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Patterned fibre constrained layer damping for composite materials

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ABSTRACT

Vibration damping is an important consideration in the design of fibre reinforced composite structures as these stiff, lightweight materials often have undesirable vibration transmission characteristics. If not properly addressed, high vibration levels can propagate throughout a composite structure, leading to significant noise levels and reductions in equipment longevity. It is possible to incorporate viscoelastic damping layers into a composite laminate's construction to achieve improved damping properties. Inclusion of embedded viscoelastic layers results in a constrained layer damping configuration, where the damping capacity is governed by the shear strain in the damping layer. A new composite damping arrangement is proposed where patterned fibre constraining layers are used to increase damping capacity of a viscoelastic mid-layer by inducing additional shear strains. This paper details the design of materials in such a configuration, and the methods used to fabricate and test the damping performance of these patterned fibre constrained layer damping treatments.

Keywords: Vibration damping, Composite, Viscoelastic, Constrained layer
I-INCE Classification of Subjects Number(s): 47.2, 47.3

1. INTRODUCTION

The use of fibre-reinforced composite materials is becoming increasingly prevalent in a wide range of industries. Many of the application areas for such materials are in structures and environments where high levels of vibration are also present. The strength-to-weight properties that often make composite materials desirable can also result in high levels of structural vibration transmission, as it takes less energy to excite these stiff lightweight materials. Consequently, vibration damping is an important consideration in the design of fibre-reinforced composite structures. If not properly addressed, high vibration levels can lead to significant noise propagation throughout a structure and reductions in equipment longevity.

Passive vibration damping can be added with the use of viscoelastic materials which convert mechanical energy to heat through the straining and relaxation of their molecular microstructures. Constrained layer damping treatments are commonly used and are comprised of a viscoelastic layer sandwiched between the surface of a structure and a stiff constraining layer, typically aluminium. Cyclical deflection of the substrate structure causes cyclical shear strains within the constrained viscoelastic material resulting in removal of a portion of the mechanical energy.

When using layered composite materials it is possible to incorporate viscoelastic layers between fibre layers to increase damping performance. In this case the comparatively stiff fibre layers act as the constraining layers to the damping material. The orthotropic nature of laminated fibre-reinforced composites allows for deformation behaviour that varies appreciably from homogeneous structures. When asymmetry exists between fibre orientations of adjacent layers, coupling can occur between extension, twist and bending behaviour. Such behaviour can be exploited to influence the shear strains, and hence damping behaviour, of embedded viscoelastic layers.

This paper details the fabrication and testing methods used to evaluate damping behaviour of a three layer beam comprised of asymmetric patterned fibre layers surrounding a viscoelastic core.

2. PATTERNED FIBRE CONSTRAINED LAYER DAMPING

The effect of deliberate asymmetry between fibre layers surrounding a viscoelastic core has been explored by various authors (1, 2, 3). Early work using asymmetric fibres found that the fibre angle of each layer

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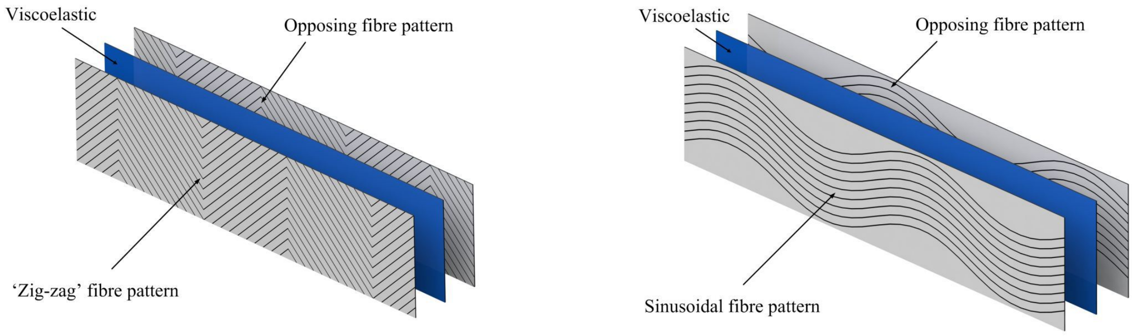
influenced the damping performance of these constrained layer configurations. The concept of asymmetric constraining layers was developed further using alternating fibre segments to create opposing ‘zig-zag’ fibre patterns on the constraining faces (4, 5, 6, 7). Under axial loading significant transverse in-plain shear strains were induced in the viscoelastic core at the points where the fibre segments changed direction. The use of a ‘zig-zag’ fibre pattern was analogous to a segmented constraining layer (8) which achieves multiple areas of high shear strain in the viscoelastic layer. Modification of the ‘zig-zag’ design resulted in constant sinusoidal fibre patterns (9). This damped composite arrangement was tested in various geometries used in aerospace application, including cylinders, hat-stiffened panels and sandwich beams (10, 11, 12, 13). It was found that the fibre pattern used, specifically the wavelength and maximum fibre angle, along with the Young’s modulus of the fibres, influenced the damping spectrum of the three layer beams tested. The wavelength of the fibre patterns affected the frequency at which maximum damping occurred, while maximum fibre angle determined the maximum damping values achieved (14). Examples of the ‘zig-zag’ and sinusoidal patterns can be seen in Figure 1.



(a) ’Zig-zag’ arrangement (b) Simple sinusoidal arrangement

Figure 1 – Previous asymmetric fibre arrangements

Having established that fibre pattern influences damping behaviour, it is of interest to investigate how more complex sinusoidal patterns affect damping response with the aim to achieve greater control over a damping spectrum. Figure 2 provides an example of a more complex sinusoidal pattern.

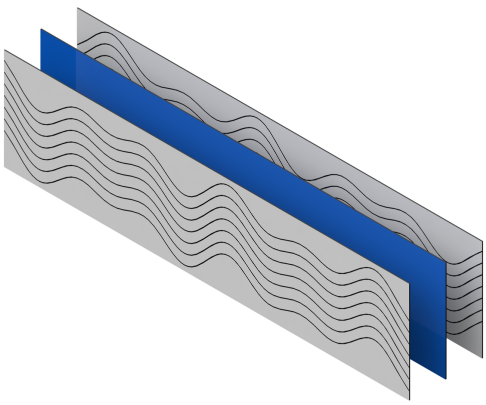


Figure 2 – Example of proposed complex fibre arrangement

The starting point for this work was the selection of a pattern set to explore. The major considerations for this initial investigation were manufacturability and comparison to the earlier work performed. It was advantageous for the patterns to fit a Design of Experiments (15) schedule in order to facilitate later investigations. Four patterns were selected, two used superposition of sine waves, and two used swept sine waves. A maximum fibre angle of 30° was selected for each pattern. The pattern specifications can be seen in Table 1. These values were selected as they had previously been investigated for constant sinusoids (10, 11, 12).

Table 1 – Fibre pattern details

	Pattern 1	Pattern 2	Pattern 3	Pattern 4
Waveform	$\lambda_1 + \lambda_2$	$\lambda_1 + \lambda_2$	$\lambda_1 \rightarrow \lambda_2$	$\lambda_1 \rightarrow \lambda_2$
λ_1 (mm)	125	125	125	125
λ_2 (mm)	50	75	50	75
θ_{max} ($^\circ$)	30	30	30	30

3. FABRICATION

A suitable method for producing damped beam test specimens for the various fibre patterns was developed. The manufacturing process was broken into:

1. Weaving of the required fibre patterns
2. Addition of the damping tape
3. Infusion of the damped fabric
4. Cutting the test specimens to shape

3.1 Weaving

Carbon fibre was selected for the fibre reinforcement as previous research indicated that increased stiffness and damping values were achieved if a fibre with high Young's modulus was used (12). Initial attempts at shaping standard sheets of unidirectional carbon into the required patterns proved unsuccessful as lateral movement was restricted by the tight packing of the fibres and the binding cross-threads. Flexible unidirectional carbon tapes were also investigated, but buckling of the fabric and inconsistent fibre distribution made this material unsuitable for use.

A new method of fabrication which would allow the fibre strands greater flexibility was devised. The required patterns were created by twisting ribbons of unidirectional carbon tow into threads and inserting the threads into a mould of each pattern. Twining of the ribbons created a rope-like strand of carbon which provided the flexibility required for the fibre to follow the curvature of each pattern (Figure 3). High strength 12k carbon tow was used, with each wound thread containing approximately 12,000 carbon fibrils.

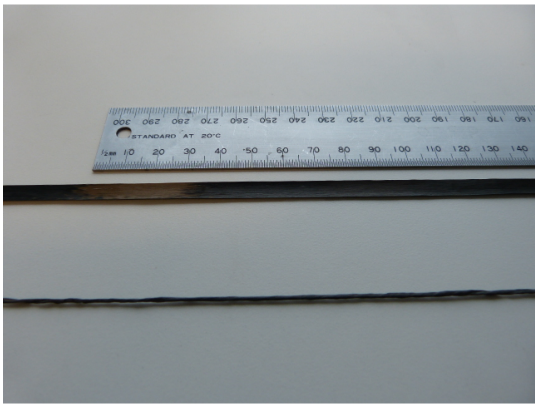


Figure 3 – 12k carbon tow (top) and wound strand (bottom)

Moulds for each fibre pattern were created by machining a series of 1 mm wide, 1 mm deep channels into polyvinyl chloride (PVC) sheets using a CNC router, with approximately 0.2 mm separation between channels. The length of the moulds was set at 600 mm in order to achieve several full wavelengths of the longest wave in each pattern. Sufficient channels were cut to allow the finished beams to have a width of 80 mm. The mould used to create Pattern 1 is shown in Figure 4.

Carbon bundles were tightly wound and inserted into each channel of the mould by hand. Once placed, the strands were free to unwind slightly until further expansion was prevented by the channel walls. Ideally, the spacing between channels would be as small as possible to allow for greater fibre volume fraction in the laminated beams. The channel separation used was the smallest that could be achieved with the materials and machining process used.

Weaving of the fibres in this manner was practical for creating the limited number of prototype beams required for testing. It would not be suitable for large scale production due to the significant resources required to wind and lay the fibres.

Figure 4 – Fibre weaving mould for Pattern 1

The winding of the carbon strands introduced some irregularity within the beams. Some strands were wound tighter than others, or unwound to a lesser degree once placed. This resulted in slight variation between individual strand diameters across the width of each beam, and thus a varying beam thickness. The winding process also introduced unknown effects on damping and stiffness of the beams as single carbon fibrils within each strand spiralled around one another along the length of the beam. Some pre-stress was observed as twist in several test beams. This was likely caused by the individual strands trying to unwind. When multiple strands were laid in the same direction, the rotation of each strand would act in the same direction and result in noticeable twist in the global structure.

3.2 Addition of Damping Layer

The damping material selected for use in this analysis was tesa® 4965 (Figure 5), a double-sided self-adhesive tape with high shear and temperature resistance. The tape consisted of a PET core with a modified acrylic adhesive on each side and was provided in 48 mm wide rolls, with a thickness of 205 μm. The tape itself was transparent and was backed with a red polymer release liner.

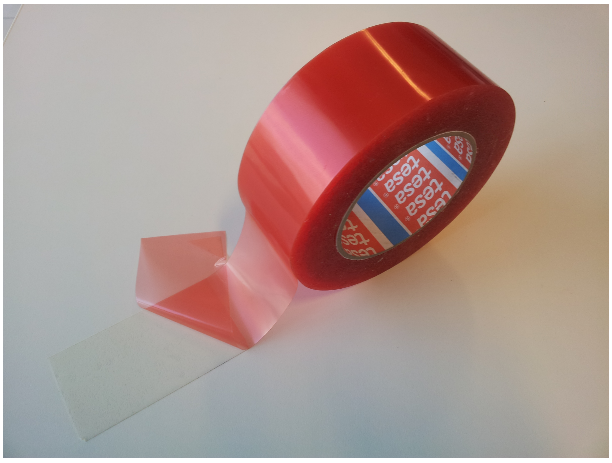


Figure 5 – Viscoelastic damping tape, tesa® 4965

Strips of damping tape were applied directly to the first face of woven carbon fibre strands while they were still housed in the mould. Care was taken to ensure that the edges of the tape were flush and did not overlap one another.

A roller was then used to press the tape firmly against the fibres and top face of the mould. Prior to rolling, fibre bundles tended to protrude from the channels of the mould. The rolling process flattened the bundles allowing for a better contact area between the tape and fibre layer.

The damping tape and first side of carbon were peeled from the mould, with the damping tape holding the fibres in the required pattern. The next set of strands were then wound and inserted into the mould. Once the second carbon face had been woven, the first fibre layer with damping tape applied was aligned and combined with the second fibre layer. Care was taken to ensure the peaks and troughs of the two carbon layers were aligned before the layers were pressed together and rolled once more.

The three-layer fabric was then removed from the mould ready for infusion.

3.3 Infusion

Vacuum infusion was used for lamination of the three-layered test beams. This infusion technique involved the matrix resin being drawn into a mould and through the fabric using a vacuum pump. The fabric and mould were enclosed in a vacuum bag to contain and control the resin flow. Once fully impregnated with resin, the composite material was heated to cure the matrix material.

In this case flat beams were required so a smooth glass table with embedded heating elements was used as the mould. Given the size of the table and strength of the vacuum pump used, up to fourteen test beams could be infused simultaneously.

The fabric beams were laid in rows on the table. Gauze material was placed between the beams and at the infusion initiation end of each beam to promote greater resin flow in these areas. Peel ply layers were also added in various configurations to increase resin flow and wick away excess resin. A vacuum bag was then laid over the moulding table and sealed around the resin inlet and outlet tubes. Peel ply layers were used in three different configurations. Two arrangements used only a single layer of peel ply, the first against the vacuum bag face (on top of the fabric beams), and the second against the glass table face (under the beams). The third configuration used peel ply layers on both faces of the fabric beams. The major effects of the different peel ply configurations was the surface finish of the beam faces and the rate at which resin would penetrate the fabric during infusion. As the resin was unable to penetrate through the damping layer, sufficient layer spacing and resin draw was required to allow both faces of carbon to infuse simultaneously.

Epoxy matrix material was drawn from a reservoir onto the table where it was heated to approximately 25 °C. The temperature increase was required in order to improve flow and penetration of the epoxy into the fabric. The table layout is shown in Figure 6.

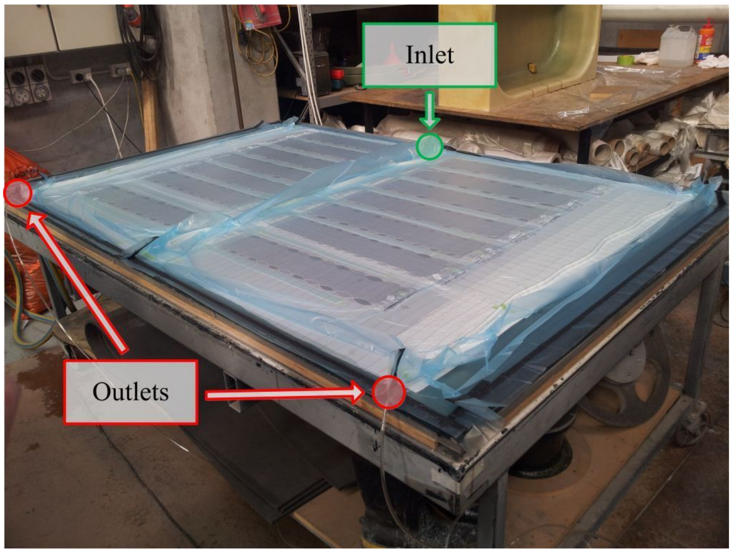


Figure 6 – Table mould with resin inlet and outlets indicated

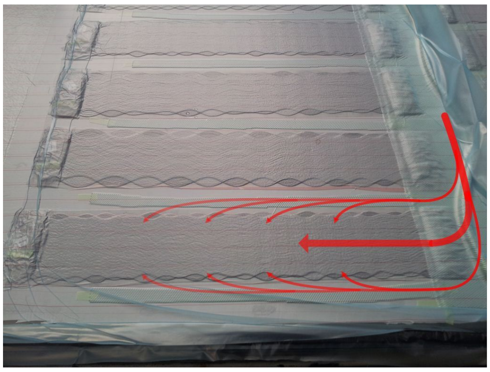
The matrix resin flow path for a single fabric beam is shown in Figure 7(a). The green gauze allowed the resin to flow more freely, facilitating penetration from one end and both edges. The resulting flow behaviour can be seen in Figure 7(b), the impregnated sections of fibre appear black.

Once the resin had fully penetrated the beams, the supply was cut off and the table temperature was increased to approximately 70 °C for around 12 hours to cure the epoxy matrix.

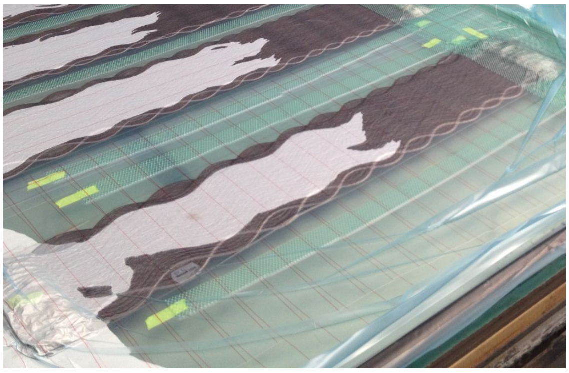
3.4 Cutting the beams to shape

The beams needed to be uniform in width and length. Beams within the same pattern group needed to start and end at the same point of the fibre pattern. A water jet cutter was used to achieve the required beam dimensions and produced a clean cut with no fraying of the fibres at the edges. Each beam was cut to a width of 80 mm and a length of 480 mm. The deviation from the original 600 mm length occurred due to imperfections near the ends of some beams, requiring the shortening of all beams to meet the equal length requirement.

The geometry of the original fibre patterns and the final beam sizes can be seen in Figure 8. The final beams are surrounded by red lines. Ten test samples were produced for each pattern, giving a total of 40 beams.

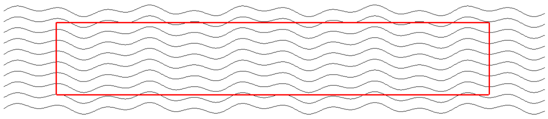


(a) Resin flow path

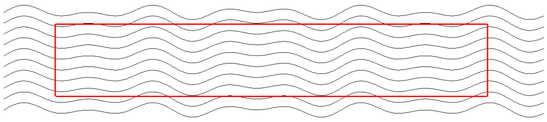


(b) Resin infusion

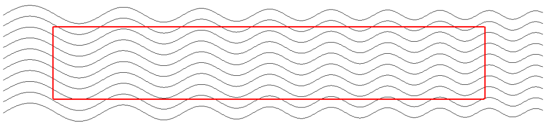
Figure 7 – Resin infusion of three-layer beams



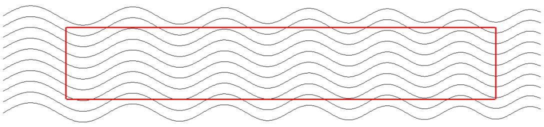
(a) Pattern 1



(b) Pattern 2



(c) Pattern 3



(d) Pattern 4

Figure 8 – Final beams cut from their original patterns

4. FIBRE VOLUME FRACTION ASSESSMENT

A microscopic investigation was performed to assess the fibre volume fraction present in the infused composite beams. This was of interest as the twining of the strands and strand separation due to the mould channel spacing produced an unknown packing arrangement within the woven fibre layers. Fibre samples were cut at a peak/trough location to obtain a cross-section with the strands normal to the cut surface. Once set in a housing epoxy, the specimen was ground and polished.

The sample was investigated using a Leica DM IRM optical microscope. Images were taken at a range of magnifications and the contrast between fibres and the surrounding matrix was used to determine the fibre volume fraction of the sample area investigated. Images using 5× magnification are shown in Figure 9.

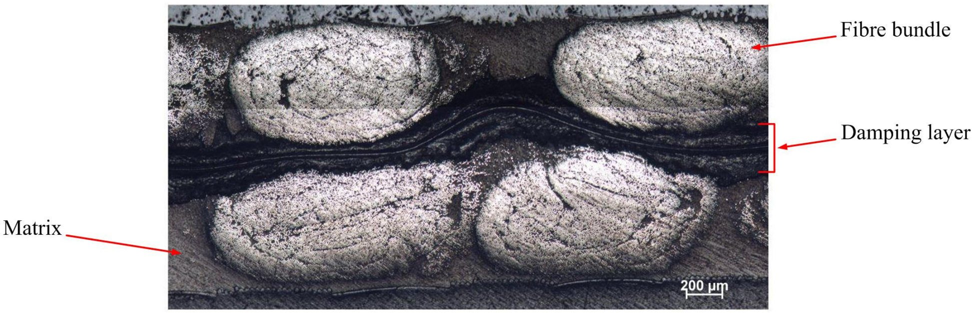


Figure 9 – Cross-section of 3-layer beam at 5× magnification

The fibre fraction within the bundles was approximately 63%, however given the spacing between bundles, the fibre volume fraction for a single layer of woven fibre was approximately 34%. This is far lower than would normally be required for a working laminate but was acceptable for investigation at this stage of material development.

It can be seen in Figure 9 that the fibre bundles are partially unwound as indicated by the varying bundle diameters, fibril separation and gaps within the bundles. The damping layer is also shown to follow a curved path due to the apparent irregularities in bundle spacing. Consequently, the matrix thickness also varies along the width of the sample.

These issues would likely be reduced if an alternative weaving process were used. Fibre fraction and material consistency would benefit from weaving of the required patterns into fibre sheets. This would result in more uniform fibre distribution and fewer irregularities in the damping layer profile and matrix thickness.

5. TESTING METHOD

The measurable properties required from the test beams were the modal frequencies and associated damping loss factor values. These values were determined using the half-power bandwidth method from the frequency response data of each beam. Loss factors for each mode were calculated using Equation 1.

$$\eta = \frac{f_2 - f_1}{f_r} \tag{1}$$

Where f_r is the resonant frequency of the mode, f_1 is the lower frequency which occurs 3 dB lower than the peak at f_r, and f_2 is the upper frequency which also occurs 3 dB lower than the peak at f_r.

In order to measure the frequency response curves, appropriate end conditions and excitation signals were required. Unconstrained end conditions were selected for the mounting of the samples. Cantilevering the beams was initially considered as it would more closely simulate the ISO (16) and ASTM (17) test methods. This end condition was ruled out as it would reduce the length of the fibre patterns exposed to excitation. The variation in thickness of the test samples also made an effective clamping arrangement infeasible.

Unconstrained end conditions were approximated by suspending each beam vertically by a string running through a hole 30 mm from one end. Horizontal suspension, like that used in the ISO method (16), was not used as the suspension fibres would require relocation for each mode of interest. There were also concerns that the horizontal suspension would have a noticeable effect on the measured response due to the large width and low weight of the beams.

Excitation was provided using an impact hammer and the response measured using a single axis accelerometer.

5.1 Configuration

Each beam had a 1 mm hole punched on the centreline and 30 mm from one end to facilitate vertical suspension. Care was taken while punching each hole to ensure that damage to the sample, particularly fracture between fibre strands, was minimised. Test specimens were suspended 300 mm below a section of rod by inelastic thread.

A PCB 352C42 accelerometer was attached to each test specimen using wax. The accelerometer was placed on the midline of the test specimen, approximately 10 mm from the bottom edge. This location was selected to capture as many bending modes as possible without altering the natural response significantly due to the point mass of the accelerometer or the stiffness provided by the accelerometer cable. Torsional modes were not captured using this location as the accelerometer was lying on a nodal line. The weight of the accelerometer was approximately 2% of the beam weight; this was considered small enough to have minimal effect on the response.

The accelerations were recorded and passed through a Fast Fourier Transform (FFT) function using a Brüel & Kjær PULSE multi-analysis platform. A measurement frequency range of 0 - 500 Hz was sufficient to capture the first four bending modes. Modes 5 and above often had either indistinct peaks or a peak height less than 3 dB, rendering them unusable for calculation and comparison purposes. The maximum resolution for the FFT was used to accurately capture the first bending mode.

Three impact locations were used on each specimen. These were located on the lower half of the beams and on the centreline to minimise rotation about the longitudinal axis. The three impact points were selected to excite both odd and even bending mode shapes. Each impact point was struck a total of five times to give fifteen impacts per frequency response curve measured. Ten frequency responses were recorded for each test specimen to gain an acceptable measurement sample population. Impacts were produced using a PCB 086C03 impact hammer with a medium hardness tip. Care was taken when impacting the beams to ensure clean single strikes were achieved. Double hits were often audible and could be seen in the frequency response as it was being reported in real time. A time domain signal was also used to verify impact occurrence and quality. Measurement data was discarded if a double hit was detected. The test apparatus configuration can be seen in Figure 10.

Figure 10 – Testing apparatus configuration

As the test specimens were suspended from a single point with inelastic thread, the beams were prone to swinging after each impact. Rotation about the longitudinal centreline was minimised due to both impact locations and the stiffness provided by the accelerometer cable. The lack of rotation was considered not to have a large effect on the measured response as the single axis accelerometer only measured accelerations transverse to the face of the beams. Swinging of the beams after each strike was observed in the measured frequency response. The frequency of this movement was much lower than the first bending mode, and was consequently considered to have negligible effect on the beam modal frequencies and damping loss factors.

5.2 Environmental Conditions

Tests were performed at two environmental conditions, ambient temperature and sub-ambient temperature. Ambient temperature measurements were made at temperatures ranging from 23 °C - 27 °C, with a target measurement temperature of 25 °C. This represented a temperature range that could be reasonably expected in common application. Sub-ambient temperature measurements were also performed in an attempt to better capture the temperature and frequency dependence of the damping properties. A cool store facility located at the University of Canterbury was used for the sub-ambient testing. This room was refrigerated to 4 °C but cycled between 3 °C and 7 °C during testing. In both ambient and sub-ambient conditions, the temperature was recorded using a hot-wire anemometer.

Particular care had to be taken with the impact excitation during the sub-ambient testing as air was circulated within the cool store by a fan. The forced air movement often caused the test specimens to swing, making clean strikes of the beams difficult.

6. FINAL REMARKS

The use of asymmetric complex sinusoidal fibre patterns in a constrained layer damping arrangement is of interest. The effect that the complex fibre patterns have on the damping spectrum of these composite materials is desired. A fabrication method for production of prototype test specimens has been detailed and test beams for four fibre pattern configurations have been produced. The fabrication method was suitable for this preliminary investigation but was resource intensive and produced lower than practical fibre volume fractions making it unsuitable as a large scale production method. A test method based on the half-power bandwidth technique has been described for determining modal frequencies and associated damping loss factors of the test specimens. Results from this testing will be used in the validation of a finite element model developed for these damped composite materials.

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