Composite Structures 140 (2016) 582–589

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Bending energy absorption of self-reinforced poly(ethylene terephthalate) composite sandwich beams

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ARTICLE INFO

Article history:
Available online 2 January 2016

Keywords:
Ductile composites
Structural properties
Energy absorption
Sandwich beams

ABSTRACT

Fully recyclable corrugated sandwich beams made from self-reinforced poly(ethylene terephthalate) SrPET are manufactured and tested in quasi-static three-point bending. For a constant areal mass, the influence of mass distribution on peak load and energy absorption is investigated. Beams with a higher proportion of their mass distributed in the core generally show higher peak loads and energy absorption. A finite element (FE) model was developed using an anisotropic visco-plastic constitutive material law. The FE predictions are in excellent agreement with the measurements. When comparing to sandwich beams with similar weight and geometry of different materials, the SrPET sandwich beams outperform corrugated sandwich beams made from aluminium in terms of peak load and energy absorption.

1. Introduction

Composite materials such as carbon or glass fibre reinforced polymers have high weight specific stiffness and strength making them suitable for a wide range of lightweight applications. These composites however have some drawbacks: they are inherently brittle resulting in catastrophic failure modes and low energy absorption capacity. Long fibre composites also have time consuming manufacturing processes and poor recyclability which inhibits the use in automotive applications.

Several approaches has been used to develop ductile and recyclable composites materials. One approach is to make reinforcing fibres and matrix material out of the same recyclable ductile polymer family [1–3]. These composite materials are termed self-reinforced polymer (SrP) composites (or single-polymer or all-polymer composites). They can be recycled more easily and have high ductility. As they are fully thermoplastic, they can also be manufactured in a rational and cost effective way suitable for e.g. the automotive industry. In comparison to traditional carbon or glass fibre reinforced polymers, they have a lower stiffness and strength but provide higher energy absorption capacity [4].

Considerable research has been performed to develop and enhance the manufacturing processes for SrPs as well as to investigate their quasi-static mechanical properties [2–6]. Efforts have also been made to create fully recyclable sandwich materials with lattice and prismatic cores using SrPs [7,8]. These materials were tested in uniaxial compression and showed good quasi-static and dynamic mechanical properties and indicated the potential of producing high energy absorbing structures.

In this work we manufacture all SrP sandwich beams with prismatic cores and investigate their flexural properties with emphasis on their energy absorbing capabilities. The outline of the paper is as follows. We start by describing the manufacturing route used to produce the fully recyclable SrP-corrugated sandwich panels. Secondly, we present the results from an experimental investigation of the energy absorption capacity of corrugated sandwich beams with varying mass distribution between the face sheets and the core. A finite element model is developed and validated against experiments in order to create predictive capabilities for this new group of composite materials. The developed model is finally used to investigate the effect of non-symmetric mass distribution of the sandwich structure face sheets in order to maximize energy absorption.

2. Materials and manufacturing

2.1. Description of the constituent material and consolidation routine

The material used to manufacture the corrugated sandwich beams is a self-reinforced poly(ethylene terephthalate) (SrPET) fabric comprising of commingled yarns with 50 wt.% high tenacity PET (HTPET) reinforcing fibres and 50 wt.% amorphous PET fibres acting as matrix material. The matrix material PET is chemically

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http://dx.doi.org/10.1016/j.compstruct.2015.12.043
0263-8223/

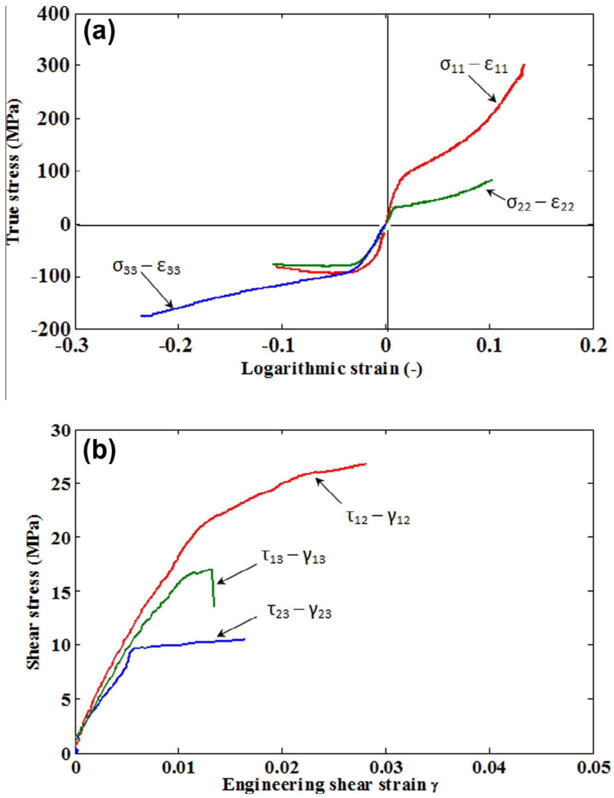

Fig. 1. (a) The measured true tension and compression stress versus strain responses [6] and (b) shear stress versus engineering shear strain of the SrPET composites for loading in the three principal material directions x_1, x_2 and x_3 at an applied strain rate 10^{-4} s^{-1} [6].

modified to melt at 160–180 °C whereas the reinforcing HTPET material melts at 260 °C. The tensile modulus of the HTPET fibres and the matrix material are reported as 15.2 GPa and 2.8 GPa respectively [4].

The yarns are woven to a 4/1 warp/weft direction plain weave where 80% of the reinforcing fibres are in the warp (termed x_1 direction) and the remaining 20% in the perpendicular weft direction (termed x_2 direction) where the x_3 direction is the thickness direction of the laminate. The woven fabric, with a surface weight of 0.555 kg m^{-2}, was made by Comfil® APS [9] and is labelled by the supplier as an unidirectional fabric since the majority of the fibres lies in the warp direction.

Prior to consolidating the fabric to a laminate, the SrPET fabric was dried for 24 h in a climate chamber at a relative humidity of 15% and a temperature of 50 °C. Finally, the SrPET fabric is consolidated in a hot-press under 1 bar pressure above the ambient pressure at consolidation temperatures of 220 °C for around 20 min.

2.2. Properties of constituent material

The uniaxial tensile, compression and shear properties of SrPET laminates manufactured from a 4/1 plain weave have been investigated by Kazemahvazi et al. [6]. Fig. 1a presents the experimental true tensile stress versus logarithmic strain response (σ_{11}–ε_{11} and σ_{22}–ε_{22}) for a strain rate $\varepsilon = 10^{-4}$ s^{-1}. Both tensile responses show an initial linear elastic response followed by strain hardening. As expected, the tensile stress response in the x_1 direction is significantly higher because of the higher amount of reinforcing fibres. The strain-to-failure for loading in x_1 and x_2 direction is 13% and 10%, respectively which is significantly higher than that of typical carbon or glass fibre reinforced polymers loaded in the fibre direction.

The measured true compression stress versus logarithmic strain response (σ_{11}–ε_{11}, σ_{22}–$_{22}$ and σ_{33}–ε_{33}) for a strain rate of $\dot{\varepsilon} = 10^{-4}$ s^{-1} are also included in Fig. 1a. In the x_1 and x_2 direction, an initial linear elastic response is observed followed by a plateau stress while in the x_3 direction a linear elastic response is observed followed by a strain hardening. The shear stress versus engineering shear strain response (σ_{12}–γ_{12}, σ_{13}–γ_{13} and σ_{23}–γ_{23}) are presented in Fig. 1b. Here, a linear elastic response is observed followed by progressive damage until catastrophic failure occurs. For further information about the material properties of SrPET the reader is referred to [4,6].

2.3. Manufacturing of corrugated sandwich beams

Corrugated sandwich panels were manufactured in an aluminium mould where the pre-dried fabric and mould parts were placed in five steps. First, the pre-dried layers of SrPET fabric for the bottom face sheet were stacked onto the mould as shown in ① in Fig. 2. Thereafter, aluminium moulds with a trapezoidal cross-section of height h = 19 mm, an inclination angle of ω = 60° and a top distance of 10 mm were coated with a Tygovac RF260 Fluoropolymer FEP release film in order to guarantee successful de-moulding. One set of aluminium moulds with a trapezoidal cross-section were placed on top of the bottom face sheet fabric (see ② in Fig. 2). Next, the SrPET fabric for the core webs was stacked on top of the aluminium mould as shown in ③ in Fig. 2. Thereafter, the aluminium profiles coated with release film were placed in between the previously placed aluminium mould and on top of the SrPET fabric for the core webs (see ④ in Fig. 2). Finally, the fabric for the top face sheet was stacked on top of the core (see ⑤ in Fig. 2).

The stack of aluminium profiles and SrPET fabric was then consolidated in a hot-press under 1 bar pressure above ambient pressure. The temperature was raised with a rate of 10 °C/min up to 220 °C where it was held constant for 20 min and thereafter subsequently cooled at 10 °C/min back to room temperature. After the consolidation, all aluminium profiles were de-moulded to obtain a sandwich panel consisting only of SrPET. To check the consolidation process of the corrugated sandwich panel, several optical micrographs were taken where only little/no porosity was detected. This sandwich panel was cut into sandwich beams with the dimensions specified in Table 1.

2.4. Sandwich beams for 3-point bending test

To investigate the influence of mass distribution on the flexural peak load and energy absorption, various sandwich panels with approximately the same areal mass of 8–8.5 kg m^{-2} were manufactured. To manufacture corrugated sandwich beams within the above defined areal weight range, only 14 layers of SrPET fabric could be used. These layers of fabric could be stacked in the core web, top- or bottom face sheet to reach different mass distributions. To achieve a sandwich structure with good properties, the fabric was aligned so that the direction with a higher amount of fibres is in the loading direction of the sandwich beam (see Fig. 2). At least two layers of fabric where used in each of the web and face sheets in order to obtain a practical sandwich design.

The dimensions of the corrugated sandwich beam-geometries are depicted in Fig. 3a and Table 1. The different sandwich configurations are labelled to show the percentage distribution of mass between the front face, core and back face (top/core/bottom). In for instance the sandwich beam configuration 29/43/28, 29% of