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Numerical and experimental investigations of the damping behaviour of hybrid CFRP-elastomer-metal laminates

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ABSTRACT

Monolithic material solutions hardly fulfil the required characteristics profile of new products. Owing to this fact, an optimal mix of materials is desirable as already realised by e.g. fibre-metal laminates (FML). In this case, the combination of aluminium and carbon-fibre-reinforced plastics (CFRP) promises highest lightweight potential, but it also entails complex challenges concerning the corrosion potential and the mismatch of the coefficients of thermal expansion. To avoid these prospective disadvantages, one possibility is to introduce an elastomer ply into a CFRP-based FML and hence developing it to a Hybrid CFRP-elastomer-metal laminate (HyCEML). This approach allows not only a reduction of the thermal expansion mismatch between fibre-reinforced plastics (FRP) and metal, but also prevents galvanic corrosion and, especially, enables a smart design of products with regard to adaptable laminate damping behaviour. The subject of this contribution is the investigation of the damping material behaviour different configurations of HyCEM laminates by numerical studies.

1. Introduction

Fibre metal laminates, the combination of sheets of fibre reinforced plastics and metals, can be found in various aerospace applications nowadays [1]. They show good mechanical properties and outstanding fatigue behavior [2]. The most common combination of glass fibre reinforced plastics with aluminum sheets is distributed under the short name GLARE (glass laminate aluminium reinforced epoxy). By substituting glass fibres with carbon fibers even higher specific mechanical properties can be achieved, though the combination of aluminum sheets with carbon fibres often leads to galvanic corrosion in the interface. Also the big mismatch in thermal expansion coefficients between these materials leads to high residual stresses after the curing process in a hot mould. Different approaches to isolate the aluminium from the CFRP layers have been investigated by adding layers of glass fibres [3,4]. Another approach is to isolate the aluminium sheets by adding an elastomeric interlayer. Therewith not only galvanic corrosion can be prevented [5], but also the damping properties can be influenced.

Light and stiff plates often tend to be prone to vibrations [6], hence additional damping treatment has to be applied to reach the high standards for noise vibrations harshness in modern transportation vehicles. A common damping method for flat panels is called constrained

layer damping (CLD) [7]. Here a soft viscous elastic damping layer is constrained between two stiff layers. When this laminate is bent the induced shear in the soft interlayer is mostly responsible for the damping. This phenomena was analytically described for a three layer system by Ross et al. and is often referred to as the RKU analysis [8,9]. Detailed analysis for different CLD setups on the basis of this analysis with various numbers of damping layers can be found in [10]. Investigations on the damping behavior of various FML configurations by using a one sided clamped configuration have been done by different authors. Botelho et al. showed that composites and FML with carbon fibers exhibit lower loss factors than GFRP based FML or pure aluminum [11]. Damping of FML could be increased by using self-reinforced polypropylene as composite material, which results in an decrease of the Young's modulus [12]. Studies on the damping properties of fibre metal elastomer laminates (FMEL) with GFRP, elastomeric interlayers and steel sheets showed that thicker rubber layers increased the loss factors of the laminate. However, the elastomer layer was attributed only small influence on the damping properties of the laminate due to the high loss factors of the GFRP layers [13]. For CFRP laminates it was shown that the integration of a viscoelastic elastomer interlayer increased the damping properties of the laminates [14].

To conclude, the use of various materials can offer a high potential to affect the mechanical and in particular the damping properties of a

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laminate as requested out of the list of requirements. To get a better understanding of the influencing damping properties of FML, a first experimental and numerical study is presented. On the basis of changes concerning the elastomer properties, such as thickness and stiffness but also the variation of the HyCEML lay-up, the technical possibilities to affect the damping is presented and discussed.

2. Materials and methods

2.1. Material characterisation of hybrid CFRP-elastomer-metal laminates

For this study common CFRP prepreg material HexPly M77/38%/UD150/CHS (provided by Hexcel Corporation), elastomer (El) Kraibon SAA9579-52 (provided by Gummiwerk Kraiburg GmbH & Co. KG) and aluminium (Al) alloy 2024-T3 ALCLAD sheets (provided by Kastens Knauer GmbH) were used. Hybrid CFRP-elastomer-metal laminates (HyCEML) of 400 mm × 400 mm are laid-up by hand and are consolidated in a hot mould with a pressure of 40 bar at a temperature of 150 °C for 300 s as recommended by the manufacturer. The lay-up is varied depending on the setup of the analysis. However, CFRP layers are always stacked as [0/90]_s. Afterwards specimens (l × w = 250 mm × 15 mm) are cut out by using water-jet cutting technology. The nominal thickness of specimens is t = 2.5 mm.

The elementary quasi-static material properties of CFRP and elastomer are identified by performing appropriate tensile tests based on EN ISO 527-4 [15] and ISO 37 [16] by using an universal testing machine Zwick 200kN and Zwick 2.5kN, respectively. For both testing setups digital image correlation (DIC) are applied to measure the strain and consequently to determine the Poisson's ratio. Furthermore, material properties concerning the transverse shear modulus G₃₂ of CFRP prepreg material are calculated applying the rule of mixture [17] assuming that the Poisson's ratio ν₃₂ ≈ 0.4. All mechanical data are summarised and provided for the numerical study in Table 1 for CFRP, in Table 2 for elastomers and in Table 3 for aluminium, respectively.

For numerical studies, linear-elastic material behaviour is assumed owing to the fact of small deformations. In addition, it is assumed, that shear of the visco-elastic elastomer layer is mainly responsible for damping of the laminates. Visco-elastic material behaviour of the elastomer is implemented in Abaqus by using a Prony series in frequency domain. Therefore, dynamic mechanical analysis (DMA) tests on GABO Eplexor 500N based on ISO 6721-4 [18] are performed to gain data of storage and loss modulus by testing the elastomer in a frequency range of f = 0.5 Hz 50.0 Hz at constant temperatures between T = -80 °C to +50 °C and a temperature step size of 3°. By using Williams-Landel-Ferry approach a master curve of storage and loss modulus can be created by shifting every curve of constant temperature T to a base curve, usually to the curve at glass transition temperature (T_{ref} = -52.7 °C). The shift factor a_T can be determined by, as shown in Eq. (1)

$$\log(a_T) = \frac{-c_1(T-T_{ref})}{c_2 + (T-T_{ref})}, \quad (1)$$

where c₁ and c₂ are empirical constants. In a following step storage and loss modulus master curves have to be transformed to the temperature T_{ref} at which numerical studies are applied. Hence, constants c'₁ and c'₂

Table 1

Elastic material properties of CFRP M77/CHS (t_{CFRP} = 0.15 mm) provided by Hexcel.

Elastic modulus GPa	Poisson's ratio / -	Shear modulus / GPa	Density kg/m ³
E ₁ = 113.7	ν ₂₁ = 0.3371	G ₂₁ = 3.76	ρ = 1496
E ₂ = 7.75	ν ₃₁ = 0.3371	G ₃₁ = 3.76	
E ₃ = 7.75	ν ₃₂ = 0.4000	G ₃₂ = 2.75	

Table 2

Elastic material properties of elastomer (t_{el} = 0.5 mm) provided by Kraiburg.

Type	Elastic modulus /MPa	Poisson's ratio / -	Density / kg/m ³
SAA9579-52	E = 48.00	ν = 0.4800	ρ = 1180

Table 3

Elastic material properties of aluminium alloy sheets AL2024-T3 (t_{Al} = 0.3 mm).

Elastic modulus / GPa	Poisson's ratio / -	Density / kg/m ³
E = 73.1	ν = 0.3054	ρ = 2780

can be determined by

$$c'_1 = \frac{c_1 c_2}{c_2 + (T'_{ref} - T_{ref})} \text{ and } c'_2 = c_2 + (T'_{ref} - T_{ref}), \quad (2)$$

respectively. Subsequently, storage (Eq. (3)) and loss modulus (Eq. (4)) data can be fitted by using a non-linear least-squares method to determine the Prony series parameters g_i and τ_i by minimizing an error function.

$$E'(\omega) = E_0 \left(1 - \sum_{i=1}^N g_i \right) + E_0 \sum_{i=1}^N \frac{g_i \tau_i^2 \omega^2}{1 + \tau_i^2 \omega^2} \quad (3)$$

Here, ω is the angular frequency, E₀ is the instantaneous modulus and N is the number of terms, where N should be typically not more than the number of logarithmic decades spanned by the test data [19].

$$E''(\omega) = E_0 \sum_{i=1}^N \frac{g_i \tau_i \omega}{1 + \tau_i^2 \omega^2} \quad (4)$$

Finally, owing to the assumption of incompressibility of the elastomers, the storage E' and loss modulus E'' will be transferred to appropriate shear modulus G ≈ E/3. The Prony series is chosen for visco-elastic modelling, since it is suitable for soft elastomers in tension mode and includes a convenient parameter identification procedure. The here determined and used Prony series is summarised in the following Table 4.

2.2. Model, boundary conditions and FE mesh

Based on ISO 6721-3, a cantilever beam (l × w = 250 mm × 15 mm) is modelled in Abaqus which is clamped on one side and is excited by a harmonic force F on the opposite side, see Fig. 1. The free length of the specimen is l₀ = 180 mm.

The setup is suitable to determine the vibration and damping behaviour of laminates and can be used for a frequency range of f = 10 Hz to 1 kHz [20]. Several lay-ups are evaluated by using different finite-elements to optimise the mesh fineness and to reduce the calculation

Table 4

Prony series of elastomer Kraibon SAA9579-52 at a reference temperature of T_{ref} = 22.8 °C.

i	τ _i /s	g _i /-
1	7.2500 × 10 ⁻¹¹	4.9519 × 10 ⁻¹
2	1.2504 × 10 ⁻⁹	3.0478 × 10 ⁻¹
3	2.2678 × 10 ⁻⁸	8.7607 × 10 ⁻²
4	4.0844 × 10 ⁻⁷	2.9863 × 10 ⁻²
5	5.2444 × 10 ⁻⁶	1.5416 × 10 ⁻²
6	5.8889 × 10 ⁻⁵	1.1105 × 10 ⁻²
7	6.2176 × 10 ⁻⁴	9.5733 × 10 ⁻³
8	6.1707 × 10 ⁻³	9.2759 × 10 ⁻³
9	5.4881 × 10 ⁻²	9.0497 × 10 ⁻³
10	4.6058 × 10 ⁻¹	8.0827 × 10 ⁻³

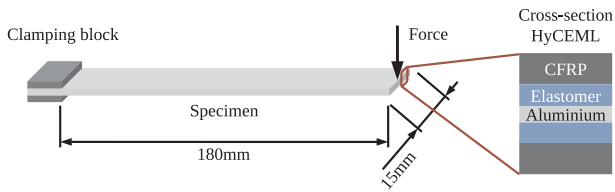


Fig. 1. Test-setup based on ISO 6721-3 [20] (left) and a schematic image (right) of HyCEML cross-section.

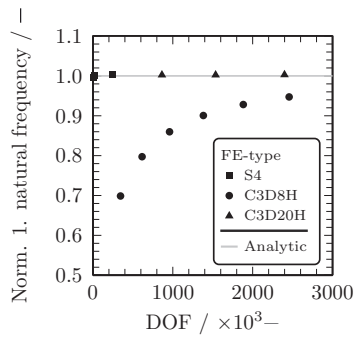


Fig. 2. FE mesh fineness (DOF) dependent on Abaqus FE-type (S4: four-nodes shell element, C3D8H: eight-nodes volume element, C3D20H: twenty-nodes volume element) with regard to normalised first natural frequency of a 2mm thick aluminium cantilever beam.

time. Fig. 2 shows the comparison of general-proposed elements out of Abaqus element library by studying the deviation of the first natural frequency dependent on the degrees of freedom (DOF) of the model to the analytical solution.

As shown in Fig. 2, four-nodes shell elements (S4) as well as 20-nodes volume elements (C3D20H) capture with a high accuracy the first natural frequency by a low applied number of degrees of freedom for a 2mm thick aluminium cantilever beam. However, the eight-nodes volume elements (C3D8H) is unsuitable owing the fact, that even with a high DOF the analytical approach is never reached. To depict the transverse deformation with a high accuracy a detailed multi-layer finite element model (out of C3D20H elements) is generated offering high flexibility in terms of the geometry of the model, type and number of finite elements, especially in the laminate thickness direction. A minimum of three elements per layer through thickness is chosen. For evaluation of the vibration and damping behaviour of the laminates, the amplitude of the specimen is measured all over the specimen and is normalised to the static displacement [21].

In the following, first, results of modal analysis of several lay-ups and the influence of the visco-elasticity of the elastomer is presented. Second, the vibration and the damping behaviour, respectively, of HyCEML is shown. In this case, the influence of thickness and stiffness of the elastomer as well as the influence of lay-up changes is evaluated.

3. Results

3.1. Modal analysis

Based solely on experimental studies, the direct influence of damping based on visco-elastic effects in the elastomer is hardly identifiable. Hence, the advantage of numerical investigations is highlighting this effect by taking into account or neglecting the visco-elasticity of the elastomer, as illustrated in Fig. 3.

The graph shows the numerically-determined natural frequency versus the first five modes of undamped and damped Al-El laminate. The frequency dependent on the temperature defined and implemented Prony series at 22.8°C (room temperature). It can be observed, that there is almost no influence on the first and second natural frequency. Above

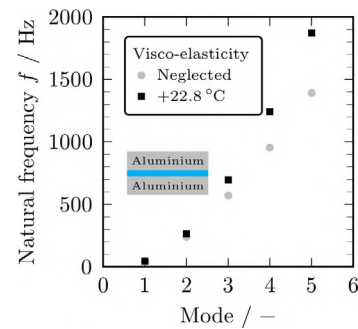


Fig. 3. Influence of temperature on natural frequency of Al-El-laminate out of modal analysis.

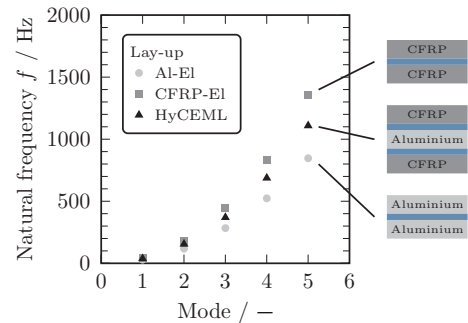


Fig. 4. Natural frequencies of several lay-ups.

the second natural frequency, the influence of the increasing storage modulus becomes stronger and the affect of the visco-elasticity becomes visible.

Comparing several laminates, the CFRP-El laminate shows the highest natural frequencies even though the flexural bending stiffness is similar to an Al-El laminate, see Fig. 4. The natural frequencies of HyCEM laminate are in between. This behavior depends on the bending stiffness of the laminate and in particular the stiffness and the location of the elastomer.

3.2. Damping of HyCEML

Because of clarity, for all further graphs just the amplitude of the first two natural frequencies are presented. All following natural frequencies exhibit the same behaviour as the second natural frequency.

First, the effect of elastomer thickness is investigated and presented by a steady state dynamic analysis. In Fig. 5 the amplitude as a function of frequency is plotted for an elastomer thickness between 0.01mm to 0.50mm. It can be pointed out, that the first natural frequency $f \approx 60$ Hz is damped whereas the second natural frequency shows a shift to a higher frequency. Except for a thickness of 0.5 mm a shift also

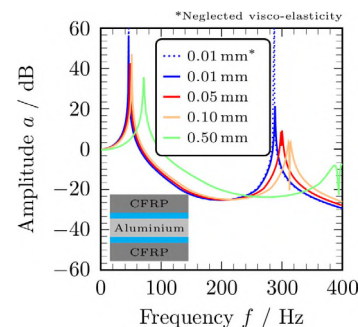


Fig. 5. Influence of elastomer thickness on amplitude with regard to the frequency.

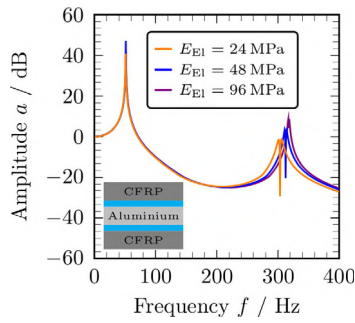


Fig. 6. Influence of elastomer stiffness on vibration and damping behaviour of HyCEML.

occurs for the first natural frequency. Both, the reduction of the amplitude as well as the frequency shift of the natural frequency show strongly non-linear responses. It should be noted that the discontinuity of the curve, in particular the second natural frequency can be traced back to the breakthrough of the beam within the simulation. Furthermore, the amplitude of both, the first and the second natural frequency are increased beyond the static displacement leading to the assumption that the elastomer has, especially for high frequencies, an enormous influence on the material vibration behaviour.

Second, the influence of the material stiffness of the elastomer is studied. Therefore, the initial modulus is varied: one time the modulus is reduced and the other time the modulus is increased. The amplitude of the harmonic excited beam over the frequency is shown in Fig. 6. The first natural frequency is damped and the second natural frequency is shifted to a lower frequency with decreasing of the elastomer stiffness. It should be noted at this point, that the effect of damping and shifting is less obvious than before.

Third, the impact of the lay-up on the vibration amplitude is examined and illustrated in Fig. 7. Two different lay-ups are presented, whereby just the order of CFRP and aluminium layer is interchanged as a restriction which is still relevant due to the galvanic corrosion. However, vibration behaviour of these two composites is similar in comparison to the studies before: the first natural frequency is almost unchanged i.e. hardly affected by the lay-up and the second natural frequency shows a shift to a higher or a lower frequency depending on the lay-up.

Finally, an experimental modal analysis of a HyCEML specimen is conducted with the same setup as shown in Fig. 1. Therefore, the specimen is loaded with a force, so that the tip is deflected to 10mm. After that, the force is removed and the specimen vibration decay is measured with an optoNCDT 2300 laser triangulation sensor by Micro-Epsilon. A typical decay curve can be seen in Fig. 8, whereat the first natural frequency is determined to $f_1^{\text{exp}} = 63$ Hz. In comparison to that, the numerical study shows a slight higher first natural frequency $f_1^{\text{num}} = 67$ Hz but less damping effects over the time. In this case, damping is characterised by the logarithmic decrement.

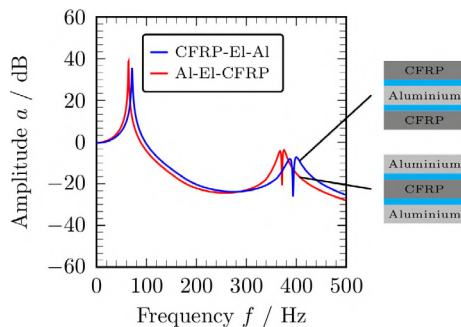


Fig. 7. Comparison of different HyCEML lay-ups on its damping behaviour.

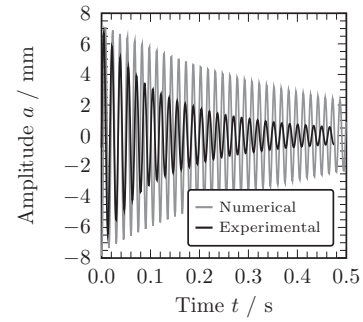


Fig. 8. Decay curve of experimental and numerical analysis of HyCEML.

Experimentally, the logarithmic decrement decreases regressively from 0.15 to 0.04, whereat numerically the logarithmic decrement asymptotically reach a value of 0.025.

4. Discussion

In general, an experimental determination and comparison of damped and undamped material behaviour of laminates is hardly possible. Given the specific effects of damping such as visco-elasticity of materials leading to energy dissipation can not be considered and neglected, respectively, in the same way within experimental studies. Even numerical investigations require a fundamental knowledge of material behaviour and an elementary basis of mechanical properties to reliably simulate structures under real load conditions. In addition, diverse models, e.g. Prony series, but also approaches of finite elements are committed to providing numerical approaches to capture the mechanical material behaviour. It should be noted, that especially custom simplifications for numerical studies, such as assumptions of linear-elastic material behaviour, lead to deviations in contrast to experimental investigations as it is shown in Fig. 8.

The number of different materials and the high number of possible material configurations (lay-up, fibre orientation and volume content, stiffness, etc.) complicate the detailed view on specific effects leading to damping of hybrid CFRP-elastomer-metal laminates. It is obvious, that the assumption of linear-elastic material behaviour of CFRP is not satisfying if further damping effects of e.g. fibre reinforced plastics will be considered [13]. However, in a first step, the influence of mechanical and geometrical characteristics of the elastomer is presented and shows varying effects on vibration behaviour of HyCEML. The main effect on damping and shifting of natural frequencies can be reached by increasing the elastomer thickness. With increasing of the elastomer thickness the slip between CFRP and aluminium will increase. Besides the elastomer thickness the elastomer stiffness leads to a less distinct influence. Especially the major difference between stiffness of CFRP/aluminium and elastomer leads to challenges in modelling the transverse properties of HyCEML. With increasing elastomer stiffness the model shows a better representation of the actual properties and it is easier to implement a model of great similarity. Numerical studies showed, that for even small changes in elastomer stiffness or visco-elastic material behaviour, the natural frequency could be significantly affected. Hence, the first natural frequency could be determined out of mechanical tests with a deviation of 10%. Overall, determination of parameter should be carefully considered.

5. Conclusion

The presented work shows the effect of lay-up changes, elastomer thickness and elastomer stiffness on the damping behaviour of hybrid CFRP-elastomer-metal laminates. Owing to the large variety of possibilities to investigate the different influencing factors on the damping behaviour, numerical studies are conducted in a first step. Especially,

the first natural frequency is influenced by the thickness of the elastomer. Second and higher natural frequencies are also essential affected by the thickness, but also affected by the stiffness of the elastomeric layer and the lay-up of the laminate. It means in effect, that by carefully chosen parameters of thickness, type of elastomer (concerning the stiffness) as well as corresponding lay-up, the natural frequencies can be shifted outside the range of application.

Further scientific studies will be carried out to take into account the influence of e.g. the orthotropic visco-elastic material behaviour of CFRP layers on the damping behaviour of HyCEM laminates. And, of course, the results of the numerical studies also will be validated by experimental tests to get a better knowledge about factual events and to derive possible design guidelines for structures with regard to damping or to high stiffness in their mechanical characteristics.

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