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

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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.

Keywords: Ductile Composites, Structural properties, Energy absorption, Sandwich beams

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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 have been used to develop ductile and recyclable composite 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 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 15.2GPa and 2.8GPa 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 $0.555kg\ m^{-2}$, 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 24h 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 1bar pressure above the ambient pressure at consolidation temperatures of 220°C for around 20min.

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 ($\sigma_{11} - \varepsilon_{11}$ and $\sigma_{22} - \varepsilon_{22}$) for a strain rate $\dot{\varepsilon} = 10^{-4} s^{-1}$. 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 ($\sigma_{11} - \varepsilon_{11}$, $\sigma_{22} - \varepsilon_{22}$ and $\sigma_{33} - \varepsilon_{33}$) 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 ($\sigma_{12} - \gamma_{12}$, $\sigma_{13} - \gamma_{13}$ and $\sigma_{23} - \gamma_{23}$) 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 $h = 19 \text{ mm}$, an inclination angle of $\omega = 60^\circ$ and a top distance of 10mm 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

Figure 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].

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).

Figure 2: Schematic illustration of the assembly steps to manufacture the SrPET corrugated sandwich panels. (1) Placement of the bottom face sheet fabric. (2) Placement the aluminium mould on the bottom face sheet fabric, (3) Placement of the fabric for the core webs, (4) Placement the aluminium mould on the core web face sheet fabric and (5) placement of the top face sheet fabric. (All dimensions in mm).

The stack of aluminium profiles and SrPET fabric was then consolidated in a hot-press under 1bar 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 20min 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 Tab. 1.

Table 1: Geometry of the corrugated beams, corrugation angle $\omega = 60^\circ$, height $h = 19mm$, distance $d = 10mm$ and the total beam length was of $250mm$ was held constant for all configurations.

Sandwich beam mass distribution (%)	Layers of SrPET fabric	W (mm)	H (mm)	t_c (mm)	t_{ft} (mm)	t_{fb} (mm)	$\bar{\rho}$ (kgm^{-2})
29/43/28	5/4/5	57.0	24.8	1.5	1.8	1.7	8.2
24/53/23	4/6/4	57.6	24.9	2.1	1.5	1.4	8.3
16/69/15	3/8/3	57.5	24.7	2.7	1.0	0.9	8.4
11/78/11	2/10/2	57.2	24.8	3.4	0.7	0.7	8.5

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 $8 - 8.5kg\ m^{-2}$ 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 were 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 the material is distributed in the top face sheet, 43% in the core web and the remaining 28% in the bottom face sheet.

3 Experimental protocol

The schematics of the 3-point bending test setup is presented in Fig. 3b. Test were performed in an Instron 4045 equipped with a 100kN load cell and a testing speed of $\dot{\delta} = 0.017 \text{ mm s}^{-1}$. The midpoint displacement δ was measured using a single camera non-contact digital speckle photography measuring system from GOM [10]. A speckle was applied on the indenter and supports rolls to allow for a virtual extensometer to measure the vertical displacement. For all configurations, a minimum of three specimens were tested.

Figure 3: Schematic of (a) beam cross section and (b) the 3-point bending setup (All dimensions in mm).

4 Summary of experimental results

The load versus normalized midpoint deflection δ (normalised by the beam half-span $L = 75 \text{ mm}$) curves are plotted in Fig. 4. Only one single curve for each investigated configuration is shown in order to enhance clarity. Images captured during testing at various δ/L ratios are presented in Fig. 5 and 6.

We start by discussing the results for the sandwich beam with the thinnest tested core webs, the 29/43/28 sandwich beam (see Fig. 4 and 5). The measured load versus δ/L response shows a linear response up to 2100N followed by non-linear hardening and then reaches a peak load of 3094N at $\delta/L = 0.06$. From the captured images, it can be seen that the top face bends towards the sandwich beam centre. With further deformation, the load - δ/L response shows softening until it reaches a plateau load at 2400N.

Figure 4: Load versus normalized midpoint deflections δ by the beam half-span $L = 75\text{mm}$ with identical number of fabric layers in top- and bottom face sheets. The solid lines are representing the measurements whereas the dashed lines are FE- predictions

Increasing core mass portion from 43% to 52% and in parallel reducing the mass portion in the face sheets results in a 25/52/23 sandwich beam. This beam shows a linear load - δ/L response up to 2500N followed by non-linear hardening until it reaches peak load of 5124N at $\delta/L = 0.15$. With further loading, the load - δ/L response shows a softening behaviour (see Fig. 4). From the captured images (see Fig. 5), it can be seen that the top face sheets is already highly deformed at $\delta/L = 0.07$.

Figure 5: Montage of captured images during 3-point bending testing and of FE predictions at various δ/L of corrugated sandwich beams a) 29/43/28 and b) 24/53/23 with an identical number of SrPET fabric layers in the top- and bottom face sheet.

A further increase of core web mass to 69% and 78%, results in the sandwich beams 16/69/15 and 11/78/11. The load - δ/L responses of these two sandwich beams are very similar. Both show a linear response up to 2500N followed by non-linear hardening up to $\delta/L = 0.2$. Peak load for these sandwich beams were reached at $\delta/L = 0.2$ and were 5641N and 5613N respectively (see Fig. 4). When comparing the captured images, it can be seen that the top

face sheet of the 11/78/11 sandwich beam deforms in a more “wavy” shape than the 16/69/15 which could be a result of a top face sheet - core web delamination (marked with arrows in Fig. 6). This delamination was observed already at $\delta/L = 0.07$.

Figure 6: Montage of captured images during 3-point bending testing and of FE prediction for various δ/L of corrugated sandwich beams a) 16/69/15 and b) 11/78/11 with an identical number of SrPET fabric layers in the top- and bottom face sheet.

5 Finite element analysis

FE analyses of corrugated sandwich beams were performed with following objectives:

- (i) To develop a predictive tool that is able to simulate the complex deformations and energy absorption that occur when a corrugated sandwich beam out of SrPET is subject to bending.
- (ii) To build a fundamental understanding of the deformation mechanisms which give rise to the measured response presented in Section 4.
- (iii) To investigate the 3-point bending response of corrugated sandwich beams with non-symmetric mass distribution between the face sheets.

We intentionally modelled a beam section rather than a representative volume element (RVE) so that we can compare the modelled results with the experimental results directly and efficiently. Once the model has been established a panel or panel section represented as a RVE with periodic boundary conditions can be analysed.

A three dimensional finite element (FE) model of the corrugated sandwich beams was constructed in the commercial FE package ABAQUS Explicit (6.13). From the experimental testing it could be seen that the specimens only showed limited failure at the face sheet- core interfaces and therefore in all configurations a perfect bonding between the core and face sheets was assumed. The used material model (explained in section 5.2) was written for eight-noded linear brick elements (C3D8), hence, this element type with reduced integration was used to discretize the sandwich beam. The mesh size of the largest element was 0.6mm. A further mesh refinement did not improve the accuracy of the predictions significantly.

To reduce the calculation time, a fixed mass scaling factor of 10^6 was used resulting in a stable time increment $\Delta t = 10^{-5}$. A sensitivity study was performed which showed that the

mass scaling factor only had marginal influence on the accuracy of the simulations. The indenter and the support rolls were modelled as analytical rigid shells.

5.1 Boundary conditions

Only one quarter of the beam was modelled using symmetry boundary conditions along the two centre mid-plates. The contact condition between the sandwich beam and indenter / supports was assumed to be frictionless and the contact was modelled using the ABAQUS Explicit general contact algorithm. The same algorithm was used to model self-contact in the beam. The supports rolls were fixed whereas a constant velocity was prescribed for the indenter roll.

5.2 Constitutive law and material data

The SrPET composite material was modelled using the material model developed by Kazemahvazi et al. [6]. The material model was developed for ductile anisotropic SrPET composites and captures elastic-plastic deformation but not failure. The model was implemented as a user material (VUMAT) using a backward Euler integration scheme. The elastic material properties for SrPET are presented in Table 2. The plastic stress-strain behaviour of the material is given in Fig. 1 and more details are found in [6].

Table 2: Elastic material properties for SrPET composite [6]

$E_{11}(MPa)$	$E_{22}(MPa)$	$E_{33}(MPa)$	$G_{12}(MPa)$	$G_{23}(MPa)$	$G_{13}(MPa)$	ν_{12}	ν_{23}	ν_{13}
6000	4000	3300	2000	2000	2000	0.29	0.64	0.48

5.3 Comparison between measurements and predictions

The FE-predictions for sandwich beams with identical portion of mass in the core, top and bottom face sheets as in the experiments are included in Fig. 4-6 as dashed lines. The deformation of the beam cross-section at mid span is given in view A-A in Fig. 5 and 6. To

elucidate the deformation in the FE-predictions, arrows with different colours are used. Bending of the free end of the top face sheet into the sandwich beam centre is highlighted with blue arrows whereas bending of the bottom face is marked with a red arrow. In some configurations, the free end of the bottom face sheet (thick area where core webs and face sheet are joined) rotates into the sandwich beam centre which is marked with green arrows. Some sandwich beams show local indentation of the core webs which is marked with a black arrows.

5.3.1 Load versus δ/L response and sandwich beam deformation

From Fig. 4 it can be seen that the FE load - δ/L response and predicted deformations are in excellent agreement with the measurements. Predicted and measured peak loads are summarized in Table 3.

Table 3: Predicted and measured peak load and absorbed energy for corrugated sandwich structures with identical mass portions in the top- and bottom face sheets

Sandwich beams / Mass distribution	P_{exp} (N)	P_{FE} (N)	E_{exp} (Nm)	E_{FE} (Nm)
29/43/28	3102 ± 115	3094	17.4 ± 0.4 *	17.77*
24/53/23	4861 ± 109	5124	58.9 ± 0.5	62.44
16/69/15	5641 ± 88	5614	64.5 ± 0.8	66.79
11/78/11	5613 ± 149	5970	61.1 ± 0.7	68.07

*Energy absorbed until $\frac{\delta}{L} = 0.1$

The FE peak load prediction of the 29/43/28 sandwich beam is the same as the experiment up to $\delta/L = 0.1$ after which material failure was observed in the experiment which cannot be captured by the FE-model. The predicted deformations (see Fig. 5) show local indentation as well as top- and bottom face sheet deformation already at peak load ($\delta/L = 0.05$). With increased bending deformation, the load - δ/L response shows a softening as a result from the sandwich beam deformation.

For the 24/53/23 sandwich beam, the FE –prediction overestimates the peak load slightly. The predicted deformation shows first top- and bottom face sheet deformation followed by additional deformation of the free ends of the bottom face sheet. At $\delta/L = 0.2$ the predicted sandwich beam deformation shows local indentation which results in softening (see Fig. 4 and Fig. 5).

The FE-prediction of the 16/69/15 sandwich beam is the same as in the experiments. In contrast to the previous sandwich beams, no local indentation could be seen in the predicted deformation up to $\delta/L = 0.2$ (see Fig. 6). Only deformation of the top- and bottom face sheets as well as of the free ends of the bottom face could be detected and therefore, the load - δ/L response shows no softening (see Fig 4).

The prediction for the 11/78/11 is slightly overestimating the measurements. Recall that during the sandwich beam deformation significant delamination failure was observed between the top face sheet and the core (already at $\delta/L = 0.07$ as seen Fig. 6). As the developed finite element model does not capture failure or delamination, the FE-predictions slightly overestimates the measurements in this case. The face sheet - core delamination is also influencing the predicted deformation of the top face sheet (see Fig. 6). Due to the separation the top face sheet deformation is more distinct in the experiments.

5.3.2 Energy absorption capability

The absorbed energy E is calculated by

$$E = \int_0^{\delta=15mm} P(\delta) d\delta \quad (1)$$

where P is the applied load and δ the indenter displacement. The energy is calculated up to an indenter displacement $\delta/L = 0.2$ except for the 29/43/28 where it was only computed up to $\delta/L = 0.1$ due to material failure. The absorbed energy from the experiments, E_{exp} , and FE-prediction, E_{FE} , are summarized in Table 3 and show good agreement.

From the FE-predictions it can be seen that the absorbed energy is increasing with increasing core web mass and the highest E_{FE} could be reached where 78% of the material is used for the core. E_{exp} shows the highest value for the sandwich beam with 69% of the material in the core. With further increase in core web mass, the capability of absorbing energy was reduced due to top face sheet core - web interface separation. Increasing the interface strength to prohibit separation could be done by stitching core webs and face sheets together [11].

5.4 Sensitivity of the sandwich beam response to proportion of mass in the face sheets

From the previous sections we know that the peak stress and energy absorption are dominated by the core web mass/thickness. In this section we will investigate the influence of mass proportion in the face sheets on peak load and energy absorption.

The sandwich beam 29/43/28 showed low peak load and energy absorption capability because the core web failed by local indentation. Therefore, this investigation will be done with a core web mass proportion fixed at 53% and 69%.

As good agreement of was found between experimental results and FE-predictions, this investigation is only performed using FE-simulations. Beam geometry, peak load and absorbed energy are summarized in Table 4. Fig. 7 shows the load versus δ/L predictions for sandwich beams with 53% and 69% mass in the core web.

Figure 7: FE prediction of the load versus normalized midpoint deflections δ by the beam half-span $L = 75\text{mm}$ with different mass portions in the top and bottom face sheet. For completeness and easier comparison between the different configurations, the FE- prediction for the 24/53/23 and 16/69/15 sandwich structures are included.

Recall the sandwich beam 24/53/23 which showed softening at $\delta/L = 0.15$ (see Fig.4). Decreasing the mass proportion of the top face sheet, and in parallel increasing it on the bottom face sheet, results in softening at $\delta/L = 0.10$ (see Fig. 7). If instead the mass proportion in the top face sheet is increased, no softening behaviour could be observed.

The highest peak load was reached with an increased mass proportion in the top face sheet whereas sandwich beams with identical mass face sheets have the overall highest energy absorption capability.

Table 4: Geometry, peak load and absorbed energy for corrugated sandwich beams with different mass portions in the face sheets

Sandwich beams/ mass distribution	Layers of SrPET fabric	W (mm)	H (mm)	t_c (mm)	t_{ft} (mm)	t_{fb} (mm)	$\bar{\rho}$ (kgm^{-2})	P_{FEM} (N)	E_{FEM} (Nm)
11/53/36	2/6/6	57.2	24.9	2.1	0.7	2.2	8.3	4773	57.34
36/53/11	6/6/2	57.2	24.9	2.1	2.2	0.7	8.3	5299	61.58
11/69/20	2/8/4	57.5	24.7	2.7	0.7	1.2	8.4	5382	65.19
20/69/11	4/8/2	57.5	24.7	2.7	1.2	0.7	8.4	5302	63.70

For the sandwich beam with 69% of the mass in the core, decreasing the top face sheet mass proportion results in softening at $\delta/L = 0.12$. In contrast, increasing of the top face sheet mass proportion shows a lower load response but no softening. This response is a result of the thin bottom face sheet where the stresses are high resulting in significant plastic deformations. Again, the highest energy absorption was achieved with the sandwich beam with identical mass proportions in the front and bottom face sheet.

6 Discussion and comparison with competing materials

The results presented in this paper confirm the high energy absorption capability of corrugated sandwich beams made out of SrPET. To reach a high peak load and energy absorption capability, the mass portion in the core web has to be high. The same behavior has been reported for corrugated sandwich beams from polyester reinforced with a chopped E-glass fiber mat [12] or stainless steel [13].

To put the performance of the SrPET corrugated beams into perspective we compare them to an aluminum alloy and a CFRP foam core sandwich beam.

The beams have the same overall geometry, i.e. a total thickness of ~23 mm, length of 225 mm and width of 50 mm. A detailed description of the beam manufacturing and performance is given by Kazemahvazi et al [14] and can be summarized as follows. The CFRP/foam sandwich beam was designed for maximized energy absorption with as high core density, core ductility and core thickness as possible [give reference to Tagarielli et al papers on GRP/divinycell beams]. In order to achieve the same areal mass with the 6061-T6 aluminum beam, the thicknesses of the core webs and face sheets had to be scaled down to approximately 0.8 mm. This posed significant challenges in the manufacturing of the beams and in order to achieve sufficient geometrical accuracy, the beams were manufactured by CNC folding the core webs followed by a dip brazing to bond the core web to the face sheets. The governing collapse mode of the 6061-T6 beams is buckling of the core web which could be improved by further thickening the core webs and thinning the face sheets but this was not achievable in practice as the thin face sheets significantly warped during the heat treatment. Hence, the CFRP and the 6061-T6 beams are as close to the optimal configurations as we could manufacture within reasonable development work. It is however important to highlight that if the same comparisons would be made at considerable higher areal mass; the performance differences would be smaller as the 6061-T6 beam cores would be less sensitive to buckling/indentation failure. The chosen areal mass is however representative of many lightweight structure applications.

Fig. 8 presents the load versus δ/L response for the CFRP, AL and SrPET 16/69/15 sandwich beams. As expected, the AL sandwich beam showed the highest stiffness followed by the CFRP and SrPET. This is a result of the base material Young's modulus which is highest for the aluminium alloy followed by carbon fibre reinforced epoxy and SrPET.

The AL sandwich beam reaches a peak load of 3590N followed by softening. The CFRP sandwich beam reaches peak load at 7320N followed by a more than 50% load drop due to

core failure. In contrast to this, the SrPET sandwich beam which has a peak load at 5641N did not show any softening or load drop.

Due to the high peak load, the CFRP sandwich beam absorbed 72.7Nm (calculated to $\delta = 15\text{mm}$ or $\delta/L = 0.2$) which is more than twice that of the AL beam which absorbed only 32.2Nm. The SrPET sandwich beam absorbed 64.5Nm and therefore shows higher energy absorption than the AL beam and can compete with the CFRP sandwich beam.

Worth highlighting is however the fact that the SrPET sandwich beam is recyclable whereas the CFRP sandwich beam consists of several different materials making recycling very difficult and costly. In addition, the SrPET material cost is considerably lower than both CFRP and the aerospace grade 6061-T6 aluminum alloy. These two factors are key in e.g. the automotive industry and hence SrPET sandwich beams might serve as interesting candidates for these applications.

7 Concluding remarks

Fully recyclable corrugated sandwich beams made from only SrPET have been manufactured and tested in quasi-static 3-point bending. The following conclusions have been made:

- i. Beam configurations which have a higher portion of their mass distributed to the core generally show higher peak loads and energy absorption. For configurations with very high portion of mass in the core (and thus very thin face sheets), a loss of performance is observed due to severe buckling of the face sheets followed by delamination and separation between core and face sheets.
- ii. A finite element model has been developed using an anisotropic visco-plastic constitutive material law. The FE-predictions of the SrPET sandwich beams during 3-point bending are in excellent agreement with the measurements and both peak load and energy absorption can be predicted with good fidelity.

- iii. When compared to similar weight and geometry structures of different materials, herein the corrugated SrPET sandwich beams outperforms corrugated sandwich beams out of aerospace grade aluminium in terms of flexural peak load and flexural energy absorption. SrPET beams have a lower stiffness and peak load than a CFRP/foam sandwich beam of same weight but the energy absorbing capability is similar to CFRP beams. This cannot be made as a general conclusion. If the geometries are changed SrPET-configurations do not necessarily outperform other materials or material combinations. Anyhow, the SrPET sandwich beam structures show impressing energy absorption capacity which can compete with state-of-the-art materials.

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