Hartley, J. W., Bogucki, P., Snudden, J. P., Withers, E. M., Ward, C., & Kratz, J. (2016). Reclaiming in-process composite waste for use in energy absorbing sandwich structures. Paper presented at SAMPE Long Beach 2016, Long Beach, CA, United States.

Peer reviewed version

RECLAIMING IN-PROCESS COMPOSITE WASTE FOR USE IN ENERGY ABSORBING SANDWICH STRUCTURES

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ABSTRACT

The growing demand for carbon fibre reinforced polymers (CFRP) has led to a significant increase in the amount of carbon fibre waste generated. This paper investigates the reuse of in-process waste as a non-woven complex for use in energy absorbing applications. Composite sandwich coupons were manufactured and tested in quasi-static edgewise compression. Three laminate configurations were used, a continuous fibre unidirectional layup, a fully reclaimed layup and a hybrid of the two. The unidirectional material showed the most efficient energy absorbing performance, with the fully reclaimed showing the lowest. The hybrid laminate displayed traits of both the material types, whilst also showing a more consistent performance across each of the coupons tested.

1. INTRODUCTION

The growing demand for carbon fibre reinforced polymers (CFRP) has led to a significant increase in the amount of carbon fibre waste generated [1]. Up to now the primary solution to this is to send the waste to landfill, which is both costly and harmful to the environment [2]. As a result, a need has been created for manufacturers to develop methods of recycling [3]. Whilst the technology for recycling end-of-life (EOL) carbon fibre already exists, it has seen very limited application to date due to the slow rate of recycling currently possible, as well as doubts of the mechanical performance attainable. At the moment, applications of recycled carbon fibre are limited to only non-critical structures, where low strength materials can be used.

Another significant issue is the waste produced during the manufacturing process. This waste is created from expired or off-spec material as well as cutting and trimming operations, and can contribute as much as 50% of the total CFRP waste generated [4]. One method for reclaiming the scrap is to collect it, break it down into small pieces and reform the fibres into a discontinuous random mat. Provided the scrap material is not mistreated once it is separated from the cut preforms, it will not require any additional cleaning and will therefore potentially be more valuable than material recycled from end-of-life composites [5].

Limited applications currently exist for recycled CFRP, but those that do can be broadly classified for use in one of three categories of application: semi or non-structural; structural; and novel. The non-structural material is usually produced by grinding or shredding the waste material into a particulate or very short fibre state [6-7], which can then be further processed into a Sheet Moulding Compound (SMC) type material [8]. While it is possible to process waste to recycle material for these applications quickly and relatively inexpensively, the mechanical properties of the original material are lost. Therefore in order to retain the value of the original fibre, the scrap must be reformed into a structural material or used in other high value applications. Several high value applications have been investigated, such as antistatic flooring, industrial paints, cement and road surfacing [9], and in electromagnetic interface shielding [10]. These applications are relatively niche compared with quantities of scrap that require recycling, therefore a solution that produces a reformed material that can be used in structural applications would be desirable in both financial and environmental aspects.

Little research into recycling processes that produce a reformed material with high retention of properties have been reported to date. One study undertaken has shown that it is possible to produce tapes of highly aligned reformed material in a continuous process that will have vastly superior mechanical properties to the SMC type materials other processes produce [11]. This method however requires substantial processing [12], which would increase costs and rate at which the reformed material is produced. An advantage of this method however is that since the fibres are short and cleaned, the quality of the recyclate has little effect on the performance of the reformed material, something that has been shown to be an issue with other recycled materials [13-14].

Whilst ideally it would be possible to use recycled composites to replace virgin feedstock, it is clear that other applications must be investigated since recycled carbon fibre strengths will never reach or exceed those of virgin material. It has been shown that continuous fibre composites can be highly efficient energy absorbing structures [15-17], dissipating energy through frictional losses at ply interfaces as well as the overall deformation of the structure [18]. Composites containing reclaimed carbon fibre seem to be good candidates for energy absorption as they show potential in having a high inter-laminar shear strength due to their random fibre orientation [19]. Reclaimed fibres may be also more suited because the random fibre orientation will naturally offer progressive slipping at ply interfaces to absorb additional energy when compared to continuous fibre composites. An additional benefit of energy absorption as an application is that static strength is not usually the primary driver in the design of the component, instead the specific energy absorption (SEA) of the material combined with the deceleration times required will dictate the design requirements.

The aim of this research was to test the energy absorbing capability of reclaimed carbon fibre materials and compare them to more prevalent continuous fibre materials. The potential of having reclaimed carbon fibre in a hybrid structure will also be observed in this to attempt to combine useful properties from the two different architectures.

2. MATERIALS AND METHOD

2.1 Coupon Design

No standardised test methodology currently exists to test the energy absorption of sandwich structures under edgewise crushing loads. Sample geometry, crush initiation mechanism design, stacking sequences and test conditions greatly affect the measured SEA of the material tested, therefore comparing different testing conditions is difficult. Regardless of the test chosen, the specimen must have a trigger mechanism to initiate stable progressive crushing in a quasi-static compression test [20]. The trigger mechanism tends to be of a geometric nature where stress concentrations would occur, such as a sharp discontinuity found in the vertex of a triangle. It has been shown that even with a trigger mechanism, a specimen with a constant cross sectional area could still become unstable, yet in the trigger region the test revealed progressive crushing [20]. This was further explored by increasing the size of the trigger region and considering it as the new test region. From the success seen in [20], the same geometry with slightly different dimensions was used in this project. The chosen coupon geometry is shown in Figure 1.

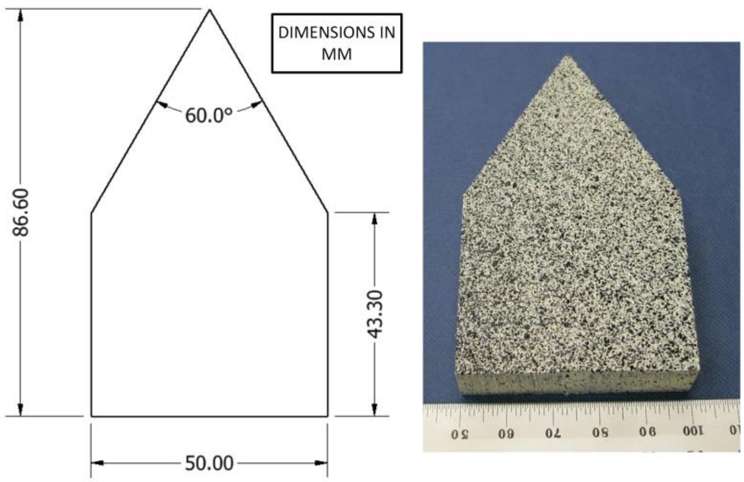

Figure 1. Coupon geometry and dimensions.

2.2 Materials

The sandwich panels used for testing were manufactured using the Vacuum-Assisted Resin Transfer Moulding (VARTM) method. A total of three carbon sandwich preforms were created, one using only unidirectional material, one using only reclaimed material and a third which was a hybrid of the two materials. The layups of the three panels are shown in Table 1. The unidirectional material was a uniweave carbon fibre fabric from SGL Automotive (300 g/m^2), whilst the reclaimed material was a RECATEX™ type 62 nonwoven complex (300 g/m^2), also from SGL. The reclaimed material is processed using a carding technique, therefore the material supplier indicated that better in-plane properties would be found along the roll. The roll direction was therefore aligned with the loading axis, resulting in the lay-ups indicated in Table 1. The core material was a Rohacell® 110 IG-F closed-cell foam by Evonik, with a density of 110 kg/m^3. The preforms were infused at 40 °C using EPIKOTE® resin RIM 935 and EPIKURE® curing agent RIM 936 from Momentive Speciality Chemicals, Inc. The cure cycle was two hours at 60 °C, followed by two hours at 90 °C. The test specimens were machined using a water jet cutter.

Table 1. Laminate Configurations for Coupon Skins

Laminate	Skin lay-up sequence	Average specimen thickness (mm)
Unidirectional	$[45/0/-45]_s$	14.5
Reclaimed	$[0_{RE}/0_{RE}/0_{RE}]$	13.5
Hybrid	$[0_{RE}/0/0_{RE}]$	13.5

RE – Reclaimed layer (0 indicates roll direction)

2.3 Test Method

Static testing was carried out using a Zwick 1466 test machine. Coupons were clamped into an end support at the base and positioned at the centre of the loading plates. Figure 2 shows the positioning of the specimen within the test machine. A displacement control programme was used to provide a constant quasi-static crushing rate of 6 mm/min. Testing was terminated after approximately 40 mm of displacement. A total of five samples were tested for each configuration. A Dantec digital image correlation (DIC) system was used to obtain the strain field within the coupons during crushing.

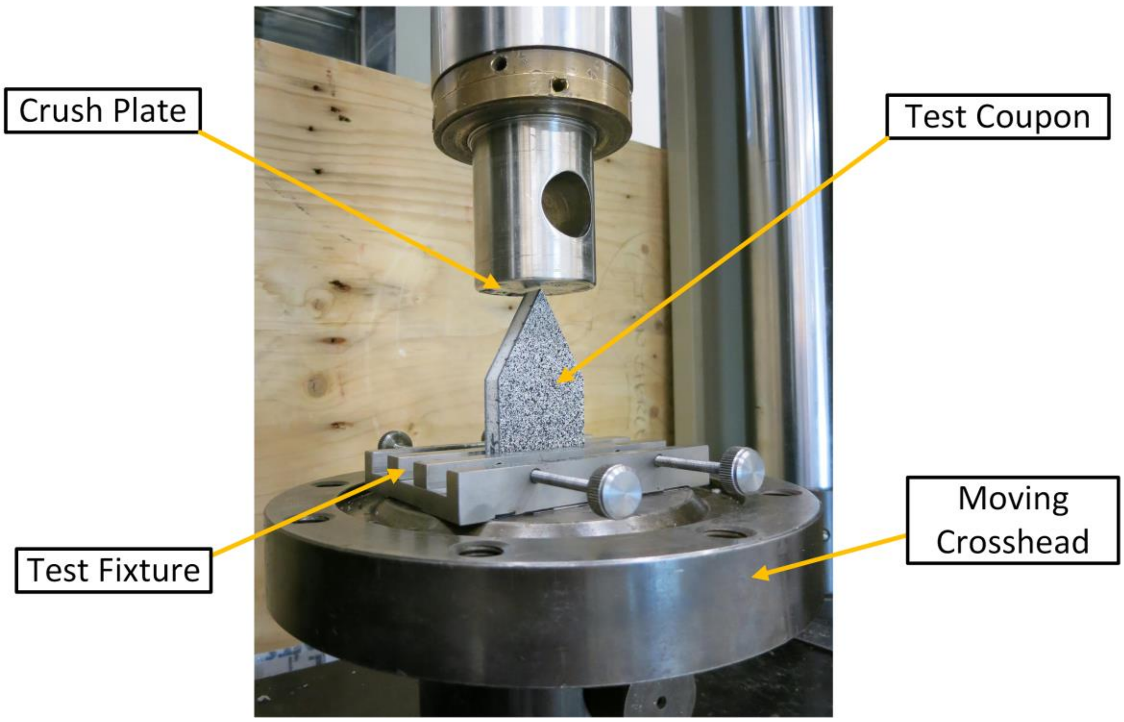

Figure 2. Experimental test setup.

3. RESULTS AND DISCUSSION

3.1 Static Testing

Different failure mechanisms were observed during testing, as presented in Figure 3. The unidirectional coupons failed in a stable manner, with progressive peeling and delamination of the skins as they separated from the core. The fully reclaimed coupons failed in a much different manner, with fracturing and fragmentation of the skins as the dominant failure mechanism. In a number of the reclaimed coupons, disbonding of the skins was also observed away from the crush zone. Figure 4 shows some examples of these failure mechanisms. The hybrid coupons showed a combined failure behaviour, with both the progressive folding of the unidirectional material and fragmenting of the reclaimed material observed in Figure 3c.

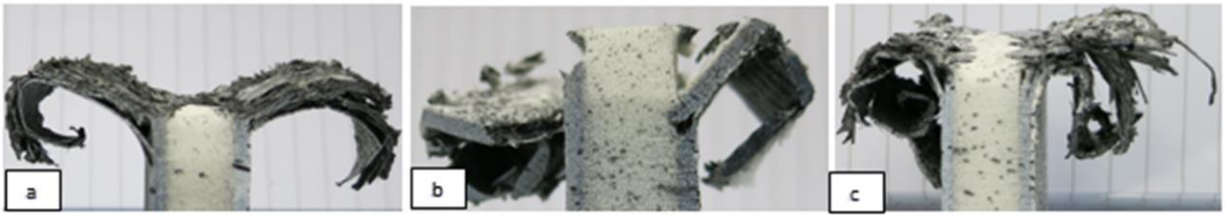

Figure 3. Pictures showing crush front after test showing a) mostly delamination in fully unidirectional specimens b) fragmentation in fully reclaimed specimens c) on a combination of the two mechanisms in hybrid specimens.

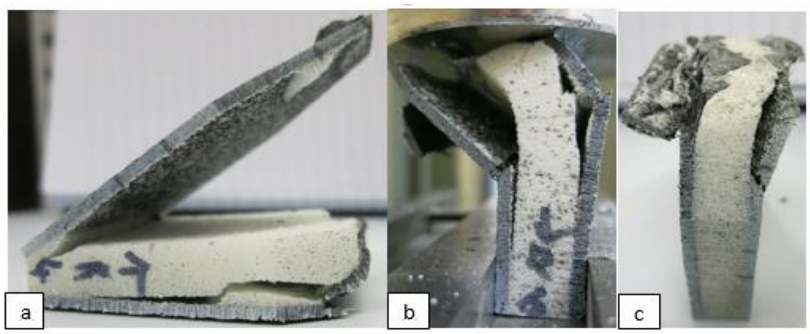

Figure 4. Possible failure mechanisms: a) skin to core de-bonding b) core compression failure and c) skin compressive failure.

Representative load-displacement traces of the three material configurations are shown in Figure 5. As with the failure mechanisms, this plot indicates different behaviours for the three configurations tested. The unidirectional material showed a relatively smooth load increase, whilst the hybrid and fully reclaimed coupons showed a more unstable behaviour, with several dramatic drops in the load carried by the coupon. By comparing the loads carried by the coupons, the unidirectional coupon clearly sustained the highest load of the three configurations, followed by the hybrid, with the fully reclaimed sample sustaining the lowest.

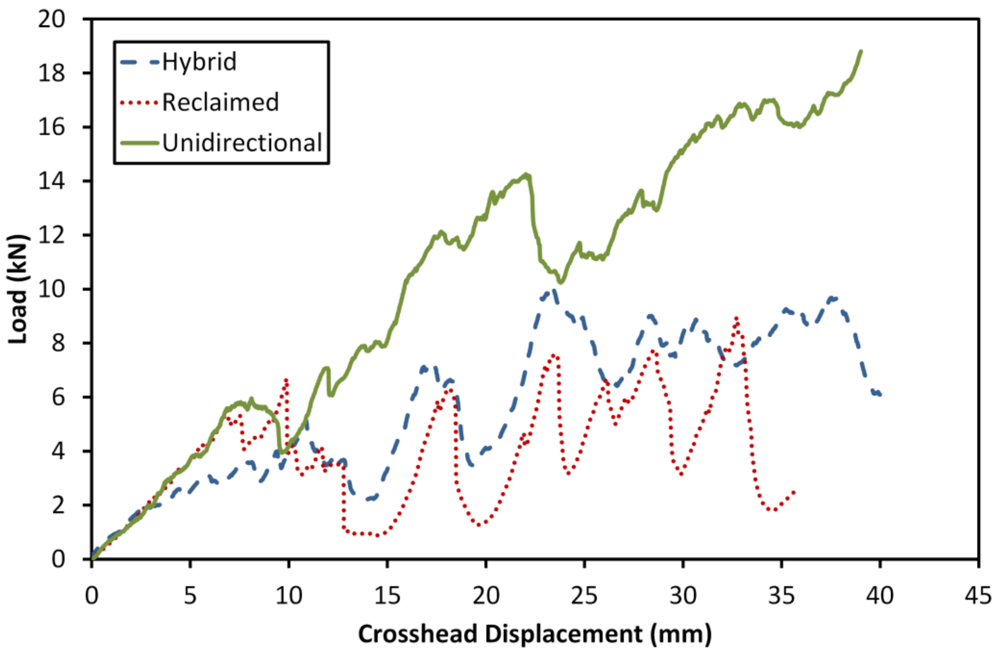

Figure 5. Representative load-displacement results for each coupon configuration.

Figure 6 shows representative strain patterns obtained from the DIC imaging. In the unidirectional material shows the highest strain values located right at the crush zone where failure occurs. Within the hybrid specimens the strain distribution is expanded, with the highest strain located over a slightly larger area in front of the crush zone. Within the reclaimed material this change is even more significant. The area of highest strain takes up a significant part of the test coupon, and higher strain values are observed in the constant width base of the test coupon.

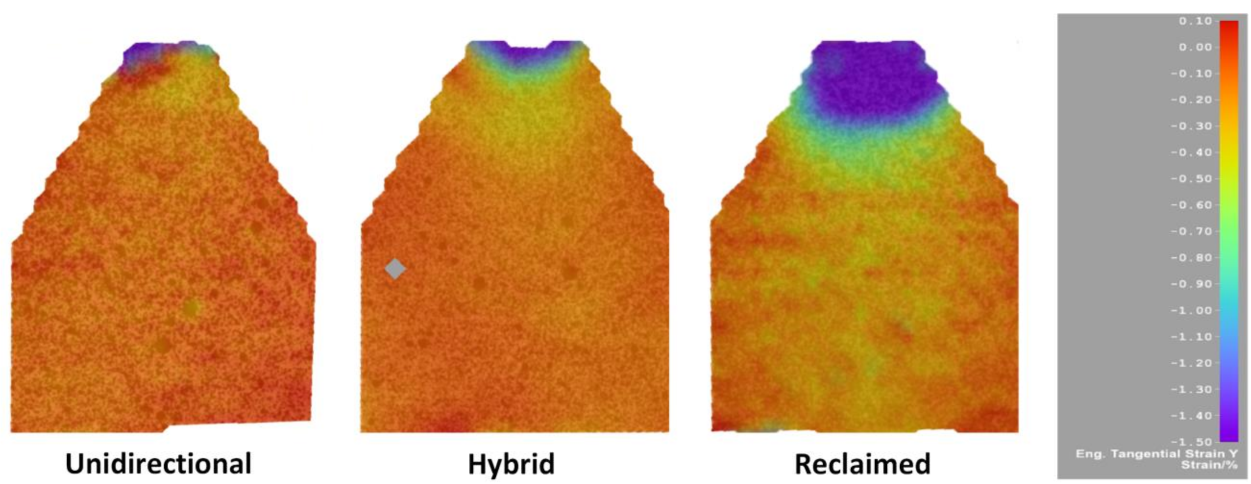

Figure 6. Representative strain distributions obtained using DIC.

By comparing the data presented in Figures 3, 4, 5 and 6, the highest performing material was the reference unidirectional material. The unidirectional coupons showed the most stable failure mode through a progressive folding mechanism, and also showed the highest forces sustained during crushing. On the other hand, the reclaimed specimens, mostly failed by fragmentation. This was demonstrated by the big, mostly undamaged, pieces that broke off in Figure 4. This is also shown in the Figure 5 where there are regular substantial drops in the sustained load as the skin fractures. The reason behind this unstable fragmentation mode could arise from the high inter-laminar shear strength. Delamination and fragmentation are competing failure mechanisms [21], and due to the higher interlaminar strength of the reclaimed material, attributed to the random fibre orientations, fragmentation was the more dominant failure mode.

The hybrid coupons behaved in a more complex manner, displaying several different failure modes. Some fluctuation in the load was observed, similar to the fully reclaimed samples, albeit at a higher load level. However the connection between skin and core was maintained ahead of the crush site, which meant these fluctuations were simply fracturing of the skins rather than the disbonding observed in the reclaimed coupons. These results indicate that the additional unidirectional layers within the skin were supporting the structure to maintain stability during failure.

The DIC results within Figure 6 show that the material choice significantly effects the strain distribution with the test coupon. The unidirectional coupons showed an almost constant strain distribution across the entire specimen, except at the crush zone where failure is occurring. Within this localised region the strain is at its highest as the material is being crushed. The addition of reclaimed layers with the hybrid begin to shift this high strain region away from the failure zone over a greater part of the specimen. This becomes even more significant within the fully reclaimed samples, where this region covered a significant portion of the test coupon.

3.2 Energy Absorption

To further compare the different test configurations, the specific energy absorption (SEA) values were approximated using Equation 1:

$$SEA = \frac{W}{\rho A \delta} = \frac{\int_0^\delta F dx}{\rho A \delta} \qquad [1]$$

where W is the work done on the structure during crushing (force × displacement), and $\rho A \delta$ defines the mass of the crushed material. The energy absorbed by the coupon was found by taking the area under the force-extension graph shown in Figure 5. The crushed mass of each coupon was approximated by assuming a constant density across the coupon and thus using the crushed area of the material to predict the mass. Due to some tests ending at different crushing distances it was decided to cap the distance over which the energy was measured to 35 mm.

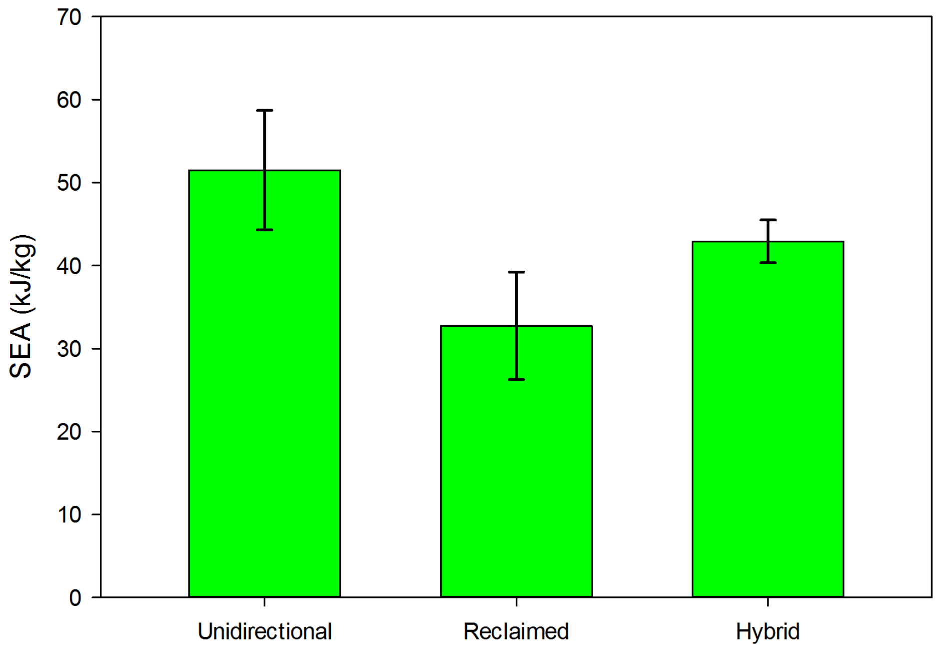

Figure 7. Averaged SEA results.

Figure 7 shows a comparison of the averaged SEA results from the different test configurations. As a result of the stable failure mode and relatively high load level sustained during testing, the unidirectional coupons showed the most efficient energy absorption of the three configurations tested. Due to the unstable failure mode of the reclaimed material, the performance was much lower, showing a 40 % drop in performance compared to the unidirectional material. The addition of unidirectional material to the reclaimed mat improved the performance, and partially restored the SEA to the level of the unidirectional material. The hybrid coupons showed a 31 % increase over the reclaimed material, reaching a level that was effectively an average of the other two configurations.

Also displayed within Figure 7 is the variation within the results. The hybrid coupons showed the most consistent results, whereas the unidirectional and reclaimed coupons showed relatively high variation. This difference in consistency may partly arise from the stability of the failures. As the fully reclaimed coupons failed by disbonding and fragmentation of the skins at various locations away from the crush area the energy absorption varied more significantly. The assumption used in the calculations also only considered the mass of the specimen inside the crush zone. If failure occurred away from the crush zone it could give rise to inaccuracies because only a portion of the failed material was considered when calculating the SEA.

The high variation in the unidirectional specimens appeared to be due to sensitivities to discontinuities in the material. Small defects such as voids or fibre misalignment would significantly reduce the load carrying ability of the skins and thus result in less energy absorption. The hybrid coupons appeared to overcome this, by stabilising the failure mode and smearing the effect of any defects. This occurs because the reclaimed layers are effectively adding localised defects through short fibres at the crush zone. The random fibre orientations of the reclaimed mat would have also reduced the effect of any fibre misalignment in the unidirectional layers.

A material with a high SEA may introduce such high deceleration forces that they kill or injure the human occupant they are intended to protect during an impact event. Despite the relatively low SEA of the reclaimed material, it may still offer some benefit in these energy absorbing applications. Given the performance of the hybrid material combining both the unidirectional and reclaimed material forms, structural performance tailoring becomes possible. The greater predictability and potential to deal with off-axis loading, as well as this tailoring ability suggests the hybrid energy absorbing structure is a potential use of reclaimed carbon fibre waste.

4. CONCLUSIONS

Edgewise crushing tests have been carried out on composite sandwich coupons to investigate the use of a reclaimed carbon fibre materials within an energy absorbing structure using a small rectangular samples with a triangular trigger mechanism. This was compared to a continuous fibre layup as well as a hybrid of the two. The testing showed that the fully reclaimed coupons failed in an undesirable fragmentation mode compared to the progressive crushing observed in the unidirectional material. This resulted in a significant drop of 40 % in the specific energy absorption of the material. By forming a hybrid of the two materials, the performance was partially restored, and resulted in a more stable and consistent failure mode. These results demonstrate the potential use of reclaimed carbon waste in energy absorbing structures.

5. ACKNOWLEDGEMENTS

This work was conducted within the framework of a G8-2012 project on Material efficiency: A first step towards sustainable manufacturing, between the University of Southern California, McGill University, the Technische Universitat Munchen, and the University of Bristol. Funding for this work was provided by the UK Engineering and Physical Science Research Council (EPSRC), under grant no. EP/K025023/1. Authors J. Hartley and E. Withers would like to acknowledge the EPSRC Centre for Doctoral Training in Advanced Composites for Innovation and Science (ACCIS) grant no. EP/G036772/1.

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