THE INVESTIGATION OF MODIFIED 'BRICK AND MORTAR' COMPOSITE ARCHITECTURE WITH IN-PLANE WAVY SEGMENTS FOR PSEUDO-DUCTILITY

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Abstract

Discontinuous 'brick and mortar' composite architectures can display limited pseudo-ductile behaviour in tension due to the localisation of failure at the weakest set of overlaps through the specimen thickness. A modified, continuous 'brick and mortar' composite architecture with in-plane wavy segments (in place of discontinuities), to overcome the localisation of failure, was produced and tested in tension. Failure of first overlap was observed at ~0.25% strain after which the wavy segments straightened and stiffened. The second overlap failed at ~0.85% strain and the specimen continued to straighten and stiffen until the ultimate tensile failure at ~1.8% strain. 'Brick and mortar' composites with wavy segments exhibited prolonged pseudo-ductility in tension with a failure strain which exceeded that of the pristine unidirectional carbon fibre/epoxy composite.

1. Introduction

Discontinuous 'brick and mortar' carbon fibre/epoxy composite architectures have been investigated with a desire to produce high performance yet ductile composites, as shown in Figure 1 [1, 2]. The unit cell of these 'brick and mortar' architectures can exhibit a pseudo-ductile behaviour when loaded in tension, either due to the complete yielding of the matrix in the overlap region, or due to cracks which initiate at the brick ends and propagate towards the centre of the overlap region. Unfortunately, in a composite containing many overlaps along the length of the specimen, the failure tends to localise in a single column of overlaps (i.e. one set of overlaps running across the thickness of the specimen) and so little, if any, pseudo-ductility will be achieved in practice.

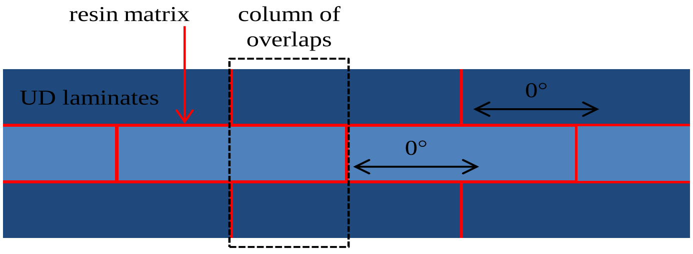
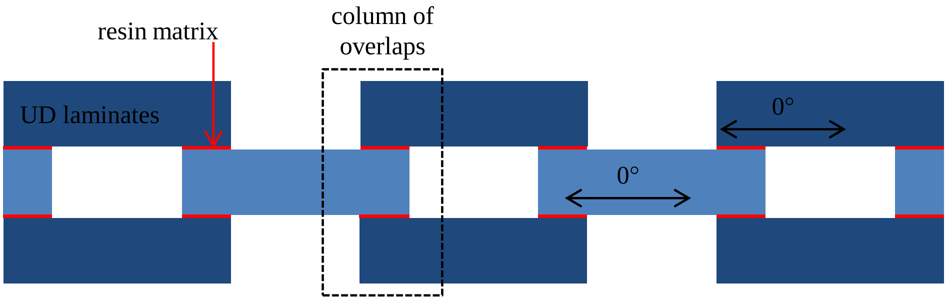
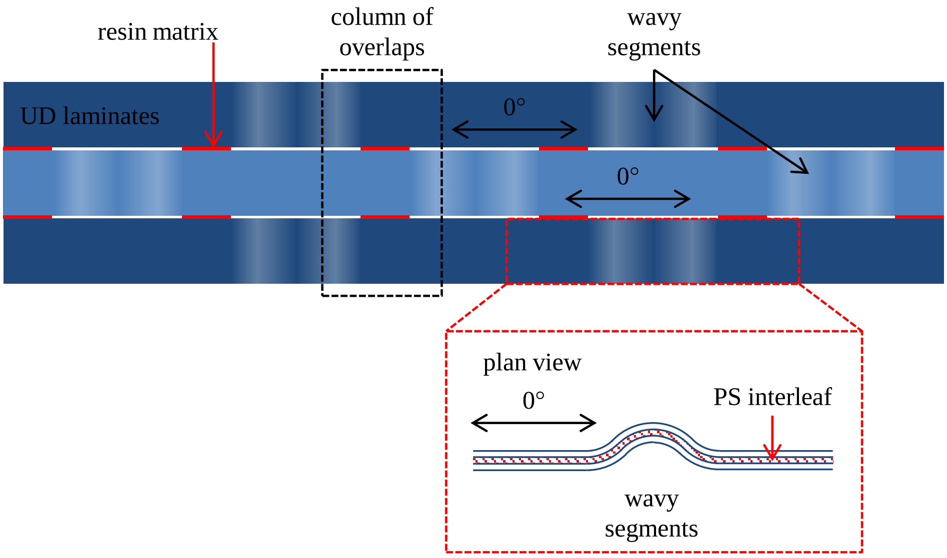


Figure 1. A sketch of a discontinuous 'brick and mortar' composite architecture concept. Dark blue and light blue sections represent (cut) unidirectional (UD) laminate composite bricks to highlight the pattern more clearly.

A modified ‘brick and mortar’ composite architecture is proposed, with in-plane wave segments in place of discontinuities to prevent the localised failure of the composite in an attempt to achieve the desired pseudo-ductile response in tension. Figure 2a shows a ‘brick and mortar’ arrangement in which the gaps at the discontinuities have been enlarged. For the modified architecture, shown in Figure 2b, these gaps are replaced by in-plane wavy segments which connect together the unidirectional bricks. The intention is that these wavy segments will extend and stiffen after one column of overlaps fails, such that the applied load can be transmitted to the adjacent overlaps. The localised failure in a column of overlaps will be prevented and this architecture should therefore permit a more pseudo-ductile behaviour.



(a) discontinuous ‘brick and mortar’ configuration



(b) modified ‘brick and mortar’ configuration with in-plane wavy segments

Figure 2. Sketches of (a) discontinuous 'brick and mortar' composite architecture concept which has been expanded, and (b) continuous 'brick and mortar' composite with in-plane wavy connected segments. Dark blue and blue sections represent unidirectional (UD) laminate composite bricks to highlight the pattern more clearly.

It is important to ensure that the in-plane wavy segments will extend and carry the load after failure of the adjacent overlaps. To achieve this, the composite must exhibit shear cracking between the plies in the wavy region, allowing the composite to extend and stiffen as the fibres become straighter. To ensure this mechanism will occur, a relatively weak (in shear) thermoplastic interleaf was used in the composite laminate (see the plan view in Figure 2b). The chosen thermoplastic for this embodiment is polystyrene (PS) which also exhibits a significant loss in flexural stiffness when heated above the glass transition temperature (T_g) [3]. This enables a relatively simple production technique to be used for wavy segments when using PS-interleaved carbon fibre/epoxy composites.

2. Experimental investigation

2.1. Materials

A carbon fibre/epoxy prepreg, T300/914 nominal thickness of 0.125 mm, was purchased from Hexcel and used for all the continuous lamina in the composite stack. The interleaved material was polystyrene which processed into a 0.1 mm thick film. The T_g of the polystyrene is 85 °C which was measured by differential scanning calorimetry. Note that for this interleaf to be suitable its T_g must be lower than the T_g of the cured epoxy matrix (180 °C via dynamic mechanical thermal analysis, Hexcel data sheet). The mechanical properties of the individual materials, at room temperature, are shown in Table 1.

Table 1. Properties of the materials used in this work.

Materials	Property	Value
Hexcel T300/914 carbon epoxy composite	E_1, GPa	135[a]
	E_2, GPa	8.5[a]
	ν_{12}	0.32[b]
	G_{12}, GPa	5.27[b]
Styrolution polystyrene	E, GPa	3.2[c]
	ν_{12}	0.35[d]
	G, GPa	1.2[e]

[a] both E_1 and E_2 of carbon fibre/epoxy composite were taken from Hexcel datasheet
[b] both ν_{12} and G_{12} of carbon fibre/epoxy composite were taken from Rana and R. Fangueiro, 2016 [4]
[c] E of PS film at room temperature were taken from Styrolution data sheet
[d] ν_{12} of PS film was from the website (http://polymerdatabase.com/polymer%20physics/Poisson%20Table.html), accessed on 2018-5-19
[e] G of PS film is derived from the equation, $G = E(2(1+\nu_{12}))^{-1}$

2.2. Specimen manufacture

To achieve the desired proposed architecture and geometry of the continuous ‘brick and mortar’ composites multiple waves and overlapped regions would be required. Initially, a smaller unit of this overall layup was fabricated. In this simplified structure (Figure 3), two strips of coupons with offset in-plane waves were fabricated and then bonded to create a specimen.

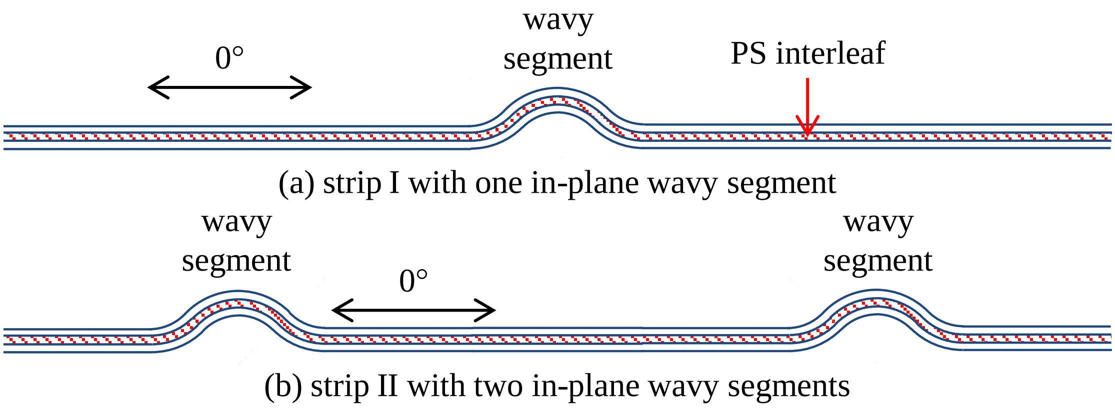
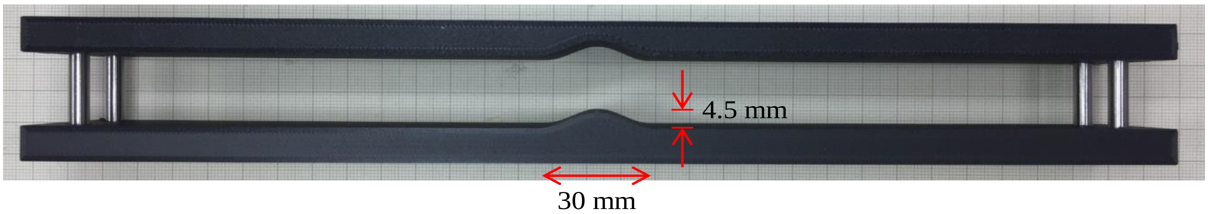


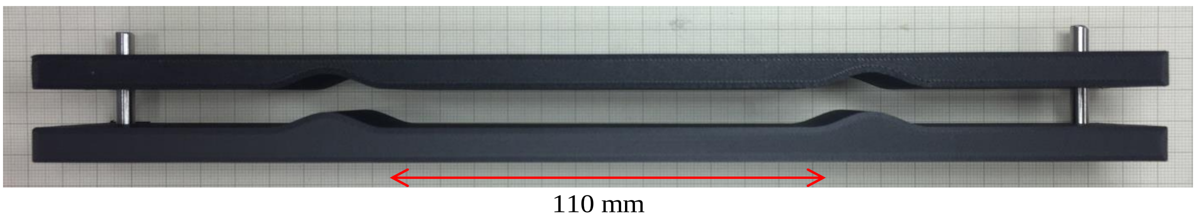
Figure 3. A schematic of the individual components of the composite specimen, (a) a strip with a single in-plane wave in the centre, and (b) a strip with two in-plane waves offset to the central in-plane wave in (a).

A flat composite panel (300 mm long and 130 mm wide) consisting of 0° unidirectional carbon fibre/epoxy laminae containing PS interleaves was manufactured in a unidirectional layup $[(0°/PS)_{23}/0°]$, with nominal thickness of 5.3 mm. The 0° fibre direction is along the longer side of the panel. The composite panel was cured in an autoclave at 175 °C at 100 psi pressure for 1 hour. The cured panel was trimmed to strips of 290 mm length and 25 mm width.

Moulds were then employed to form the waves in the flat cured composite coupons. Two types of moulds were manufactured using 3D printing made from Onyx (a micro-carbon reinforced polyamide thermoplastic with a heat deflection temperature of 145 °C, which is well above the processing temperature for PS of 120 °C). Mould A (see Figure 4a) contains a wavy shape at the mid-span, with an amplitude of 4.5 mm and a wavelength of 30 mm. Mould B (Figure 4b) contains two waves which have the same geometry as that of Mould A separated by 110 mm.



a) mould A



b) mould B

Figure 4. Photographs of Mould A (a) and Mould B (b) taken on graphical paper, one large square represents 10 mm.

The procedure to introduce waves into the composite coupons was as follows. A composite strip was placed into mould, for example Mould A. The mould with the strip was placed on a prepared aluminium plate, covered by PTFE release films, a breather cloth and a vacuum bag and sealed to the edges of the plate. The assembly was heated to the process temperature of 120 °C (not under vacuum) in an oven for 15 minutes. After this, the mould was slowly pressed together by hand to form a wave in the composite strip. A vacuum was then applied to constrain the strip in the desired geometry. The assembly was then cooled down to room temperature with the applied vacuum to retain the wave configuration in the composite strip. The process was repeated to produce laminates with two in-plane waves using Mould B by repeating the previous steps described.

The wavy composite laminates were then cut into strips of 3 mm width and these were ground to a 2 mm width.

These thin strips were bonded together on their side faces (see Figure 5) so that the wave shapes now lie in planes parallel to the bond plane. The strips, indicated as strip I and strip II in Figure 5, were bonded using a two-part epoxy adhesive (Araldite 2011, with a shear strength of up to 20 MPa, Huntsman datasheet). A non-stick film was used to prevent bonding the wavy segments to the adjacent strip surface. Specimens were then end tabbed with glass fibres composites bonded to both ends of the specimen with Araldite 2011 to form the completed specimens shown in Figure 5.

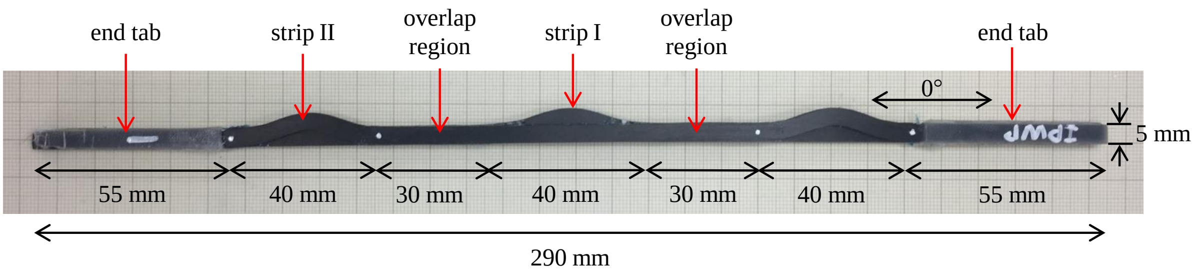


Figure 5. A photograph of a manufactured test specimen taken on graphical paper, one large square represents 10 mm.

2.3. Tensile testing

Specimens were subjected to a uniaxial tensile test at room temperature. The tests were performed on an Instron 5985 universal test machine with a 250 kN load cell at a constant crosshead rate of 1.5 mm/min until specimen failure. Load was recorded by the test machine and vertical displacement was measured using an (optical) Imetrum video gauge system. Targets for the video gauge system were made using a paint pen.

3. Results and discussion

A typical stress-strain profile of a modified continuous 'brick and mortar' composite architecture specimen is shown in Figure 6, and exhibits progressive failure. The tensile modulus of the fully straightened continuous 'brick and mortar' specimen was 75 GPa, with a tensile strength of ~650 to 700 MPa.

One overlap region at either end failed first in shear at ~0.25% strain, allowing the adjacent wave segments to straighten and stiffen. The second overlap region failed at ~0.85% strain, allowing the connected wavy segment once again to straighten and stiffen. The sample continued to straighten and stiffen until specimen failure at ~1.8% strain. As expected, this surpasses the failure strain (1.3%) for T300 fibres in a unidirectional epoxy composite (Torayca datasheet states that the fibre strain is 1.5%). The tensile stress at the first overlap failure was relatively low, ~82 MPa, due to the low shear strength of the adhesive used to bond the thin strips together. The corresponding average shear stress on the bond at the onset of this initial failure was 8 MPa.

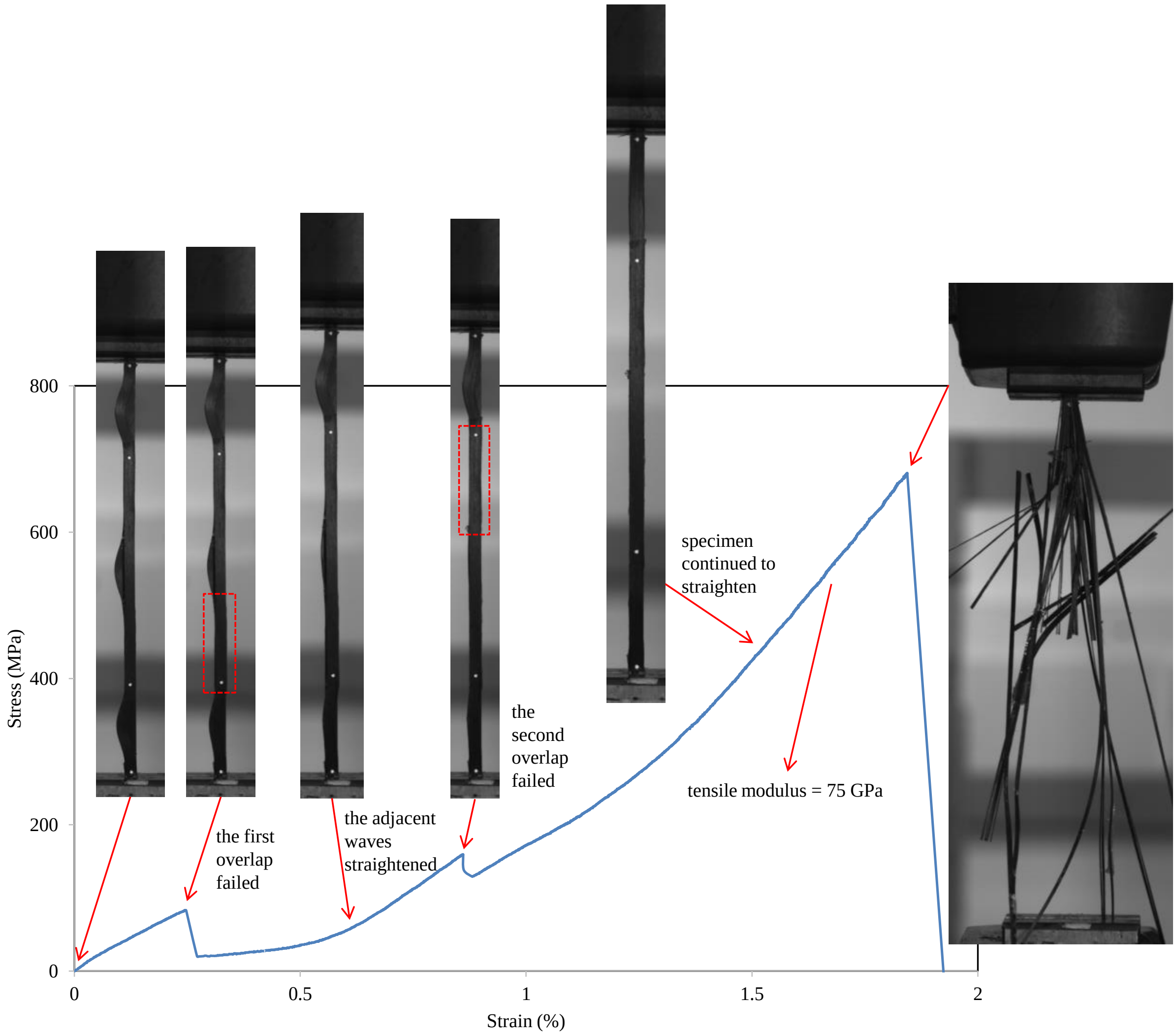


Figure 6. The tensile stress-strain relationship of a continuous interleaved 'brick and mortar' composite with in-plane wavy segments specimen under tension.

4. Conclusions

A continuous ‘brick and mortar’ composite with in-plane wave segments was successfully produced and tested in tension. Both overlap regions failed before ultimate tensile failure, indicating that localised failure observed in the conventional ‘brick and mortar’ architecture had been prevented. The resultant stress-strain plot showed a progressive pseudo-ductile behaviour. The strain-to-failure of the specimens was ~1.8% which is higher than the pristine unidirectional carbon fibre/epoxy (1.3%). Wavy continuous ‘brick and mortar’ test specimens, consisting of many waves, are currently under investigation.

Acknowledgments

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