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Effect of tufting density and loop length on the crushing behaviour of tufted sandwich specimens

Jamie W. Hartley*, James Kratz, Carwyn Ward, Ivana K. Partridge

ACCIS, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK

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ABSTRACT

A series of small scale specimens were tested to identify if local variations during the manufacturing process influence the energy absorbed during the crushing of tufted sandwich structures. Coupons with varying loop lengths and number of tufts were tested in quasi-static and dynamic edgewise compression. Results of the testing showed that the effect of a single tuft was captured at this small scale, whilst the tufting parameters changed the damage behaviour, including the response of the resin column during testing. Increasing the number of tufts at a single point, from one to two or three, gave rise to a greater energy absorption, but variations in loop length were less conclusive.

1. Introduction

Energy absorbing structures must be able to maintain loads over prolonged crushing distances or to a targeted stopping fail-safe, using a minimal amount of material. Metallic structures absorb energy through a progressive folding mechanism, however this can prove difficult to manage over a short distance, such as during a vehicle side impact, and can require a complex system design. Continuous fibre composites, on the other hand, offer potential improvements in this situation over metals [1–4] through frictional losses at ply interfaces as well as the overall deformation of the structure [5].

In the case of composite sandwich structures this becomes more difficult to achieve, as the reinforced fibre skin tends to disbond from the core, resulting in a premature, catastrophic failure. To be able to absorb the large amount of energy required in a crash situation, composite sandwich structures must be able to fail in a stable end-crushing mode by fracture and splaying of the face sheets [6]. In order to ensure this happens, buckling and disbonding of the skins from the core must be avoided. Through-thickness reinforcement employing stitching and Z-pinning methods have been previously shown to successfully increase the adhesion between skin and core, stabilising skin disbonding, and containing failure [7–16]. These studies showed improvements across a range of load cases, including static compression, out-of-plane impact and edgewise crushing.

More recently, tufting has emerged as a popular method of localised Through-Thickness Reinforcement (TTR) for dry preforms. The tufting process involves inserting a single threaded needle through a preform, where friction within the preform is responsible for holding the thread in place as the needle is retracted. On the back face of the preform a loop of thread is formed. Dell'Anno et al. [17] recently published an in depth review of tufting technology and the manufacturing process, whilst Tan et al. have investigated the manufacture of tufted sandwich panels [18].

In terms of mechanical properties of tufted continuous carbon fibre reinforced laminates, Treiber [19] and Dell' Anno [20] have studied the effects of tufting and the tufting process in detail. They observed that tufting can significantly improve the delamination resistance (by threefold) within a laminate with only a small reduction (approximately 10%) in the in-plane mechanical properties due to the disruption of the tuft on the fibre alignment. Henao et al. [21,22] have also investigated the effect of tufting, focusing on how sandwich structures fail under 3-point bending, edgewise compression and out-of-plane impact. A combination of experimental and numerical techniques were employed to conclude that tufting can offer significant improvements to sandwich structures by restricting the disbonding of the face sheets [21], with an increase in energy absorption with increasing tuft densities during out-of-plane impact [22]. However, studies into the

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* Corresponding author.
E-mail address: jh9799@bristol.ac.uk (J.W. Hartley).

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crushing performance of such materials are limited. In one study, Blok [23] focused directly on the use of tufted sandwich panels as energy absorbing structures. The author reported that tufted sandwich panels can improve energy absorption during an impact event, but the choice of core and skin materials will influence both the energy absorption and the net benefit of tufting a sandwich structure.

Despite these reported gains there is, as of yet, no real understanding of how variations within the manufacturing process may affect the performance of these structures under edgewise compression.

Even with the use of automated processing, variations in loop lengths within the same preform are still possible. Tight control of tuft formation is apparently reliant on the quality and consistency of the preform. The use of dry fabrics provides a number of opportunities for variation through ply slippage or incomplete consolidation. Any variations in thickness in the preform will change the distance the needle travels, resulting in possible variations of tuft length. The relatively low stiffness of the dry fabric and backing material will also allow the preform to bend as the needle is inserted, again changing its path and resulting in varying lengths of tufts. Upon inspecting a tufted preform, inconsistency in loop formation can be clearly seen (Fig. 1a), as well as seams lifting from the panel surface due to reduced tension in the thread (Fig. 1b).

The aim of this research was to investigate a method of testing local variations within tufted sandwich components, starting at the smallest possible level of a unit cell around a single tuft. The effect of variations in the tuft structure could be captured and characterised at this scale. For this investigation, the loop length and the number of tufts inserted at a single point were chosen as the design variables as these are directly controllable during the insertion process.

2. Material and methods

2.1. Coupon design

No standardised test methodology currently exists to test a single tuft out-of-plane, therefore the closest matching ASTM standard, C364 [24] (Edgewise Compression of Sandwich Structures), was adapted to suit the mechanical testing. A redesigned coupon geometry was required to promote a local crushing failure at the tip of the coupon. The newly proposed coupon geometry is comprised of three sections, as shown in Fig. 2. The base section consisted of a 15 mm × 15 mm square to clamp the coupon into an end support, similar to the ASTM standard. Clamping within the support stopped the specimen from slipping during the test but also restricted the skins from immediately disbonding from the core over the entire surface area. Some rotation was allowed at the base of the coupon and the upper crush plate was mounted to a spherical bearing to help align the specimen in the loading direction.

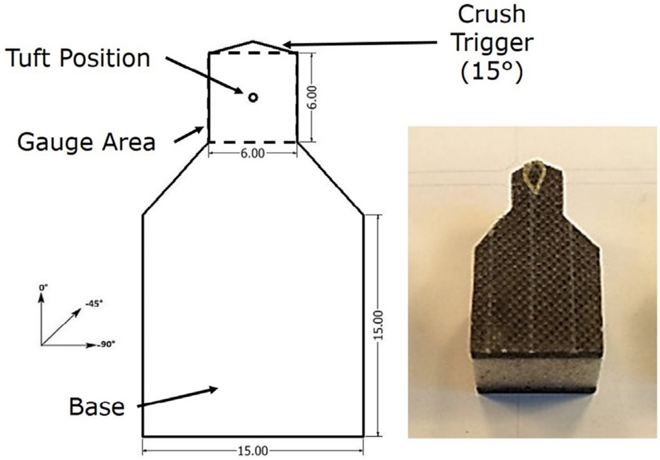


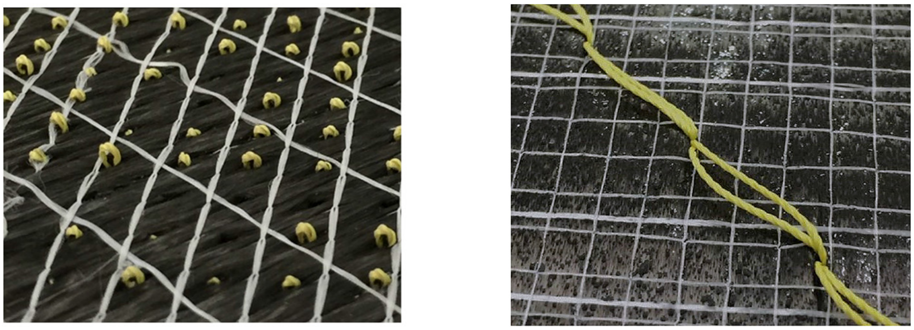
Fig. 2. Coupon geometry, **Left**: idealised, **Right**: actual.

The gauge section of the coupon was a 6 mm × 6 mm square region, with the thread of the tuft located at the centre. The sizing for this was based around a 6 mm by 6 mm tuft spacing, which has been used in previously manufactured components [23].

Finally, to initiate crushing within the gauge section of the coupon, a taper to act as a crush trigger was included within the design. The trigger acted as a stress concentration to promote failure. The design intention was such that when contact occurred between the plate and the specimen at this sharp edge, the skins would begin to collapse, and crushing of the material would continue through the rest of the coupon. An angle of 15° was chosen for this design as this is above the threshold value for stable crushing [25].

2.2. Specimen manufacture

The sandwich panel used for testing was manufactured using the Vacuum-Assisted Resin Transfer Moulding (VARTM) technique. The preform was assembled using a uniweave carbon fibre fabric from SGL Automotive (300 g/m^2), and a 10 mm thick Rohacell® 110 IG-F closed-cell foam by Evonik (110 kg/m^3) for the core. The chosen layup was $[-45/0]_s$, giving a 2 mm thick skin. The preform was heated for 2 h at 90 °C under vacuum pressure to activate the binder in the carbon fabric before tufting using the robotic tufting



(a) (b)

Fig. 1. Examples of observed variations in thread placement (representative only) **a)** variation in loop formation **b)** lifting of the thread from the preform surface.