STRESS TRANSFER IN DISCONTINUOUS ALIGNED THERMOPLASTIC COMPOSITE TAPES - AN EXPERIMENTAL AND NUMERICAL STUDY

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ABSTRACT

Discontinuous long fibre (DLF) thermoplastic composites present a promising lightweight alternative to metal replacement in high-volume applications, offering an ideal balance between mechanical properties and processability. This study examines the stress-transfer mechanism across discontinuities in aligned polyamide-6 (PA6) glass-fibre reinforced tapes through experimental and computational approaches. Mechanical tensile tests and 2D digital image correlation (DIC) were employed to investigate stress-transfer in aligned tape model composites, revealing critical stress-transfer lengths and stress concentrations. Double-lap shear tests further supported the findings. A progressive damage finite element analysis (FEA) model was developed to simulate the mechanical properties and stress-transfer mechanism in these composites, accounting for variability in tape properties and microstructures. Results from both experimental and numerical methods aligned well, providing insights for property optimization through the introduction of intentional discontinuities. This research lays the groundwork for the development of a multi-fidelity intelligent optimization framework to enhance the mechanical properties of DLF-based composites.

1 INTRODUCTION

The use of thermoplastic composites has been growing within the aerospace and automotive sector in recent decades, offering far shorter cycle times than thermoset composites and easier processing and recycling. Despite these advantages, thermoplastic composites based on unidirectional (UD) tapes or fabric-based organosheets are limited by their processability. Composites based on continuous reinforcements are limited to sheet metal-like stamping and forming processes rather than flow moulding processes as commonly used in the plastics world. Generally, as processability increases (with shorter fibres), mechanical properties decrease. Limited processability as in the case of stamping or thermoforming processes limits the geometries that can be formed, restricting design, functional integration and ability to use these composites in more complex components as used in the automotive sector. For example, whilst continuous fibre preforms possess excellent in-plane mechanical properties due to their high stiffness and strength, they are limited to shell-like geometries due to their low formability [1]. The industry has therefore been exploring discontinuous fibre composites, which are more flexible in terms of processability than continuous fibre composites as they can be flow moulded to create for example design features such as ribs and bosses while the mechanical properties that these composites can still be sufficient.

One subset of these materials are discontinuous long fibre (DLF) thermoplastic composites, which have recently been introduced by chopping UD tape into 'flakes' or 'chips' of a prescribed length. These materials offer attractive mechanical properties, low cycle times and high formability compared to continuous fibre composites. DLFs provide a trade-off solution between the excellent mechanical properties of continuous fibre composites and the processability of short fibre composites. The current work presented here addresses the properties of aligned DLFs in tape form, where the structure of the individual tapes is maintained after processing.

Discontinuous composites rely on stress-transfer through shear to transfer the load. A critical fibre length is required to effectively transfer a mechanical load. Below this fibre length, the maximum stress reached in the fibre will be below its maximum tensile strength. This has been considered in analytical modelling by the introduction of an efficiency of load-transfer parameter such as the generalised rule of mixtures. Given this, identifying the critical stress transfer length is key to achieve effective reinforcement. Analytically, the load carrying capacity at the critical length is 50%. A fibre that is twice the critical length will carry effectively 75% load compared to a continuous fibre, as can be inferred from Fig. 1. Previous work has expanded on these studies to develop model composite brick and mortar geometries at both the fibre and tape level [2]–[4]. As demonstrated in Fig. 2 a location with discontinuities has half the volume fraction of other locations, and therefore has half the total strength.

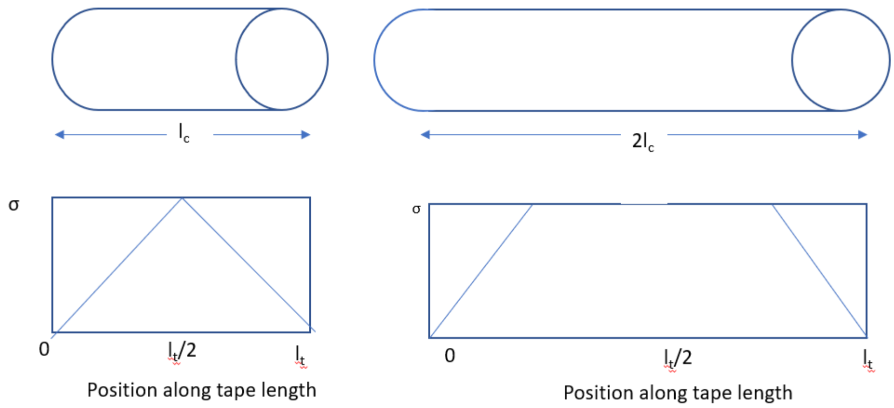


Figure 1: The analytical distribution of stress through a tape of critical length l_c (left) and twice critical length $2l_c$ (right).

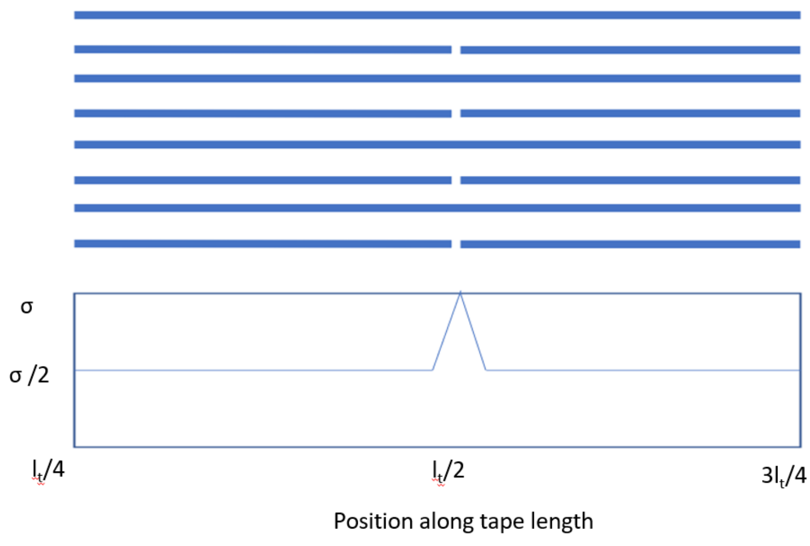


Figure 2: A schematic of the analytical effect on stress σ through a tape of length l_t of stacking discontinuities at location $l_t/2$. In this diagram, stress is only shown in the middle of the tape, which is assumed to be several times longer than the stress-transfer length.

Existing work has characterised the stress transfer phenomenon at the fibre level [5], but so far there has been limited work addressing stress-transfer across discontinuities in aligned composite tapes, particularly when joining tapes (from single lap-joints to more complicated structures). In this work, the stress-transfer and failure modes in aligned polyamide-6 (PA6) glass-fibre reinforced tape structures is evaluated using idealised experiments on double-lap shear joints. This is used to develop a Finite Element model which, alongside experiments, is used to explore the mechanical properties of tape-based composites as a function of tape length for a model ‘brick-and-mortar’ composite. The identification of the minimum tape length is crucial in developing DLF thermoplastic composites that achieve an ideal balance between mechanical properties and processability. Therefore, it is essential to determine the optimal reinforcement or tape length through experiments and simulations to achieve the desired balance of properties in the composite material.

2 EXPERIMENTAL CHARACTERISATION

SPECIMEN PREPARATION

Double-lap joint specimens were manufactured by manually placing a double-lap joint of varying lengths to two discontinuous tapes, as shown in Fig. 3. Given the difficulty of adhesively bonding two thermoplastic materials, tabs made of PA6-GF60 are placed at the ends of the tapes to ensure failure does not occur in the gripped region of the specimen and are bonded to the tapes in subsequent processing. Polytetrafluoroethylene (PTFE) films are placed either side of the single tapes to maintain the shape of the samples during compaction processing. Samples are processed under vacuum-bagging conditions at 240 °C and 1 bar pressure for 12 min.

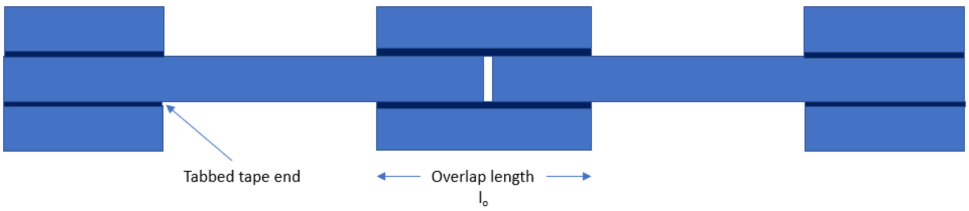


Figure 3: Double-lap shear test specimen geometry.

Aligned “brick-and-mortar” composites were produced by laying discontinuous sheets of UD tape by stacking a total of 9 layers, alternating between two layers which were identical except for the presence of an offset equal to half the tape length, creating a brick-and-mortar structure. Samples were produced with a tape length of 25 mm, 50 mm, 75 mm, 100 mm, 125 mm and 150 mm and processed under vacuum-bagging conditions at 240 °C and 1 bar pressure for 16 min.

MECHANICAL TESTING

Both the brick-and-mortar and double-lap shear test samples were tested in tension in line with ASTM D638 using a Zwick Z250 testing machine. Whilst the thickness of the brick-and-mortar specimens was calculated by averaging the thickness at three random points, the thickness of the double-lap shear specimens used for strength calculations was measured by repeating this process at the regions of the tape outside the taps and overlaps. A gauge length of 150 mm and a cross-head speed of 1 mm/min were used during testing.

In this study, 2D Digital Image Correlation (DIC) was performed using the Zwick videoXtens biax-2-150 HP system to evaluate local stresses for the characterisation of the stress-transfer. A white elastic spray paint was used to spray a speckled pattern onto the specimen surface. In order to ensure validity of the 2D analysis, images taken before the specimen was placed under tension were removed from the computation, ensuring no out-of-plane motion. The system provides a maximum camera resolution of 0.1 – 0.15 μm and a maximum frame rate of 500 Hz. The field of view was 103.9 x 69.4 mm. Both the double-lap joint samples and brick-and-mortar samples were imaged using the DIC system. Brick and mortar samples were also imaged from the side to qualitatively investigate the stress-transfer.

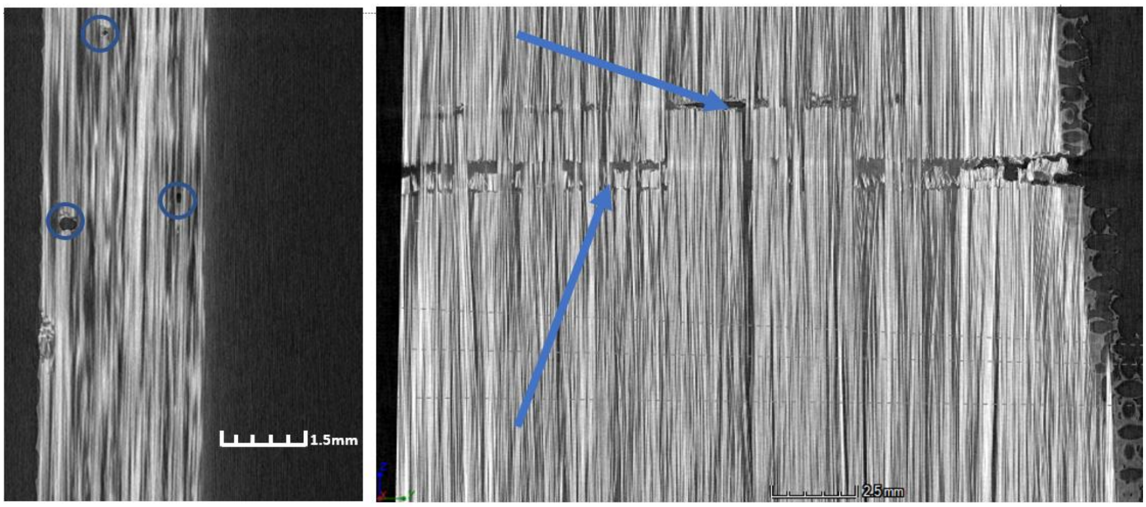
FAILURE ANALYSIS USING SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy (SEM) was used to investigate the failure modes of the double-lap shear specimens of various overlap lengths, demonstrating the effect of different joint lengths on failure mode. Failed samples were coated with a thin layer of gold and observed using a Hitachi TM3030 Desktop SEM with accelerating voltage of 15 kV.

CHARACTERISATION FOR FINITE ELEMENT MODELLING

Given the importance as identified in literature on the location of discontinuities in discontinuous tape-based composites [6], accurately characterising the location of these discontinuities in the brick-and-mortar structures is necessary to ensure that the geometry of the finite element model is accurate. Due to inherent variability in the manufacturing process (the accurate placement of discontinuities and placement of the layers in the structure), the location of discontinuities is accounted for by fitting the offset from a baseline location for several discontinuities to a normal distribution.

Zeiss Xradia Versa 410 Micro-CT system with a voxel size of 10 μm, an accelerating voltage of 60 kV and a power of 15 W were used in this system. The specimens were rotated 360° and 2879 projections with two frames per projection at 1050 sec exposure time were collected on a charge-coupled device detector. An aluminium filter of 1 mm thickness and a Source Detector Distance (SSD) of 1200 mm were used. To obtain clear images, results from μ-CT system were reconstructed using Zeiss built-in reconstruction software and the scans were calibrated using a voxel scaling method[7]. Two example μ-CT images used to quantify the offset between discontinuities are shown in Fig. 4. In Fig. 4a, the location of the discontinuities is indicated. In Fig. 4b, the discontinuities of two separate plies are visible as slicing in this instance is not entirely plane with the fibre direction. The offset between two discontinuities is clearly visible. Broken fibres are visible at the location of the lower of the two discontinuities.



a b

Figure 4: Geometry of the aligned brick-and-mortar showing the location of discontinuities.

The location of discontinuities was recorded relative to a baseline location. 15 locations were measured and used to calculate a normal distribution which represents the probabilistic nature of the location of discontinuities. The parameters of the normal distribution were a standard deviation σ = 2 mm and mean μ = 0 mm.

Previous studies have also indicated the dependence on the stochastic strength of fibres in composites. In line with the theories of stochastic mechanics (for instance the fibre break propagation model of Zweben and Rosen [8]), accounting for the stochastic variation in strength of fibres rather than their average strength value reduces the overall strength of the composite, as the inclusion of these variations in the material causes a non-uniform stress-field. To determine tensile strength, 30 specimens of UD tape with a length of 250 mm were tabbed using the same method as for the double-lap shear specimens and were tested for tensile strength. Weibull statistical analysis was used to determine the Weibull modulus and characteristic strength, and describes the size effect in the materials used in this study [9]. The Weibull modulus was calculated to be 18.96, and the characteristic strength was 824.1

MPa. The Weibull modulus for the tape is significantly higher than that reported for glass-fibres (which has been reported as between 2 and 6 [10]), indicating less scatter in strength values for the tape than individual fibres.

3 NUMERICAL MODELLING

Finite element modelling (FEM) is used in this study to estimate the performance of discontinuous aligned tape composites. Whilst tape properties are assumed to remain constant, interfacial properties are not clearly defined and require an experimental study to be better understood. Given that the double-lap shear experiments may identify the transition from interface dominated failure (tape pull-out) to fibre dominated failure (tape fracture), these experiments are used as a benchmark to estimate the interface properties between the UD tapes. Whilst short tape length brick-and-mortar composites are difficult to manufacture, modelling the interface failure using an estimated cohesive law allows assessment of producing composites at shorter (< 25 mm) tape lengths and identification of a critical reinforcement length. The interface properties are also used in studying the performance of 3D randomly oriented tape composites which is not detailed in this paper. Due to the non-linearities present in the solution, an explicit finite element solver is used. The sum of the kinetic energy is kept minimal with respect to the total energy dissipated.

To accurately model the double-lap shear experiments, a 2D finite element model is produced in Abaqus and loaded in displacement control, as shown in Fig. 5. The model is constrained in the *y*-direction, and displacement is only applied in the *x*-direction.

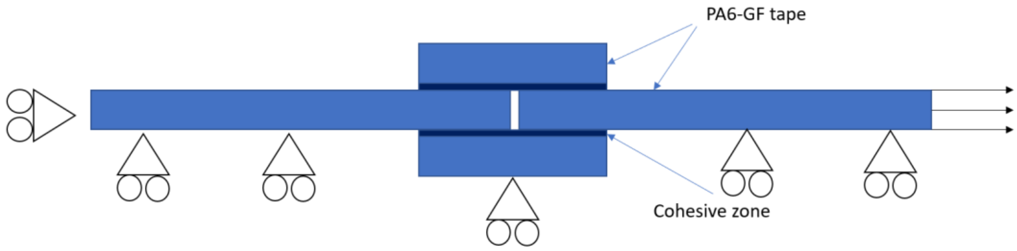


Figure 5: FEA model of the double lap shear specimens.

Interface cohesive zone models have been shown to effectively model propagation of interlaminar damage under quasi-static analysis [11]. A 2D cohesive law is inserted between two PA6-GF layers, as shown in Fig. 5. The cohesive elements are small enough in length to ensure that more than 8 cohesive elements are present within the fracture process zone.

A bilinear cohesive law was used to model the Mode I and Mode II traction-separation laws of the interface region. This has a linear softening shape and is defined by two parameters, the peak traction and critical energy. Given that stress is transferred in shear, Mode II is predominant in this model. Mode I is assumed to be the same as Mode II in this study, but given the dominance of Mode II, this has a negligeable effect on the results of this analysis.

The interface region is taken to be an elastic-plastic material using J2 plasticity theory. The tapes are modelled as a linear elastic material with elastic properties acquired from mechanical testing on UD tapes, and strength properties defined using the Weibull parameters calculated through experiments.

The modelling of the aligned brick-and-mortar structure was performed in a similar manner to the double-lap shear structure. Given that there is no variation in the orientation of the tapes in the manufacturing method in this study, a 2D finite element model with plane strain elements is assumed. The properties of the tape and interface in this model are the same as those in the double-lap shear simulations, as are the parameters of the cohesive law. In addition, the number of elements in the fracture process zone was again kept above 8. The location of the discontinuities is introduced in line with the normal distribution calculated previously. Non-zero nodal displacements are applied to all nodes at one tape end, whilst nodes at the opposite tape end are constrained in the x direction. The geometry of this model is shown in Fig. 6.

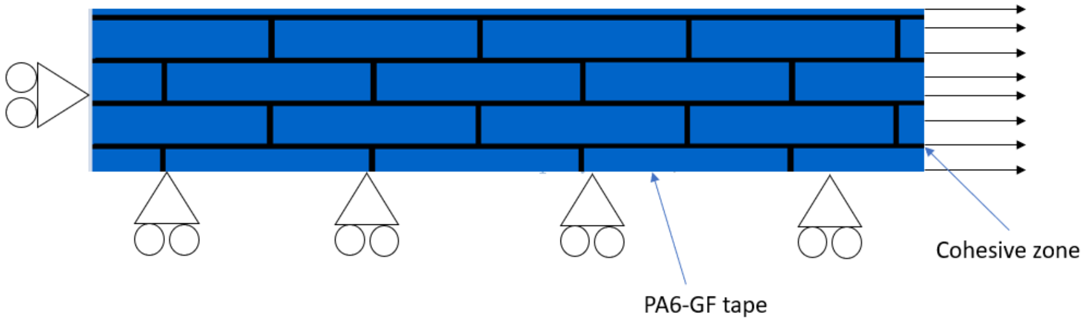


Figure 6: FEA model of the aligned brick-and-mortar specimens.

4 RESULTS

FAILURE MODES

To investigate the effect of tape overlap length on failure modes, SEM images are taken of the broken double-lap shear test specimens. Analysing the macroscale and mesoscale of the double-lap shear specimens demonstrates a clear difference in failure mode between short overlap and longer overlap length specimens. At shorter tape lengths, the composites fail by a cohesive failure mode at the interface of the tapes. This is demonstrated in Fig 7., which shows an SEM image of the surface of the double-lap shear joint at 5 mm, clearly showing where the tape has been pulled out of the double-lap joint. The tape end is imaged separately in Fig. 8a and has clearly separated from the rest of joint. This cohesive and interface dominated failure is further demonstrated by the intact glass fibres within the pulled-out tape, as shown in Fig. 8b. The apparent layering of the fibre ends in this image is attributed to a processing artifact where the inner fibres of the tape are pushed inwards. Inspection of the tape ends in Fig. 8c further demonstrates that the fibres did not break through the thickness of the tape.

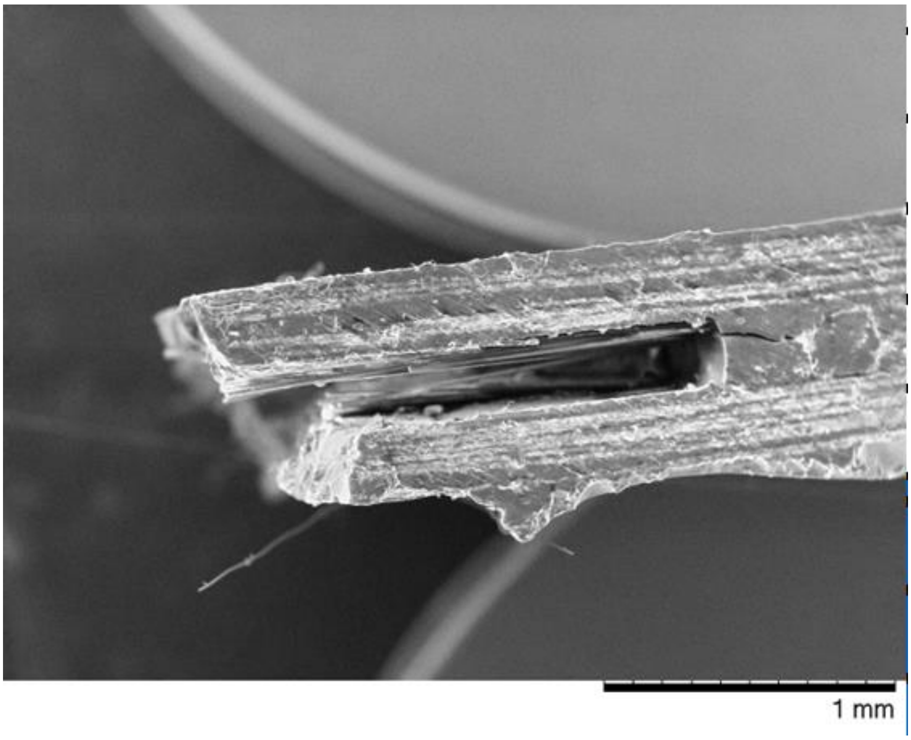
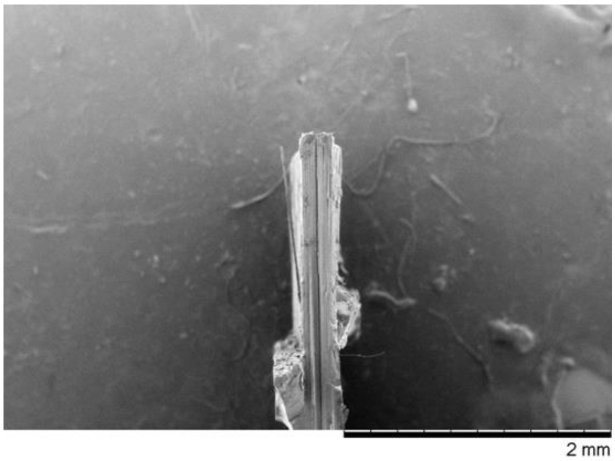
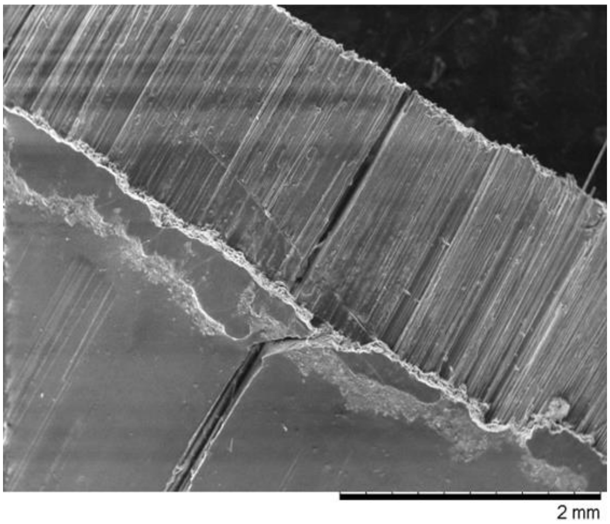


Figure 7: Remainder of double-lap shear joint after tape pull-out (x60 magnification).



(a)



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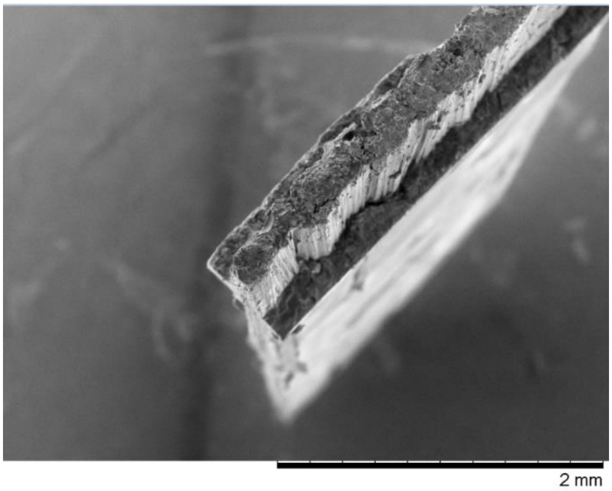

(c)

Figure 8: SEM images showing intact fibres of the pulled-out tape.

At higher overlap lengths, the failure changes and becomes dominated by fibre fracture within the tape. This is demonstrated in Fig. 9, which clearly shows fibre breakage at the end of the overlap across the specimen thickness. For all specimens which showed fibre fracture dominated failure modes (i.e. > 5 mm), it should be noted that the failure region occurred between the tabs and the overlap, with no visible fibre breakage occurring in the overlap region. This is attributed to the sudden changes in geometry at the end of the overlap and the tab regions and therefore the transfer of stress from shear between the tape and tab to tensile stress within the specimen. This causes a stress concentration in this region, causing failure in this area.

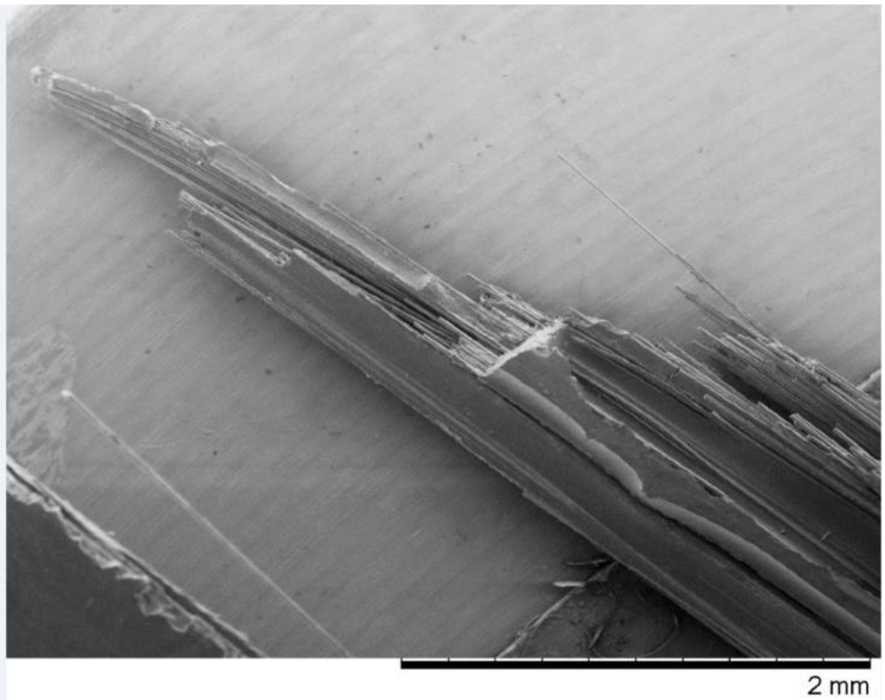

Figure 9: Broken fibres at 100 mm tape length (x50 magnification).

ESTIMATION OF INTERFACE COHESIVE LAW THROUGH COHESIVE ZONE MODELLING

The evolution of failure stress of the double-lap shear samples was studied as a function of the tape overlap length and is shown in Fig 10. This graph demonstrates the effect of overlap length on tensile strength, showing a sharp rise in strength up to 5-10 mm, before the strength plateaus. This curve provides insight into the minimum tape length for effective reinforcement, a result analogous to the well-known critical fibre length concept in composite micromechanics. The overlap length required to achieve around 50% reinforcing efficiency is approximately 3 mm. Given that the overlap length is twice the length of the overlap on each tape, the stress-transfer length reported is half the overlap length determined to achieve 50% reinforcement, i.e. 1.5 mm.

The interface cohesive law is estimated by varying the fracture energy of the FEA model whilst maintaining a constant interface strength and vice versa. The results of the FEA model are then compared to the results of the double-lap shear experiments to determine optimal parameters for the model. Whilst comparing the variation of axial and shear strain of DIC and FEA results along a section in the fibre direction would further validate the results, the estimated fracture energy and cohesive peak traction is an accurate approximation.

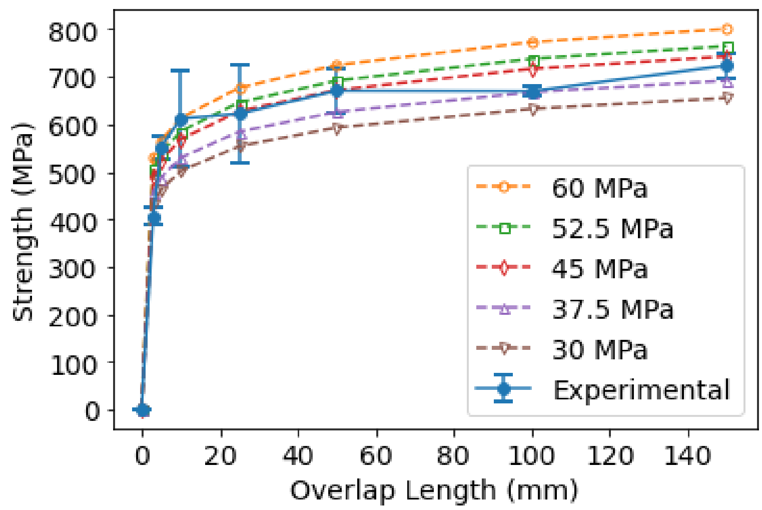

Figure 10: The effect of varying the peak traction in the cohesive zone model on FEA tensile strength predictions together with experimental data.

Fig. 11 shows the effect of varying peak traction on the FEA results for a constant interfacial fracture energy. From these results, it is estimated that a peak traction of 45 MPa provides an accurate prediction of tensile strength, which agrees reasonable well with the shear strength of PA6 [12]. After calibrating the interface cohesive law based on peak traction, calibration is performed by varying the fracture energy. Fig. 11 shows the effect of varying fracture energy on strength, showing that this has very limited impact on mechanical properties. A selected fracture energy of 2.5 kJ/m² is taken as it provides a comparatively accurate fit, and agrees well with experimental data reported for interlaminar fracture toughness [13].

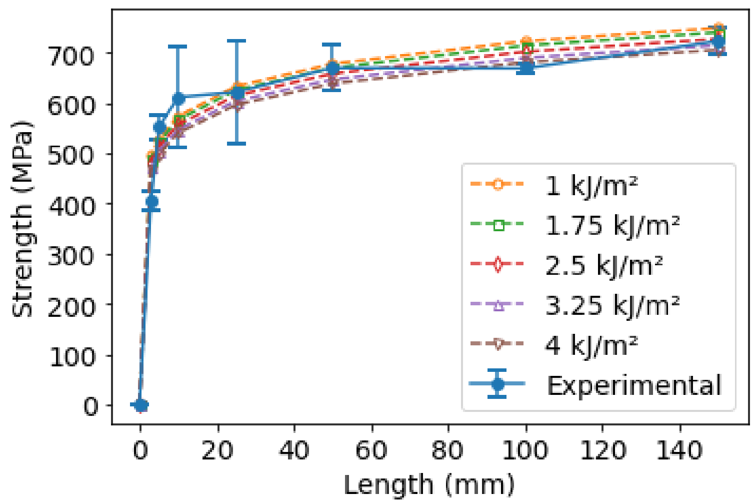

Figure 11: The effect of varying the interface fracture energy on strength for FEA simulations together with experimental data.

Fig. 12 shows the FEA predictions for strength of the aligned discontinuous tape composites of various tape lengths. The results show that the experimental results are accurately modelled by the FEA model. Due to the difficulties of manufacturing brick-and-mortar samples at short tape lengths (< 10 mm), these are modelled using the FEA model. As expected, at very small overlap lengths (~ 4 mm), the FEA model predicts failure to be dominated by cohesive failure, whilst at higher tape lengths, both experimental and FEA studies demonstrate that failure is fibre dominated. This is in line with the results of the double-lap shear experiments, which demonstrate that the stress transfer length is approximately 2 mm. The FEA model therefore demonstrates the tape length at which strength sees no significant improvement, which in this case is approximately 15 mm.

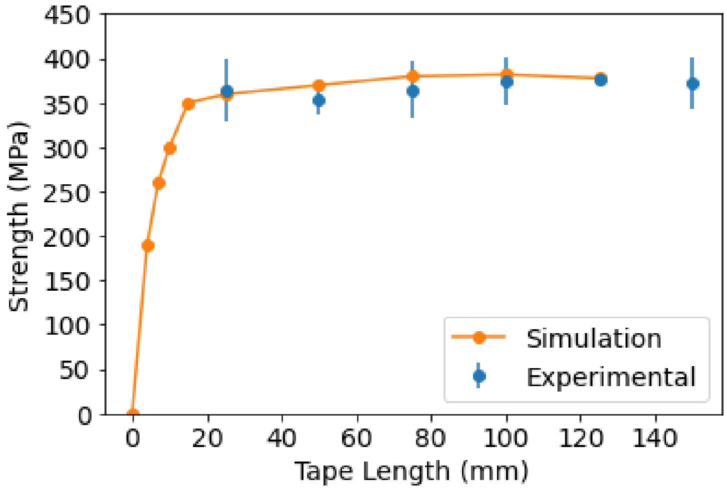

Figure 12: Influence of tape length on tensile strength of aligned discontinuous tape composites; FEA simulations versus experimental data.

DIC RESULTS AND STRESS TRANSFER

In Fig. 13, the axial strain profile across a discontinuity is shown for a brick-and-mortar specimen of 125 mm tape length just before ultimate failure. After sectioning, the axial strain is plotted along the section across the discontinuity. Given that the spatial resolution allows computation of strains within the stress transfer region, there is confidence that both the stress transfer length and shape are representative of the mechanics. The curve demonstrates the shape of the stress-transfer curve, approximately a bilinear curve. In addition, the stress transfer length at failure is shown, which is approximately 2 mm. The DIC results are then compared with the stress-transfer across a discontinuity in the FEA model. The results demonstrate that the stress-transfer is accurately modelled in the FEA model. It is noted that whilst the DIC measurement of strain is taken out of plane to the 2D FEA model, this provides more accurate results for comparison of stress-transfer, as the presence of edge-effects when imaged side-on would reduce the stress observed by DIC. Despite this, for qualitative evaluation, the in-plane stress transfer is imaged in Fig 13 by plotting shear strains. This clearly demonstrates the presence of ‘hot spots’ where the discontinuity is located and shows a characteristic ‘H-shape’ through the variation of positive and negative shear strains.

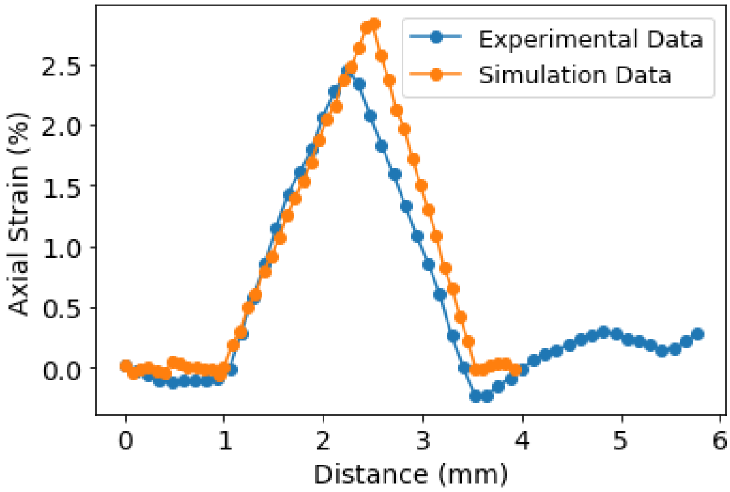

Figure 13: Axial strain by DIC and FEA versus distance from a discontinuity in fibre direction.

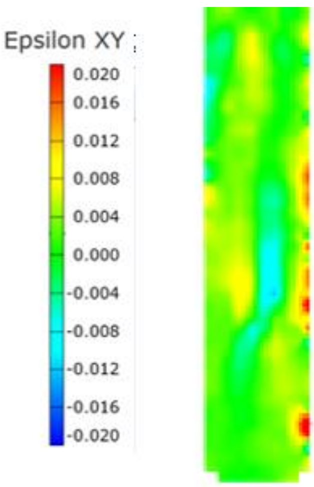

Figure 14: Characteristic H-shape at a tape discontinuity.

5 CONCLUSIONS AND FUTURE WORK

In this work, the mechanics of stress transfer was characterised using idealised model experiments and DIC. A stochastic finite element model was developed using the experimental data and used to study the mechanical properties of aligned discontinuous composite tapes alongside experiments.

It is shown through the double-lap shear experiments that the primary failure mode for composite tape joints at shorter tape lengths (< 4 mm) is interfacial, whilst at longer tape lengths failure is fibre dominated. Given that the double-lap shear joint is representative of the joints in structural aligned tape composites, this provides real insight into the failure mechanism of these structures. In addition, these tests allow initial evaluation of the stress transfer length. This was verified by DIC experiments, which show a bilinear curve of stress transfer across a discontinuity, and a ‘H-shape’ profile when specimens are viewed in plane. These results were used to develop an experimentally validated FEA model to predict the optimum reinforcement or tape length for brick-and-mortar structured aligned discontinuous composites.

Further work is ongoing to use acoustic emission to validate the failure modes of the FEA model. A 3D model using the mechanical parameters determined in this study will also be used to study the performance of randomly oriented strand (ROS) tape composites. Finally, the influence of variability in location of the discontinuities is further investigated through an optimisation framework which seeks to identify the ideal location of discontinuities to achieve optimal mechanical objectives in single- and multi-objective studies.

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