ANISOTROPIC DAMPING BEHAVIOR OF REINFORCED PLASTIC PARTS FOR NVH SIMULATIONS

Sylvain CALMELS, Sylvain Mathieu, Maxime LESUEUR
e-Xstream engineering

Abstract

Reinforced plastic materials show a very interesting characteristic which helps to improve the acoustic comfort of car passengers. Their damping behavior is much better than metals and this specific performance became a very important criteria to evaluate the global quality of vehicles. Predicting the acoustic level inside a passenger cell and also outside of the car is a very difficult challenge as it depends on many parameters. The first step is therefore to be able to efficiently capture the noise generated by a single component. This is already not a simple task when the part is made of reinforced plastics.

Predicting the acoustic response of a component requires accurate simulation of its vibrational behavior, meaning its stiffness and damping. When the part is made of reinforced plastics, the design engineer has to deal with a material fully dependent on the local fiber organization. In such a part, the microstructure usually shows a high degree of heterogeneity and anisotropy in terms of stiffness and vibrational response. Only a material model based on the matrix and fiber properties and taking into account the fiber orientation distribution, throughout the part, can accurately predict the stiffness response, and eventually the vibrational response, of said component. This also requires a material model able to capture its damping behavior, itself anisotropic and dependent on the local definition of the microstructure.

This paper will address the current research and developments of e-Xstream engineering regarding the prediction of reinforced plastic material behavior applied for frequency domain analyses. We will demonstrate how simulation can be improved, for safety design simulations in particular, in the automotive industry, helping to reduce design delay, cost and weight of structures.

Introduction

Over the years, the study of noise and vibration propagation became common practice in the automotive industry for assessing the acoustic comfort of passengers. While this practice has been used for a long time on assemblies or parts made of metal alloys, the emergence of the fiber-reinforced plastics (FRPs) in this industry is bringing new challenges to the NVH field.

Indeed, predicting the acoustic response of a given component requires accurately simulating its vibrational behavior, i.e. its stiffness and damping. For parts made of FRPs, the challenge for the design engineer is linked to dealing with a material fully dependent on a local fiber architecture, while showing a high degree of heterogeneity and anisotropy, initially, in terms of stiffness.

It is common practice in the industry to try to circumvent such difficulties by employing the so-called equivalent isotropic and homogeneous material models inside a Finite Element Analysis (FEA). However, these simplified material models show no frequency dependence of
the stiffness and damping properties and thus will fail to predict certain localized behaviors present in FRPs that might generate harsh vibrations, or maybe even fracture, if taken from a vibrational fatigue point of view.

The previous section illustrates one thing: the importance of material modeling and calibration. Indeed, as referred to in section 1, a thorough understanding of the viscous, i.e. strain-rate dependent, behavior of the different constituents is critical in building an accurate material model. This also implies testing the material and thus, another question arises: What is/are the best mechanical testing procedure(s)?

As presented in section 1, our experimental data comes from a Dynamic Mechanical Analysis (DMA) testing procedure. In this particular experiment, a specimen of our studied material (PA66/GF35) was subjected to this dynamic testing in order to extract data in terms of both stiffness and damping. However, the DMA specimen has to be of very small dimensions. In the present study they were 4x5x40mm, and thus have a high probability of not being representative of the materials heterogeneous microstructure, e.g. specimens cut in the center or on the edges of an injected FRP plate. This shows us, for instance, the importance of adding a quasi-static tensile test to re-calibrate the stiffness properties given by the DMA testing procedure.

All of the previous considerations are ultimately being applied to an automotive beam subjected to a dynamic three-point bend test in six different scenarios (see Table 1) that aim at exhibiting the influence of different assumptions on the NVH analysis of a part made of FRP.

ANISOTROPIC DAMPING BEHAVIOR OF REINFORCED PLASTIC PARTS FOR NVH SIMULATIONS

Chopped fiber reinforced plastic materials exhibit better behavior than metals regarding the performances targeted for NVH needs in the automotive industry. Carmakers do not choose these multi-phases materials solely for light-weighting purposes when it comes to designing parts for this particular type of performance. There are already vehicles available which utilize this characteristic in “under the hood” areas, like engine mounts or engine covers, where the high damping provided by reinforced plastics helps reduce the noise in the passenger cell. However, accurately predicting the behavior of such parts and its effect on the noise level heard by passengers still remains a huge challenge due to the fact that, as well as for stiffness and failure, the local damping behavior and its dependency on the frequency are closely linked to the local orientation of fibers induced by the manufacturing process.

This paper addresses e-Xstream Engineering’s second step in building a method and a numerical workflow dedicated to the accurate prediction of short fiber reinforced plastic behavior from the materiel engineering level to the structural level.

The presentation is decomposed into four main sections:

1. Material engineering
   - Calibration of a multi-scale viscoelastic material models from DMA test data
   - Observations on stiffness anisotropy and frequency dependency
   - Observations on damping anisotropy and frequency dependency

2. Structural engineering: application on the frequency response of a roof front beam.
o Initial model: homogeneous isotropic stiffness – homogeneous isotropic frequency dependent damping

o 1\textsuperscript{st} step: effect of a local anisotropic stiffness model

o 2\textsuperscript{nd} step: effect of a local anisotropic stiffness and damping model
  - K & D calculated at 1Hz
  - K & D calculated at 300Hz

o 3\textsuperscript{rd} step: effect of a local anisotropic and frequency dependent stiffness and damping model

o 4\textsuperscript{th} step: effect of the manufacturing process

3. Summary

Material Engineering: characterization of the anisotropic and frequency dependent damping behavior of a SFRP

The constitutive modeling of the frequency response of short fiber reinforced polymer composites is achieved by mean-field homogenization, which derives composite properties through the frequency dependency of its constituents.

Material modelling is done using tensile tests and dynamic mechanical analysis (DMA) experimental data retrieved from A. Launay [1]. These tests were conducted on a short glass fiber reinforced polyamide. The material of study is a polyamide 66 containing 35 wt\% of short glass fibers, provided by DuPont de Nemours (DuPont\textsuperscript{TM} Zytel® 70G35 HSLX). This material is currently employed for automotive applications. ISO 527 tensile tests were carried out on this material at various strain rates. A DMA was performed to study the composites viscoelastic response at low strains, with a sweep from 1 to 500Hz. Two relative humidity (RH) states were tested. In this paper, only the RH50 material is considered due to it being more dissipative, and thus more sensitive to frequency excitation.

Mean-field homogenization

As composite properties depend on material microstructure, including fiber amount and orientation, they are adequately modeled from micromechanics. In particular, mean-field homogenization combines the properties of the underlying constituents of a multi-phase material, allowing original heterogeneous material to be represented by an equivalent homogeneous one. Implemented in the Digimat software [2], this technology has proven effective for a broad range of materials. For the studied SFRP, we represent the matrix material as isotropic viscoelastic, the fiber material as isotropic elastic and account for the local fiber orientation. Mean-field homogenization provides access to per-phase properties, thus enabling a finer interpretation of simulation results as it distinguishes the matrix from the fiber behavior. Mean-field homogenization also provides an avenue to investigate the origin of experimental variability of composite properties by revealing their sensitivity to micromechanical parameters.
Experimental DMA data

In DMA, a sinusoidal displacement signal is imposed, at an angular frequency $\omega$. The testing device records the amplitude as well as the phase lag of the load. This enables, in the frame of the viscoelastic theory (see ISO 6721-1), to evaluate the storage modulus $E'$, the loss modulus $E''$, and the loss factor $\tan\delta$. The storage modulus represents the elastic part and measures the stored energy while the loss modulus represents the viscous part and measures the dissipated energy. As for the loss factor, it is the ratio between dissipated and stored energies.

The DMA was conducted at room temperature at frequencies ranging from 1 to 500 Hz [1]. The samples, of dimension 4x5x40mm$^3$, were cut from the homogeneous area of an injection molded ISO527 tensile specimen. Experimental data recorded is plotted in figure 1. An expected increase in stiffness with the excitation frequency rise is seen on the measured data. However, no clear dissipative peak appears in the frequency range, making the identification of a characteristic time difficult.

![Figure 1: DMA in tensile mode. Frequency sweep at room temperature on RH50 material](image)

Frequency-dependent material modeling

The studied material is composed of two phases: the short glass fiber inclusions and the polyamide 66 matrix. The short glass fiber material is modeled by an isotropic elastic material. A linear isotropic viscoelastic model is defined using a 4 term Prony series for the polyamide 66 matrix. A linear viscoelastic constitutive model is defined as:

$$\sigma(t) = G(t):\varepsilon(0) + \int G(t - \tau):\dot{\varepsilon}^{(we)}(\tau)d\tau$$

With $\varepsilon(0) = \lim_{t \to 0}\varepsilon(t)$ and $G(t) = 2G_R(t)I^{dev} + K_R(t)I \otimes 1$

The integral equation represents the memory effect. This means that the stress $\sigma(t)$ at time $> 0$ depends on all the strain history up to that time, i.e., $\sigma(t)$ depends on $\varepsilon(s)$, $s \leq t$. $G(t)$ are the relaxation moduli which, in the isotropic case, are represented by time-dependent shear and bulk moduli $G_R(t)$ and $K_R(t)$, respectively. That leads us to introduce the isotropic viscoelasticity as a Prony series of the shear modulus $G(t)$ and of the bulk modulus $K(t)$, which are defined in the following way:
\[ G_R(t) = G_0 \left[ 1 - \sum_{i=1}^{n} w_i \left( 1 - e^{-\frac{t}{\tau_i}} \right) \right] \]

Where \( G_0 \) is defined as the initial shear modulus (at \( t = 0 \)) and \( \tau_i \)'s and \( w_i \)'s are the characteristic times and associated weights of the Prony series. Those are the parameters needed to define the deviatoric part of the constitutive behavior. The same equations can be derived with the bulk modulus \( K_R(t) \) instead of the shear modulus \( G_R(t) \) to represent the volumetric behavior. With the objective of a calibration from DMA data, the expression of the shear and bulk moduli can be derived as a function of angular frequency instead of time. A complex dynamic modulus is then obtained:

\[
G_R(\omega) = G'_R(\omega) + iG''_R(\omega) \\
G'_R(\omega) = G_0 - G_0 \sum_{i=1}^{n} \frac{w_i}{1 + \omega^2 \tau_i^2} \\
G''_R(\omega) = G_0 \sum_{i=1}^{n} \frac{w_i \omega \tau_i}{1 + \omega^2 \tau_i^2}
\]

Where prime and double prime symbols define, respectively, the storage and loss moduli. The same equations can be written with the bulk modulus.

From a microstructural point of view, the short glass fibers are treated as inclusions distributed inside a matrix. They have an aspect ratio of 30 and are considered to be mainly oriented along the loading direction. An orientation tensor \( a_{ij} \) is defined to capture the orientation distribution of the short glass fibers [3]. A strong alignment of the fibers along the loading direction is chosen:

\[
a = \begin{bmatrix}
0.85 & 0 & 0 \\
0 & 0.13 & 0 \\
0 & 0 & 0.02
\end{bmatrix}
\]

A reverse engineering is then run to fit the frequency dependent material behavior based on the DMA data. The only phase being reverse engineered is the viscoelastic matrix: the instantaneous bulk and shear moduli, as well as the relaxation times and weight of each of the Prony series. Because the frequency dependence of the Young's modulus is our only available input, a simplification was in order. This simplification assumes that the bulk and shear relaxation times and weights are identical. This leads to assuming a constant Poisson’s ratio over all frequencies. However, it is worth noting that, while often assumed constant in harmonic calculations, the Poisson’s ratio commonly decreases with increasing frequency. The resulting model, as well as experimental data, is plotted in figure 2.
Figure 2: DMA in tensile mode. Frequency sweep at room temperature on RH50 material and calibrated material model.

Once identified, the resulting material and microstructure can be used to predict the frequency response in other loading directions or short fiber distributions. Responses in the transverse direction and with a perfectly random fiber orientation are detailed in figure 3.

![Graph of DMA results](image)

Figure 3: Storage modulus and loss factor predictions as a function of frequency: in the longitudinal (L) and transverse (T) directions (a) and with random fiber orientation (b)

Experimental tensile data correlation

It is known that DMA tests provide meaningful information on a physical level, but non-harmonic calculations based on the calibrated model should not be relied on a priori. The weak local strains (0.1%) and the limited experimental frequency range may not be representative of the true loading conditions or of the underlying physics of the polymer under study. Comparison with tensile test data would confirm the consistency of the material model.

Static tension tests were performed with stress loading rates spanning four orders of magnitude, from 2.5 to 2500 MPa/s [2]. Influence of the stress rate on the stiffness is visible from the very beginning of the loading on these tensile specimens. The evolution of the surface temperature during loading corroborates the influence of the stress rate on the dissipative effects from the very beginning of the loading. This clearly highlights short-term viscoelastic
effects with a large characteristic scale time of about 1s. This order of relaxation time cannot be calibrated from the DMA conducted, as frequencies below 1 Hz would be necessary. As a result, the previously calibrated data cannot fully represent the time response of the material.

However, in order to validate the identified viscoelastic model, the lowest stress rate tensile test can be used as a comparison. In this case, where the loading rate is low, one can expect the short term viscoelastic effects to be overridden so that they do not impact and stiffen the initial behavior. The comparison between the experimental tensile tests performed at 2.5 MPa/s and the numerical model prediction is shown in figure 4. The first percent of strain loading shows a good correlation between the DMA calibrated model and the low stress rate tensile test, validating the consistency of the reverse engineered behavior.

![Figure 4: Experimental/numerical comparison of initial stiffness at 2.5MPa/s](image)

Structural engineering: application on the frequency response of a roof front beam

The previous section has driven the process of creation of a multi-scale visco-elastic material model for a PA66GF35 grade capable of capturing the macroscopic behavioral dependency to local fiber orientation and frequency. This model has been validated through comparison with experimental data and is now applicable at the structural level. In this 2nd section, we will observe the effect of each level of accuracy available in this model on a frequency response analysis performed on an injected roof front beam. The following test matrix will be covered:
<table>
<thead>
<tr>
<th>Reference</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gates Positioning</td>
<td>N°1</td>
<td>N°1</td>
<td>N°1</td>
<td>N°1</td>
<td>N°2</td>
</tr>
<tr>
<td>Homogeneous isotropic stiffness</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous isotropic damping</td>
<td>V</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber orientation dependent stiffness</td>
<td>V</td>
<td>V (calculated at 1Hz)</td>
<td>V (calculated at 300Hz)</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>Fiber orientation dependent damping</td>
<td>V</td>
<td>V (calculated at 1Hz)</td>
<td>V (calculated at 300Hz)</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>Frequency dependent stiffness</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>Frequency dependent damping</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
</tbody>
</table>

**Table 1: Test matrix**

**Reference model and loadcase description**

The chosen component is a roof front beam (see figure 5). This component has an important influence on the NVH behavior of the passenger cell due to its role in constraining the roof, an important panel whose vibrations can cause undesired noise in the vehicle, as well as holding several accessories, like the sunshields. This component is, currently, mostly made with...
steel in, however it could be done using reinforced plastic materials. That is the scope of the exercise proposed here, regarding its vibrational behavior.

The reference model has been defined using an isotropic and homogeneous stiffness and damping model. The isotropic E-modulus has been defined using the commonly used ratio of 0.6, applied on the measured axial E-modulus of the composite, here, 7705 MPa. On the damping side, a homogeneous value of 0.03 has been applied on the overall model. Table 2 below summarizes this reference model approach:

<table>
<thead>
<tr>
<th>Model</th>
<th>E-modulus</th>
<th>Poisson’s ratio</th>
<th>Damping</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>4623MPa</td>
<td>0.35</td>
<td>0.03</td>
<td>1.4125e-09T/mm3</td>
</tr>
</tbody>
</table>

Table 2: Reference modeling approach

The loadcase applied is a 3 point bending frequency response case as shown in figure 6 below:

![Figure 6: Loadcase description for a driving point frequency response case 0-300Hz](image)

**Model 1 – 5: Injection simulations to predict fiber orientation distributions**

Models 1 through 5 will be defined using a multi-scale visco-elastic material model capable of capturing the macroscopic behavioral dependency to fiber orientation, both for stiffness and damping. This infers that the FE model must contain the fiber orientation distribution throughout the part, thus allowing us to take into account the material’s heterogeneity, due to the manufacturing process, in the FEA’s prediction.

Two injection simulations have been performed in order to get two different fiber orientation fields, as shown in figure 7. This will allow us to quantify the effect of using different parameters for the injection process on the components behavior. We can observe that some local differences in the fiber orientation organization appear, especially around the two holes close to the beam’s extremities. Fiber orientations in the middle of the beam look similar across the two processes.

**Model 1 – 4** will use fiber orientation field N°1
Model 5 will use fiber orientation field N°2.

Figure 7: 2 different fiber orientation distributions from 2 different set of gate positioning in Injection Process

Results on Model 1: Effect of a local anisotropic stiffness model

The material model used in model 1 is an elastic material model. This model is capable of capturing local stiffness dependency to fiber orientation and takes it into account in a FEA. This has been used in combination with the fiber orientation Field 1 shown previously. Figure 8 shows the range of behaviors which will be used locally in the FEA, depending on the local fiber orientation information available in each finite element. Visible behaviors will be applied on each material direction for each fiber orientation tensor coefficient in order to reproduce the local anisotropy due to local fiber orientations.
Figure 8: Range of stiffness behaviors captured locally by the multi-scale elastic model.

Damping modeling is the same as the reference model:
- isotropic homogeneous modal damping = 0.03

Figure 9 shows the comparison between the prediction of dynamic responses obtained with the reference model and model 1 (Local aniso K). The usage of this multi-scale stiffness model directly influences the prediction of excited frequencies, in this case, with gaps between 4% and 7%.

As the damping modeling approach is the same, there is a very negligible impact on the acceleration peak predictions.
Figure 9: The usage of a fiber orientation dependent stiffness shifts the prediction of excited frequencies compared to an isotropic and homogeneous stiffness model.

Results on Model 2: Effect of a local K & D calculated at 1Hz

Model 2 has been defined using the multi-scale visco-elastic material model calibrated in the material engineering section, in combination with fiber orientation field N°1. Hence, in this case, both the stiffness and the damping behavior take into account the anisotropic behavior of the material as a function of local fiber orientations.

No frequency dependency is modeled here. Anisotropic stiffness and damping has been calculated at 1Hz and used for the complete frequency range 0-300Hz in the FEA.

Figure 10 shows a comparison between the reference result and the model 2 (Local K&D 1Hz) result in terms of dynamic stiffness observed at the excitation point. The usage of local anisotropic stiffness calculated at 1Hz here exhibits a higher influence on the excited frequency predictions. The gap with the reference has increased from 7% to 15%. Moreover, the model 2 approach also has an influence on the modal density of the structure and predicts only one peak for the first excited frequency instead of two.

The local anisotropic damping model here, with data calculated at 1Hz, shows non-negligible differences compared to the reference for the prediction of the 1st maximum acceleration peak. The gap here is 28%, which could highly influence the final design of such a part.
Figure 10: The usage of a fiber orientation dependent damping shows non negligible differences with the reference when considering the prediction of maximum acceleration peaks.

Results on Model 3: Effect of local K & D calculated at 300Hz

The material model used for model 3 is the same as model 2, but the stiffness and damping data have been calculated at 300Hz instead of 1Hz.

The fiber orientation distribution considered is still field 1.

Figure 11 shows the comparison of results between the reference and model 3 (Local K&D 300Hz). The prediction of the structure’s dynamic stiffness is now completely different, depending on the modeling approach. The difference in terms of frequency for the 2nd peak is 32%, and in terms of the acceleration peak, the gap reaches 71%. Moreover, the high frequency behavior is completely different with a very distinctive level of acceleration, due to the frequency dependency of both stiffness and damping. The difference likely seems due to the frequency dependency of stiffness but should be confirmed by further investigation.
Results on Model 4: Effect of local K & D including frequency dependency

The material model used for model 4 is the same as model 2 and 3 but here stiffness and damping exhibit a frequency dependency, in addition to their fiber orientation dependency.

The fiber orientation distribution considered is still field 1.

Figure 12 shows the comparison of results between the reference, model 3 (Local K&D 300Hz) and model 4 (Local K&D freq dep).

At first, one interesting observation which pops up is that model 3 and 4 show very close results. During the material calibration work, it has been observed on measured data that the frequency dependence of both stiffness and damping decrease quickly starting from 100Hz. This means stiffness and damping are varying slowly while the frequency is increasing to 300Hz. Hence working with fixed data at 300Hz or with a full frequency dependent model will have a low influence in this case.

Globally, the comparison with the reference is similar to what has been observed previously on model 3 (Local K&D 300Hz). Gaps between model 3 and 4 are not negligible, but the reader could consider it low, compared to the level of complexity required to account for a full frequency dependent model. The point here is that it’s difficult to know in advance which frequencies will be excited. In this case, the 1st peak appears at frequencies close to this saturation state. If this happened at 30Hz or 50Hz, the influence of using, or not using, a full frequency dependent model would be higher. Hence, accounting for this aspect of the model behavior can be seen as a way to be more robust from the very first calculation on the prediction’s level of quality.
Results on Model 5: Effect of the manufacturing process

The aim of this last sensitivity study is to observe the influence that the manufacturing process parameters could have on the final performance of a part.

We have applied the same material model as model 4, accounting for the full frequency and fiber orientation dependency on both stiffness and damping, but with a different fiber orientation field corresponding to different gate positioning choices. For this model, the fiber orientation distribution considered is field 2.

Figure 13 shows the comparison of results between model 4 (Local K&D freq dep) and model 5 (Local K&D freq dep 2). The global “shape” of the behavior remains the same between the structure with field 1 or field 2, but some slight differences can be observed on the prediction of the excited frequencies and maximum acceleration peaks with gaps, respectively, of 6% and 5%. This is of course low compared to the previous gaps observed between the models, but here, the topic is slightly different as we are not trying to consider which mechanical parameters should be captured correctly by the material model, but how much the manufacturing process could influence the final design of a part. Hence, in this case, 5% difference in the mechanical behavior of a structure can drive us to optimize the design and potentially save mass on it.

Figure 12: In this case, accounting for a full frequency dependence does not change significantly the prediction.
Figure 13: The manufacturing process influences the final part’s behavior and become a parameter to be considered during design iterations.

Summary

In conclusion, this paper has demonstrated a procedure to calibrate a viscoelastic material model capable of capturing both fiber orientation and frequency dependency of stiffness and damping in a FEA. Once the material model has been defined, a sensitivity study was performed, at a structural level, on a frequency response analysis of a beam which allowed us to identify the first order material specificities to capture in FEA in order to be accurate.

- **Material engineering level**
  - DMA test data are required to characterize the material’s vibrational behavior in the desired range of frequencies, according to the targeted final application
  - Quasi static tensile data are required to calibrate the material’s stiffness
  - The microstructure in tested coupons is necessary to accurately calibrate a fiber orientation dependent material model
  - Final models exhibit anisotropic stiffness and damping behavior as a function of fiber orientation and frequency

- **Structural engineering level**
  - Capture, for NVH needs, the anisotropic and heterogeneous stiffness and damping behavior of reinforced plastic materials driven by the fiber orientation field throughout a part induced by the manufacturing process
  - Frequency dependency of stiffness and damping have a very important influence on the FEA prediction.
  - A full frequency dependent model is recommended as it’s impossible to know, in advance, the frequencies where maximum acceleration peaks will appear.
This paper has addressed the most advanced material modeling approach available today for NVH applications of reinforced plastic materials and has demonstrated the interest to use a multi-scale visco-elastic material model. The influence of such a model on the predictions of FEA could help NVH and Fatigue CAE teams to better predict the vibrational behaviors of parts to be designed and drive to save weight in better optimized final designs.

Bibliography