (mm)	ϕ_{cf} (%)	W_{fa} (kg m ⁻²)	σ_{fa} (MPa)	E_{fa} (GPa)	ε_{fa}^* (%)
CFRP	1	54	0.215	650	60	1.5

4.2.2 Preparation of sandwich-structured composites consisting of continuous UHMWPE fibres as through-thickness reinforcement for the epoxy foam core

In this work, sandwich-structured composites consisting of carbon fibre reinforced epoxy composite facesheet materials and an (reinforced) epoxy foam core was prepared. The epoxy foam core was prepared following a previous work [6,7]. Briefly, 70.4 g of bio-based epoxy resin and 29.6 g of amine-based hardener were added into a 2 L Pyrex glass bowl and mechanically frothed using a hand mixer (HM730B, Sainsbury's, London, UK) for 20 min operating at a maximum power output of 200 W. The resulting air-in-liquid epoxy foam template was then poured into a mould with dimensions of $(120 \times 30 \times 9)$ mm³ and cured at room temperature for 24 h to produce unreinforced epoxy foam core. To produce UHMWPE fibre yarn-reinforced epoxy foam cores, the air-in-liquid epoxy foam template was poured into a $(120 \times 30 \times 9)$ mm³ mould consisting of continuous UHMWPE fibre yarns weaved in accordance to the pattern shown in Figure 4-1

and cured at room temperature for 24 h. The UHMWPE fibre volume fraction within the epoxy foam cores were 1 vol.-% and 2 vol.-%, respectively. The carbon fibre reinforced epoxy composite facesheet materials were then glued onto the (reinforced) epoxy foam cores using an epoxy glue (Araldite 2011, Huntsman International LLC, Duxford, UK).

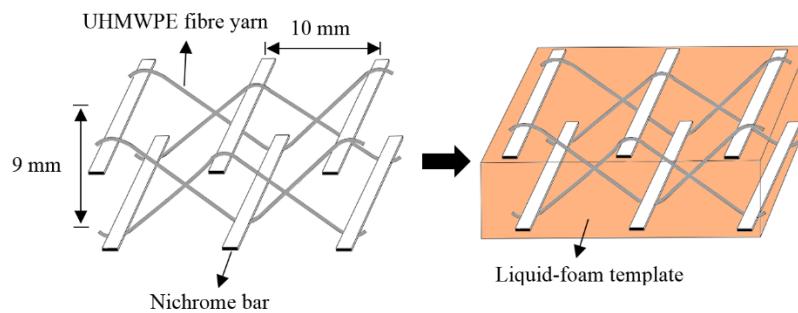


Figure 4-1 Schematic diagram of continuous UHMWPE fibre yarn reinforced epoxy foam fabrication process

4.3 Characterisation of the (reinforced) sandwich-structured composites

4.3.1 Core shear properties of the (reinforced) epoxy foam cores using 3-point bending test

The core shear properties of the (reinforced) epoxy foam cores were determined from 3-point bending test in accordance to ASTM C393 using an Instron universal testing machine (Model 5969, Instron Ltd., Bucks, UK). The span length of the test specimen and testing speed used were 60 mm and 1 mm min^{-1} , respectively. A non-contact optical extensometer (Imetrum Video Gauge, Bristol, UK) was used to measure the mid-span deflection of the test specimen during the three-point bending testing. The shear strength of the core material (τ_s^*) within the sandwich-structured composites was calculated using:

$$\tau_s^* = \frac{P_{\max}}{2bd} \quad (4.1)$$

where $P_{\max}$ is the maximum measured load, d is the distance between the centre lines of the upper and lower facesheets and b is the width of sandwich-structured composites, respectively.

The shear modulus of the core material (G_s) was calculated using the following equation:

$$G_s = \frac{lc}{4bd^2 \left(\frac{\delta}{P} \right) - \frac{l^3}{6E_f t}} \quad (4.2)$$

where c represents the thickness of the core, E_f is the Young's modulus of the facesheet material, l is the span length of test specimen, δ is the beam mid-span deflection and P is the applied load.

4.3.2 Internal morphology of the (reinforced) epoxy foam core

Scanning electron microscope (SEM) (Hitachi S-3700 N, Tokyo, Japan) was used to investigate the internal morphology of the (reinforced) foam core within the sandwich-structured composites operating at an accelerating voltage of 5 kV. Prior to SEM, the specimens were broken into two halves using pliers to expose their internal structure. The specimens were then mounted onto aluminium stubs using carbon tabs and sputter coated with Au (Agar Auto Sputter Coater, Essex, UK) at 40 mA for 40 s.

4.4 Results and Discussion

The representative load-deflection curves of the fabricated sandwich-structured composites consisting of unreinforced and reinforced epoxy foam cores are shown in Figure 4-2 and the calculated shear properties of the epoxy foam cores are summarised in Table 4-3. It can be seen from Figure 4-2 and Table 4-3 that the continuous UHMWPE fibre reinforced epoxy foam cores possessed higher shear modulus (147 MPa for 1 vol.-% continuous UHMWPE fibre reinforced epoxy foam cores and 163 MPa for 2 vol.-% continuous UHMWPE fibre reinforced epoxy foam core) compared to the unreinforced counterpart (110 MPa).

Table 4-3 Physical properties of the unreinforced and reinforced foams. ρ_{core} , φ_f , τ_s^* and G_s denote density, fibre volume fraction, core shear strength, core shear modulus, respectively

Sample	φ_f (%)	ρ_{core} (kg m ⁻³)	G_s (MPa)	τ_s^* (MPa)
Sample A	0.0	421 ± 7	110 ± 6	4.08 ± 0.15
Sample B	1.0	427 ± 7	147 ± 13	4.53 ± 0.07
Sample C	2.0	432 ± 14	163 ± 22	4.20 ± 0.11

The introduction of continuous UHMWPE fibres also increased the shear strength of the core material (see Table 4-3). This improvement in both core shear modulus and strength could be attributed to the through-thickness reinforcement with continuous UHMWPE fibres, which underwent tensile loading during the shear deformation of the reinforced epoxy foam core.

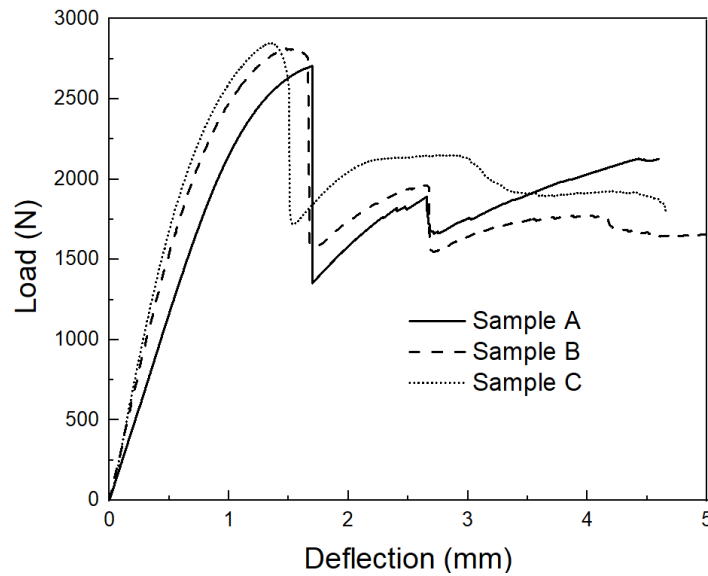


Figure 4-2 Representative load-deflection curves of sandwich structured composites consisting of (Sample A) unreinforced epoxy foam core, (Sample B) 1 vol.-% continuous UHMWPE fibre reinforced epoxy foam core and (Sample C) 2 vol.-% UHMWPE fibre reinforced epoxy foam core

The strain energy-based model described in Chapter 3 was used to calculate the maximum theoretical values of the core shear modulus and strength of the continuous UHMWPE fibre reinforced sandwich structured composites. Equation 3.8 was used to estimate the core shear modulus and equation 3.18 was used to estimate the core shear strength of the fabricated continuous UHMWPE fibre reinforced sandwich structured composites. Equation 3.18 was used as it was found that the reinforced sandwich-structured composites exhibited foam core failure.

Figure 4-3 compares the maximum theoretical core shear modulus and strength with the experimentally measured values. It can be seen from this figure that the experimental measured core shear modulus and strength deviates significantly from the values estimated from equations 3.8 and 3.18. It is hypothesised that not all UHMWPE fibres bear the load. When the sandwich-structured composites undergo shear deformation, it can be anticipated that only half the UHMWPE fibres contribute to load bearing (in tension) whilst the other half will undergo compression (and buckle). Therefore, equations 3.8 and 3.18 were further modified to only consider 50% of the fibres carry the load (see Figure 4-3). It can still be seen from this figure that the experimental values still deviate from the predicted values.

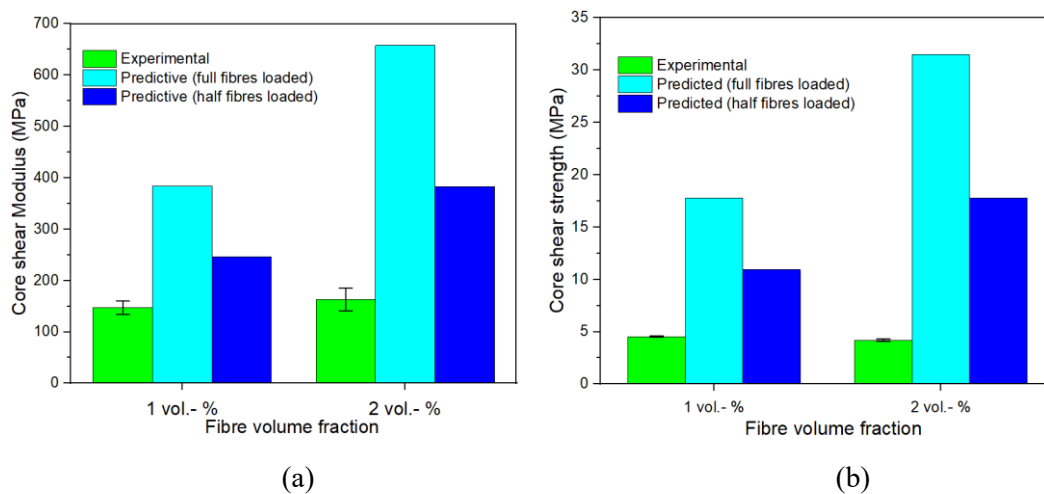


Figure 4-3 Comparison of experimental results and predicted values (a) experimental shear modulus, predicted shear modulus with full fibres loaded and half fibres loaded assumptions of the continuous UHMWPE fibre reinforced sandwich structured composites (b) experimental shear strength and predicted shear strength of the continuous UHMWPE fibre reinforced sandwich structured composites

Microscopy was further conducted to elucidate this deviation further. The SEM images of the UHMWPE fibre yarns within the reinforced epoxy foam cores are shown in Figure 4-4. The outer surface of the UHMWPE fibre yarn can be seen were surrounded by epoxy foam. However, the fibres underneath this surface layer was dry. Due to this, the applied (shear) stresses onto the reinforced epoxy foam cores could not be efficiently transferred onto all UHMWPE fibres within the fibre yarn. As a result, the improvements in shear modulus and shear strength of the reinforced epoxy foam cores deviates from theoretical calculations.

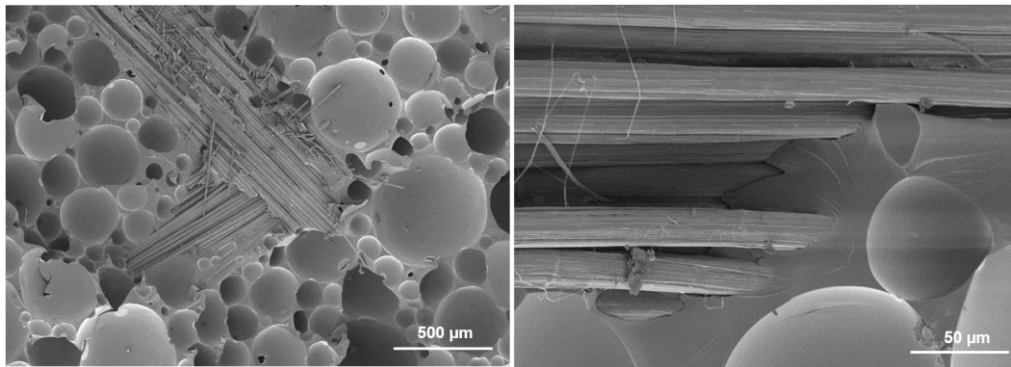


Figure 4-4 SEM images of UHMWPE fibre yarn within the epoxy foam

4.5 Summary

Sandwich-structured composites consisting of continuous ultrahigh molecular weight polyethylene (UHMWPE) fibres as through-thickness reinforcement for the epoxy foam core were fabricated in this work. Preliminary test showed that the introduction of continuous UHMWPE fibres improved the shear modulus (G_s) of the foam core by 50%, from $G_s = 110$ MPa for unreinforced polymeric foam core to $G_s = 163$ MPa for polymeric foam core reinforced with 2 vol.-% continuous

UHMWPE fibres. The shear strength of the epoxy foam core also improved by up to 10% with the introduction of continuous UHMWPE fibres.

Chapter 5 - Epoxy coated continuous UHMWPE fibre-reinforced epoxy foams

5.1 Introduction

In the previous chapter, the UHMWPE fibres embedded within the epoxy foam core was found to be dry (see Figure 4-4), which led to the lack of significant improvements in the core shear properties of the resulting sandwich-structured composites. Therefore in the chapter, the UHMWPE fibres are coated with an epoxy resin in an attempt to improve their adhesion with the surrounding epoxy foam core, as well as to improve the effective stiffness (particularly in compression) of the epoxy-coated UHMWPE fibres. The tensile, compression and core shear properties of the resulting reinforced epoxy foams are discussed in this chapter.

5.2 Experimental

5.2.1 Materials

The UHMWPE fibres, CFRP facesheets, as well as the bio-based epoxy resin system used to produce the epoxy foam core are the same as previously described (see Chapter 4). Ultra-low viscosity epoxy resin (PRIME 20 LV, $\rho = 1.12 \text{ g cm}^{-3}$,

$\eta = 1040 \pm 30$ mPa s at 20 °C) and amine-based hardener (PRIME slow hardener $\rho = 0.94$ g cm⁻³, $\eta = 23 \pm 1$ mPa s at 20 °C) were purchased from Gurit Ltd. (Newport, UK) and used as the epoxy resin to coat UHMWPE yarns.

5.2.2 Fabrication of the neat and continuous epoxy coated UHMWPE fibre-reinforced epoxy foams

The preparation of the neat and unreinforced epoxy foam follows the previous protocol (see Chapter 4). Briefly, 70.4 g of bio-based epoxy resin and 29.6 g of the amine-based hardener were mechanically frothed for 20 min to produce an air-in-resin liquid foam template. This air-in-liquid foam template was poured into a mould with dimensions of 120 (*l*) × 30 (*b*) × 11 (*c*) mm³ and cured for 24 h at room temperature. The mould was covered with polytetrafluoroethylene (PTFE) peel plies to allow for the release of the cured epoxy foam core from the mould.

To produce epoxy-coated UHMWPE fibre-reinforced epoxy foam, a skeletal structure of the through-thickness UHMWPE fibre reinforcement for the resulting epoxy foam was first produced by weaving (manually) the fibre yarns according to the pattern shown in Figure 5-1 (a). All the wooden sticks used were wrapped with polyethylene coated adhesive tape and coated with a silicon-based release agent. The gap between two release agent coated wooden sticks was 10 mm (lengthwise) and 11 mm (heightwise). The overall length of the skeletal structure was 120 mm.

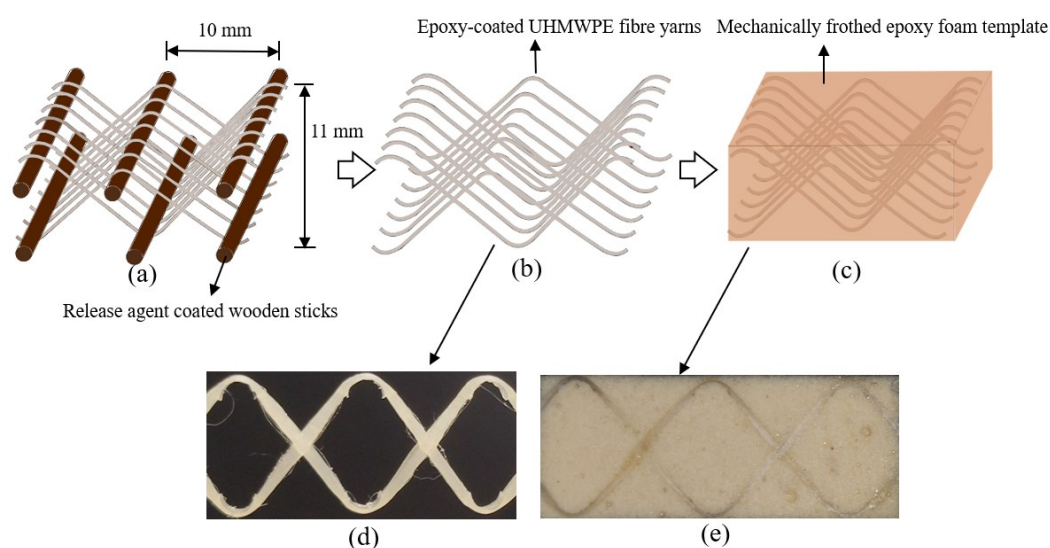


Figure 5-1 (a)-(b) Schematic diagram of epoxy coated continuous UHMWPE fibre reinforced epoxy foam manufacturing process, (d) photographic image of epoxy coated continuous UHMWPE fibres and (e) photographic image of cured epoxy coated continuous UHMWPE fibre reinforced epoxy foam

The ultra-low viscosity epoxy resin and its amine-based hardener was then mixed at a weight ratio of 4:1 in a paper cup and gently stirred to avoid the trapping of air bubbles. The mixed resin system was then pipetted onto the UHMWPE fibre yarns to coat the fibres. After coating, the weaved skeletal structure was left to cure at room temperature for 24 h. As the wooden sticks were coated with a release agent, they could be removed and the final epoxy-coated continuous UHMWPE fibre yarns are shown in Figure 5-1 (b). The epoxy-coated UHMWPE fibre yarns were then immersed into a mould that contains the mechanically frothed air-in-epoxy foam template, prior to curing at room temperature for 24 h to produce the continuous epoxy-coated UHMWPE fibre-reinforced epoxy foams. The photographic images of epoxy coated continuous UHMWPE fibres and the epoxy coated continuous UHMWPE fibre reinforced epoxy foam are shown in Figure 5-

1 (d) and (e). Unreinforced foam core, foam core reinforced with epoxy coated continuous UHMWPE fibres with a loading fraction of 2 vol.-% and 4 vol.-% are herein termed samples **E0**, **E2** and **E4**, respectively.

5.2.3 Characterisation of the neat and epoxy coated continuous UHMWPE fibre-reinforced epoxy foams

5.2.3.1 Density and porosity of the (reinforced) epoxy foams

The mechanically frothed air-in-liquid epoxy foam template was poured into a cylindrical Falcon[®] tubes with diameter (d) of 15 mm and height (H) of 115 mm, respectively and cured at room temperature for 24 h. The cured sample was then cut into cylinders using bandsaw with a height (h) of 30 mm. The density of the epoxy foam (ρ_f) was then determined by the following equation:

$$\rho_f = \frac{4m_f}{\pi d^2 h} \quad (5.1)$$

where m_f is the mass of the cut sample. The true density of the cell wall material of the epoxy foam (ρ_e) was measured using a He pycnometer (Accupyc II 1340, Micromeritics Ltd, Hexton, UK) on bulk polymerised epoxy block. The porosity of the epoxy foam (P_f) was calculated using:

$$P_f = \left(1 - \frac{\rho_f}{\rho_e}\right) \times 100\% \quad (5.2)$$

5.2.3.2 Structure and morphology of the (reinforced) epoxy foams

Scanning electron microscope (SEM) (Hitachi S-3700 N, Tokyo, Japan) was used to investigate the morphology and internal microstructure of the reinforced epoxy foams and the epoxy coated UHMWPE fibres. SEM specimens of the (reinforced) epoxy foams were prepared by cutting a $30 \times 11 \times 10 \text{ mm}^3$ cuboid off the original sample and broken into two halves with a pair of pliers to expose the internal structure. All samples were attached onto aluminium stubs using conductive carbon tabs. Prior to SEM, the samples were coated with Au using sputter coater (Agar Scientific Ltd, Essex, UK) operated at a coating current of 40 mA for 40 s. The pore size distribution was determined by measuring 300 pores from the SEM images at $\times 50$ magnification. The architecture of the weaved UHMWPE fibre network within the reinforced epoxy foams was investigated using an X-ray nanoCT[®] computed tomography system (GE Sensing & Inspection Technologies GmbH, Wunstorf, Germany). The specimen possessed a dimension of $30 \times 30 \times 11 \text{ mm}^3$. The specimen was scanned at an operating power of 100 kV/10W. Reconstructed computed tomography 3D image data was visualised and analysed using the commercial software VGSTUDIO MAX.

5.2.3.3 Flatwise compression properties of the (reinforced) epoxy foams

Flatwise compressive test was performed in accordance with ASTM D1621-16. Prior to the test, test specimens with dimensions of $30 (l) \times 30 (b) \times 11 (c) \text{ mm}^3$ were cut (see Figure 5-2). The test specimen was compressed between two flat and parallel polished plates using an Instron universal tester (Model 5969, Norwood,

USA) equipped with a 50 kN load cell. A testing speed of 1.1 mm min^{-1} was used (corresponded to 10% of the thickness of the test specimen per minute, in accordance with the test standard). A non-contact video extensometer (Imetrum Video Gauge, Bristol, UK) was used to measure the strain of the test specimen. The compressive modulus of the test specimen was calculated from slope of the compressive stress-strain curve below the proportional limit of the test specimen. The compressive strength of the test specimen was determined as the stress at the yield point if yield happens before 10% strain or the stress at 10% strain if no obvious yield point.

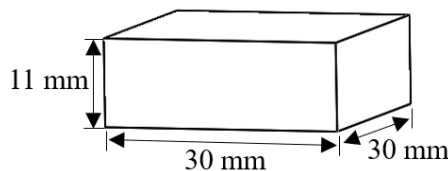


Figure 5-2 Schematic geometry of flatwise compressive test specimen

5.2.3.4 Edgewise tensile properties of the (reinforced) epoxy foams

Edgewise tensile test was conducted on test specimen with dimension shown in Figure 5-3. The test specimen possessed an overall length (l) of 120 mm, width (b) of 30 mm and thickness (c) of 11 mm. Prior to the test, $30 \times 30 \text{ mm}^2$ glass fibre-reinforced polyester end tabs with a thickness of 1.5 mm were adhesively bonded onto the test specimen (see Figure 5-3). The end tabs possessed a chamfer angle of 135° (normal to the test specimen surface). After the gluing of the end tabs, the exposed length of the test specimen was 60 mm. Two 10 mm diameter holes were drilled through the end tabs such that the test specimen can be mounted on to the

test machine with testing pins. Tensile test was conducted at a rate of 1 mm min^{-1} and a non-contact video extensometer (Imetrum Video Gauge, Bristol, UK) was used to monitor the strain of the test specimen. The tensile modulus of the test specimen was from slope of the tensile stress-strain curve below the proportional limit of the test specimen. The tensile strength of the test specimen was defined as the maximum stress achieved.

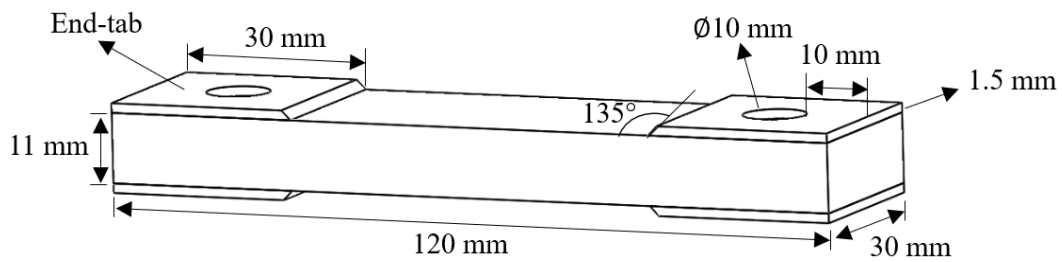


Figure 5-3 Schematic geometry of edgewise tensile test specimen

5.2.3.5 Core shear properties of the (reinforced) epoxy foams

The core shear properties of the (reinforced) epoxy foams were determined using three-point bending test in accordance with ASTM C393. Prior to the test, two 1 mm thick CFRP facesheets were glued onto the (reinforced) epoxy foam with dimensions of $120 (l) \times 30 (b) \times 11 (c) \text{ mm}^3$ (see Figure 5-4), forming a sandwich-structured composites consisting of the (reinforced) epoxy foam as the core. A testing speed of 2 mm min^{-1} was employed in this test and the span length used was 60 mm. A non-contact optical extensometer (Imetrum Video Gauge, Bristol, UK) was used to quantify the mid-span deflection of the test specimen during the three-point bending test. The core shear modulus and strength of the test specimen were determined using equations 4.1 and equation 4.2.

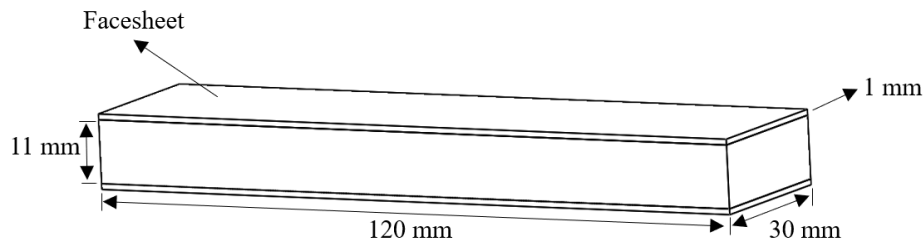


Figure 5-4 Schematic geometry of three-point bending test specimen

5.3 Results and discussions

5.3.1 Structure and morphology of the epoxy coated UHMWPE fibres and the (reinforced) epoxy foams

Figure 5-5 shows the reconstructed micro-CT images of the epoxy coated UHMWPE fibre network inside the reinforced epoxy foam (samples **E2** and **E4**). The epoxy foams were digitally removed in the images to reveal the fibres.

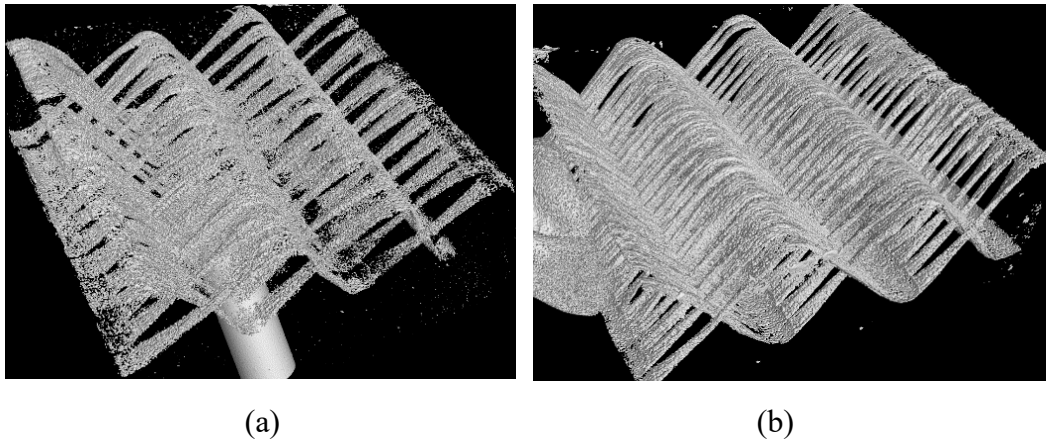


Figure 5-5 Reconstructed computed tomography 3D images of (a) **E2** and (b) **E4**

The SEM images of the epoxy coated UHMWPE fibres are shown in Figure 5-6. It can be seen from see Figure 5-6 that the epoxy resin coated only the external

surface of the UHMWPE fibre yarn. Within the fibre yarn, the UHMWPE fibres were found to be dry. These results show that the epoxy coating did not successfully coat the UHMWPE fibres at a single fibre level. This can be attributed to the coating process, whereby UHMWPE fibre yarn was first weaved into the structure depicted in (see Figure 5-1 (a)) prior to applying the epoxy coating. After forming the weaved pattern, the fibre yarn is postulated to be in tension (so that the weaved pattern can be held together). This caused the individual UHMWPE fibres to form a tighter packing, leading to impregnation difficulties. Even though the epoxy coating did not fully infiltrate into the fibre yarn, the applied epoxy coating held up the weaved pattern (see Figure 5-1 (b)), which allowed for subsequent production of continuous UHMWPE-reinforced epoxy foams. This was not possible if the manufacturing technique described in Chapter 4 was used as the nichrome bar used to form the skeletal structure (see Figure 4-1) will also be embedded into the final product.

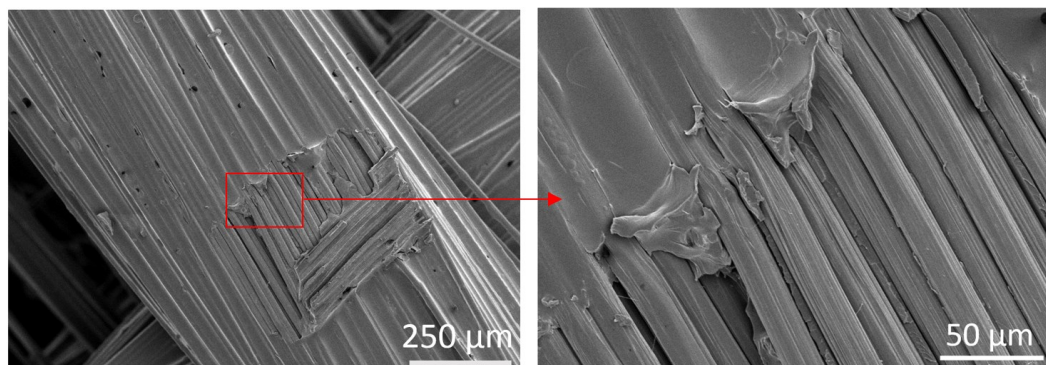


Figure 5-6 Scanning electron microscope images of epoxy resin coated UHMWPE fibres

The SEM images of the epoxy coated UHMWPE fibres, neat epoxy foam, as well as reinforced epoxy foams containing 2 vol.-% and 4 vol.-% epoxy coated

UHMWPE fibres are shown in Figure 5-7. It can be seen from Figure 5-7 (a)-(c) that the pores of all the samples possessed spherical closed-cell shape. This implies that the entrained air bubbles are in equilibrium prior to gelation as spherically shaped air bubbles minimise surface tension [64]. Next to the SEM images shown in Figure 5-7 (a)-(c) are the pore size distribution of the respective fabricated (reinforced) epoxy foams, averaged over 300 pores in 50 $\times$ magnification. The average pore diameter of each sample is presented in Table 5.1, along with the density and porosity of the fabricated (reinforced) epoxy foams.

Sample **E0** possesses a porosity of 69% and an average pore diameter of $\sim 110\ \mu\text{m}$ (see Table 5-1). These values are consistent with the porosity and average pore diameter reported for mechanically frothed epoxy foams [7]. The introduction of the epoxy coated UHMWPE fibres did not reduce the porosity of the reinforced epoxy foams as the loading fraction of UHMWPE fibres are low. Similarly, no significant differences were observed in the average pore diameters of the reinforced epoxy foams as an air-in-liquid foam template was first made, prior to the introduction of epoxy coated UHMWPE fibres into the liquid epoxy foam. The similarity in the porosity, average pore diameter, pore size distribution of the fabricated (reinforced) epoxy foams allow us to compare the measured mechanical properties in a consistent manner.

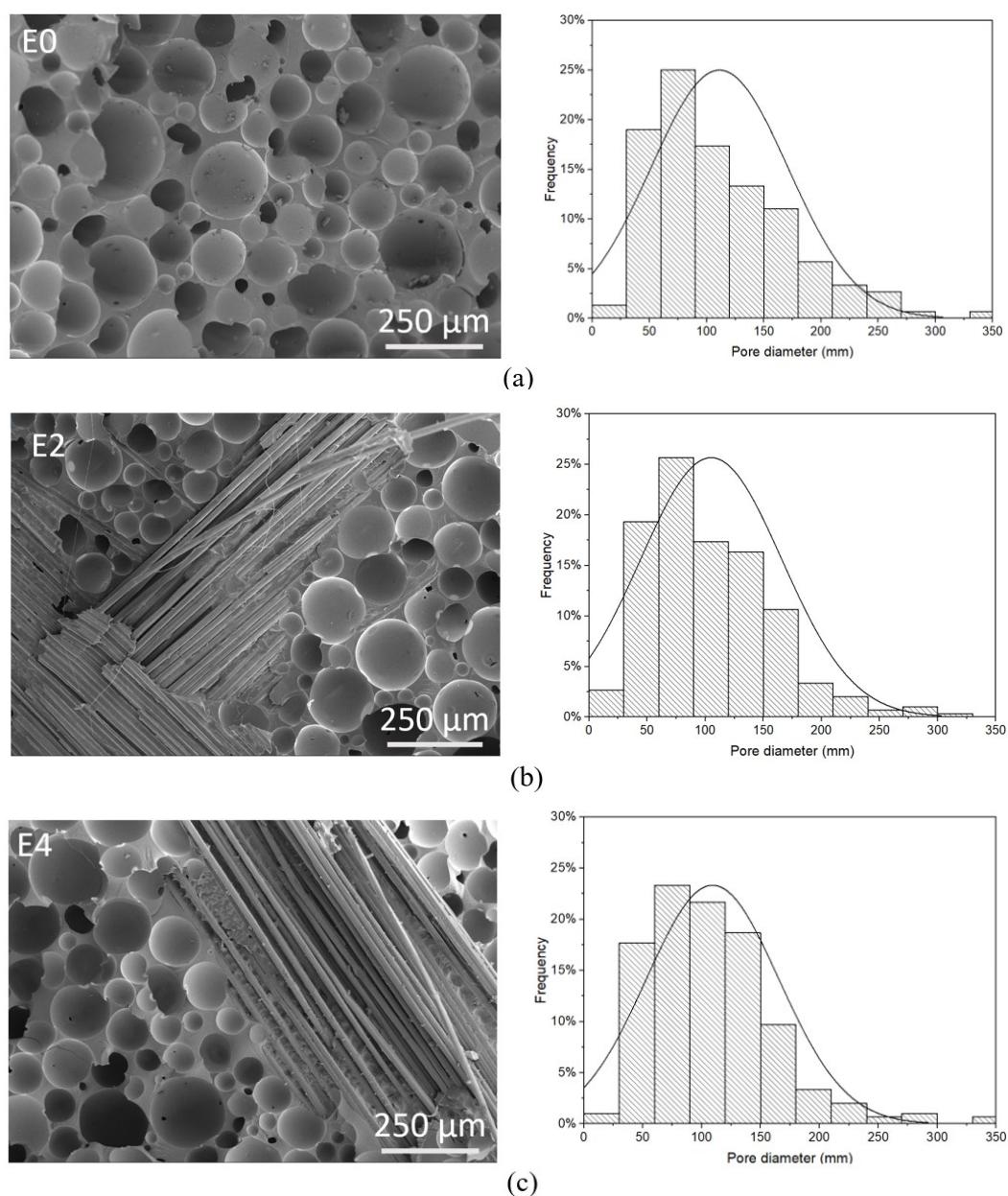


Figure 5-7 SEM images of (epoxy resin coated continuous UHMWPE fibre reinforced) epoxy foams and pore diameter distributions of (epoxy resin coated continuous UHMWPE fibre reinforced) epoxy foams (a) **E0** (b) **E2** and (c) **E4**

Table 5-1 Physical and morphological properties of (epoxy resin coated continuous UHMWPE fibre reinforced) epoxy foams (**E0**, **E2** and **E4**). ρ_e , ρ_f and P_f denote the density of the bulk epoxy polymer greenpoxy 56, the density of epoxy foam, the porosity of the test sample. S_p and D_p denote the average pore diameter determined from the maximum length of the observed pore and the average pore diameter calculated in accordance with ASTM D3576 – 15, respectively.

Sample	ρ_e (g cm ⁻³)	ρ_f (g cm ⁻³)	P_f (%)	S_p (μ m)	D_p (μ m)
E0	1.18 $\pm$ 0	0.36 $\pm$ 0.01	69 $\pm$ 1	111 $\pm$ 60	215 $\pm$ 23
E2	1.18 $\pm$ 0	0.36 $\pm$ 0.01	69 $\pm$ 1	105 $\pm$ 61	185 $\pm$ 14
E4	1.18 $\pm$ 0	0.36 $\pm$ 0.01	69 $\pm$ 1	109 $\pm$ 56	186 $\pm$ 5

5.3.2 Flatwise compressive properties of the (reinforced) epoxy foams

The representative flatwise compressive stress-strain curves of the (reinforced) epoxy foams are shown in Figure 5-8. The stress-strain curves exhibit the typical three-stage compressive behaviour of elastoplastic porous material [65]. The initial linear stage of the flatwise compressive stress-strain curves is associated with the elastic deformation of pore walls. The stress-strain curves then smoothly transitioned to the plateau stage at ~ 4 % strain, which corresponds to the plastic collapse of the pores. The compressive stress of all samples remained almost unchanged at this stage. When all the pores collapse and the pore walls in the loading direction are in contact, the compressive stress increases dramatically, signifying the start of the densification stage.

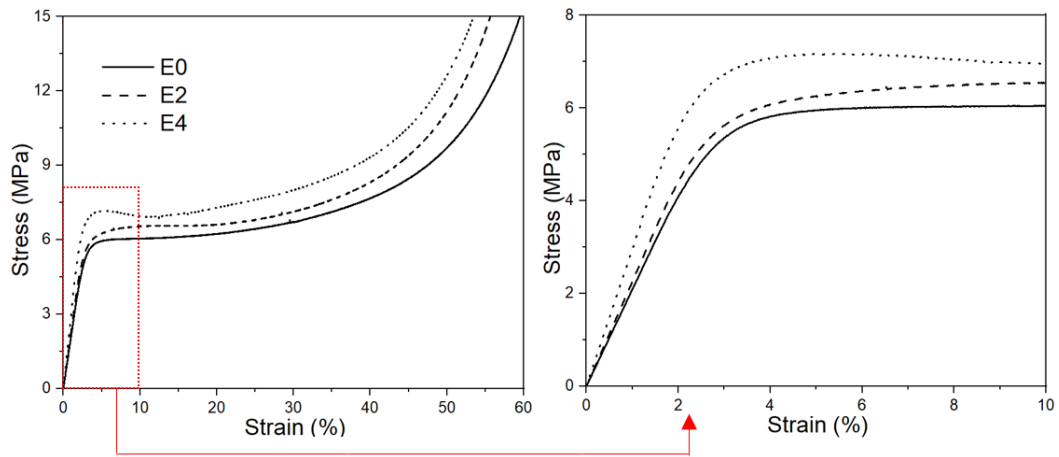


Figure 5-8 Representative flatwise compressive stress-strain curves of sample **E0**, **E2** and **E4**

It can be seen from Figure 5-8 that the epoxy foams containing the epoxy coated continuous UHMWPE fibres (samples **E2** and **E4**) possessed higher plateau stresses, as well as higher modulus especially for sample **E4** (initial slope of the stress-strain curves) compared to neat and unreinforced epoxy foam (sample **E0**). Both the plateau stress and modulus were also found to increase with increasing loading fraction of the reinforcing epoxy coated UHMWPE fibres. The flatwise compressive modulus and compressive strength of samples **E0**, **E2** and **E4** are summarised in Table 5-2. Sample **E0** possessed a flatwise compressive modulus (E_c) and a flatwise compressive strength (σ_c^*) of 202 MPa and 5.90 MPa, respectively. Compared to sample **E0**, there was no significant improvement in the E_c of sample **E2** but sample **E2** possessed a higher σ_c^* of 6.53 MPa. Sample **E4** was found to possess higher E_c and σ_c^* , measured to be 286 MPa and 7.23 MPa, respectively, compared to sample **E0**. This can be attributed to the introduced UHMWPE fibres, which provided support towards compression.

Table 5-2 Flatwise compressive properties of (epoxy coated continuous UHMWPE fibre reinforced) epoxy foams (**E0**, **E2** and **E4**). E_c and σ_c^* denote the flatwise compressive modulus and flatwise compressive strength, respectively

Sample	E_c (MPa)	σ_c^* (MPa)
E0	202 ± 23	5.90 ± 0.28
E2	204 ± 41	6.53 ± 0.04
E4	286 ± 22	7.23 ± 0.10

Equation 3.15 and equation 3.23 derived in chapter 3 is used to compare the experimentally measured flatwise compressive properties of the reinforced epoxy foam with the theoretical maximum compressive modulus of the reinforced epoxy foams (see Figure 5-9). The experimentally measured compressive moduli of the reinforced epoxy foam were found to be 75% lower than the theoretical maximum values in both 2 vol.-% and 4 vol.-% UHMWPE fibre-reinforced samples. This is hypothesised to be due to the buckling of the reinforcing fibres. The previously measured compressive strength of UHMWPE fibre by other authors ranged from 100 MPa – 877 MPa [101,102]. An UHMWPE fibre with compressive strength of 877 MPa was used for the calculation of the compressive strength of the reinforced epoxy foam. The predicted compressive strength of the UHMWPE fibre-reinforced epoxy foams was found to be significantly higher than the experimentally measured results (see Figure 5-9 (b)). This could be due to the fact that the UHMWPE fibres buckles, instead of failing in compression, a result of poor epoxy impregnation.

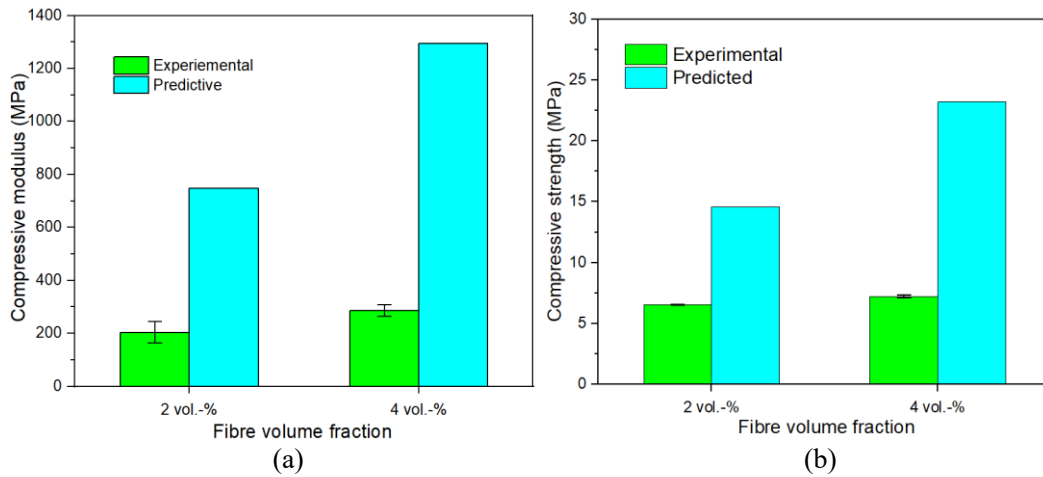


Figure 5-9 Comparison of experimental and predicted results (a) flatwise compressive modulus and (b) flatwise compressive strength of epoxy coated UHMWPE fibre reinforced epoxy foams

5.3.3 Edgewise tensile properties of the (reinforced) epoxy foams

The representative edgewise tensile stress-strain curves of the (reinforced) epoxy foams are presented in Figure 5-10. Unreinforced epoxy foam sample **E0** exhibited an initial linear elastic response, followed by catastrophic failure when peak stress was reached. For the reinforced epoxy foams consisting of the continuous epoxy coated UHMWPE fibres (samples **E2** and **E4**), the samples exhibited a progressive failure. After the initial linear elastic response, the samples reached their first peak stress, which was then accompanied by a slight drop in stress, followed by an increase in stress again until the second peak stress was reached. This cycle then repeats itself. As no fibre failure was observed (the maximum load to fail a reinforcing fibre yarn was significantly higher than the measured load), this load decrease-increase response is attributed to the spreading of the damage within the epoxy foam across a larger area.

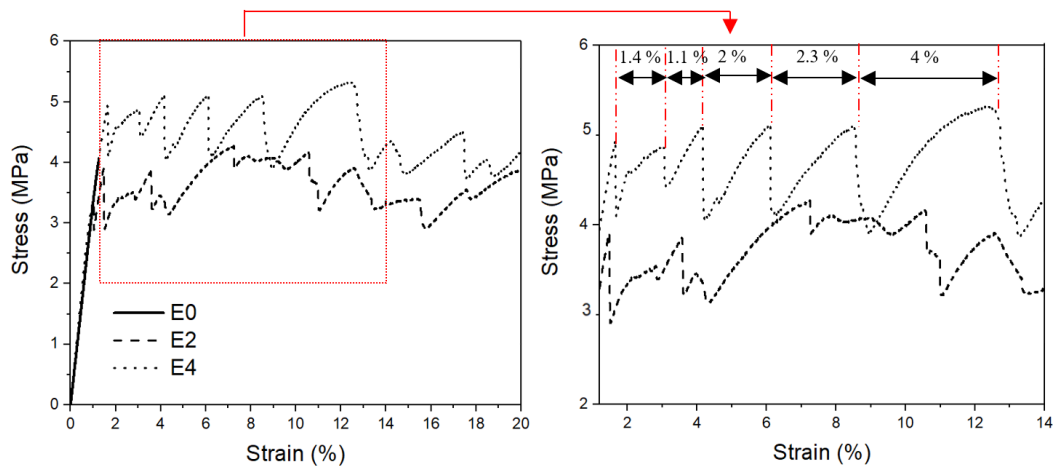


Figure 5-10 Representative edgewise tensile stress-strain curves of **E0**, **E2** and **E4**

Essentially, the reinforcing UHMWPE fibres held the epoxy foam structure together, even when failure within the epoxy foam occurred. It can also be seen from Figure 5-10 that the strain between two adjacent peak stresses increased from the second peak to the sixth peak. This is further evidence that the damage of the epoxy foam spreads across larger strain, which is hypothesised to reach a maximum value when all the UHMWPE fibres are aligned in the direction of load. It should be mentioned that the complete failure of the reinforced epoxy foams (i.e. where all the fibre fractures) could not be achieved as the end tabs of specimen could no longer hold the specimen and failed during the prolonged test. The representative progressive failure of the reinforced epoxy foam (sample **E4**) during the edgewise tensile test is shown in Figure 5-11 to further illustrate this. Even though the foam cracked, it did not fail catastrophically into two (or more) fragments.

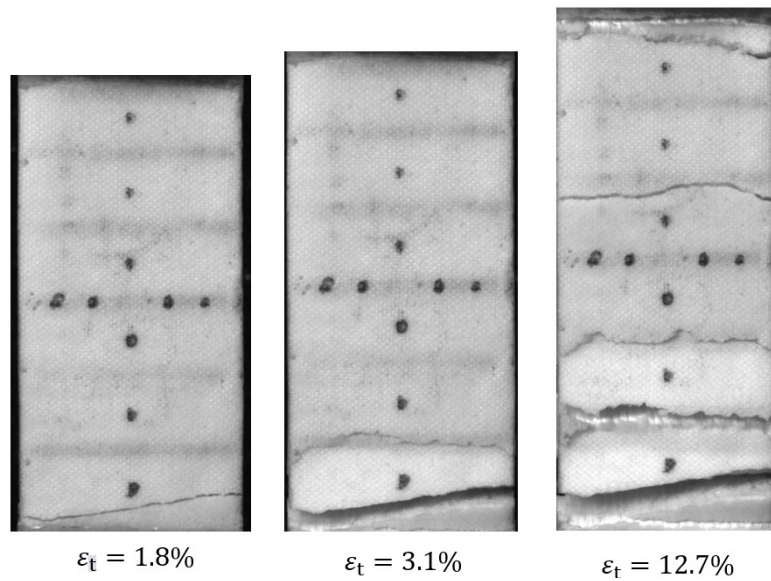


Figure 5-11 Progressive fractographic images of sample **E4** during the edgewise tensile test

Table 5-3 summarises the tensile properties of the (reinforced) epoxy foams. Sample **E0** possessed an edgewise tensile modulus (E_t) and a maximum edgewise tensile stress (σ_t^*) of 306 MPa and 3.80 MPa, respectively. No significant increase in E_t was found for samples **E2** and **E4**. This is due to the waviness of the reinforcing fibres (see Figure 5-12) within the structure.

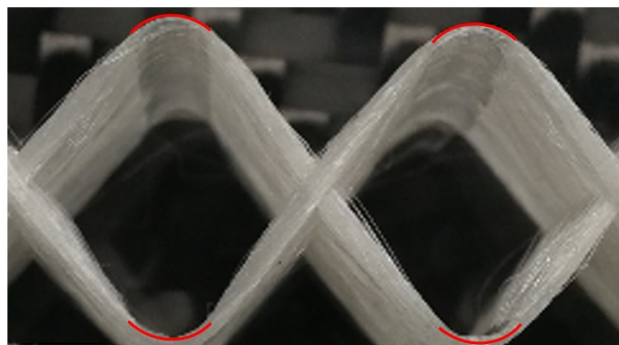


Figure 5-12 Epoxy coated UHMWPE fibres

As the fibres are at an angle of $\pm 45^\circ$ relative to the load, as well as the low fibre volume fraction, the contribution to the overall stiffness of the reinforced epoxy foams are minute. Furthermore, the fibres will first undergo alignment during tensile loading prior to the full utilisation of the tensile modulus of the fibres. Nevertheless, both the reinforced epoxy foams possessed higher edgewise tensile stresses. Samples **E2** and **E4** were found to possess σ_t^* of 4.17 MPa and 4.98 MPa, respectively, which represents up to $\sim 30\%$ increase compared to unreinforced epoxy foam.

Table 5-3 Edgewise tensile properties of (epoxy resin coated continuous UHMWPE fibre reinforced) epoxy foams (**E0**, **E2** and **E4**). E_t and σ_t^* denote the edgewise tensile modulus and maximum edgewise tensile stress, respectively

Sample	E_t (MPa)	σ_t^* (MPa)
E0	306 ± 28	3.80 ± 0.08
E2	310 ± 29	4.17 ± 0.16
E4	317 ± 43	4.98 ± 0.40

The theoretical maximum edgewise tensile modulus and tensile strength of the reinforced epoxy foams were calculated using equations 3.15 and 3.22 derived in Chapter 3. The comparison between the experimental results and predicted values are shown in Figure 5-13. It can be seen from the figure that both predicted edgewise tensile modulus and edgewise tensile strength of epoxy coated continuous UHMWPE fibre reinforced epoxy foams are significantly higher than the experimental values. This mismatch is attributed to fibre waviness, which leads

to fibre alignment (particularly related to modulus) as well as the dry fibres inside the UHMWPE fibre yarn.

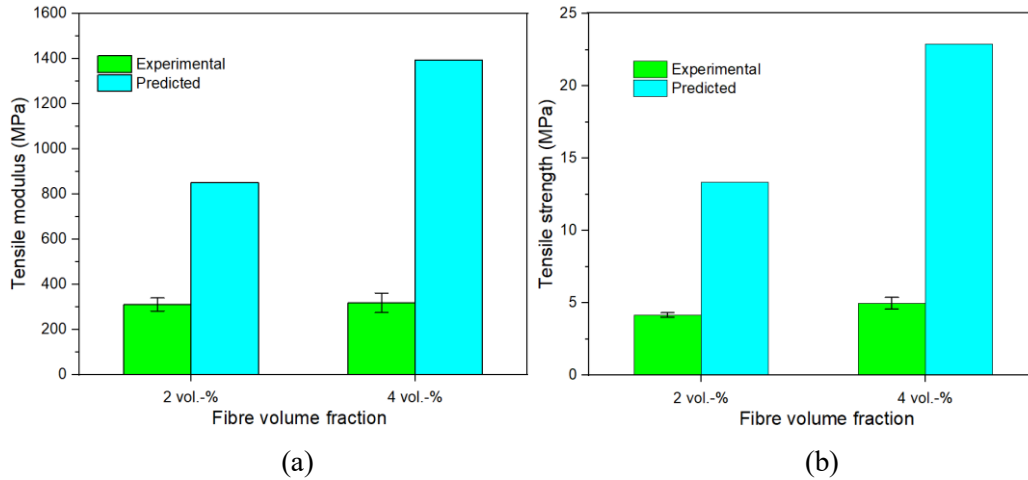


Figure 5-13 Comparison of experimental and predicted results (a) edgewise tensile modulus and (b) edgewise tensile strength of epoxy coated UHMWPE fibre reinforced epoxy foams

5.3.4 Shear properties of the (reinforced) epoxy foams

The representative load-deflection curves of the (reinforced) epoxy foams tested in three-point bending mode are shown in Figure 5-14. For all samples, the load-deflection curves exhibited an initial linear elastic response, followed by the yielding of the epoxy foam. After yielding, however, the load-deflection curve of neat and unreinforced epoxy foam (sample **E0**) exhibited a different behaviour compared to the reinforced epoxy foams (samples **E2** and **E4**). For sample **E0**, the core shear response exhibited a long plateau stress after peak stress was reached, followed by the catastrophic failure of the core. These results also contradict the load-displacement curves obtained in Chapter 4, whereby no prolonged plateau stress region was observed (see Figure 4-2). For samples **E2** and **E4**, two load

drops could be seen after peak stress was reached. This is more consistent with the results reported in Chapter 4 (Figure 4-2).

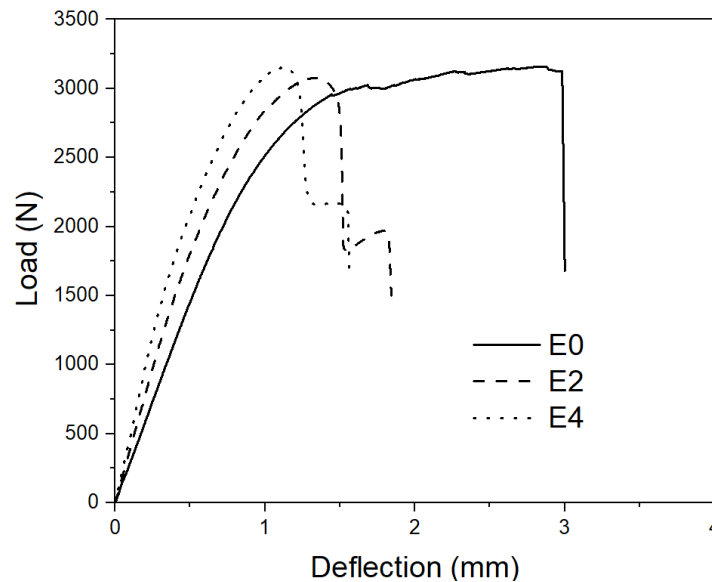


Figure 5-14 Representative three-point bending load-deflection curves of **E0**, **E2** and **E4**

To elucidate this, Figure 5-15 presents the morphology of the test specimens at the point of catastrophic failure. Sample **E0** exhibited the typical core shear failure of a foam core loaded in three-point bending in a sandwich construction, with an incline crack at $\sim 45^\circ$ angle (Figure 5-15 (a)). Multiple inclined cracks can be seen on samples **E2** and **E4** (see Figure 5-15 (b) and (c)) but these cracks did not propagate through the thickness of the epoxy foam core. Whilst these results could be attributed to the presence of epoxy-coated UHMWPE fibres, it is worth noting that all the core shear test specimens deviated from the idealised post core shear failure morphology. In fact, core indentation can be observed at the point of test specimen failure. This signifies that the maximum stress observed in Figure 5-14 might not be due to pure core shear but a combination of core shear and core indentation.



Figure 5-15 Failure modes of the (epoxy resin coated continuous UHMWPE fibre reinforced) epoxy foam core sandwich-structured composites. (a) **E0** (b) **E2** (c) **E4**

To further confirm this, the critical loads for core indentation (P_{in}), pure core shear (P_{cs}) and microbuckling of the facesheet (P_{fm}) when the test specimen is loaded in three-point bending mode are calculated using equations 2.16-2.18:

$$P_{in} = bt \left(\frac{\pi^2 d E_{fa} \sigma_c^{*2}}{3S} \right)^{1/3} \quad (5.3)$$

$$P_{cs} = 2bd\tau_s^* \quad (5.4)$$

$$P_{fm} = \frac{4dbt\sigma_{fm}}{S} \quad (5.5)$$

where t and E_{fa} are the thickness and Young's modulus of the facesheet, respectively, S is the supported span length, σ_{fm} is the face microbuckling strength

and here the compressive strength the CFRP composite facesheet was used for prediction. The term $d = c + t$.

The values of G_s and τ_s^* were obtained from Chapter 4 ($G_s = 110$ and $\tau_s^* = 4.08$). The anticipated critical loads for each type of failure are shown in Figure 5-16. Whilst the critical load for the microbuckling of the facesheet (P_{fm}) is large, the critical load for pure core shear failure (P_{cs}) and core indentation (P_{in}) were found to be very similar (~ 3000 to 4000 N). These results indicate all samples are prone to both core shear and core indentation failure when loaded in three-point bending mode, making the identification of the failure modes difficult. This is also consistent with the mechanical response of sample **E0**, whereby a plateau stress region is observed after peak stress, which can be attributed to core indentation. It is worth mentioning at this point that such a mechanical response was not observed in Chapter 4 during the core shear testing in the same mode as the core thickness used in this chapter was 20% thicker than the core thickness used in Chapter 4.

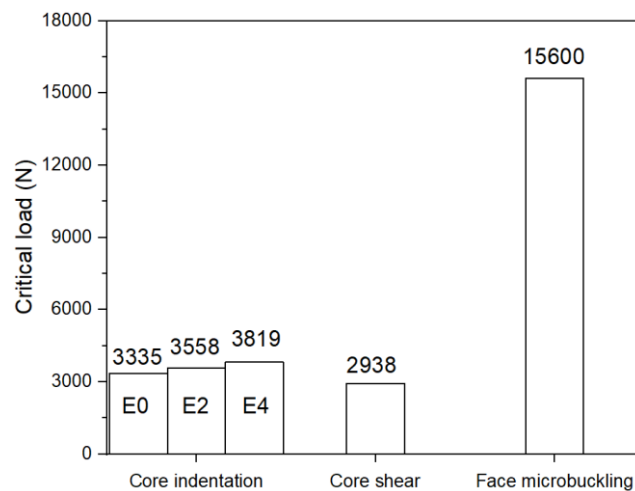


Figure 5-16 Estimated critical loads of core indentation, core shear and face microbuckling of **E0**, **E2** and **E4** in three-point bending

The representative load displacement curves of samples **E0**, **E2** and **E4** are further shown in Figure 5-17 (a), (b) and (c) respectively, along with the morphology of the test specimen at selected strain. It can be seen that at the plateau load (see Figure 5-17 (a)-3, (b)-3 and (c)-3), the foam core under the loading nose has been compressed. It was therefore decided to define the core shear strength as an offset strength, e.g. the stress that corresponds to an arbitrary point that intersects the stress-strain curve and with a line parallel to the modulus. A 0.5% offset shear strain was chosen as there was no obvious core indentation at this offset shear strain. The position of 0.5% offset shear strain is also marked on each figure.

From these results, a core shear yield strength at 0.5% offset was tabulated to compare the properties of the fabricated (reinforced) epoxy foams. These results are summarised in Table 5-4, along with the core shear modulus of the samples. It can be seen from this table that sample **E0** possessed a core shear modulus (G_s) of 116 MPa and an offset core shear yield stress (τ_s^{ys}) of 3.56 MPa. The introduction of epoxy coated continuous UHMWPE fibres led to an increase in G_s . At 2 vol.-% UHMWPE fibre, the G_s of sample **E2** increased to 146 MPa. Increasing the loading fraction of UHMWPE fibres to 4 vol.-% further increased G_s of sample **E4** to 216 MPa. However, no increase in the τ_s^{ys} was observed. This is hypothesised to be due to the fact that as the failure is dominated by the foam instead of the reinforcing fibres.

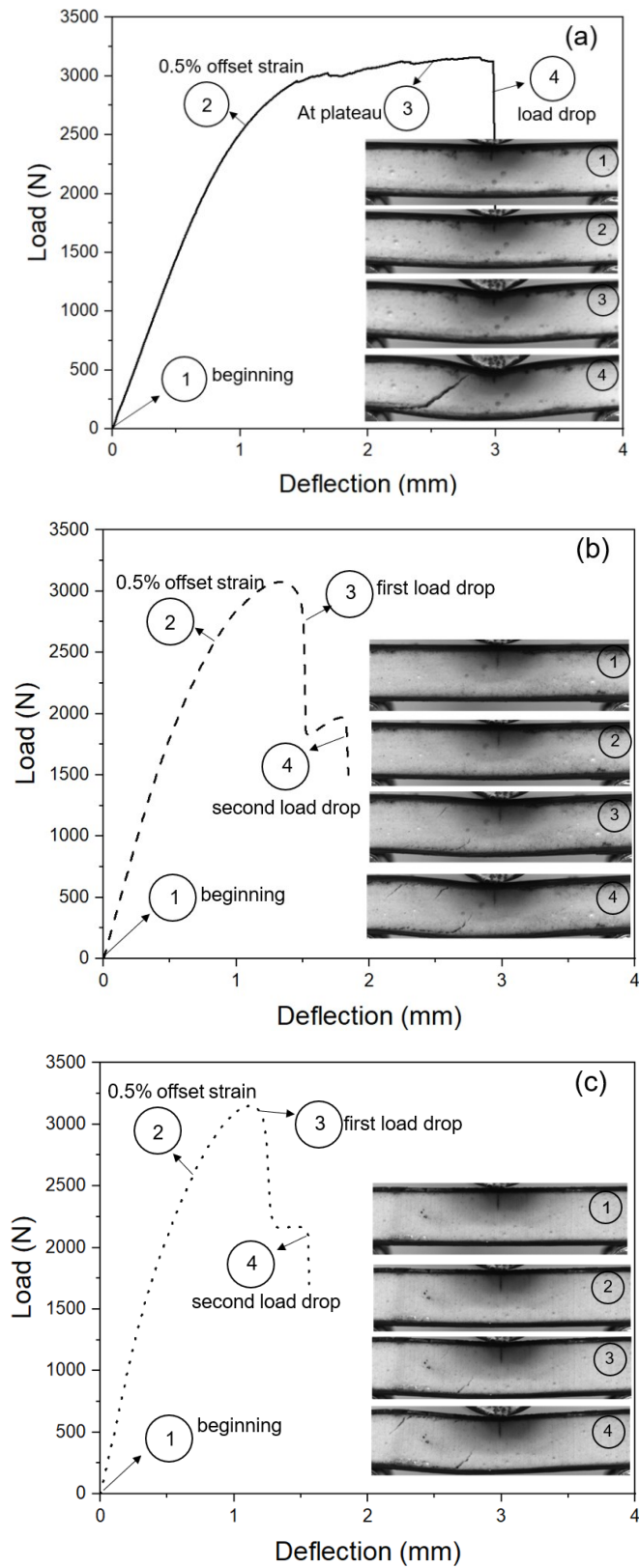


Figure 5-17 The representative load displacement curves of samples **E0**, **E2** and **E4** with the morphologies of the test specimen at select strain (a) **E0** (b) **E2** and (c) **E4**

Table 5-4 Three-point bending properties of the (epoxy resin coated continuous UHMWPE fibre reinforced) epoxy foam core sandwich structured composites (**E0**, **E2** and **E4**). G_s and τ_s^{ys} denote the core shear modulus and 0.5% offset core shear yield stress of **E0**, **E2** and **E4**, respectively

Sample	G_s (MPa)	τ_s^{ys} (MPa)	γ_s^{ys} (%)
E0	116 ± 11	3.56 ± 0.2	3.78 ± 0.34
E2	146 ± 7	3.52 ± 0.11	2.87 ± 0.19
E4	216 ± 32	3.55 ± 0.21	2.34 ± 0.39

Figure 5-18 compares the experimental core shear properties with the theoretical predicted (equations 3.8 and 3.18) core shear properties of the reinforced epoxy foams. Significant deviation from the theoretical maximum values are observed. As discussed in chapter 4, only half the UHMWPE fibres will contribute to the overall load bearing capability of the epoxy foam in shear as half of the fibres will undergo compression (and buckle). Even with this correction, the experimental values still deviate from the theoretical maximum values, suggesting that the maximum potential of this novel technology has not been fully utilised yet.

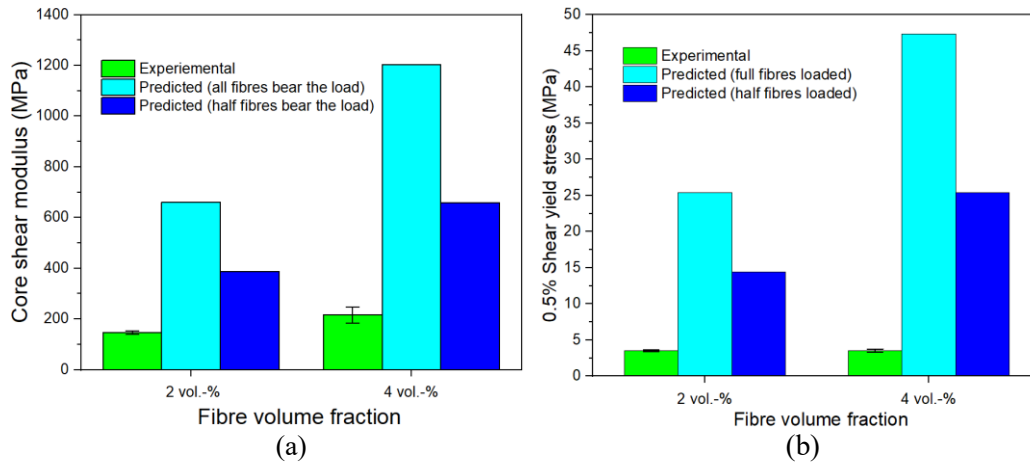


Figure 5-18 Comparison of experimental and predicted results (a) core shear modulus with full fibres loaded and half fibres loaded assumptions and (b) 0.5% core shear yield stress of epoxy coated UHMWPE fibre reinforced epoxy foams with full fibres loaded and half fibres loaded assumptions

5.4 Summary

In this chapter, UHMWPE fibres were coated with an epoxy resin in an attempt to improve the stress transfer efficiency between the epoxy foam core and the UHMWPE fibres. However, it was found that the UHMWPE fibre yarns could not be impregnated at a single fibre level (at least based on the technique used in this chapter). Nevertheless, the introduction of such continuous UHMWPE fibre network increased the tensile properties (especially the strain-at-break) of the resulting reinforced epoxy foam core. Both the compressive modulus and compressive strength of the reinforced epoxy foam core improved over their unreinforced counterpart. However, the introduction of UHMWPE fibres increased the core shear modulus without leading to an increase in the core shear strength of the epoxy foams.

Chapter 6 - Sandwich-structured composite with continuous UHMWPE fibres weaved through the facesheets

6.1 Introduction

The work discussed in the previous chapters suffered from facesheet-foam core debonding, which limited the reinforcing potential of sandwich-structured composites containing continuous UHMWPE fibres as through-thickness reinforcements. A key aspect to improve the performance of the continuous UHMWPE fibre weaved sandwich-structured composites is to prevent the debonding of the facesheets from the epoxy foam core such that the fibres could contribute more to the overall mechanical properties of the sandwich-structured composites. In this chapter, continuous UHMWPE fibres are weaved through both the facesheets and the epoxy foam core. The core shear, flatwise tensile and Charpy impact properties of the resulting continuous UHMWPE fibre weaved sandwich-structured composites with the reinforcing fibres waving through both the facesheets and the epoxy foam core are discussed and compared with unweaved sandwich-structured composites and sandwich-structured composites

weaved with discontinuous UHMWPE fibres as the through-thickness reinforcements. As elucidated in Chapter 5, applying a liquid epoxy resin does not produce well-impregnated UHMWPE fibres. Therefore in this chapter, all the UHMWPE fibres are used as received and not coated with liquid epoxy resin.

6.2 Experimental

6.2.1 Materials

UHMWPE fibres and the epoxy resin system were used as previously described. Carbon fibre reinforced composite laminates (3 mm thick, weaved with 2/2 twill woven and $\pm 45^\circ$ carbon fabrics) were purchased from Easy Composites Ltd (Staffordshire, UK) and used as the facesheets for the sandwich-structured composite. Two component toughened methacrylate adhesive system Araldite[®] 2022-1 was obtained from Huntsman Advanced Materials UK Ltd (Cambridge, UK).

6.2.2 Fabrication of the (UHMWPE fibres weaved) sandwich-structured composites

Three types of sandwich-structured composites were prepared in this work: unweaved, continuous UHMWPE fibre weaved and discontinuous UHMWPE fibre weaved (see Figure 6-1). As it will be elucidated in the next section, different mechanical tests (core shear, flatwise tensile and Charpy impact) require different

test specimen geometries. However, the thickness of the epoxy foam core was kept constant at 10 mm for all test specimens produced.

Unweaved sandwich-structured composite was prepared by first preparing the epoxy foam core following previously described steps (see Chapters 4 and 5). The mechanical frothing time employed in this study was 10 min. CFRP facesheets were then adhesively bonded onto the manufactured epoxy foam core (see Figure 6-1 (a)).

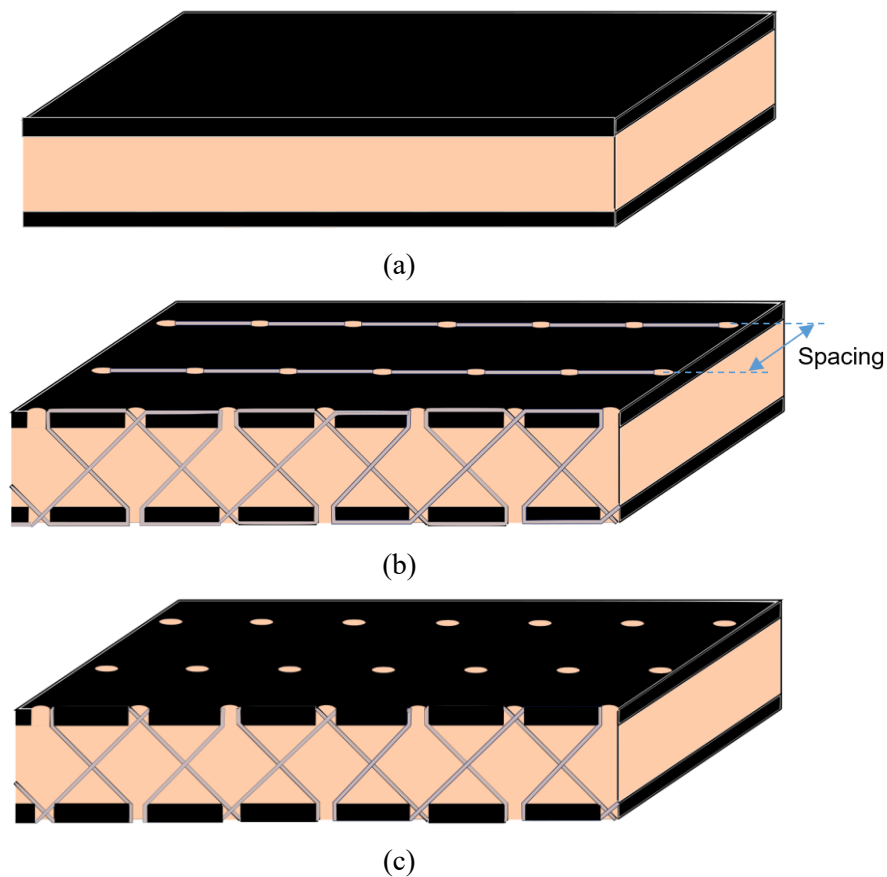


Figure 6-1 Schematic diagrams of (a) unweaved sandwich-structured composite, (b) weaved sandwich-structured composite and (c) discontinuous weaved sandwich-structured composite

To produce continuous UHMWPE fibres weaved sandwich-structured composites with the continuous UHMWPE fibres weaved through both the facesheets and the epoxy foam core, holes were drilled through the CFRP facesheet to allow for the weaving of continuous UHMWPE fibres. The diameter of the drilled holes was 2.5 mm and the spacing between the holes on the CFRP facesheet were 7.5 mm and 5 mm, which corresponded to a UHMWPE fibre volume fraction of 0.6 vol.-% and 0.9 vol.-% relative to the epoxy foam core, respectively, in the resulting foam-templated weaved sandwich-structured composites (see Figure 6-1 (b)). The UHMWPE fibres were then weaved through two parallel and drilled CFRP facesheets manually. The angles of the weaved UHMWPE fibres were $\pm 45^\circ$ relative to the horizontal plane. Figure 6-2 shows a schematic diagram of the weaving process.

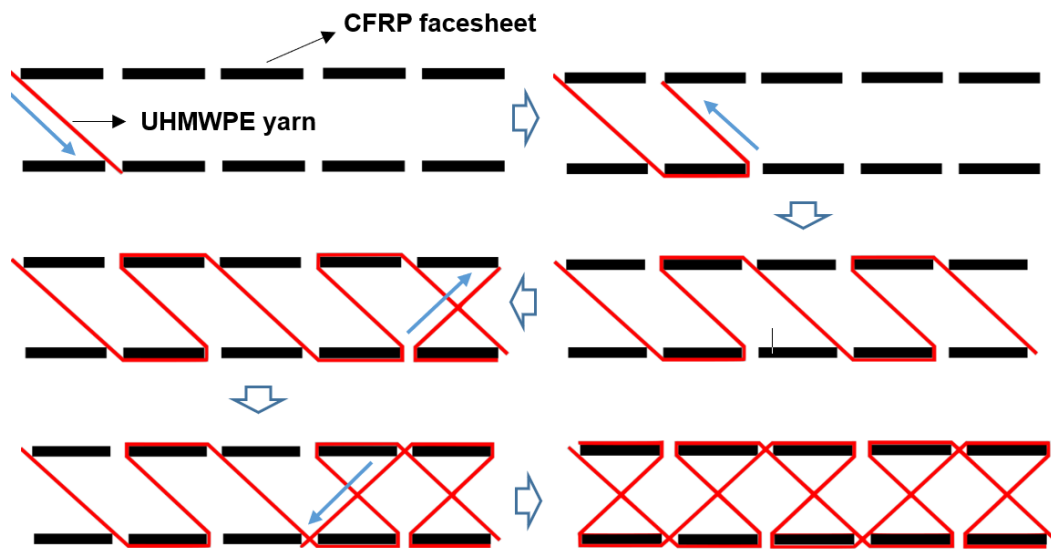


Figure 6-2 Schematic diagram of the weaving process

The gap between the two facesheets were kept at 10 mm. Mechanically frothed liquid epoxy foam was then poured into gap between the two CFRP facesheets and left to cure at room temperature for 24 h (see Figure 6-3).

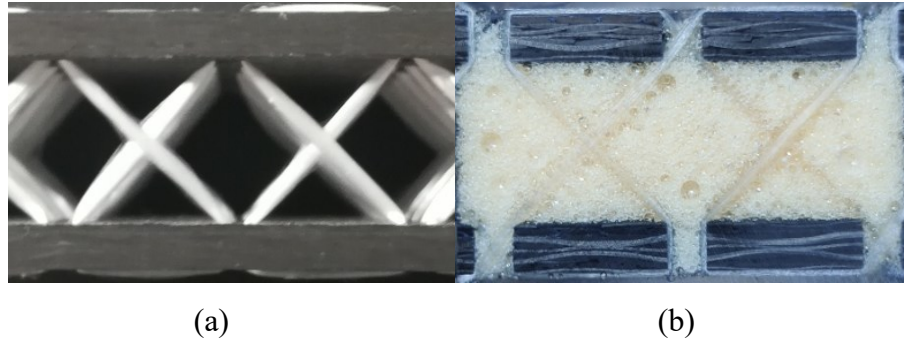


Figure 6-3 Woven sandwich-structured composite (a) after the weaving of UHMWPE fibres through the two parallel facesheets and (b) after the liquid epoxy foam template have been poured and cured

To fabricate sandwich-structured composites consisting of discontinuous UHMWPE fibres as through-thickness reinforcements, continuous through-thickness UHMWPE fibre woven sandwich-structured composites were first manufactured as previously described. The UHMWPE fibres were then cut from the surface of the facesheets carefully using a sharp scalpel to ensure that the UHMWPE fibres were still embedded within the epoxy foam core (i.e. no fibre pull out occurred) (see Figure 6-1 (c)).

Unwoven sandwich-structured composites, continuous UHMWPE fibre woven sandwich-structured composites containing 0.6 vol.-% and 0.9 vol.-% fibre reinforcement, as well as discontinuous UHMWPE fibre woven sandwich-

structured composites containing 0.6 vol.-% and 0.9 vol.-% fibre reinforcements are herein termed **samples U0, S0.6, S0.9, D0.6 and D0.9**, respectively.

6.2.3 Characterisation of the (UHMWPE fibres weaved) sandwich-structured composites

6.2.3.1 Density, porosity of foam core and areal density of the (UHMWPE fibres weaved) sandwich-structured composites

Prior to pouring the mechanically frothed liquid epoxy foam in between the UHMWPE fibre weaved facesheets, the liquid epoxy foam template was poured into cylindrical Falcon[®] tubes with diameter (d) and height (H) of 15 mm and 115 mm then cured in the room temperature for 24 h. The cured foams were released from the tubes and cut into cylinders with a height (h) of 30 mm. The density of the epoxy foam (ρ_f) was then determined by the following equation:

$$\rho_f = \frac{4m_f}{\pi d^2 h} \quad (6.1)$$

where m_f is the mass of the measured of cylinder foam. The true density of the epoxy (ρ_e) was determined by He pycnometry (Accupyc II 1340, Micromeritics Ltd, Hexton, UK). The porosity (P_f) of the foam was calculated by the following equation:

$$P_f = \left(1 - \frac{\rho_f}{\rho_e}\right) \times 100\% \quad (6.2)$$

To determine the areal density of the (UHMWPE fibres weaved) sandwich-structured composites. Rectangular samples with length (h) and width (b) of 35 and 30 mm of foam-templated (weaved) sandwich-structured composites were prepared and the areal weight (W_A) was determined using the following equation:

$$W_A = \frac{m_s}{hb} \quad (6.3)$$

where m_s is the mass of the (UHMWPE fibres weaved) sandwich-structured composite.

6.2.3.2 Scanning electron microscopy (SEM) of the (UHMWPE fibre weaved) sandwich-structured composites

The internal microstructure of the of the (UHMWPE fibres weaved) sandwich-structured composites was analysed using a large chamber scanning electron microscope (Hitachi S-3700 N, Tokyo, Japan). An accelerating voltage of 5 kV was used. Prior to SEM, the facesheets of the sandwich-structured composites were cut off using a bandsaw, leaving behind only the (weaved) epoxy foam core. The (weaved) foam core was then clamped on a vice and broken with a pair of pliers to expose its internal structure. The samples were glued onto aluminium SEM stubs using conductive adhesive and sputter coated (Agar Scientific Ltd, Essex, UK) with a thin Au layer using a coating current of 40 mA for 40 s. The average pore diameter (D_p) was determined by measuring the pore diameter of 300 pores from the SEM images at $\times 50$ magnification.

6.2.3.3 Core shear test of the (UHMWPE fibres weaved) sandwich-structured composites

In the previous chapters, the core shear properties of the fabricated sandwich-structured composites were determined using three-point bending. However, it was observed in Chapter 5 that the highly weaved nature of the epoxy foam core (and hence the sandwich-structured composite itself) led to a high core shear failure load. As a result, the test specimens were more likely to fail in core indentation instead of core shear. Therefore in this chapter, a different core shear test based on the modified single block core shear testing method described in BS ISO-1922 was employed. The schematic diagram showing the test specimen geometry and the stitch pattern are shown in Figure 6-4. The test area has a dimension of 150 mm (l) $\times$ 30 mm (b) $\times$ 10 mm (t). A length-to-thickness ratio of 15:1 was used to reduce end effects. Two 13 mm thick metal block were adhesively bonded onto the overhang of the CFRP facesheets and a 12.7 mm diameter hole were drilled through the aluminium block and the CFRP facesheet it was bonded to (see Figure 6-4, 20 mm from the edge of the specimen to the centre of the hole) such that testing pins can be inserted and load the specimen onto an Instron machine. Another two 20 mm thick steel block were adhesively bonded onto the outer surface of the facesheets (see Figure 6-4) to minimise test specimen distortion. Prior to the bonding, the bonding surfaces of metal blocks and CFRP facesheets were sand-blasted and degreased by using isopropyl alcohol.

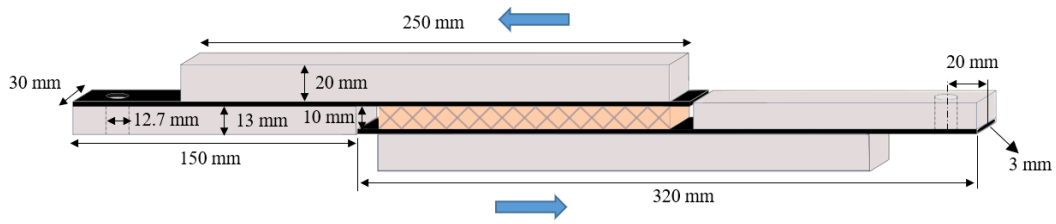


Figure 6-4 Schematic diagram of the core shear testing geometry (as well shown the weaving pattern of the fibre weaved samples)

Core shear test was conducted using a universal Instron test machine equipped with a 50 kN load cell. A constant crosshead displacement speed of 0.5 mm min^{-1} was used. A non-contact video extensometer (Imetrum Video Gauge, Bristol, UK) was used to measure the relative displacement (δ_s) between the two facesheets of the core shear test specimen. Core shear modulus (G_s) was calculated from the initial slope of the linear elastic portion of the stress-strain curve using the following equation:

$$G_s = \frac{Pt}{\delta_s bl} \quad (6.4)$$

where P is the load, t is the thickness of the core, b and l are the width and length of the foam core, respectively. Core shear strength (τ_s^*) was calculated from the maximum load $P_{\max}$ using the following equation:

$$\tau_s^* = \frac{P_{\max}}{bl} \quad (6.5)$$

The shear modulus of toughness (U_{ts}) of is the amount of shear strain energy absorbed per unit volume by the foam core before the failure and this was determined from the area under the shear stress-strain:

$$U_{ts} = \int_0^{\gamma_s^*} \tau_s d\gamma_s \quad (6.6)$$

where τ_s and γ_s are the shear stress and shear strain of the foam core, γ_s^* is the failure shear strain of the foam core.

6.2.3.4 Flatwise tensile test of the (UHMWPE fibres weaved) sandwich-structured composites

Flatwise tensile test was conducted in accordance with ASTM C297. The test specimen possessed a length (h) of 35 mm and a width (b) of 30 mm. The test specimen was adhesively bonded onto the test fixture (see Figure 6-5). The test was conducted in a universal Instron test machine equipped with 50 kN load cell. A crosshead displacement speed of 0.2 mm min^{-1} was used in this test. The extension of the foam core (δ_t) was monitored using a non-contact video extensometer (Imetrum Video Gauge, Bristol, UK).

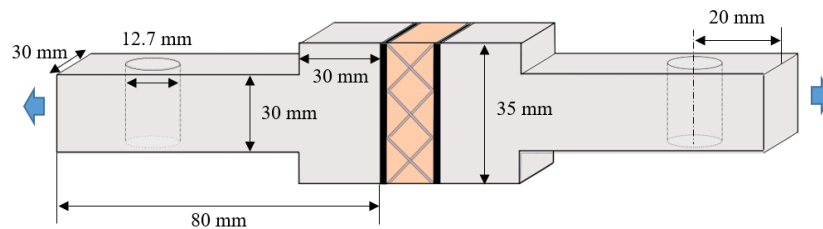


Figure 6-5 Schematic diagram of the flatwise tensile testing geometry (as well shown the weaving pattern of the fibre weaved samples)

Flatwise tensile modulus (E_t) was calculated from the initial slope of the linear elastic portion of the stress-strain curve using the following:

$$E_t = \frac{Pt}{\delta_t bh} \quad (6.7)$$

Tensile strength (τ_t^*) was calculated from the maximum load $P_{\max}$ using the following equation:

$$\tau_t^* = \frac{P_{\max}}{bh} \quad (6.8)$$

The tensile modulus of toughness (U_{tT}) corresponds to the amount of tensile strain energy absorbed per unit volume of the foam core before was calculated using:

$$U_{tT} = \int_0^{\varepsilon_t^*} \sigma_t d\varepsilon_t \quad (6.9)$$

where σ_t and ε_t are the tensile stress and shear strain of the foam core, ε_t^* is the failure tensile strain of the core. Only failure in the foam core was considered as a valid failure mode (i.e. if the test specimen failed at the CFRP facesheet-epoxy foam core interface, the results from the test specimen were discarded).

6.2.3.5 Charpy impact of the (UHMWPE fibres weaved) sandwich-structured composites

Charpy impact test was conducted in accordance with BS ISO 179-1:2010 using a pendulum impact tester (Zwick/Roell RKP 450, Ulm, Germany) equipped with a 450 J pendulum. The striker possessed an edge radius of 2 mm and the impact

speed was estimated to be 5 m s^{-1} . Unnotched test specimens with a length (l) of 60 mm and width (b) of 15 mm were placed on the supports with a span length of 40 mm. The pendulum hammer was then released from its rest position to strike the middle of the test specimen. For both discontinuous and continuous UHMWPE fibre weaved sandwich-structured composites, the strike point was fixed between the two rows of drilled CFRP holes (see Figure 6-6). Only completely failed test specimen with both facesheets broken was considered as a valid failure. The results were averaged over 5 number of test specimens.

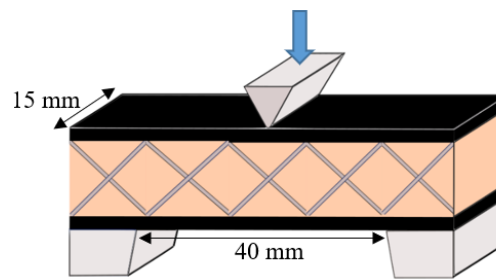


Figure 6-6 Schematic diagram of the Charpy impact testing geometry (as well shown the weaving pattern of the fibre weaved samples)

6.3 Results and discussions

6.3.1 Structure and morphology of the (UHMWPE fibres weaved) sandwich-structured composites

The SEM images of the (UHMWPE fibres weaved) epoxy foam core are shown in Figure 6-7. Similar to the previous chapters, it can be seen from these SEM images (See Figure 6-7 (a)-(c)) that all the epoxy foams (both unweaved and UHMWPE fibre weaved) possess an isotropic cellular structure, i.e. spherical pores, with a closed-cell structure. This indicates that the trapped air bubbles are always in

equilibrium in the air-in-resin liquid foam templates (with or without short carbon fibres), as spherically shaped air bubbles minimise surface tension [64]. It can also be seen from the figure (Figure 6-7 (d)) that the UHMWPE fibres appeared to be dry, with no impregnation of epoxy resin into the yarn. This was attributed to the high viscosity of liquid epoxy foam template.

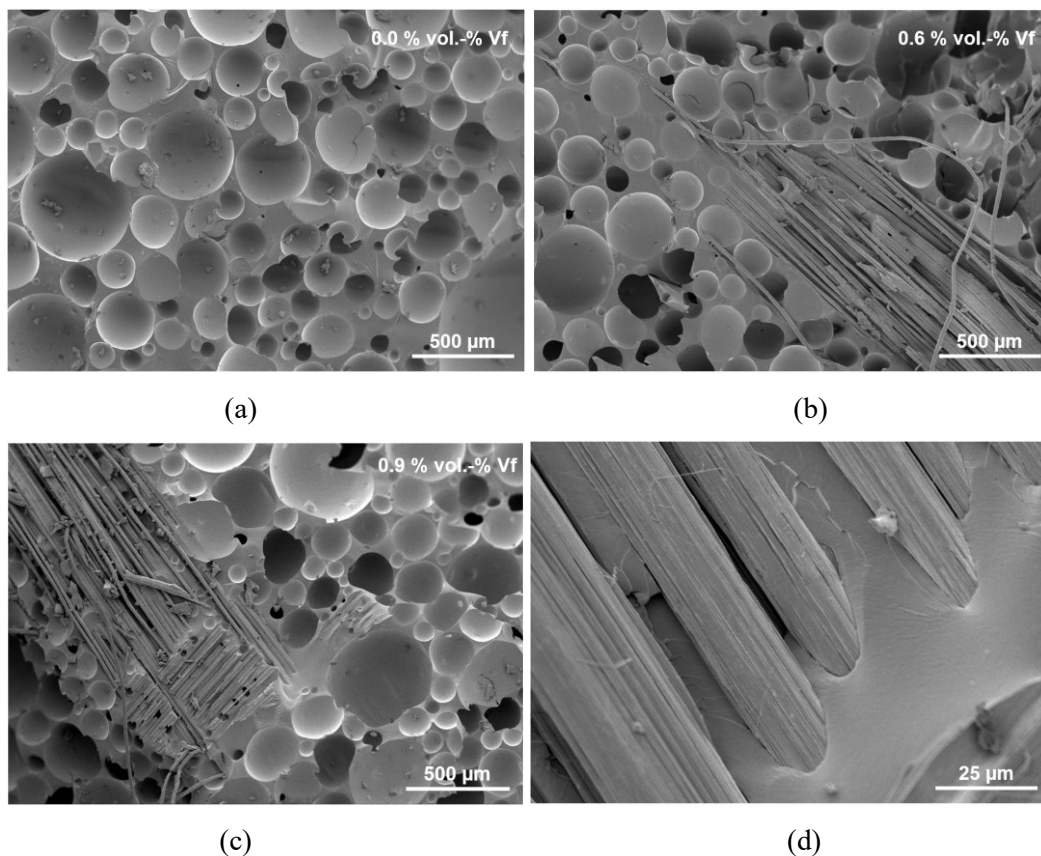


Figure 6-7 SEM images of (a) Unweaved epoxy foam (b) UHMWPE fibre weaved epoxy foam at 0.6 vol.-% fibre volume fraction (c) UHMWPE fibre weaved epoxy foam at 0.9 vol.-% fibre volume fraction and (d) UHMWPE fibres in the epoxy foam core

Figure 6-8 shows the pore size distributions of the fabricated (weaved) epoxy foams and the average pore diameters, along with the porosity of the (weaved) epoxy foams are summarised in Table 6-1. The epoxy foam core of all the manufactured sandwich-structured composites possessed a porosity of 70% and an

average pore diameter of $\sim 170 \mu\text{m}$. The average pore diameter in this study is larger than values obtained in Chapter 4. This was attributed to the shorter mechanical frothing time (10 min vs 20 min), leaving more time for bubble to coalescence and form larger pores prior to resin gelation [6].

A previous study has shown that the presence of a second phase, such as carbon fibres, will affect the cellular structure of the mechanically frothed fibre-reinforced epoxy foam [103]. However, this was not observed in this work. The presence of UHMWPE fibres does not affect the cellular structure of the epoxy foam core as the liquid epoxy foam was pre-made, prior to pouring into mould containing the fibres. In the case of reference [103], carbon fibres were mechanically frothed along with the epoxy resin, which caused phase separation of the liquid epoxy foam.

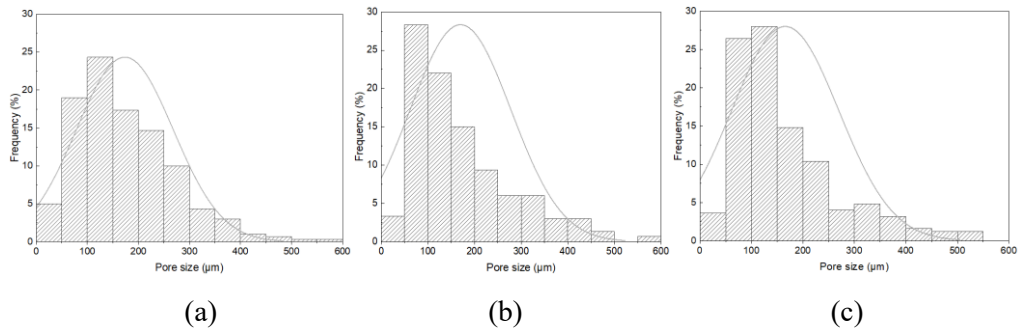


Figure 6-8 Pore diameter distributions of (UHMWPE fibres weaved) sandwich-structured composites containing fibre volume fraction (a) 0.0% (b) 0.6% (c) 0.9%

Table 6-1 Physical and morphological properties of unweaved (**U0**), continuous UHMWPE fibre weaved (**S0.6**, **S0.9**) and discontinuous UHMWPE fibre weaved (**D0.6**, **D0.9**) sandwich-structured composites. W_A , ρ_f and P_f denote areal weight of sandwich-structured composite, foam core density and foam core porosity. S_p and D_p denote the average pore diameter determined from the maximum length of the observed pore and the average pore diameter calculated in accordance with ASTM D3576 – 15, respectively.

Sample	W_A ($\text{g} \cdot \text{cm}^{-2}$)	ρ_f ($\text{g} \cdot \text{cm}^{-3}$)	P_f (%)	S_p (μm)	D_p (μm)
U0	1.22 ± 0.02	0.36 ± 0.2	70 ± 1	173 ± 95	331 ± 18
D0.6	1.14 ± 0.01	0.36 ± 0.1	70 ± 1	168 ± 96	346 ± 21
D0.9	1.15 ± 0.01	0.36 ± 0.1	70 ± 1	169 ± 102	349 ± 40
S0.6	1.15 ± 0.01	0.36 ± 0.1	70 ± 1	170 ± 108	347 ± 51
S0.9	1.16 ± 0.02	0.36 ± 0.1	70 ± 1	166 ± 104	344 ± 38

6.3.2 Core shear properties of the (UHMWPE fibres weaved) sandwich-structured composites

Figure 6-9 shows the representative stress-strain curves of the (UHMWPE fibres weaved) sandwich-structured composites tested in core shear. The initial linear elastic part of the stress-strain curves corresponded to the elastic deformation of the epoxy foam core. Samples **U0**, **D0.6** and **D0.9** fractured catastrophically immediately after the epoxy foams have yielded (strain-at-break $\gamma_s^* \approx 6\%$). For samples **S0.6**, the sample did not fail immediately after foam core yielded. Instead, the sample could still sustain load up to $\gamma_s^* \approx 20\%$ prior to the catastrophic failure. During this period, a series of sound could be heard which corresponded to the breakage of UHMWPE fibres. At a higher UHMWPE fibre volume fraction,

Sample **S0.9** exhibited a stress increase with increasing strain until failure occurred at $\gamma_s^* \approx 29\%$. This is hypothesised due to the reorientation of the UHMWPE fibres prior to the failure of the fibres in the direction of loading.

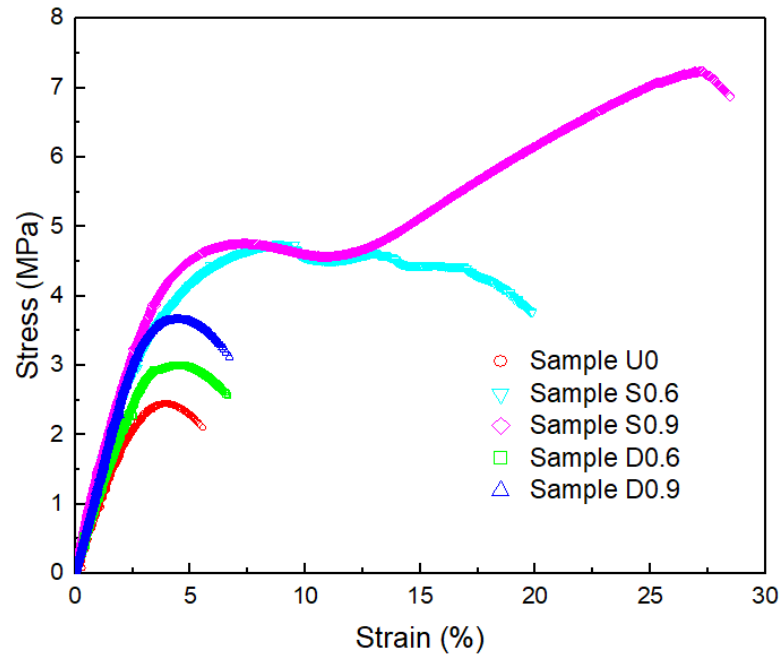


Figure 6-9 Representative stress-strain curves of unweaved (**U0**), continuous UHMWPE fibre weaved (**S0.6**, **S0.9**) and discontinuous UHMWPE fibre weaved (**D0.6**, **D0.9**) sandwich-structured composites in core shear testing

The calculated core shear modulus and strength of the (UHMWPE fibre weaved) sandwich-structured composites are summarised in Table 6-2. Sandwich-structured composites consisting of the unweaved epoxy foam core (sample **U0**) possess a core shear strength (τ_s^*) of 2.39 MPa and core shear modulus (G_s) of 96 MPa. The measured core shear properties in this chapter were found to be slightly lower than the core shear properties measured in Chapter 4. This is due to the fact that the core shear properties of the sandwich-structured composites were determined using three-point bending in Chapter 4 whilst a modified a single block

core shear test was employed in this chapter. It should be noted that the core shear strength determined using this method is typically lower than the core shear strength determined by three-point bending test [104]. The stress concentration at the corner of loading plate could lead to a pre-mature failure due to the distortion by the design of the BS test itself where the bending moment was exerted during the test because of asymmetry of the test specimen [105].

Table 6-2 Core shear properties of (UHMWPE fibre weaved) sandwich-structured composites. G_s , τ_s^* , γ_s^* and U_{ts} denote shear strength, shear modulus, shear strain-at-break shear modulus of toughness, analytical shear strength and analytical strength modulus, respectively

Sandwich-structured composites	G_s (MPa)	τ_s^* (MPa)	γ_s^* (%)	U_{ts} (kPa)
Sample U0	96 ± 5	2.39 ± 0.07	5.8 ± 0.3	104 ± 4
Sample D0.6	120 ± 8	3.04 ± 0.04	6.4 ± 0.9	142 ± 19
Sample D0.9	140 ± 8	3.71 ± 0.08	6.1 ± 0.3	174 ± 14
Sample S0.6	148 ± 11	4.83 ± 0.23	20.8 ± 0.6	849 ± 53
Sample S0.9	177 ± 23	6.77 ± 0.48	29.2 ± 2.5	1478 ± 125

The core shear modulus and strength of the sandwich-structured composites consisting of discontinuous UHMWPE fibre as reinforcement were measured to be 120 MPa and 3.04 MPa, respectively, for sample **D0.6** and 140 MPa and 3.71 MPa, respectively, respectively, for sample **D0.9** (see Table 6-2). This represents an increase of up to 46 % and 55 % in core shear modulus and strength compared

to sandwich-structured composites consisting of unweaved epoxy foam core. When continuous UHMWPE fibres were used as reinforcement, the core shear modulus and strength of the resulting continuous UHMWPE fibre weaved sandwich-structured composite improved significantly. At a loading fraction of 0.6 vol.-%, core shear modulus and strength of 148 MPa and 4.83 MPa, respectively, were measured. This represents a 54 % and 102 % increase compared to unweaved sandwich-structured composite. At a loading fraction of 0.9 vol.-%, this increase is even more pronounced; 84 % and 183 % increase in core shear modulus and strength, respectively, over unweaved sandwich-structured composite. This is also accompanied by significant increase in the shear modulus of toughness (see Table 6-2).

Figure 6-10 shows the visual appearance of the unweaved, discontinuous UHMWPE fibre weaved and continuous UHMWPE fibre weaved sandwich-structured composites containing a UHMWPE fibre loading of 0.9 vol.-% at the point of structural failure. Unweaved sandwich-structured composite failed catastrophically in shear, initiated from the characteristic crack at a 45° angle across the through-thickness of the foam core and the crack propagated to the foam core-facesheet interface (see Figure 6-10 (a)), leading to subsequent sandwich-structured composite failure. When UHMEPWE fibres were in a discontinuous form, a different failure mechanism was observed. No characteristic crack at a 45° angle was observed. Instead, the appearance of the crack was at the edge of the test specimen at a shear strain of 4.5 % (a region with high stress concentration [105]).

The crack propagated through the foam facesheet-core interface and failed the specimen at a shear strain of 6.4 %. The similarity between the failure modes of unreinforced sandwich-structured composite and discontinuous fibre-reinforced sandwich-structured composite corroborated with the results that both sandwich-structured composites possessed similar shear strain-at-failure and the catastrophic failure was initiated from the weakest component in the structure, i.e. the epoxy foam facesheet-core interface. The higher core shear modulus and strength of the discontinuous fibre weaved sandwich-structured composite can be attributed to the presence of the high strength/stiffness UHMWPE fibres. For the continuous UHMWPE fibre weaved sandwich-structured composite, at a shear strain of 11.5 %, a similar crack as the discontinuous UHMWPE fibre weaved sandwich-structured composite initiated at the corner of the foam core. The ultimate failure at a strain of 28.5 % when an inclined crack across the through-thickness of the foam core and then propagated through the facesheet-core interface. It was observed that the introduction of continuous UHMWPE fibres delayed the failure of the overall sandwich-structured composite as the load exerted on the structure is carried efficiently by the continuous UHMWPE fibres, leading to the observed higher shear strength values of samples **S0.6** and **S0.9** compared to samples **U0**, **D0.6** and **D0.9**. Similar delay mechanisms have also been exploited by Diao et al. [106], who enhanced the tensile strain-at-failure of carbon fibre-reinforced polyamide-12 composites with “wavy fibres”.

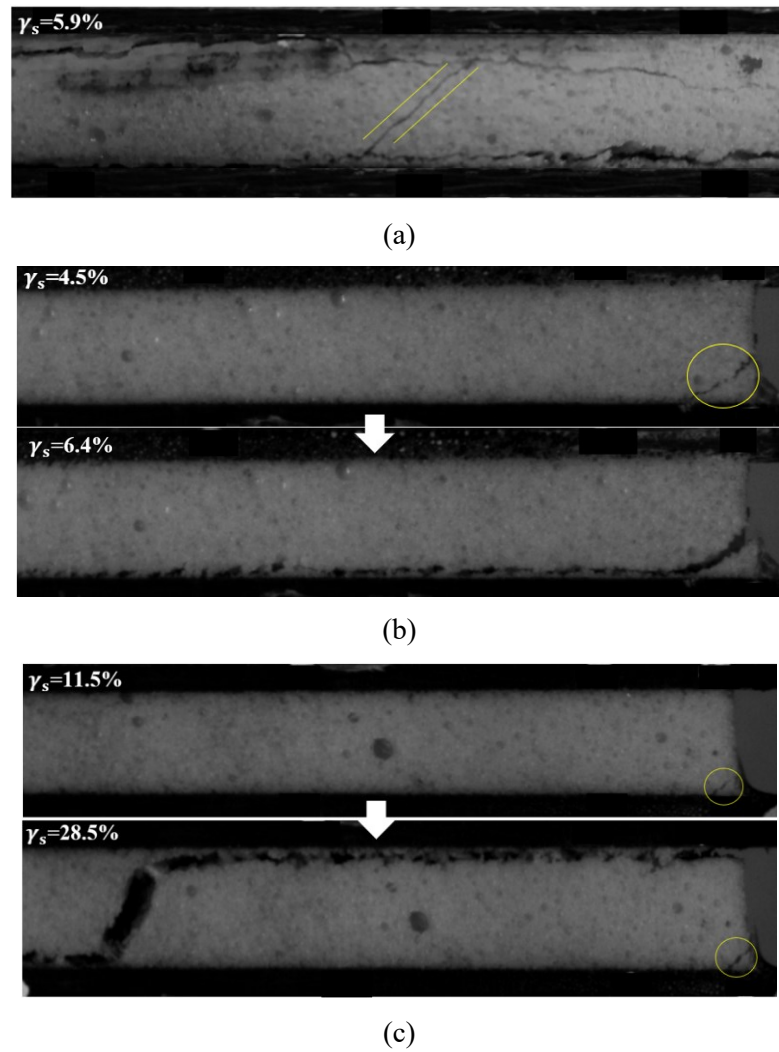


Figure 6-10 Failure modes of the (a) unweaved, (b) discontinuous UHMWPE fibre weaved and (c) continuous UHMWPE fibre weaved sandwich-structured composites containing a UHMWPE fibre loading of 0.9 vol.-% at the point of structural failure

The core shear properties obtained experimentally were also compared (Figure 6-11) with the theoretical core shear properties calculated from equation 3.8 and 3.18 and 3.19 derived in Chapter 3. The properties of neat epoxy foam core used in equations are obtained from sample U0. It can be seen from this figure that the experimentally determined core shear modulus values still lagged behind the theoretical core shear modulus. However, considering the fact that 50% of the

UHMWPE fibres will undergo tension whilst the other 50% will buckle, equations 3.8 was further modified (see Figure 6-11 (a)), the experimentally determined core shear moduli were found to be in good agreement with the theoretical core shear modulus values. Unlike CFRP pins discussed in chapter 2, unimpregnated UHMWPE fibres do not possess any compressive properties. As a result, our weaved sandwich-structured composite could not utilise the full potential of discontinuous or continuous UHMWPE fibre reinforcement.

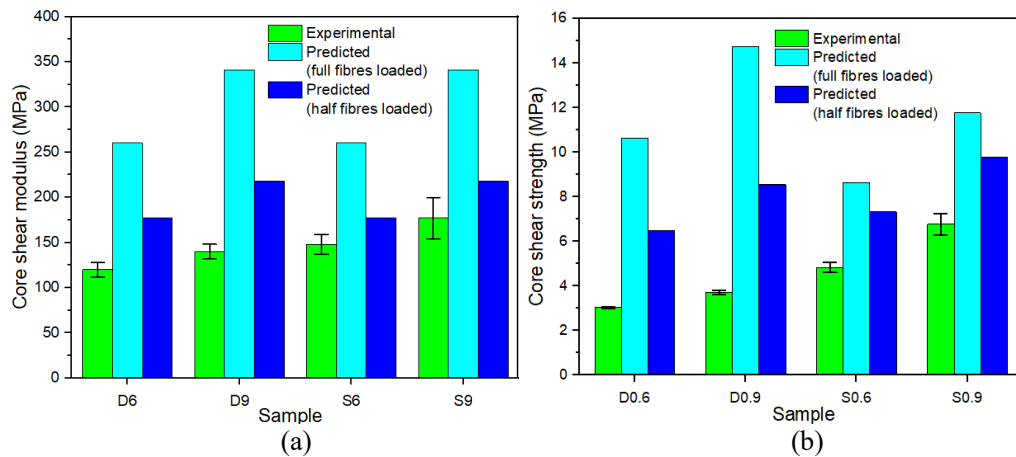


Figure 6-11 Comparison of experimental results and predicted values (a) experimental core shear modulus, predicted core shear modulus with full reinforcement loaded and half reinforcement loaded assumptions of the (dis)continuous UHMWPE fibres weaved sandwich-structured composites (b) experimental core shear strength and predicted core shear strength with full reinforcement loaded and half reinforcement loaded assumptions of the (dis)continuous UHMWPE fibre weaved sandwich structured composites

The experimentally determined core shear strength values were also compared with the theoretical predictions derived in Chapter 3 (see Figure 6-11 (b)). Equation 3.18 was used to calculate the theoretical value for samples **D0.6** and **D0.9**. However, equation 3.19 was used to obtain the theoretical values for samples **S0.6** and **S0.9** due to differences in failure mode of the continuous UHMWPE fibre

weaved sandwich-structured composite (fibre-dominated failure). It can be seen from this figure that there is a mismatch between the experimentally measured core shear strength and the expected (theoretical) core shear strength values. If equations 3.18 and 3.19 are adjusted to account for the fact that only half of the reinforcing UHMWPE fibres (in tension) contribute to the overall core shear performance of the weaved sandwich-structured composites, the experimentally measured core shear strength values for samples **D0.6** and **D0.9** possessed ~50 % of calculated shear strength could be attributed to the premature failure initiated at the edge of the test specimen and propagated through the facesheet-core interface.

Figure 6-11 (b) also shows that the experimentally determined core shear strengths of samples **S0.6** and **S0.9** that had smaller discrepancy than **D0.6** and **D0.9** with the theoretically predicted core shear strength values assuming that 50% of the reinforcing fibres do not contribute to the overall load. The discrepancy can be attributed to the reorientation of the UHMWPE fibres due to their continuity within the sandwich-structured composites and non-simultaneous failures of few fibres. Unlike samples **D0.6** and **D0.9**, where catastrophic failure of the sandwich-structured composite occurred after the yielding of the epoxy foam core, samples **S0.6** and **S0.9** could still bear load as the continuous UHMWPE fibres held the structure together, increasing both the core shear strain-at-failure, as well as the core shear strength.

6.3.2 Flatwise tensile properties of the (UHMWPE fibres weaved) sandwich-structured composites

Figure 6-12 presents the representative flatwise tensile stress-strain curves of the (dis)continuous UHMWPE fibre weaved sandwich-structured composites. Their flatwise tensile modulus (E_t), tensile strength (σ_t^*) and tensile modulus of toughness (U_{tT}) are summarised in Table 6-3. All samples failed catastrophically at the epoxy foam core once peak load was reached (see Figure 6-13).

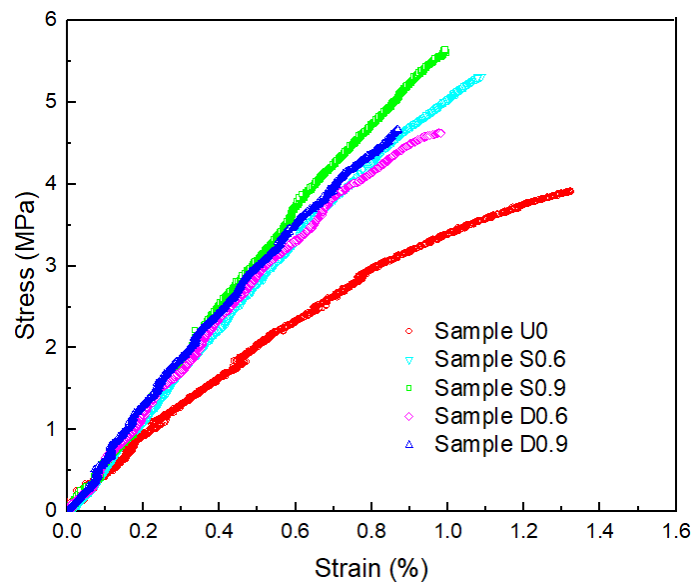


Figure 6-12 Representative stress-strain curves of unwoven (U0), woven (S0.6, S0.9) and discontinuous woven (D0.6, D0.9) sandwich-structured composites in flatwise tensile testing

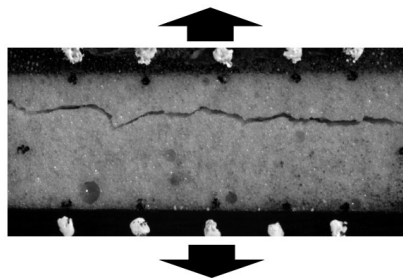


Figure 6-13 The visual appearance of the flatwise tensile test specimen at the point of structural failure, with a visible crack across the epoxy foam core

Table 6-3 Flatwise tensile properties of foam-templated (weaved) sandwich-structured composites. σ_t^* , E_t , ε_t^* , and U_{tT} denote tensile strength, tensile modulus, tensile strain-at-break and tensile modulus of toughness, respectively

Sandwich-structured composites	E_t (MPa)	σ_t^* (MPa)	ε_t^* (%)	U_{tT} (kPa)
Sample U0	360 ± 39	4.06 ± 0.12	1.5 ± 0.1	365 ± 58
Sample D0.6	528 ± 56	4.05 ± 0.46	0.9 ± 0.2	237 ± 21
Sample D0.9	530 ± 57	4.30 ± 0.39	0.8 ± 0.1	200 ± 18
Sample S0.6	535 ± 34	5.49 ± 0.18	1.1 ± 0.1	337 ± 60
Sample S0.9	583 ± 13	5.87 ± 0.34	1.0 ± 0.1	343 ± 64

The tensile strain-at-failure was found to be ~1%. Such low strain-at-failure values are typical of the tensile strain-at-failure of rigid foams [107,108]. The flatwise tensile properties of unweaved epoxy foam sandwich-structured composite were measured to be 360 MPa (E_t) and 4.06 MPa (σ_t^*), respectively. These values are consistent with the values obtained in Chapter 5. The introduction of both discontinuous and continuous UHMWPE fibre reinforcement led to ~62 % increase in the flatwise tensile modulus of the sandwich-structured composites compared to their unweaved counterparts. Whilst there were no significance differences between the flatwise tensile moduli of the discontinuous and continuous UHMWPE fibre weaved sandwich-structured composite, the tensile strength of the weaved sandwich-structured composite showed otherwise. The tensile strength of the continuous UHMWPE fibre weaved sandwich-structured composite was found to be 5.5-5.9 MPa (samples **S0.6** and **S0.9**) whilst discontinuous UHMWPE fibre weaved sandwich-structured composite possessed a tensile strength of only 4.0-4.3 MPa (samples **D0.6** and **D0.9**). The continuous

UHMWPE fibres increased the overall load bearing capability of the weaved sandwich-structured composite under flatwise tensile loading.

The experimentally determined flatwise tensile properties of the weaved sandwich-structured composite were also compared with the theoretical (equations 3.15 and 3.22) predictions (see Figure 6-14). The measured tensile moduli of continuous UHMWPE fibre weaved sandwich-structured composite are in good agreement with the theoretical predictions. However, there is a discrepancy between the experimentally measured tensile strength and the theoretically predicted tensile strength of the discontinuous weaved sandwich-structured composite. This discrepancy can be attributed to the discontinuous fibres pulling out from the facesheets. As a result, the full tensile strength of the UHMWPE fibres cannot be utilised prior to the failure of the epoxy foam core in samples **D0.6** and **D0.9**. The continuous UHMWPE fibres within the sandwich-structured composites (**S0.6** and **S0.9**) allowed for the full utilisation of the tensile strength of the UHMWPE fibres.

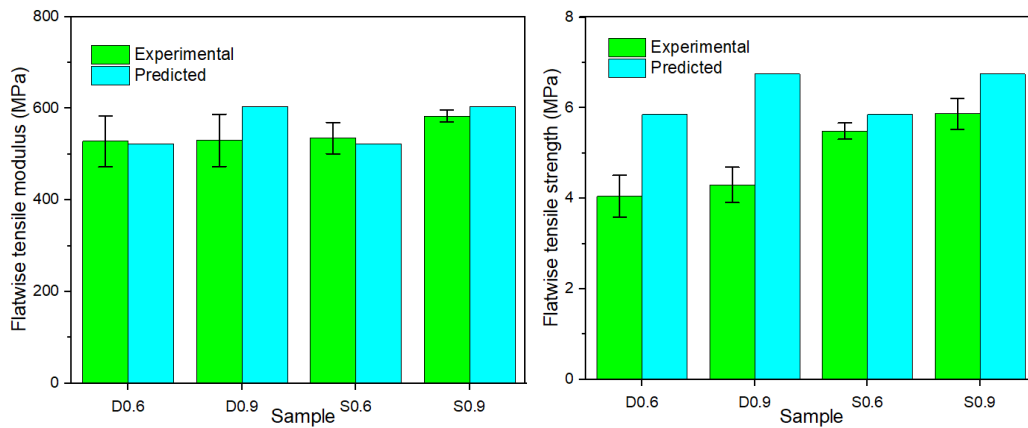


Figure 6-14 Comparison of experimental results and predicted values (a) experimental flatwise tensile modulus, predicted flatwise tensile modulus of the (dis)continuous UHMWPE fibres weaved sandwich-structured composites (b) experimental flatwise tensile strength and predicted flatwise tensile strength of the (dis)continuous UHMWPE fibres weaved sandwich structured composites

6.3.3 Charpy impact properties the continuous UHMWPE fibre-reinforced sandwich-structured composites

In light of the better mechanical performance (in both core shear and flatwise tension) of the continuous UHMWPE fibre weaved sandwich-structured composite, Charpy impact test was conducted only on this sample to further determine its impact energy absorption ability. Table 6-4 summarises the Charpy impact strength of samples **U0**, **S0.6** and **S0.9**. Unreinforced sandwich-structured composite possessed a Charpy impact strength of 128 kJ m^{-2} absorbed energy. The introduction of 0.6 vol.-% of continuous UHMWPE fibres increased the Charpy impact strength to 145 kJ m^{-2} (sample **S0.6**). A further increase in the UHMWPE fibre volume fraction to 0.9 vol.-% further increased the Charpy impact strength to 186 kJ m^{-2} (sample **S0.9**).

Table 6-4 Charpy impact strength of unreinforced sandwich-structured composites and continuous UHMWPE fibre-reinforced sandwich-structured composites

Sandwich-structured composites	Charpy impact strength (kJ m^{-2})
Sample U0	128 ± 9
Sample S0.6	145 ± 15
Sample S0.9	186 ± 16

The Charpy impacted test specimens are shown in Figure 6-15 to illustrate the influence of continuous UHMWPE fibres on the Charpy impact properties of the reinforced sandwich-structured composites. For unreinforced sandwich-structured composite, the upper CFRP facesheet at the striking point fractured completely and the foam under the striking area was crushed. Two inclined cracks happened at the span and transmitted through the foam core but one of the cracks branched into the lower facesheet. The other branch passed through the foam-face interface near the bottom facesheet. The inclined cracks were shear-dominated failures caused by the “shear wave” [109] and typically occur in stiff/thick facesheets and relatively brittle core sandwich-structured composites [110]. It can also be inferred from this figure that the improvement in Charpy impact strength with increasing loading fraction of UHMWPE fibres could be attributed to the added energy absorbed to break the fibres. For sample **S0.6**, similar failure mode was also observed, whereby an inclined shear-dominated failure occurred on the epoxy foam core. For sample **S0.9**, no core shear failure was observed (the absence of the inclined cracks). Instead, a core crush under the striking point was observed and a facesheets-core interface failure was at the low face.

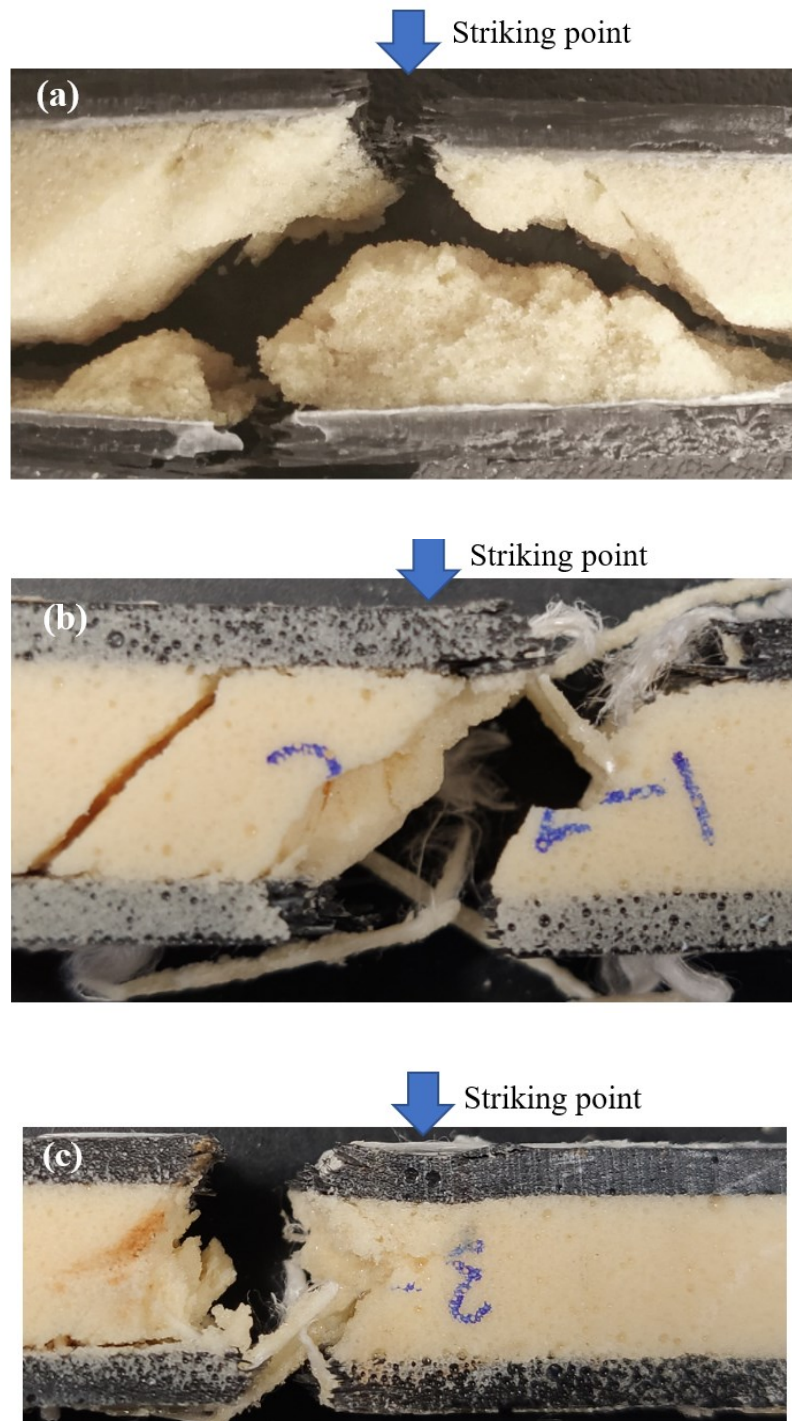


Figure 6-15 Fractographic images of samples (a) U0 (b) S0.6 (c) S0.9 in Charpy impact testing

6.4 Summary

In this chapter, UHMWPE fibres were weaved through both facesheets and epoxy foam core to form sandwich-structured composites with an integrated structure. The reinforcing efficiency of continuous UHMWPE fibre was also compared with discontinuous UHMWPE fibres in this chapter. Overall, sandwich-structured composites containing continuous UHMWPE fibres possessed better core shear and flatwise tensile properties. Charpy impact test was also conducted on continuous UHMWPE fibre-reinforced sandwich-structured composites to ascertain their impact properties.

Chapter 7 - Conclusions and future work

7.1 Conclusions

This thesis has demonstrated the use of continuous UHMWPE fibre as through-thickness reinforcement to enhance the mechanical properties of the resulting reinforced epoxy foams, as well as its sandwich-structured composite. The main conclusions from this thesis are as follow:

- The successful derivation of simple strain-energy based analytical models to calculate the upper bound mechanical properties in tension, compression and shear of fibre-reinforced foam, whereby the fibres are arranged in an “X pattern”;
- Core shear testing showed that the introduction of neat (non-epoxy coated) continuous UHMWPE fibres improved the shear modulus of the foam core by 50%, with 2 vol.-% loading fraction of UHMWPE fibres. The shear strength of the epoxy foam core also improved by up to 10 % with the introduction of UHMWPE fibres. However, it was observed that the UHMWPE fibres-epoxy foam core matrix interface was poor;
- The UHMWPE fibres were then coated with an epoxy resin in an attempt to improve the stress transfer efficiency between the epoxy foam core and the UHMWPE fibres. It was found that the UHWMPE fibre yarns could not be

impregnated efficiently at a single fibre level (at least based on the technique used in this thesis). Nevertheless, the introduction of such continuous UHMWPE fibre network increased the tensile properties (especially the strain-at-break) of the resulting reinforced epoxy foam core. Both the core shear modulus and compressive modulus of the reinforced epoxy foam core improved over their unreinforced counterpart. However, these improvements still lagged behind the theoretically expected mechanical properties of reinforced epoxy foams. This can be attributed to the facesheet-foam core debonding, which led to earlier failure of the composite structure. As a result, the full potential of UHMWPE fibres cannot be efficiently utilised;

- Sandwich-structured composites with continuous UHMWPE fibres weaved through both the facesheets and the epoxy foam core have also been fabricated. At 0.9 vol.-% fibre loading, the reinforced sandwich-structured composites possessed significant higher core shear modulus and a core shear strength compared to their unreinforced counterpart. This is due to the fact that the continuity of the UHMWPE fibres held the sandwich structure together even when facesheet-foam core debonding has occurred. Charpy impact test further showed that the reinforced sandwich-structured composites consisting of continuous UHMWPE fibres weaved through the structure possessed a Charpy impact strength of 186 kJ m^{-2} , a significant improvement over unreinforced sandwich-structured composites (128 kJ m^{-2}).

7.2 Future work

The results from this thesis has paved the way for the development of continuous UHMWPE fibre-reinforced sandwich-structured composites. Suggested future work include:

(1) Improving the impregnation of UHMWPE fibres with a suitable resin that is also compatible with the epoxy foam core

It can be anticipated that if the UHMWPE fibres were efficiently impregnated with a suitable resin, such as polyurethane which is compatible with UHMWPE fibres, the mechanical properties of resulting UHMWPE-reinforced composite fibres will serve as a better through-thickness reinforcement for the sandwich-structured composites (similar to CFRP pins in Z-pinned foams). Polyurethane resin is also anticipated to have good adhesion to an epoxy system [111–113].

(2) Injecting mechanically frothed liquid epoxy foam into a 3D net-shape carbon fibre preform

Chapter 6 has demonstrated the properties of continuous UHMWPE fibre-reinforced sandwich-structured composites and this demonstration was achieved by physically drilling holes into the CFRP facesheets. It can be anticipated that if the through-thickness reinforcement can be weaved into the reinforcing woven fabric of the facesheets, the reinforcing effect can be even more pronounced. The concept behind this is further illustrated in Figure 7-1, whereby two facesheets directly connected by carbon fibre yarns. This is proposed to be achieved by using 3D net-shape carbon fibre preforms. The injection of the mechanically frothed uncured liquid epoxy foam will also cause the inflation of the 3D net-shape preform. Following the liquid epoxy foam curing, the carbon fibre fabrics will be

impregnated with a resin, followed by heat consolidation to produce carbon fibre-reinforced polymer facesheets co-bonded with the manufactured foam core.

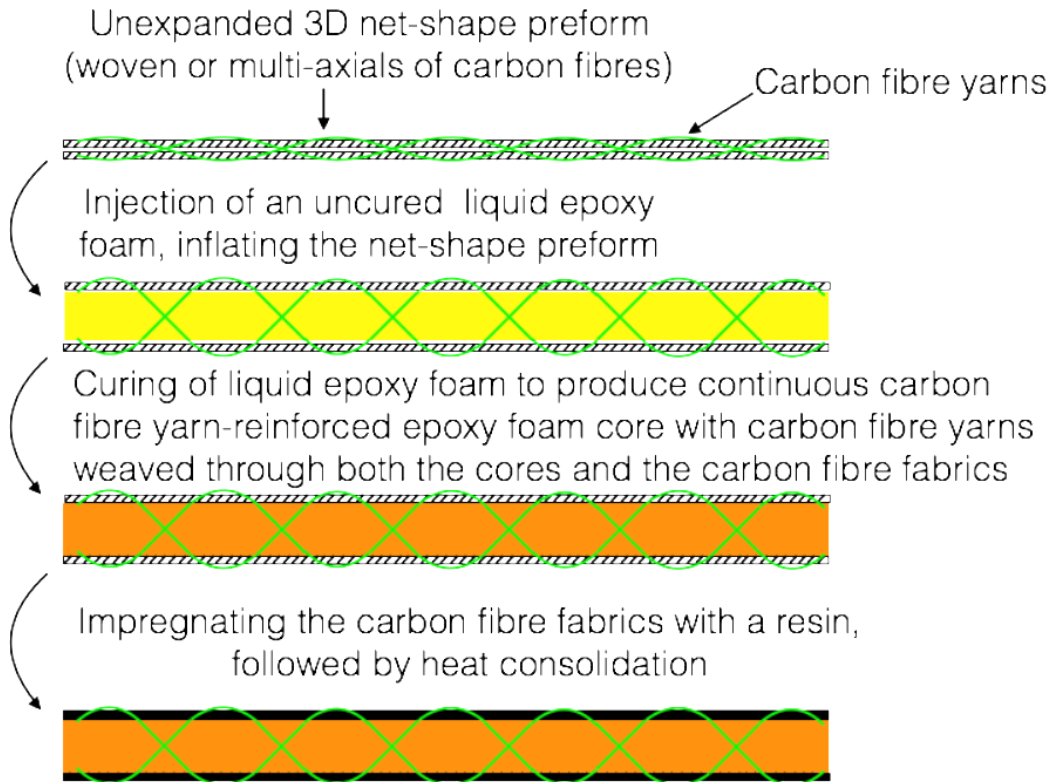


Figure 7-1 Concept of manufacturing process of continuous carbon fibre through-thickness reinforced sandwich-structure composite with injection of mechanically frothed liquid epoxy foam into 3D net-shape carbon fibre preforms

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