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Constrained Layer Damping Treatment: Analysis of multi-strip application on thin plates

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Abstract. This paper focuses on analysing the effects of using multiple strips of Constrained Layer Damping (CLD) treatments to cover entirely a thin aluminium plate and assess the vibration performance for various strips orientation. In particular, for a fixed type of CLD treatment, three strips orientation are considered: (i) parallel to the long axis of the plate, (ii) perpendicular to the long axis, and (iii) 45° to the long axis. By using both experimental and Finite Element (FE) modelling, it is shown that depending on the mode shape curvature and corresponding nodal line positions, the strip orientation would strongly affect the amount of energy that can be dissipated at one particular resonance. An approximate topology optimisation technique is investigated to target the first bending mode of the structure and is validated experimentally. This technique involves optimising a uniform CLD topology for maximum stiffness (using a topology optimization feature of a FE commercial software) and then manually locating optimal strip placement by taking into account orientation effects.

1. Introduction

Constrained Layer Damping (CLD) is a type of passive damping treatment commonly used in the aerospace and automotive industries for dissipating vibrations in lightweight structures. It consists of a viscoelastic polymer layer, with a high loss factor, sandwiched between the structure and a constraining metal layer with a high modulus. The vibrational energy is dissipated by shear distortion of the damping material when out-of-plane vibrations of the structural element occur, especially when resonant behaviour is dominant [1]. The efficiency of the CLD treatments is dependent on frequency and temperature, given the strong dependence of the complex modulus of the viscoelastic material to these two parameters. CLD treatments are commercially sold as rolls of varying widths, and can be custom-made for larger footprints. Often larger footprints are covered by using multiple strips. This paper focuses on assessing the performance of a plate fully covered with multi-strip CLD treatment using Finite Element (FE) models and its validation with experimental data, and on the selection of the strips orientation.

Previous research by Moreira and Rodrigues [2, 3] has shown that the effects on the response of CLD treatment applied uniformly to a thin panel can be investigated by using the FE method. The complex modulus approach was used to model viscoelastic properties, obtaining good agreement with experimental results. Furthermore, several papers have investigated the topology optimization of CLD patches on planar structures. In particular, Chia et al. [4] employed a Cellular Automaton algorithm to optimally place CLD on a plate assuming a fixed temperature and frequency. Their approach considered the highest strain modal energy of an



untreated plate to locate one cell of damping treatment. Then the patch was extended to zones which give highest damping effectiveness [4].

To the best of the authors knowledge, no studies so far have explicitly investigated experimentally and numerically the effects of employing non-overlapping multiple strips to cover large footprints, nor the effects of the orientation of the multi-strips treatment.

In this paper, thin aluminium plates measuring 300 mm x 200 mm x 2 mm are covered uniformly with non-overlapping CLD strips of 50 mm width, and three different orientations are considered: (i) parallel to the long axis of the plate, (ii) perpendicular to the long axis, and (iii) 45° to the long axis. Experimental Modal Analysis is performed to yield the Frequency Response Function. It is shown that strip orientation strongly affects the amount of energy that can be dissipated at one particular resonance because of the mode shape curvature and nodal line positions. Also presented is a comparison of these experimental results with FE models developed using the commercial FE software ANSYS, showing good agreement.

Finally, an approximate topology optimisation technique is investigated to target the first bending mode of the plate and is validated experimentally. This technique involves optimising a uniform CLD topology for maximum stiffness (using ANSYS topology optimization feature) and then manually locating optimal strip placement by taking into account orientation effects from the findings above.

To this end, this paper is split into a number of sections; Section 2 is focused on the Finite Element Model. The experimental set up is presented in Section 3, followed by analysis of orientation effects and validation of the FE model with respect to experimental data in Section 4. Finally an approximate topology optimisation approach is presented in Section 5.

2. Finite Element Modelling

The system to be modelled consists of an aluminium plate measuring 300 mm x 200 mm x 2 mm (density $\rho = 2800 \text{ Kg/m}^3$, Young's modulus $E = 70 \text{ GPa}$ and Poisson ratio 0.3). The damping layer is characterised by a top aluminium layer of 0.20 mm and 0.14 mm damping polymer [7], and has a width of 50 mm. A number of special considerations have to be taken into account when developing FE models involving Constrained Layer Damping treatments. The first of which is the choice of elements and mesh density. It is well known that the mesh density required to reasonably predict dynamic behaviour of structural components is at least 6 elements per wavelength of deformation obtained at twice the maximum frequency of interest [5]. For this study, a density of 60 elements along the long axis of the aluminium plate, and 40 along the short axis is used to provide good model accuracy. Regarding choice of elements; solid 20-node hexahedral elements are used to model both the aluminium and viscoelastic layers. This ensures no issues will arise due to shear locking. Contact between the viscoelastic polymer and constraining metal layers was assumed to be perfect and therefore bonded contact was used to model this.

Another important consideration is the modelling of the constrained layer. This involves selecting an appropriate method for modelling viscoelastic material properties, which are both frequency ω and temperature T dependent. The approach used in this paper follows Johnson et al. [8] and Moreira et al. [3], whereby viscoelastic properties are modelled using the complex modulus method. Specifically, the modulus of the viscoelastic material is expressed as:

$$G(\omega, T) = G'(\omega, T) + jG''(\omega, T) \quad (1)$$

Where G' represents the shear storage modulus and G'' represents the shear loss modulus. The storage and loss modulus for the viscoelastic material are provided by the manufacturer in the form of a reduced-frequency nomogram [7]. This data is hand read for a fixed temperature (shown in table 1) and implemented into the commercial FE software ANSYS [6] by fitting data points using a Prony model [6].

Table 1. Storage and Loss modulus data for 3M 435 polymer @ 20°C

Frequency (Hz)	G' (MPa)	G'' (MPa)
10	0.11	0.23
100	0.22	0.30
200	0.28	0.31
300	0.30	0.32
400	0.33	0.32
500	0.38	0.32

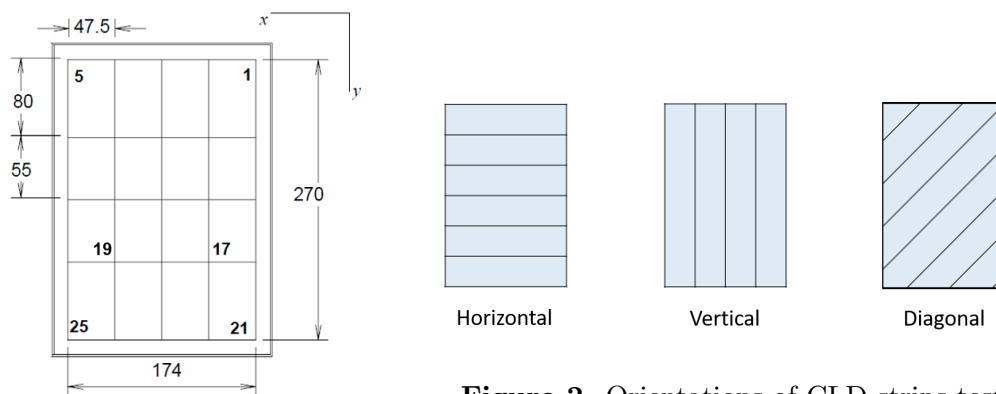
With this approach, the frequency response of the plate with constrained damping layer subject to a deterministic point load F (to yield the Frequency Response Function) is obtained by solving:

$$-\omega^2[M]X + \{[K_a] + [K_v(\omega, T)]\}X = F \quad (2)$$

Where M is the mass matrix, K_a represents the stiffness matrix for the aluminium plate and top aluminium constraining layer, $K_v(\omega, T)$ is the complex stiffness matrix of the viscoelastic layer, and X is the vector of the displacement response of the system. The Harmonic Response module of ANSYS [6] is used to evaluate the virtual Frequency Response Function.

3. Experimental analysis

Experimental Modal Analysis (EMA) [9, 10] was performed to evaluate the Frequency Response function. The tests were performed on 3 aluminium alloy plates with CLD layers applied in varying layouts: (i) parallel to the long axis of the plate, (ii) perpendicular to the long axis, and (iii) 45° to the long axis, as shown in Figure 2. Care was taken to ensure no overlap and contact between adjacent strips. To ensure these free-free boundary conditions, a suspension system was devised to hang the plates (Figure 3).

**Figure 2.** Orientations of CLD strips tested.**Figure 1.** Measuring grid adapted from [2].

A measuring grid was employed for taking measurements on the plate (Figure 1). Each plate is excited by using a modal shaker (2004E mini-shaker) and the response is measured by using a single pointer Laser Doppler Vibrometer (Polytec NLV-2500). For this study, a sinusoidal

chirp excitation is applied to the test structure through a modal shaker attached at point 17, with the force input to the system recorded by using an impedance head (PCB 288D01). The velocity response to this excitation is measured at point 19. A sampling frequency of 10kHz was implemented. The Frequency Response Function (in terms of acceleration divided by Force) and the modal parameters are evaluated by carrying out the appropriate signal processing strategies [9, 10].

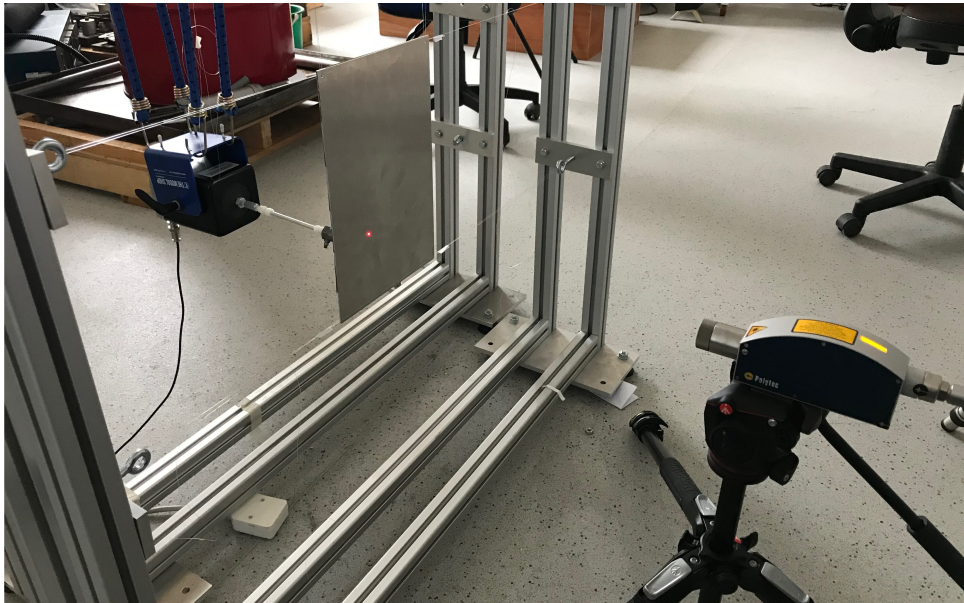


Figure 3. Experimental setup showing system used to suspend test items.

4. CLD Strip Analysis: experiments and modelling

In this section the FRF for the multi-strip orientations shown in Figure 2 are evaluated experimentally and compared with FE models.

The FRFs obtained experimentally for the three multi-strip orientations are compared in Figure 4. From this figure it is possible to observe that the orientation of the strips affects the damping performance in terms of FRF peak amplitude and resonant frequency shift.

This effect can be understood by considering for example the first two bending mode shapes (obtained with the FE model), as shown in Figures 5 and 6. The vertical multi-strip orientation performed better for the first bending mode, whilst the multi-strip horizontal orientation performed better for the second bending mode. The CLD strips aligned perpendicularly to the nodal lines show a better ability for dissipating vibrational energy for this particular resonance. On the contrary, strips aligned parallel to nodal lines show poor damping performance. In the case of torsional modes, the diagonal orientation was most effective. This can be explained by the fact that when the strip of damping layer is parallel to the nodal lines, the bending deformation, and therefore the consequent shear deformation of the viscoelastic material, would be minimal.

To validate the effectiveness of FEA at modelling the orientation effects, equivalent FE models of test structures from Figure 2 were developed and compared with experimental data. During this study, it was found that the aluminium plates were manufactured using a rolling method, which leads to anisotropic material properties. To model this, orthotropic elastic modulus was implemented for the aluminium alloy. The values used were 67.5 GPa along the rolling direction and 72.5 GPa perpendicular to roll direction.

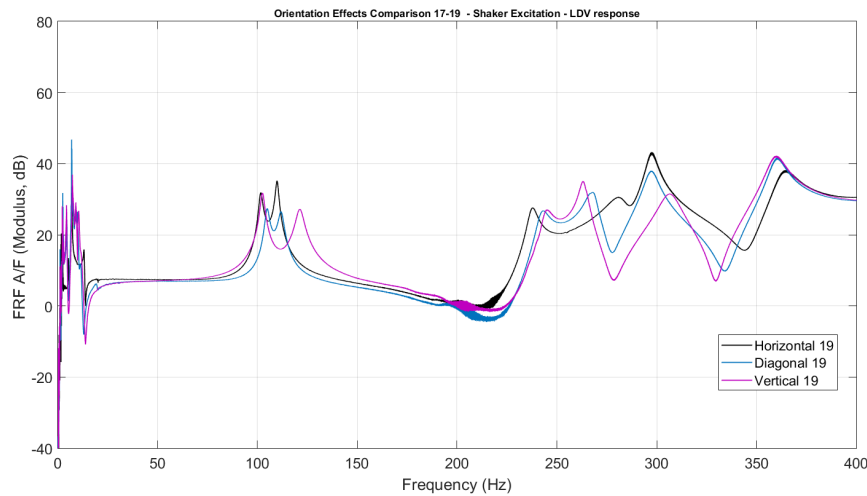


Figure 4. Graph showing comparison between the three orientations of CLD treatment tested experimentally.

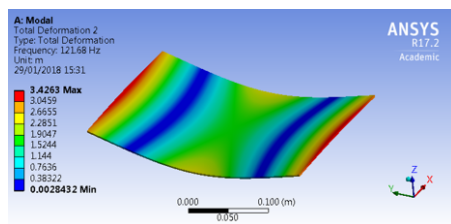


Figure 5. First bending mode

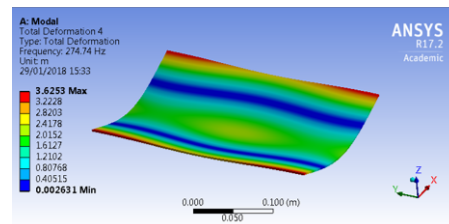


Figure 6. Second bending mode

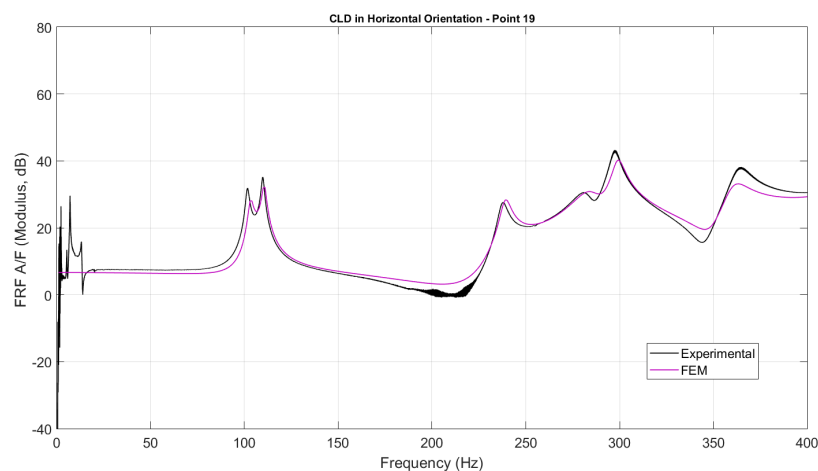


Figure 7. Comparison of FEM with experimental data for strips in horizontal orientation.

The Figures 7 and 8 show a comparison of the experimental and FE results for the horizontal and diagonal orientation. It is possible to observe in general a good agreement between the FEM and the experimental Frequency Response Functions computed.

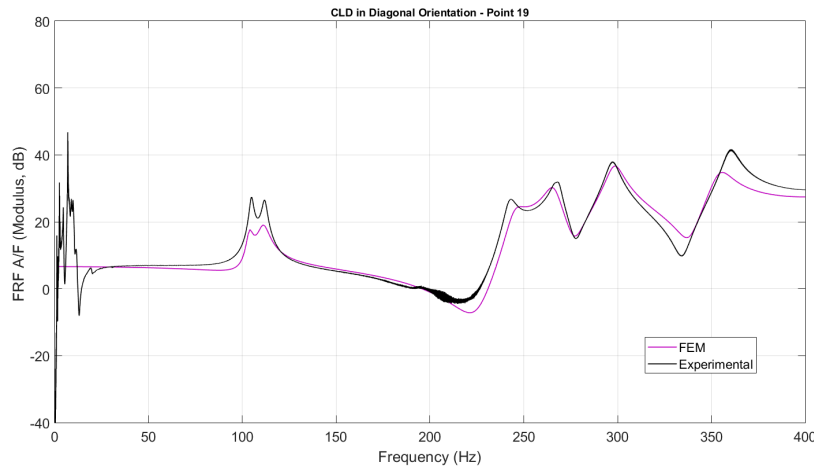


Figure 8. Comparison of FEM with experimental data for strips in diagonal orientation.

5. Optimal Placement of Strips

This section is focused on the description on an approximate approach for selection of optimal location of the CLD strips. The advantage of using CLD strips is that treatment can be selectively applied to target certain modes of vibration. As seen in the previous section, the orientation of strips has a large impact on the damping performance achieved, and this should be taken into account when deciding application of strips.

In this study, an approximate method is devised to locate the optimal placement of strips for suppressing the first bending mode of the structure (Figure 5). This mode of vibration occurs at around 121 Hz and is the second resonant peak on the FRF. The proposed approximate approach uses a combination of two metrics to decide on optimal placement.

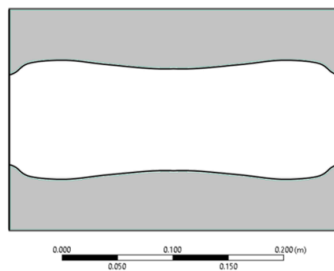


Figure 9. Stiffness optimised layout for first bending mode.

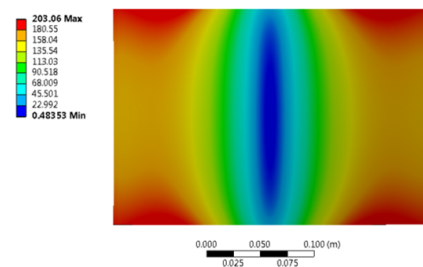


Figure 10. Shear strain distribution in viscoelastic layer for first bending mode.

The first metric is an optimisation for the CLD topology. The built-in ANSYS *Topology Optimization* [6] module is used to carry out this function. The objective of this optimisation is to evaluate the layout of CLD treatment on the plate that will maximise stiffness for the approximate modal deformation shape, with the constraint that 50% of the surface should be covered. The idea being that it is the stiffness provided by the constraining metal layer which is responsible for shearing within the viscoelastic layer. The results for this optimisation is shown in Figure 9.

The second metric is the shear strain distribution in the viscoelastic layer for the particular

modal deformation. The rationale here being that areas of highest strain should ideally be covered with CLD as viscoelastic shearing is the main mechanism by which energy is dissipated by this treatment. Figure 10 shows the maximum shear strain distribution for the targeted mode shape.

Examining both metrics suggests the layout shown in Figure 9 should be ideal for targeting this mode of vibration as the areas of greatest shear strain lie within the optimised region. This is further reinforced by prior findings on orientation effect which suggest strips should be aligned perpendicular to the nodal line of this mode shape (to achieve highest curvature). To verify this, a plate configured with this layout of CLD is tested experimentally.

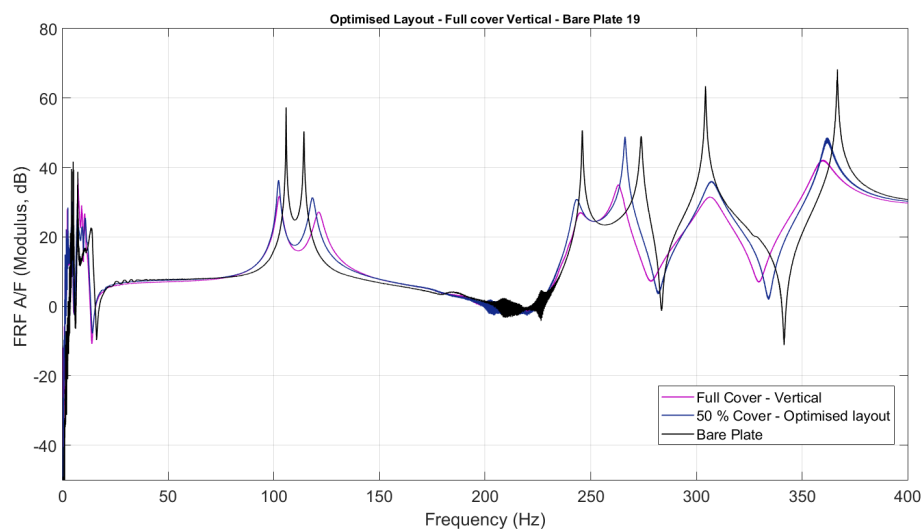


Figure 11. FRF of layout optimised for targeting the second mode of vibration. Bare plate and full cover vertical FRF included for comparison.

The results (Figure 11) show this layout was effective at damping the first bending mode of the structure, providing a reduction of almost 20dB from the bare plate with just 50% coverage. When compared to a fully covered plate (CLD in vertical orientation), the optimised layout was very close in terms of performance displaying a difference of about 4dB. These results further reinforce the findings on orientation effects as this layout provided almost no damping for the fourth mode of vibration (bending mode 2), for which the strips were aligned parallel to nodal lines.

6. Conclusions

Constrained Layer Damping (CLD) treatments provide an effective means of suppressing unwanted noise and vibrations in thin planar structures. Findings in this paper show that when a multi-strip CLD configuration has to be implemented, the orientation of the strips is an important parameter to take into account. The energy dissipated by the treatment was found to be strongly dependant upon alignment of strips with nodal lines of particular mode shapes. This was investigated both experimentally and with Finite Element models. In conclusion, findings suggest that strips should be placed to obtain the largest curvature for a specific modal shape, and in particular for bending mode shapes the strips should be placed perpendicular to the node lines in order to achieve best damping performance.

An approximate approach for optimal placement of strips was successfully devised for targeting a bending mode of vibration. The CLD topology was optimised for maximising stiffness

for a particular modal deformation. Placement of the CLD was then located manually by taking into account orientation effects.

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