UHMWPE FIBRE YARN ESTABLISHED CONTINUOUS WAVY NETWORK CONSTRUCTION REINFORCED EPOXY FOAM COMPOSITE

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Abstract

Sandwich-structured composites consisting of continuous ultrahigh molecular weight polyethylene (UHMWPE) fibre yarn as through-thickness reinforcement for the epoxy foam core were fabricated in this work. Preliminary test showed that the introduction of continuous UHMWPE fibers improved the shear modulus (G_c) of the foam core by 50%, from G_c = 110 MPa for un-reinforced polymeric foam core to G_c = 163 MPa for polymeric foam core reinforced with 2 vol.-% continuous UHMWPE fibre yarns. The shear strength of the epoxy foam core also improved by up to 10% with the introduction of continuous UHMWPE fibre yarns. The internal morphology of the reinforced epoxy foam cores is also discussed in this work.

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 yarns (Structiso™) or dry fibre rovings (Airbus Tied Foam Core) [3] in regular foams. For X-Cor™, the reinforcing pins extends beyond the thickness of the polymer foam to enhance mechanical interlocking with the face sheet materials. For K-Cor™, the pins are uncured carbon fibre-reinforced epoxy pre-pregs that are punched through the structural foam core. The extended length of uncured carbon fibre-reinforced pre-preg pins are folded back [4] and co-cured with the face sheet materials. Reinforced structural foam cores offer superior compressive strength and better delamination resistance than that of their unreinforced counterparts [5]. However, these reinforced foam cores still possess low tensile and shear strengths. The reinforcing pins are inserted through only the 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 machining the block to the desired shape, followed by insertion of the reinforcement.

We have recently developed a simple, scalable and waste-free manufacturing process of epoxy foam cores with densities as low as 180 kg m^{-3} without the need of a blowing agent. 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 [6,7]. 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 core. The previously introduced air bubbles formed the pores or cells of this epoxy foam core. Unlike the production of conventional foam core materials, no expansion or shrinkage occurred during curing. The final shape and geometry of the epoxy foam core is determined by mould used for liquid epoxy foam. The porosity of these mechanically frothed macroporous polymers could further be controlled by the heat applied during the curing process [6]. This provides us with 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. Therefore in this work, we report our preliminary work on enhancing the shear properties of foam-templated epoxy foams with continuous ultrahigh molecular weight polyethylene (UHMWPE) fibre yarn as through-thickness reinforcement for epoxy foam cores.

2. Experiemental section

2.1. Materials

Ultra high molecular weight polyethylene (UHMWPE) fibres (Dyneema® SK-78) was kindly provided by DSM and used as the continuous fibre reinforcement for the polymeric foam core of the sandwich-structured composites. Epoxy resin with 56 % biomass content (Greenpoxy 56, $\rho = 1.20 \pm 0.01$ g cm^{-3}, $\eta = 2500$ mPa s at 15 °C) and amine-based hardener with 58 % biomass content (GP 505 v2, $\rho = 0.99 \pm 0.01$ g cm^{-3}, $\eta = 1800$ 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 composites.

2.2 Preparation of sandwich-structured composites consisting of continuous UHMWPE fibre yarn 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 our previous work [6,7]. Briefly, 70 g of bio-based epoxy resin and 29.4 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 $(120 \times 30 \times 9)$ mm^3 and cured at room temperature for 24 h to produce un-reinforced epoxy foam core. To produce UHMWPE fibre yarn-reinforced epoxy foam cores, the air-in-liquid epoxy foam template was poured into a $(120 \times 30 \times 9)$ mm^3 mould consisting of continuous UHMWPE fibre yarns weaved in accordance to the pattern shown in **Figure 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 face sheet materials were then glued onto the (reinforced) epoxy foam cores using an epoxy glue (Araldite 2011, Huntsman International LLC, Duxford, UK).

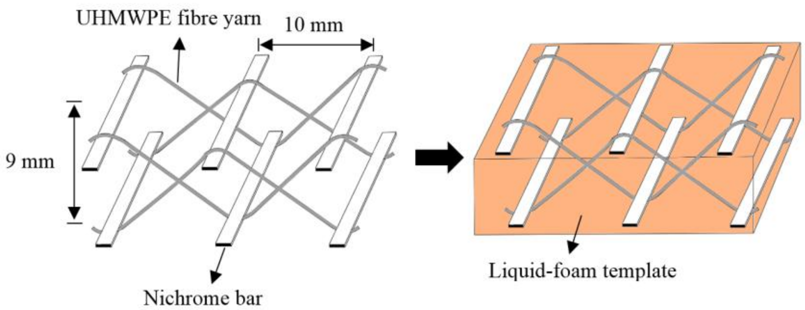


Figure 1. Schematic diagram of continuous UHMWPE fibre yarn reinforced epoxy foam fabrication process

2.3 Characterisation of the (reinforced) sandwich-structured composites

2.3.1 Shear properties of the (reinforced) epoxy foam cores using 3-point bending test

The shear properties of the (reinforced) epoxy foam cores were determined from 3-point bending test in accordance to ASTM C393 (to evaluate the shear strength of foam cores) and ASTM D7250 (to evaluate shear modulus of foam cores) using an Instron universal tester (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 was used to measure the mid-span deflection of the test specimen during the 3-point bending test. The shear strength of the core material (τ) within the sandwich-structured composites was calculated using:

$$\tau_c = \frac{P_{\max}}{(d+c)b} \tag{1}$$

where $P_{\max}$ is the maximum measured load, d is the thickness of the sandwich-structured composites, c represents the thickness of core material and b is the width of sandwich-structured composites, respectively. The shear modulus of the core material (G_c) was calculated using the following set of equations:

$$D = \frac{E(d^3 - c^3)b}{12} \tag{2}$$

$$U = \frac{PS}{4\left[\Delta - \frac{PS^3}{48D}\right]} \tag{3}$$

$$G_c = \frac{U(d-2t)}{(d-t)^2 b} \tag{4}$$

where D represents the flexural stiffness of the sandwich-structured composites, E is the Young's modulus of the facesheet material, S is the span length of test specimen, Δ is the beam mid-span deflection, U is transverse shear rigidity and t is the thickness of the facesheet materials, respectively.

2.3.2 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 5kV. 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.

3. Results and Discussion

The representative load-deflection curves of the fabricated sandwich-structured composites consisting of un-reinforced and reinforced epoxy foam cores are shown in **Figure 2** and the calculated shear properties of the epoxy foam cores are summarised in **Table 1**. It can be seen from **Figure 2** and **Table 1** that the continuous UHMWPE fibre yarns reinforced epoxy foam cores possessed higher shear modulus (147 MPa for 1 vol.-% continuous UHMEPW fibre yarns reinforced epoxy foam cores and 163 MPa for 2 vol.-% continuous UHMEPW fibre yarns reinforced epoxy foam core) compared to the un-reinforced counterpart (110 MPa). The introduction of continuous UHMWPE fibre yarns also increased the shear strength of the core material (**Table 2**). This improvement in both core shear modulus and strength could be attributed to the through-thickness reinforcement with continuous UHMWPE fibre yarns, which underwent tensile loading during the shear deformation of the reinforced epoxy foam core. Nevertheless, theoretical calculation shown that the improvement in G_c and τ of the epoxy foam core reinforced with continuous UHMWPE fibre yarns should be significantly higher (for Sample B, $G_{\text{theoretical}} = 261$ MPa and $\tau_{\text{theoretical}} = 18$ MPa, respectively and for Sample C, $G_{\text{theoretical}} = 411$ MPa and $\tau_{\text{theoretical}} = 29$ MPa, respectively). We attribute this to the poor wetting out of the UHMWPE fibre yarns by the air-in-liquid epoxy foam template during the foam core fabrication process. The SEM images of the UHMWPE fibre yarns within the reinforced epoxy foam cores are shown in **Figure 3**. The outer surface of the UHMWPE fibre yarns can be seen coated with a layer of epoxy resin. However, the fibre yarns 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.

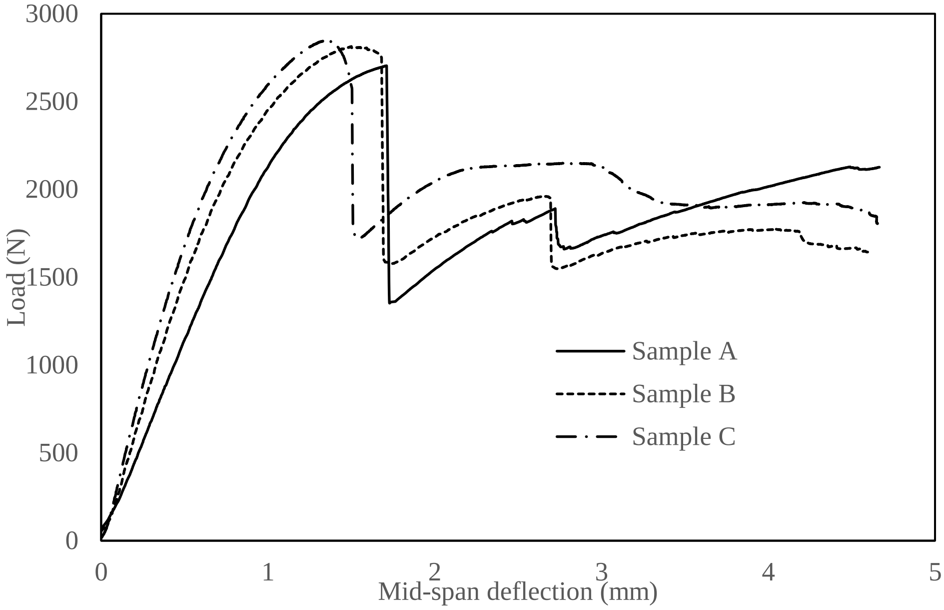
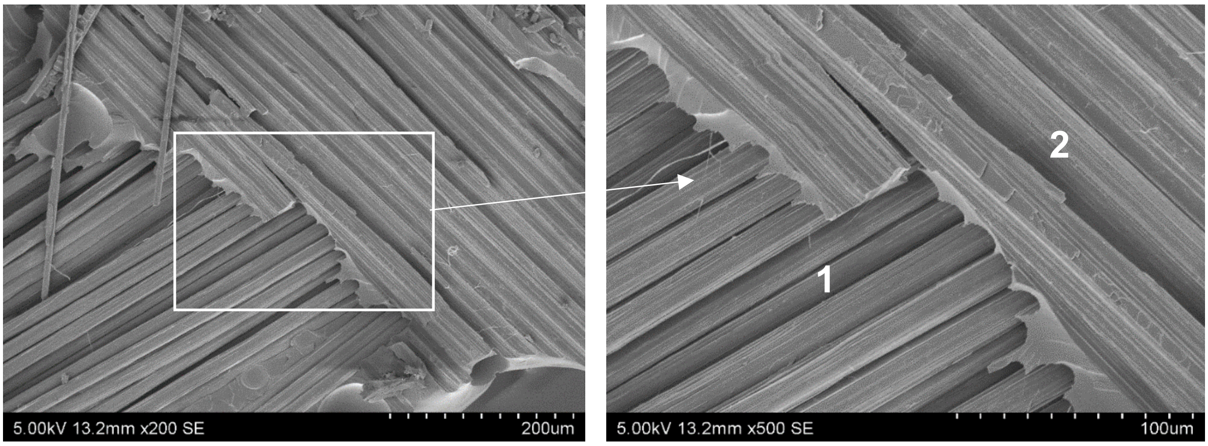


Figure 2. Representative load-deflection curves of sandwich structured composites consisting of (Sample A) un-reinforced epoxy foam core, (Sample B) 1 vol.-% continuous UHMWPE fibre yarn-reinforced epoxy foam core and (Sample C) 2 vol.-% UHMWPE fibre yarn-reinforced epoxy foam core.

Table 1. Density, fibre volume fraction and Mechanical properties of unreinforced and reinforced foams. ρ_{core}, V_f, τ_c, G_c denote density, fibre volume fraction, core shear strength, core shear modulus.

Sample	ρ_{core} ($g \cdot cm^{-3}$)	V_f (%)	τ_c (MPa)	G_c (MPa)
Sample A	0.421 ± 0.007	—	4.08 ± 0.15	110±5.58
Sample B	0.427 ± 0.007	1.0	4.53 ± 0.07	147±12.83
Sample C	0.432 ± 0.014	2.0	4.20 ± 0.11	163±21.77



(c) (d)

Figure 3. The SEM images of UHMWPE fibre yarn with a layer of epoxy resin

4. Conclusions

In this work, we demonstrated the use of UHMWPE fibre yarns as the through thickness reinforcement to enhance the shear properties of mechanical frothed epoxy foam cores. Unlike conventional structural foam cores with through-thickness reinforcement, the use of liquid foam template to produce reinforced epoxy foam cores do not damage the foam core material. It was found in this study that by reinforcing epoxy foam cores with up to 2 vol.-% continuous UHMWPE fibre yarn, the shear modulus of the reinforced foam core increased by 50% compared to un-reinforced counterparts. Nevertheless, there is still room for improvements as the UHMWPE fibre yarns were found to be dry beyond the surface of the fibre yarns.

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