

Finite Element Evaluation of Effective Damping Properties of d_{31} Piezoelectric Macro-Fibre Composites

Marcelo A. Trindade, Ayech Benjeddou

Abstract. This work presents the evaluation of effective damping properties of a d_{31} piezoelectric Macro-Fibre Composite (MFC). This is important since it is well known that the softer elastomeric components of MFCs may induce non-negligible damping, while there are no studies attempting to evaluate or quantify the effective damping or loss factor of MFCs. This is done through an analogy with the Modal Strain Energy method in which an effective loss factor may be computed for each loading case. Then, for given damping properties of the MFC components, mainly the epoxy matrix, it is possible to quantify the effective damping properties of the MFC. It is shown that the d_{31} MFC effective loss factor may attain around 5%, particularly for transverse and in-plane shear loading modes, when the epoxy matrix transitions from glassy to rubbery state. Also, due to the epoxy softening, elastic stiffness and piezoelectric stress coefficients of the MFC may be substantially reduced.

Key words: Piezoelectric macro-fibre composites, damping, finite element homogenization

1 INTRODUCTION

Piezoelectric Macro-Fibre Composite (MFC) transducers have become very popular since they combine the conformability of epoxy-matrix composites and the electromechanical energy density of piezoceramic materials [1]. Since they are heterogeneous and made of several different materials (piezoceramic fibres, epoxy matrix, electrode and protective layers), a methodology is required to relate their effective properties with the individual ones of its components [2, 3]. Previous studies have shown that the effective properties depend not only on the active layer (piezoceramic fibres and epoxy matrix) but also on electrode and protective ones [4, 5].

In particular, it is well known that the softer elastomeric components of MFCs may induce non-negligible damping, while there are no studies attempting to evaluate or quantify the effective damping or loss factor of MFCs. Indeed, Placzek and Kokot [6] have shown that the

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energy harvesting performance of MFCs decreases significantly under increased operating temperatures. Lin et al. [7] have shown that the thermoelastic properties of the epoxy matrix were extremely important on the performance of piezoelectric fibre composites, since a temperature increase induced a decrease of free strain due to the deformation of the epoxy constituents. Also, the actuation capability were even more sensitive to temperature than free strain. Williams, Inman and Wilkie [1] have shown that the apparent transverse and in-plane shear moduli of MFCs can experience a decrease of up to 30% for increasing temperature in the epoxy matrix. Hence, the dependence of thermoelastic properties on temperature should be accounted for.

Meanwhile, for vibration-based applications, such as active or passive vibration control, shunted damping, energy harvesting and so on, the effective damping added by the MFC itself may be non-negligible and, thus, affects its effective performance when it is bonded to a host structure. Hence, this work presents the evaluation of effective damping properties of a d_{31} MFC. This is done through an analogy with the Modal Strain Energy (MSE) method [8] in which an effective loss factor may be computed for each loading case. Then, for given damping properties of the MFC components, mainly the epoxy matrix, it is possible to quantify the effective damping of the MFC. A parametric analysis is also performed to assess the effect of variations in the damping properties of the components.

2 EVALUATION OF d_{31} MFC EFFECTIVE ELECTROMECHANICAL PROPERTIES

2.1 Electromechanical constitutive equations of d_{31} MFC

The d_{31} MFC is composed of an active layer, made of piezoceramic macro-fibres embedded in an epoxy matrix, which is then fully covered by electrode and protective layers, as shown in Figure 1. The piezoceramic macro-fibres are poled along the x_3 (through-thickness) direction and their top (Γ_e^+) and bottom (Γ_e^-) surfaces are fully covered with an electrode layer, such that the dominant operation (response) mode is the d_{31} that couples longitudinal strain/stress (along direction x_1) and through-thickness electric field/displacement (direction x_3) (Figure 2).

Considering linear piezoelectricity, the general 3D constitutive equation for an orthotropic

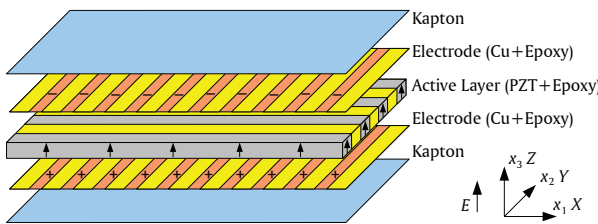


Figure 1: Schematic representation of a d_{31} MFC.

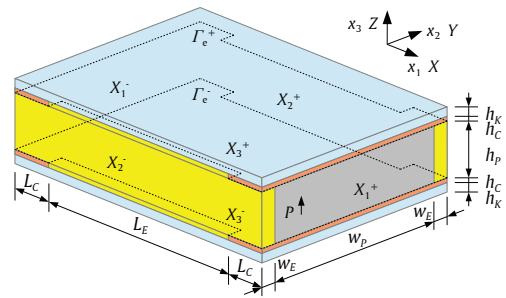


Figure 2: Representative volume element (RVE) of a d_{31} MFC.

piezoelectric material can be written as

$$\begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} c_{11}^E & c_{12}^E & c_{13}^E & 0 & 0 & 0 & 0 & 0 & -e_{31} \\ c_{12}^E & c_{22}^E & c_{23}^E & 0 & 0 & 0 & 0 & 0 & -e_{32} \\ c_{13}^E & c_{23}^E & c_{33}^E & 0 & 0 & 0 & 0 & 0 & -e_{33} \\ 0 & 0 & 0 & c_{44}^E & 0 & 0 & 0 & -e_{24} & 0 \\ 0 & 0 & 0 & 0 & c_{55}^E & 0 & -e_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66}^E & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & e_{15} & 0 & \epsilon_{11}^S & 0 & 0 \\ 0 & 0 & 0 & e_{24} & 0 & 0 & 0 & \epsilon_{22}^S & 0 \\ e_{31} & e_{32} & e_{33} & 0 & 0 & 0 & 0 & 0 & \epsilon_{33}^S \end{bmatrix} \begin{Bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ E_1 \\ E_2 \\ E_3 \end{Bmatrix}, \quad (1)$$

where T_p and S_q , with $p, q = 1, \dots, 6$, stand for the six components of mechanical stress and strain vectors in Kelvin-Voigt notation. D_j and E_j denote the electric displacements and fields in direction x_j ($j = 1, 2, 3$). In the so-called e -form of the linear piezoelectric constitutive equations (1), c_{pq}^E , e_{jp} and ϵ_{jj}^S denote the short-circuit (SC) elastic stiffness (at constant electric fields), stress piezoelectric and blocked electric permittivity (at constant mechanical strains) coefficients. These constitutive equations can also be rewritten in the so-called d -form, in which material constants are s_{pq}^E , d_{jp} and ϵ_{jj}^T , the SC elastic compliance (at constant electric fields), strain piezoelectric and free electric permittivity (at constant mechanical stresses) coefficients.

The piezoelectric e_{31}/d_{31} , elastic c_{11}^E/s_{11}^E and dielectric $\epsilon_{33}^S/\epsilon_{33}^T$ coefficients are the most important properties to qualify these composite transducers as sensors and actuators. Nevertheless, due to the anisotropy induced by the composite construction, it is important to analyze other effective properties as well and, in particular, how the properties and behaviour of each composing material affect the effective properties and behavior of the resulting MFC.

2.2 FE homogenization procedure to evaluate the effective electromechanical properties

Previous works [5, 9] presented the evaluation of the effective electromechanical coefficients of a d_{31} MFC, using the so-called average quantity-based finite element (FE) homogenization technique proposed in [4]. This technique is based on the evaluation of the average stresses, strains, electric fields and electric displacements in a FE model of a Representative Volume Element (RVE) (Figure 2) of the MFC when subjected to properly chosen mechanical and electrical boundary and periodicity conditions.

For that, a set of local problems is defined, in which the MFC RVE is loaded and its response is used to compute the averaged quantities. Considering that the MFC behaves as an orthotropic piezoelectric material, the averaged quantities are then used to evaluate the effective elastic, piezoelectric and dielectric coefficients of the MFC. The local problems and the methodology to evaluate the effective properties are described in [5, 9].

To solve the local problems and evaluate the effective properties, a FE model was built in Ansys[®], using 3D 20-Node coupled-field solid element (SOLID226) to mesh all volumes. This FE has the three displacement translations along the Cartesian coordinate system axes and the electric potential as nodal degrees of freedom. A mesh of 9900 finite elements was used

considering 25 divisions in x_1 direction (17 divisions for the Epoxy layer and 4 divisions for each electrode layer), 18 divisions in x_2 direction (14 divisions for the PZT fibre and 2 divisions for each Epoxy layer) and 22 divisions in x_3 direction (12 divisions for the PZT layer, 2 divisions for each electrode layer and 3 divisions for each protective layer). The dimensions considered for this RVE are $h_P = 180 \mu\text{m}$, $h_K = 40 \mu\text{m}$, and $h_C = 18 \mu\text{m}$, $L_E = 420 \mu\text{m}$, $L_C = 80 \mu\text{m}$, $w_E = 28.35 \mu\text{m}$ and $w_P = 348.3 \mu\text{m}$. The material properties for the piezoceramic material Sonox P502, taken from [2], are: $s_{11}^E = s_{22}^E = 18.5 \text{ pm}^2/\text{N}$, $s_{33}^E = 20.7 \text{ pm}^2/\text{N}$, $s_{12}^E = -6.29 \text{ pm}^2/\text{N}$, $s_{13}^E = -6.23 \text{ pm}^2/\text{N}$, $s_{44}^E = s_{55}^E = 33.2 \text{ pm}^2/\text{N}$, $s_{66}^E = 52.3 \text{ pm}^2/\text{N}$, $d_{31} = d_{32} = -185 \text{ pC/N}$, $d_{33} = 440 \text{ pC/N}$, $d_{15} = d_{24} = 560 \text{ pC/N}$, $\epsilon_{11}^T = \epsilon_{22}^T = 1950\epsilon_0$, $\epsilon_{33}^T = 1850\epsilon_0$. The material properties for the other constituents, taken from [3], are: Epoxy – $Y = 2.5 \text{ GPa}$, $\nu = 0.42$ and $\epsilon = 4.25\epsilon_0$; Kapton – $Y = 2.5 \text{ GPa}$, $\nu = 0.34$ and $\epsilon = 3.4\epsilon_0$; and Copper electrode – $Y = 110 \text{ GPa}$, $\nu = 0.34$ and $\epsilon = 5\epsilon_0$, with $\epsilon_0 = 8.854 \text{ pF/m}$.

Comparison of the evaluated full 3D effective coefficients of the d_{31} MFC with previous analytical results and data provided by the manufacturer (Smart Material Corp., [10]) has shown satisfactory coincidence [9]. It was then concluded that the 3D FE-evaluated effective electromechanical properties represent very well the actual (manufactured) d_{31} MFC.

Nevertheless, these analyses were performed considering linear elasticity and piezoelectricity. Other previous works have shown that nonlinear piezoelectricity of the piezoceramic macro-fibres may induce corresponding nonlinear behaviour of the MFC [5]. Similarly, it is worthwhile analyzing whether an anelastic behaviour of the epoxy matrix would induce a corresponding anelastic behaviour for the d_{31} MFC.

3 ANELASTIC BEHAVIOR OF EPOXY ADHESIVES

According to Williams [11], the first prototypes of d_{33} MFCs, developed by NASA, used epoxy adhesive Loctite® Durabond EA-E-120HP (manufactured by Henkel) for the matrix. These are composed of an epoxy resin with polyamide hardener, but not much information concerning its thermomechanical properties are available besides the fact that the glass transition temperature is around 90°C . The author mentioned that a satisfactory behaviour prediction was obtained using standard material properties for generic structural epoxy.

Other similar epoxy adhesives often used in fibre-reinforced composites are Araldite® 2019 (made by Huntsman) and Scotch-Weld® DP-460 (made by 3M). Their main thermomechanical properties are a maximum elastic modulus around 2.5 GPa and glass transition temperatures in the range $75\text{--}90^\circ\text{C}$. From the manufacturers' available data, the elastic modulus can indeed decrease significantly between the maximum value (in glassy state, low temperature) and the glass transition value (around the glass transition temperature). For Araldite® 2019, for instance, the elastic modulus varies from 2.4 GPa (at -40°C) to 0.4 GPa (at 80°C) [12].

For the prediction and simulation of the epoxy matrix behaviour in higher temperatures (intermediate/transition or rubbery states), one alternative is to model it as a temperature and frequency dependent viscoelastic material, such that its elastic modulus is replaced by a temperature and frequency dependent complex modulus

$$Y^*(\omega, T) = Y_R(\omega, T) + iY_I(\omega, T) = Y_R(\omega, T)[1 + i\eta(\omega, T)]. \quad (2)$$

where Y_R and η are known as the storage modulus and the loss factor, both dependent on operating temperature and frequency. The storage modulus usually transitions between a maximum value (in glassy state, for low temperature, or in instantaneous response, for high working frequencies) and a minimum value (in rubbery state, for high temperature, or in relaxed response, for low working frequencies). The loss factor is usually negligible for very low or very high temperature and frequencies and presents a maximum value after the glass transition temperature. However, as the glass transition temperature is frequency-dependent, the loss factor presents higher values within a frequency-range that depends on the temperature. Typical temperature and frequency dependences are represented in Figure 3, which was developed using a material model presented in [13] that was fitted to experimental dynamic mechanical analysis of an epoxy resin used for the production of glass-fibre-reinforced composites manufactured by Shanghai FRP Research Institute Co. Ltd.. This epoxy resin presents basic thermomechanical properties that are similar to those available for the epoxy resins used in MFCs.

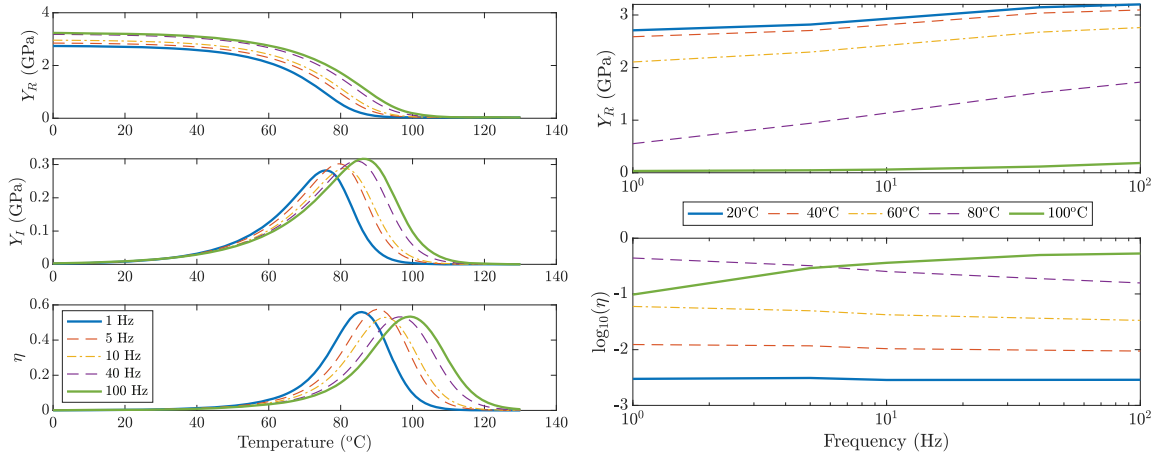


Figure 3: Temperature and frequency dependences of epoxy resin used for glass-fibre-reinforced composites based on a fitted material model proposed in [13].

For the present analysis, and based on this more detailed model, it is desired to perform a first quantification of the effect or importance of the viscoelastic behaviour, namely added damping and temperature and frequency dependences, of the epoxy matrix on the resulting MFC. In particular, it is noticeable that the material behaviour may be divided in three regions: glassy, intermediate and rubbery. In the glassy state, the resin presents a higher storage modulus and a smaller loss factor (stiffer and less damped). On the contrary, in the rubbery state, the resin presents a smaller storage modulus and a higher loss factor. The transition from a glassy state to a rubbery one may lead to a decrease of around 40% in the storage modulus (from 2.5 GPa to 1.5 GPa) and an increase of 15 times in the loss factor (from 1% to 15%) (Table 1 and Figure 4).

Table 1: Storage modulus and loss factor of the epoxy material for the three material states.

Property	Glassy	Intermediate	Rubbery
Y_R (GPa)	2.5	2.0	1.5
η_e (%)	1	8	15

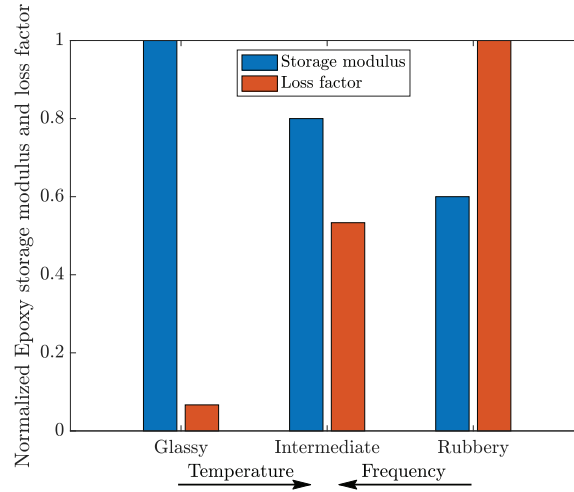


Figure 4: Relative values of storage modulus and loss factor for epoxy transitioning from glassy to rubbery state.

For the epoxy material considered in the present work (manufactured by Shanghai FRP Research Institute Co. Ltd. [13]), as a typical epoxy material used for fibre-reinforced composite, the so-called glassy state region is observed for temperatures below 45°C, for which the material behaviour is less frequency-dependent while, in the other two states, for temperatures above 45°C, the material is both temperature and frequency-dependent. The intermediate state is defined for temperature-frequency pairs in the range [55°C-1 Hz, 75°C-100 Hz]. The rubbery state is defined for temperature-frequency pairs in the range [65°C-1 Hz, 85°C-100 Hz]. Notice, however, that higher temperatures, above the glass transition temperature around 85°C, are not considered since the storage modulus reduces drastically, to below 0.5 GPa, and the loss factor can reach up to 60%.

4 EVALUATION OF d_{31} MFC EFFECTIVE LOSS FACTOR

Based on the previous observations, it is important to assess the effect of the loss factor of the epoxy matrix on the effective loss factor of a typical d_{31} MFC and, thus, to estimate the potential damping that may be induced when attaching a d_{31} MFC to a host structure.

For the evaluation of the d_{31} MFC effective loss factor, due to the epoxy matrix, it is hereby assumed that the only source of damping comes from the epoxy matrix. Also, to allow further numerical analyses, such as when attaching the MFC to a host structure, and assuming the complex modulus approach, it is chosen here to evaluate the effective loss factor induced in

each loading mode, leading to corresponding matrices of complex stiffness coefficients.

For that, an analogy with the well-known MSE method [8], in which the global structure's loss factor is approximated by the multiplication of the loss factor of a selected component and the fraction of strain energy in such component. In the MSE method, this computation is done for each vibration mode of interest (thus, a modal characteristic). Here, the MSE method is extended to the case of different loading modes of the MFC, instead of different vibration modes. Thus, the local problems used in previous works [5], for evaluating the effective elastic stiffness coefficients of the d_{31} MFC, are adapted to quantify the fraction of strain energy in the epoxy matrix in each loading mode.

Then, the effective loss factor η_i in the i -th loading mode is defined as

$$\eta_i = \eta_e f_i, \text{ with } f_i = \frac{U_{ei}}{U_i}, \quad (3)$$

where η_e is the epoxy matrix loss factor, U_{ei} and U_i are the strain energies in the epoxy matrix and in the MFC, respectively, and f_i is the fraction of the total strain energy contained in the epoxy matrix. In Ansys[®], U_{ei} is obtained by summing the strain energies computed for elements of the FE model for the epoxy material for each loading mode i , while U_i follows the same procedure but for all elements of the FE model.

Since both storage modulus and loss factor of the epoxy matrix are frequency and temperature dependent, so are η_e and f_i in (3). Thus, the computation of the effective loss factors η_i should be done for each frequency and temperature of interest. In the present work, it is considered the three generic states defined in the previous section, namely glassy, intermediate and rubbery. Each state has pre-defined storage modulus Y_R and loss factor η_e for the epoxy matrix, as shown in Table 1.

As stated previously, the loading modes follow the local problems used to evaluate the elastic coefficients of the d_{31} MFC, which consist in inducing normal strains in longitudinal (along the piezoceramic fibres, defined as direction 1), transverse (perpendicular to the piezoceramic fibres in the MFC plane, defined as direction 2) and through-thickness (along the thickness of the MFC, defined as direction 3) directions, and shear strains in planes 23, 13 and 12 (defined, respectively, as local problems 4, 5 and 6).

A small modification is proposed here in the local problems 1, 2 and 3, removing the fixed displacements boundary conditions to better approximate the loss factor of the elastic moduli in each direction, Y_1 , Y_2 and Y_3 , such that they would be replaced by

$$Y_j^* = Y_{jR}(1 + i\eta_j), \text{ for } j = 1, 2, 3. \quad (4)$$

For the shear modulus, local problems 4, 5 and 6 are used without modification, leading to corresponding complex shear moduli

$$G_k^* = G_{kR}(1 + i\eta_k), \text{ for } k = 4, 5, 6. \quad (5)$$

where the Kelvin-Voigt notation is considered ($G_4^* \equiv G_{23}^*$, $G_5^* \equiv G_{13}^*$, $G_6^* \equiv G_{12}^*$).

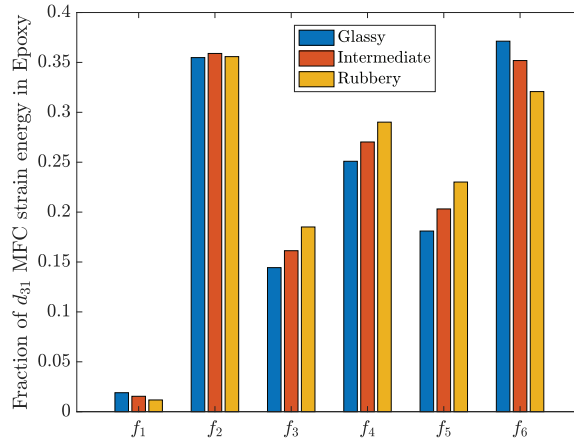


Figure 5: Fraction of strain energy contained in the epoxy matrix for each d_{31} MFC loading mode and epoxy state.

Figure 5 shows the fraction of strain energy contained in the epoxy matrix for each loading mode and epoxy state. It is noticeable that the epoxy strain energy fraction is much smaller in loading mode 1 (longitudinal), which is expected since in this case the normal stresses are concentrated in the stiffer PZT fibre and Copper electrode. On the other hand, the strain energy fraction is very important (higher than 30%) in loading modes 2 (transverse) and 6 (in-plane shear). In loading mode 2, most of the strain is concentrated in the softer epoxy matrix and the strain energy fraction does not depend much on the epoxy state. For the in-plane shear loading mode, the strain energy fraction decreases when the epoxy matrix transitions from glassy to rubbery states. As for the through-thickness (mode 3) and transverse shear (modes 4 and 5) loading modes, they lead to intermediate values for the strain energy fraction (between 15% and 30%), which all increase when the epoxy matrix transitions from glassy to rubbery states.

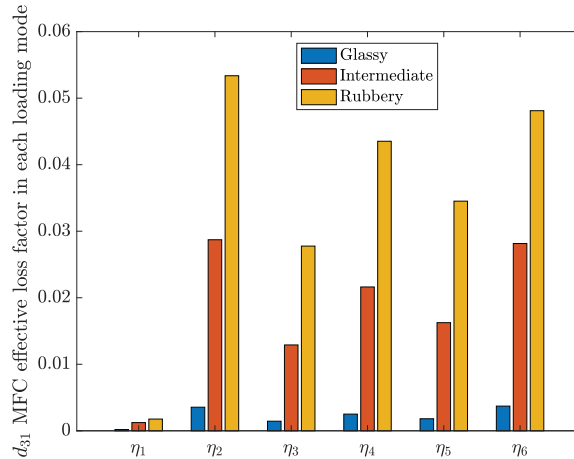


Figure 6: d_{31} MFC effective loss factors for each loading mode and epoxy state.

The d_{31} MFC effective loss factor for each loading mode and epoxy state, computed using (3), is presented in Figure 6. Since the epoxy loss factor increases substantially when the material transitions from glassy to rubbery state, as shown in the previous section, the d_{31} MFC effective loss factor in all loading modes also increases in this transition. For an epoxy matrix in glassy state, it is reasonable to admit that the effective loss factor is negligible (smaller than 0.4%). Nevertheless, even for an intermediate epoxy state, the loss factor is greater than 1% for all loading modes, with exception to loading mode 1 which, as expected, is not much affected by the epoxy matrix. The greater effective loss factors are observed for loading modes 2 (transverse) and 6 (in-plane shear), which attain 5.3% and 4.8% for a rubbery state and 2.9% and 2.8% for an intermediate one. Both transverse shear loading modes (4 and 5) may also present significant effective loss factor ($\sim 2\%$ for intermediate state and $\sim 4\%$ for rubbery one).

Table 2: Effective material properties of d_{31} MFC for the three epoxy matrix states († : values obtained post-processing data provided in [10]).

Coefficient	Glassy	Intermediate	Rubbery	Manufacturer [10]
Y_1^{E*} (GPa) (η_1 , %)	31.37 (0.02)	31.25 (0.12)	31.11 (0.18)	30.34 (–)
Y_2^{E*} (GPa) (η_2 , %)	19.69 (0.35)	18.26 (2.87)	16.56 (5.34)	15.86 (–)
Y_3^{E*} (GPa) (η_3 , %)	9.02 (0.14)	8.73 (1.29)	8.31 (2.78)	– (–)
G_{23}^{E*} (GPa) (η_4 , %)	2.16 (0.25)	2.04 (2.16)	1.88 (4.35)	– (–)
G_{13}^{E*} (GPa) (η_5 , %)	2.42 (0.18)	2.31 (1.63)	2.17 (3.45)	– (–)
G_{12}^{E*} (GPa) (η_6 , %)	5.33 (0.37)	4.92 (2.82)	4.46 (4.81)	5.52 (–)
ν_{12}^E	0.36	0.35	0.35	0.31
ν_{23}^E	0.37	0.36	0.35	–
ν_{13}^E	0.42	0.42	0.42	–
$\epsilon_{11}^T/\epsilon_0$	1019.3	1019.7	1020.2	–
$\epsilon_{22}^T/\epsilon_0$	24.1	24.1	24.1	–
$\epsilon_{33}^T/\epsilon_0$	1573.3	1575.1	1576.9	1558.6
d_{31} (pC/N)	-172.3	-173.0	-173.6	-170
d_{32} (pC/N)	-133.2	-130.5	-126.3	–
d_{33} (pC/N)	308.9	309.1	308.9	–
d_{15} (pC/N)	334.9	335.6	336.3	–
d_{24} (pC/N)	219.3	221.8	225.1	–
e_{31} (C/m ²)	-6.03	-5.87	-5.70	–
e_{32} (C/m ²)	-3.44	-3.07	-2.63	–
e_{33} (C/m ²)	1.48	1.48	1.46	–
e_{15} (C/m ²)	0.81	0.78	0.73	–
e_{24} (C/m ²)	0.47	0.45	0.42	–
k_{31}^2 (%)	6.7	6.7	6.7	6.4 [†]
k_{31}	0.26	0.26	0.26	0.25 [†]

Besides the effective loss factor, the epoxy matrix state also affects other elastic, piezoelectric and dielectric coefficients mainly because of the change in the elastic modulus of the epoxy matrix. Thus, these properties are shown in Table 2. It is noticeable that all elastic stiffness co-

efficients decrease when the epoxy matrix transitions from glassy to rubbery states, as expected, particularly for the transverse normal modulus, transverse shear modulus in the plane 23 and in-plane shear modulus, which are reduced by up to 16%, 13% and 16%, respectively. One may also notice very small increase of the dielectric coefficients (less than 0.25%).

The piezoelectric strain coefficient d_{32} decreases by around 5% for the softer epoxy matrix (rubbery state), in comparison to the case of a glassy epoxy matrix, while d_{24} increases by less than 3% in the same scenario. The effect of a softer epoxy matrix is, however, much stronger for the piezoelectric stress coefficients, such that all of them are decreased for a softer epoxy matrix, particularly for the e_{32} which is decreased by more than 23%, while the coefficient e_{31} is decreased by 5.5%. Thus, the transition to a softer epoxy matrix should affect mostly the actuator performance of the MFC, while its effectiveness as a sensor is less influenced.

5 CONCLUSIONS

A methodology to evaluate the effective damping properties of d_{31} piezoelectric MFCs was presented. In particular, the effect of the anelastic behaviour of the epoxy matrix, common to the MFCs, was analyzed. The effective loss factor induced in the MFC was evaluated using an analogy with the well-known MSE method, but for each loading mode. It was found that, following the epoxy loss factor, which increases substantially when the material transitions from glassy to rubbery state, the d_{31} MFC effective loss factor in all loading modes also increases in this transition. The greater MFC effective loss factors were observed for loading modes 2 (transverse) and 6 (in-plane shear), which attain 5.3% and 4.8% for a rubbery state and 2.9% and 2.8% for an intermediate state. Both transverse shear loading modes (4 and 5) may also present significant effective loss factor.

It was also shown that the epoxy matrix state also affects other elastic, piezoelectric and dielectric coefficients mainly because of the change in the elastic modulus of the epoxy matrix. In fact, all elastic stiffness coefficients decrease when the epoxy matrix transitions from glassy to rubbery states, particularly for the transverse normal modulus, transverse shear modulus in the plane 23 and in-plane shear modulus, which are reduced by up to 16%, 13% and 16%, respectively. The effect of a softer epoxy matrix is also important for the piezoelectric stress coefficients, such that all of them are decreased for a softer epoxy matrix, particularly for the e_{32} which is decreased by more than 23%, while the coefficient e_{31} is decreased by 5.5%. Thus, the transition to a softer epoxy matrix should affect mostly the actuator performance of the MFC, while its effectiveness as a sensor is less influenced.

Notice that the use of static analyses only to estimate dynamic characteristics, such as damping, is based on the fact that the fraction of the strain energy contained in the epoxy matrix would be the same in a harmonic analysis. Nevertheless, this approach requires a set of static analyses for each temperature-frequency pair since the latter determines the epoxy properties that should be used in the static analyses. For practical applications, in which the MFC is bonded to a host structure, the actual energy dissipation, due to the MFC epoxy matrix, would then depend on the fraction of the strain energy contained in the MFC and on how the MFC is deformed. The here obtained results suggest that the effect of the viscoelastic behaviour of the MFC on its host

structure could be important when its application requires it to deform in transverse or shear modes. The complex moduli presented in this work could then be used to predict the effective damping added by the MFC to its host structure. This will be the focus of a future work.

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