# EXPERIMENTAL ANALYSIS OF PASSIVE CONSTRAINED LAYER DAMPING TREATMENTS FOR COMPOSITE POWER PYLON STRUCTURES

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## ABSTRACT

Constrained layer damping treatments are widely used in mechanical structures to damp noise and vibrations. A viscoelastic damping layer is thereby applied to the load carrying structure which in turn is covered by a third constraining layer. In case of mechanical vibrations, the formed sandwich structure flexes and introduces shear strains in the damping layer. Energy will be dissipated through the shear deformation and lead to an increase in the structural damping. This paper documents the efficiency of constrained layer damping treatments applied to different cylindrical composite tubes representing a novel composite power pylon arm structure. Different cross sections geometries such as implemented shear webs are part of the investigation in order to study a beneficial effect on the structural damping characteristics of the tube. The viscoelastic damping layers are placed at different locations within the composite tube e.g. circumferential and/or along the neutral axis to evaluate the location-dependent efficiency of the constrained layer damping treatment. The results of the study lead to a thorough understanding of constrained layer damping treatments and to an improved damping design of the tubular composite structure representing the power pylon arm. The study has shown a maximal damping performance when placing the damping layer in the median plane perpendicular to the bending load. The results are based on a free decay test of the composite structure.

## 1 INTRODUCTION

Glass fibre reinforced plastics (GFRP) are well suited for use in high voltage applications, such as insulators or power transmission pylons, due to the inherent non-conductivity of the raw material. This enables a rigid attachment of the overhead transmission lines to the cross arm of each composite pylon, resulting in an increased dynamic interaction.

Any wind induced vibration and motion such as the severe cable vibration phenomenon known as ‘galloping’ will therefore be directly transferred to the slender composite mast structure and may lead to catastrophic failure of the entire structure due to the excessive vibration amplitudes at resonance. These low-frequent ‘galloping’ vibration amplitudes, at frequencies between 0.15 Hz and 2 Hz, depend e.g. on the cable vibration mode, the cable tension and the span length [1], and can be reduced by designing the composite power pylon to act as a damper. By introducing passive damping treatments such as constrained layer damping (CLD), the energy dissipation in the composite structure may significantly be increased due to the shear deformation of the integrated viscoelastic damping layer located between two stiff layers (layer 1: load carrying ‘base’ laminate, layer 2: constraining layer) [2].
In contrast to tuned resonance dampers, such as tuned mass dampers or tuned liquid dampers configured to damp a certain frequency, the CLD treatment is suitable to damp e.g. galloping vibrations within a certain frequency range. Furthermore, this method is robust, passive, reliable, low cost and easily implemented into the manufacturing process of the composite structure [3]. The damping layer of the CLD treatment can either be integrated into the load carrying ‘base’ laminate else applied onto the outside of the structure together with an additional constraining layer. In the first option, the structural damping is being increased, while the static bending stiffness will decrease by the soft interlayer with low shear resistance. The second approach also leads to higher damping performance, while the structural weight is significantly increased due to the added damping and constraining layer onto of the load carrying laminate. These changes will lead to a decreased dynamical stiffness and to a lower natural frequency. The trend in designing CLD treatments is therefore increasingly towards single damping patches instead of a full damping layer coverage [4]. The viscoelastic material (VEM) damping patches are implemented into the structure at locations of high shear deformation, e.g. the root end of a cantilever beam for first bending mode and the middle section for the second vibration mode [5]. For the implementation of VEM patches to the composite power pylon cross arm, the complex vibration characteristics of the whole pylon-cable-system has to be taken into account. Many possible locations with high shear deformation exist along the cross arm due to the variety of attached conductor lines - each with the potential to vibrate by itself or in combination with other cables or cable bundles. Due to these complex vibration scenarios, the study of VEM damping patches are therefore not part of this investigation yet. The focus will be on the full coverage of VEM damping layers instead.
The cross sectional shape of the composite profile will also have a great impact on the efficiency of the CLD treatments applied on the outer geometry of the structure. CLD treatments applied to rectangular profiles will result in better damping performance compared to cylindrical profiles due to a larger area of shear deformation at the flat surfaces of the rectangular shaped profiles furthest away from the neutral axis [6]. Despite the obvious advantages of rectangular cross sections with regard to damping, the overall structural design may be restricted to cylindrical shapes.

The aim of this phenomenological analysis is therefore to rethink the placement of the VEM damping layers with respect to a cylindrical cross section inspired by [7-9] in order to maximize damping. The investigations on the damping-mass relation of different generic tube cross section configurations will help to understand and to enhance the dynamic behaviour of the composite power pylon structure with regard to the galloping issue. The experimental results will later be used to validate a numerical damping analysis based on the modal strain energy approach studied by [10].

# 2 DESIGN OF THE GENERIC COMPOSITE TUBE

This section provides a detailed description about the design and manufacturing of the different generic composite tubes with and without implemented damping layers derived from the load assumptions and the laminate design of the full-scale composite power pylon arm structure at a root-end close location.

## 2.1 Composite power pylon arm structure

The power pylon structure consists of a tubular column section, supporting a pair of cantilevered and tapered composite tubes at which three pairs of twin bundle conductor lines are directly attached at each side (see Figure 1). The composite arm structure is designed for vertical and transverse loads due to the cables' weight and common climatic situations such as wind load, ice load and a combined wind-ice loading scenario as defined in [11]. The broken wire load case, which is leading to bending and torsional loads is also been taken into account.
Due to an optimized, stiffness driven design of the power pylon arms, the laminate thickness gradually decreases from the thick-walled layup configuration at the root end section for implementing the metal mounting bushings to the thin-walled shell-like zone of the tip of the arm.

Figure 1. Traditional Steel Lattice Power Pylon (left) compared to a Composite Power Pylon (right)

## 2.2 Generic composite tubes with passive damping treatment

Based on the design of the composite power pylon cross arm different generic composite tubes are derived with cross sectional properties close to the root end of the structure in the scale of about 1:10, as shown in Figure 2. At this position beyond the thick-walled root end section of the bushing reinforcement, the loading condition can be assumed to be free of clamping effects. For reasons of simplicity and comparability, all generic tubes are designed to be non-tapered, cylindrical and with a constant layup along the entire specimen.

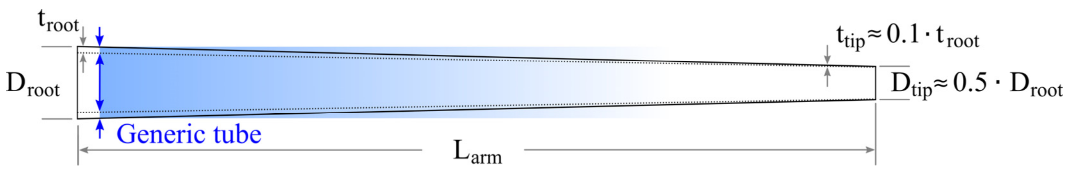



Figure 2. Overall dimensions of the composite cross arm and the generic composite tube cross section properties.

The 'base laminate' layup configuration (see Table 1) represents the scaled down 'close-to-root-end' layup definition of the composite power pylon arm structure and it is kept constant for all studied cross section configurations in this paper (see Figure 3).

| Parameter | Dimensions [cm] |
|---|---|
| Clamped length | 950 |
| Inner diameter | 7.9 |
| Wall thickness | 0.4 |
| Layup 'Base laminate' | [± 45° \| ± 45° \| ± 10° \| ± 45°] |
| Layup 'Constraining layer' | [ ± 10°] |
| Layer thickness [± 45°] | 0.088 |
| Layer thickness [± 10°] | 0.135 |
| VEM layer thickness | 0.058 |
| Spacer plate thickness | 0.3 |

Table 1. Cross sectional properties of the generic composite tube

The passive 'constrained layer damping' treatment is implemented into the laminate in order to increase the overall damping of the generic composite structure. Although the dynamic stiffness and the natural frequency of the generic tube is being reduced by adding mass of the VEM damping layer and the constraining layer, the gain of damping is of higher priority. Depending on the different damping concepts a) to i), the VEM is positioned within laminate, but outside the 'base laminate' in order to evaluate the benefit of the damping layer without decreasing the static stiffness (see Figure 3).

The VEM damping layer is equally distributed along the circumference, as the bending direction during an event of 'galloping' conductor lines can either occur in vertical or horizontal direction, depending on an "up-and-down" or an "up-up" cable vibration mode [12]. The area with the highest shear deformation will occur furthest from the neutral axis in case of a tubular structure (Figure 3a-c), so that the VEM with its stiff constraining layer is being placed preferably at the outside. The increase in damping due to the (less effective) VEM damping layer implementation at the inside of the cylindrical tube will be evaluated during the tests. In order to maximize the damping of the generic composite structure, VEM damping layers are also being placed close to the neutral axis where the shear stress attains its maximum (Figure 3f and i). The stiffening effect of the associated shear webs is evaluated by the concepts shown in Figure 3d, e, g and h). The implementation of only VEM patches at the locations with high shear deformation areas instead of a full VEM coverage has also been considered. This optimized damping treatment modification is an effective way to increase the damping-mass ratio [5] of a structure, but is not yet a feasible solution at the current stage of the research. Depending on which of the three conductor line bundles are vibrating, the areas of high shear deformation can be at multiple locations of the cross arm. In case of only the outermost bundle is vibrating, the highest bending strain will appear close to the middle cable suspension. If all conductor line bundles are vibrating in phase and at the same time, the root end section of the cross arm will experience the largest shear deformation area. In order to study the effect of different cross section concepts with implemented VEM-layers and shear webs, a full VEM coverage is being chosen.

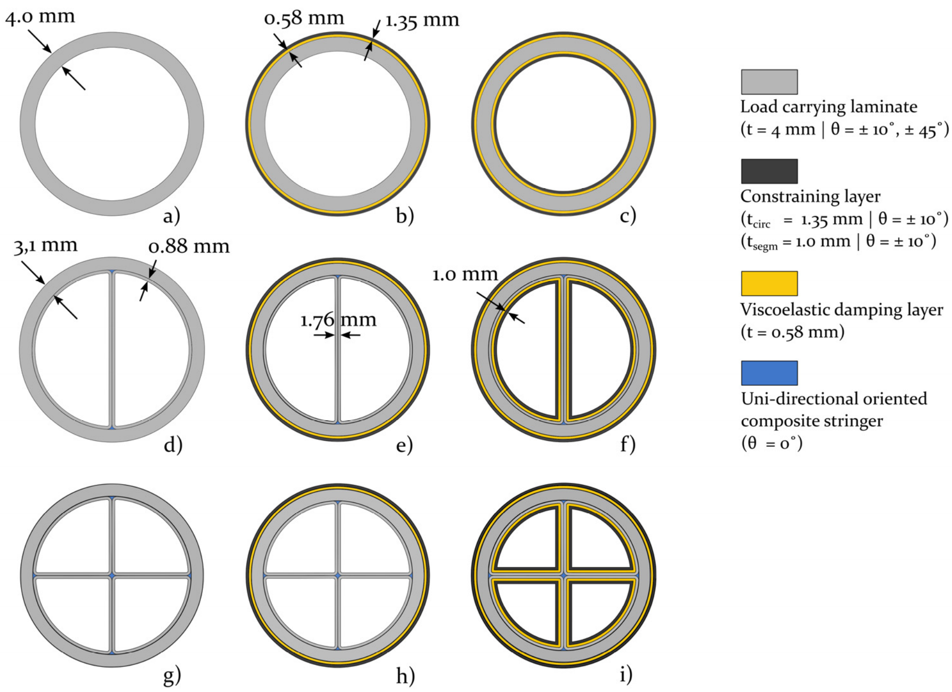



Figure 3. Overview of the various cross sectional concepts of the generic composite tube with different locations of the viscoelastic damping layers

## 2.3 Manufacturing of the generic composite tube

Filament winding is a well suited manufacturing process for these cylindrical, non-tapered composite parts with a constant layup throughout the whole specimen due to its high efficient, automated and low cost fabrication characteristics [13]. Although the typical range of fibre layup angle for filament winding is usually being seen between 20° and 89°, global or local reinforcing UD fibre sections in axial directions (0°) can be implemented during the manufacturing process by the use of pins for fibre redirection at each end of the mandrel (see Figure 4). This layup modification might be used to reinforce the compression side of slender composite structures like composite power pylon arms subjected to bending loads to prevent global buckling.


Figure 4. Fibre layup in 0° and 45° (left) as well as in 10° (right) by filament winding

The materials used for manufacturing the generic composites tubes are the same as for composite power pylon arms. The glass fibre (GF) roving EC17-2400-352 with 2400 tex and a sizing suitable for epoxy and vinyl-ester from PD Fibre Glass is used together with the PRIME 20 epoxy (EP) resin in combination with the slow hardener from Gurit. A segmentable mandrel has been designed and manufactured by CNC milling for the filament winding process to realize the different cross sectional concepts shown in Figure 3. The wet GF, impregnated by a resin bath prior the placement process, can either be wound on a single mandrel segment, a 'two-segment assembly' or the 'four-segment assembly' in order to manufacture a generic composite tube consisting of two shear webs (concepts g-i), one shear web (concepts d-f) or no shear web (concepts a-c). In case of a composite tube with only one shear web and no VEM damping layer (concept d), two tool segments are mounted together using a 3 mm thick spacer plate in between before starting the filament winding process of the inner ± 45˚ layer of the base laminate (see Table 1). The second half of the cylindrical tool containing as well a 'two-segment assembly' can be fed into a parallel filament winding process before mounting the two 'two-segment assemblies' together and finalize the winding process by placing the three remaining layers to form the cylindrical part of the 'base laminate' [± 45˚, ± 10˚, ± 45˚].

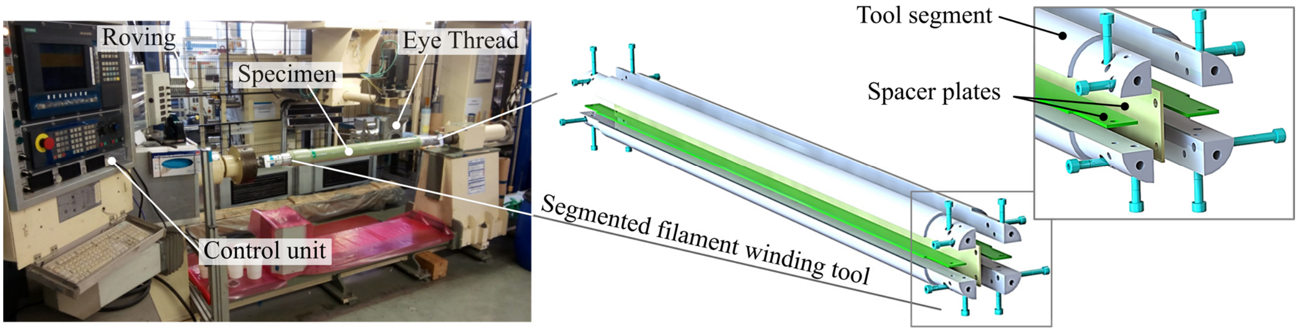



Figure 5. Manufacturing of the generic tubular structure using a filament winding machine

The VEM damping layer Dyad 601 from Soundcoat has been integrated into the manufacturing process by winding a 70 mm wide stripe manually and gap-free on the different mandrel configurations mentioned above. The mandrel with the final layup has been cured under constant rotation in a climate chamber for 10 hours at 70˚C [14].
A stiff, ± 10˚ GFRP layer has been applied to constrain the VEM damping layer to induce shear deformation during a global loading of the composite structure. One end of the generic composite tube has been partially reinforced and turned off after curing to a defined diameter of D = 100 mm for clamping purposes (Figure 6).

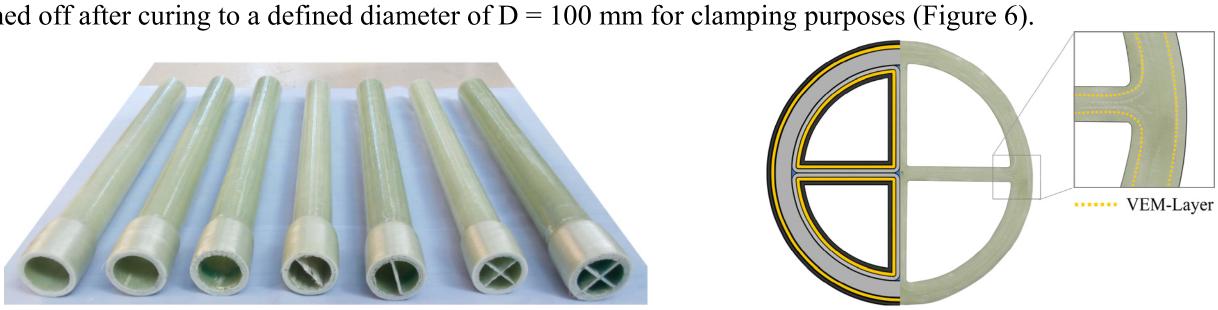



Figure 6. Manufactured GFRP tubes (left); Grinding pattern of the generic composite tube concept (i) (right)

As the laminate of all cross section configurations (see Figure 3) is based on the outer surface of the mandrel ($D_a$ = 79 mm), an exact comparison between these concepts is hardly possible. The mean radius of the load carrying laminate for e.g. concept i) is increased of about twice the thickness of the segmented VEM damping layer and the segmented constraining layer compared to concept g). This effect leads to an unintended increase in stiffness due the increased section modulus. For a fair comparability of the stiffness-damping relation, the mean radius of the load carrying laminate should be constant, which is not feasible with the current mandrel. However, a mathematical equalization should be possible by standardizing.

# 3 EXPERIMENTAL SETUP

The following section reviews the experimental test setup to evaluate the damping performance of the different cross section configurations presented in Figure 3. Based on a free vibration test of the cantilevered composite tubes, the damping will be calculated in terms of the loss factor. The aim is mainly to activate the first bending vibration mode, as this is the most relevant vibration mode activated by galloping vibration lines.

## 3.1 Free decay test rig

The generic composite tube is fixed at one end to represent the cantilevered composite power pylon arm in the scale of about 1:10 (see Figure 7).

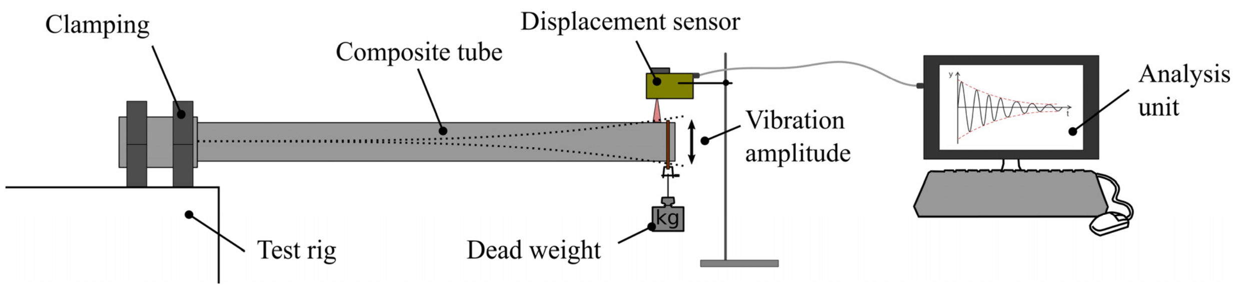



Figure 7. Free decay test setup for analysing the damping performance of the different cross section configurations of the generic composite tubes

To achieve a proper fixation of the composite tube in order to minimize clamping effects, the reinforced ends were prepared with defined allowance for interference with respect to the metal clamps. Metallic inserts are used to prevent the clamped section of the composite tube to collapse. The free length of all specimens is about 960 mm. The deflection at the free end is acquired and monitored by the contactless laser displacement sensor optoNCDT 1402 from Micro-Epsilon with a sampling frequency of 2000 Hz in combination with an analogical input module NI 9215 from National Instruments. Dead weights in various configurations are attached at the end of the beam leading to a deflection of about 10 mm. The sudden cut of the thin, load carrying steel rope results in a free vibration of the composite tube. The damping performance can then be evaluated based on the free decay curve and the relation of the logarithmic decrement $\delta$ and the loss factor $\eta$

$$\eta = 2\zeta = \frac{\delta}{\pi} \tag{1}$$

where $\zeta$ is the damping ratio associated with the activated vibration mode.

# 4 RESULTS AND DISCUSSION

The natural frequency and the structural damping represented by the loss factor η were analysed by a free decay test and are listed in Table 2. The increase in mass for all studied cross-section concepts with respect to reference concept a) are based on the analysis of the individual CAD (Computer Aided Design) data.

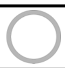
| Concept | Configuration | Natural frequency [Hz] at the 1. mode | Additional mass Δ m [%] | Loss factor η [-] at 1. mode | Δ η/ Δ m [1/m] ($10^{-4}$) |
|---|---|---|---|---|---|
| a) |  | 58,6 | - | 0,039 | - |
| b) |  | 59,8 | + 48 | 0,047 | 1,7 |
| c) |  | 59,0 | + 85 | 0,052 | 1,5 |
| d) |  | 55,3 | + 14 | 0,051 | 8,5 |
| |  | 53,4 | | 0,042 | 2,1 |
| e) |  | - | + 62 | - | - |
| |  | 54,7 | | 0,060 | 3,4 |
| f) |  | - | + 122 | - | - |
| |  | 56,0 | | 0,102 | 5,2 |
| g) |  | 52,6 | + 27 | 0,072 | 12,1 |
| |  | 52,6 | | 0,054 | 5,5 |
| i) |  | - | +157 | - | - |
| |  | 54,5 | | 0,079 | 2,5 |

Table 2. Results from the Free Decay Test (considering a vertical loading direction of Load F)

Unfortunately, the experimental data for concepts e-1), f-1) and i-1) are not available due to incorrect measuring results. However, the trend of the damping performance is clearly visible for the remaining cross section configurations and is in line with the expectations. The implementation of a CLD treatment on the outside of the composite tube (concept b)) leads to increased damping. The higher natural frequency can be explained with the added constrained layer resulting in a larger section modulus. The additional mass of the CLD treatment is therefore equalized. An additional CLD treatment on the inside of the tube (concept c) adds damping to the structure, but with lower efficiency compared to outer CLD. The damping-mass ratio is also slightly lower compared to concept b). The damping can also be increased by the implementation of shear webs (concept d-1) and g-1)) oriented parallel to the loading direction. A rotated double shear-web-configuration of about 45˚ (concept g-2)) is less effective than concept g-1) and will not be further considered. The matrix dominated material properties of the ± 45˚-shear-web-layup is contributing beneficially to the damping performance. However, the dynamic stiffness and natural frequency is decreased due to the additional mass of the shear webs. The efficiency of shear webs with respect to damping is very high. Almost the same damping performance can be achieved by either introducing a shear web in the loading direction (concept d-1)) or adding an inner and outer CLD (concept c)). At the same time, the addition of a shear web is leading only to 1/6 of the added mass compared the CLD. The additional damping of a shear web oriented perpendicular to the loading direction (concept d-2)) can be neglected, as it only leads to a decreased natural frequency due to added mass. Considering an additional CLD on the outside of the tube (concept e-2)), the damping can be increased further. The concept e-1) is expected to show much better damping performance. However, the best damping performance is assigned to the concept f) with a horizontal shear web and an additional VEM damping layer in between. In this median plane perpendicular to the loading direction, shear loading is getting maximal. By placing VEM close to that plane in combination with an outer, cylindrical CLD treatment, the structural damping can be increased by a factor 2.6 with slightly decreased dynamical stiffness.

# 5 CONCLUSION

An experimental damping analysis of generic composite tubes representing a novel composite power pylon arm has been conducted. The effect of different cross section concepts with or without implemented CLD treatments on the structural damping has been analysed. The maximization of damping performance has been the focus of the work, as additional weight on the more or less static composite power pylon structure is of minor importance and will only affect the dynamic stiffness. However, several cross sectional concepts are of great interest with respect to damping:

- The integration of shear webs within the structure can significantly increase the damping behaviour when oriented in loading direction while keeping the additional weight low.
- CLD treatments applied to the outer cylindrical surface are more efficient compared to a position on the inside.
- The implementation of VEM damping layers in the plane along the neutral axis and perpendicular to loading direction leads to maximal structural damping results.

# 6 ACKNOWLEDGEMENT

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