ANALYTICAL, EXPERIMENTAL AND NUMERICAL APPROACH OF STORAGE AND LOSS MODULI OF FIBRE REINFORCED EPOXY COMPOSITES

Efstathios E. Theotokoglou[1], Ioannis Giannopoulos[2] and Emilio Sideridis[3]

[1]School of Applied Mathematical and Physical Sciences, Dept. of Mechanics-Lab. of Strength Materials, National Technical University of Athens, Zographou Campus, Theocaris Bld., GR-0157 73, Athens, Greece
Email: stathis@central.ntua.gr, web page: http://users.ntua.gr/stathis

[2] School of Aerospace Transport and Manufacturing, Centre of Excellence for Aeronautics
Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK
Email: i.giannopoulos@cranfield.ac.uk, web page: http://www.cranfield.ac.uk/about/people-and-resources/academic-profiles/satm-ac-profile/mr-ioannis-i-giannopoulos.html

[3]School of Applied Mathematical and Physical Sciences, Dept. of Mechanics-Lab. of Strength Materials, National Technical University of Athens, Zographou Campus, Theocaris Bld., GR-0157 73, Athens, Greece
Email: siderem@central.ntua.gr

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ABSTRACT

In the numerical study presented in this article, the dynamic response of micro-mechanically modelled unidirectional fibre reinforced composites was investigated. The aim was to use numerical analysis for providing with an insight to the material properties that would be used for initial assessment of the dynamic response of composite materials. Assumption to the investigation was the known dynamic response of the matrix material in terms of its tangent and loss moduli, which were evaluated through dynamic mechanical analysis testing and therefore treated as an input to our numerically simulated problem. Consequently, composite fibre materials made of glass fibre and epoxy matrix modelled with finite elements and tested in dynamic numerical solution sequences. The results of the analyses were the prediction of the tangent and loss moduli of the composite material. The results were correlated with analytical and experimental studies. The modal behavior of the material was numerically investigated as well in an effort to describe the structural damping properties in terms of fibre volume content.

1 INTRODUCTION

Dynamic Mechanical Analysis (DMA) is an experimental set of testing methods generally employed for extracting polymer material property information. Information like the material storage and loss modulus curves can be extracted by the use of these methods. DMA is more often conducted on specimens where load or displacement is applied at a constant frequency, while the testing temperature is varied. The opposite technique is also applicable, i.e. keeping the specimen temperature constant and varying the applied loading testing frequency. The storage and loss modulus curves of the material are used for the approximation of the polymer material Glass Transition Temperature (Tg) which is an important parameter for understanding the polymer material behavior and its usage spectrum.

Structural applications employing polymer composite materials are in the need of high material stiffness, high damping and large utilization spectrum in terms of environmental temperature exposure. Unfortunately, polymer materials generally are not used beyond the temperature region of the Tg, so it is quite advantageous to use polymer matrices with high glass transition temperatures. Polymer materials with high Tg's, are generally very stiff with low fracture toughness and low structural damping. Thus material scientists are compromising some properties in order to achieve acceptable overall material response. Nanomaterials are employed in this sense in order to augment the original polymer matrix base mechanical behavior [1,2]. Another example of DMA testing is to test polymer matrix fibrous composites specimens in order to verify the application range of the composite material upon specific structural applications [3].

Micromechanical analysis can be assumed as an idealized material modelling practice. Application of it on fibre reinforced composites was found to be a useful tool for material property extrapolation to the macro-material scales [4-6]. Using the modelling methods of micromechanics and the techniques of Dynamic Mechanical Analysis, the dynamic response of polymer materials or composite polymer materials can be approximated. Analytic formulas and experimental values of the dynamic response of a micromechanical model can be found in [7]. The current study employed dynamic finite element analysis in order to extract a glass / epoxy fibrous composite dynamic material properties using as an assumption only the known dynamic response of the polymer matrix.

2 METHODS

The conceptual micromechanical model of a unidirectional fibrous composite used in this study is shown in Fig.1. It comprises of concentric cylindrical domains of various properties, each one of them representing a different material or phase. The inner most cylinder models the fibre and the consecutive outer cylindrical layers covering the fibre are the interphase region and the matrix material respectively.

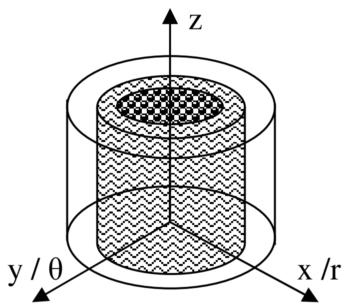

Figure 1: Micromechanical model of a unidirectional fibrous composite

The finite element model of the analysis is shown in Fig.2. Taking advantage of the symmetry of the problem, only a quarter of the domain was numerically modelled. For the initial investigation, the interphase region between the fibre and the matrix was not modelled. Commercial software package (NASTRAN) [8] was used for the numerical simulation with appropriate element and solution sequence definitions. The overall 1325 finite element nodes that constituted the model, structured up to 945 solid type elements (HEXA8 and PENTA6) that proved to provide with adequate approximation and visibility of the results.

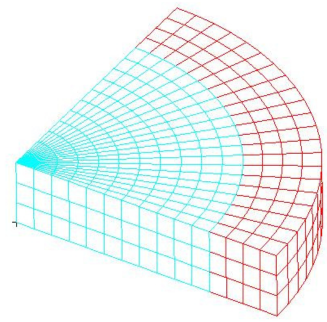

Figure 2: Finite element model of the unidirectional fibrous composite

Dynamic analysis of the numerically modelled domain can take place while loading in either longitudinal or transverse directions. In the present study, results of the transverse dynamically loaded cases are shown, since the effect of the matrix mechanical properties onto the response of the composite material are more profound in that direction. Similar investigations to the one shown herein could be established for the longitudinal loading direction.

The fibre material was glass and it was assumed that its properties were unaffected by changes in frequency or temperature. It was assumed to be a homogeneous material with modulus of elasticity E= 72 GPa and Poisson ratio ν=0.2 and with practically a zero material loss factor. The polymer matrix was made of epoxy and its dynamic properties are shown in Fig.3 as resulted from DMA testing [7].

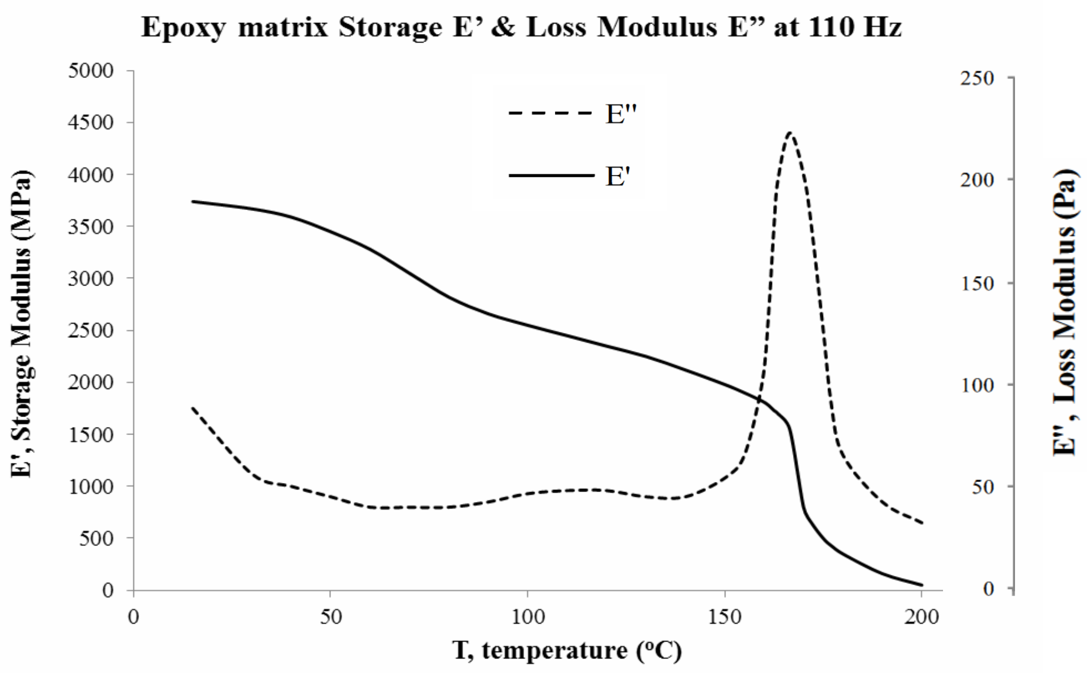

Figure 3: Storage and Loss modulus of the epoxy matrix obtained by DMA testing [7]

In Figure 4, the finite element model loaded transversely by a unit pressure load is shown.

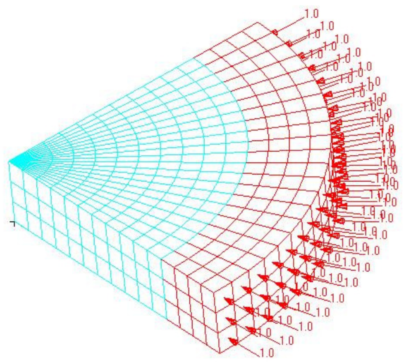

Figure 4: Unit pressure loading along the transverse direction

The dynamic analyses studied, were performed on dynamically loaded numerical models via temperature and frequency sweep through analyses.

During the temperature sweep through, numerical models were dynamically loaded with unit pressure at specific temperature values. Corresponding dynamic mechanical properties of the epoxy material from Fig.3 were employed in the model at each analysis run. The frequency of the dynamic test was kept at 110Hz in order to be consistent with the values of Fig.3, [7]. Displacement response was recorded and storage and loss moduli curves were produced for various fibre volume content composite materials.

Frequency sweep was performed at two temperature, room temperature (25^{o}C) and maximum loss temperature (approximately at 172^{o}C), based on the curve of Fig.3, values for various fibre volume contents. For the frequency sweep through numerical approach there were no experimental data available on the variance of the epoxy dynamic properties, so it was assumed that these will remain the same to the ones dictated in Fig.3. By this assumption, it became possible to observe the response of the materials in a varied frequency environment.

3 RESULTS

A. TEMPERATURE SWEEP DMA

Numerical results of the variation of the transverse storage modulus according to temperature and for various fibre volume contents are shown in Fig.5.

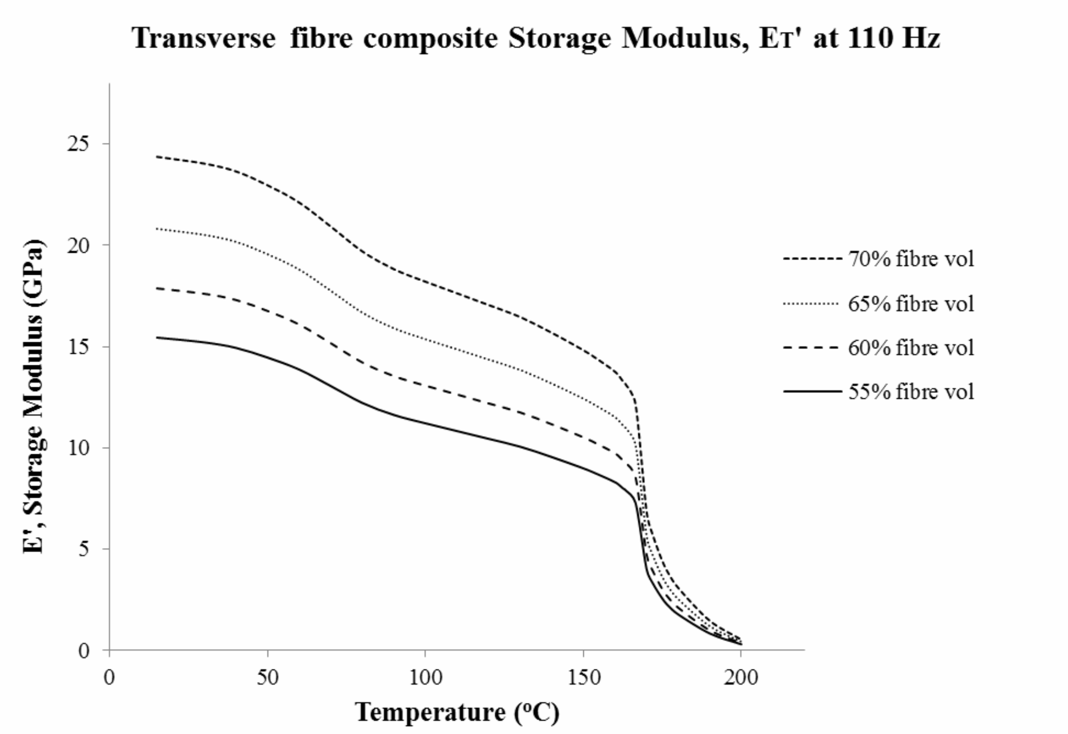

Figure 5: Storage modulus curves resulted from the numerical model for various fibre volume contents

Similarly numerical results of the variation of the transverse loss modulus according to temperature sweep and for various fibre volume contents are shown in Fig.6.

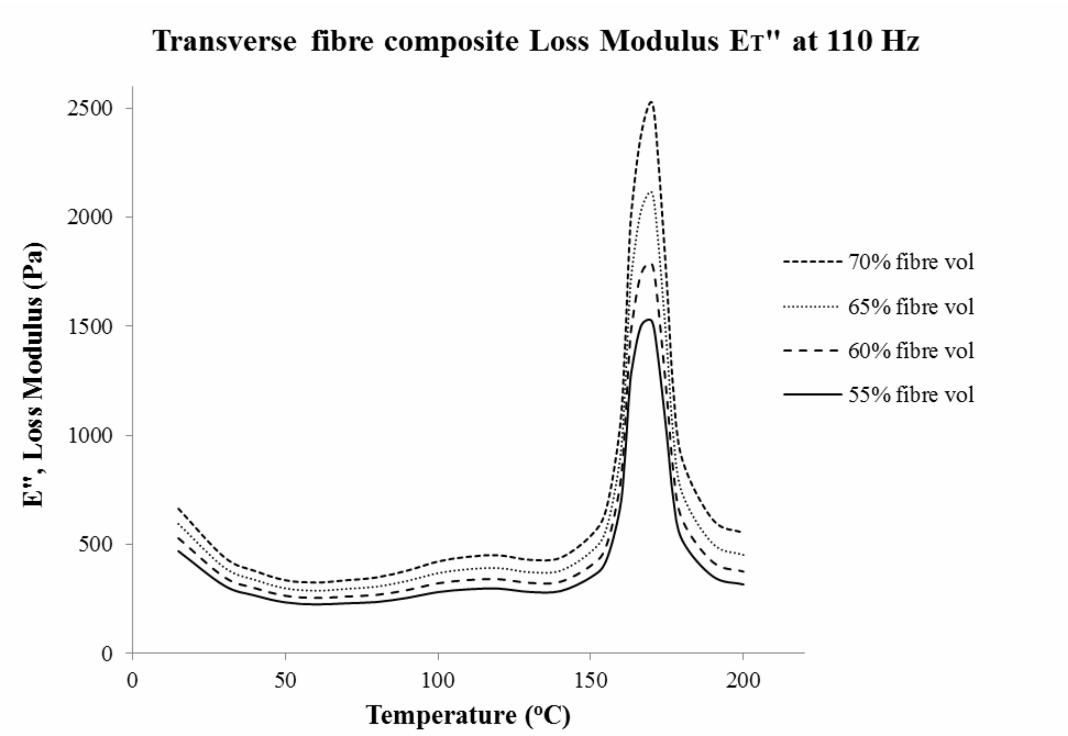

Figure 6: Loss modulus curves resulted from the numerical model for various fibre volume contents

Correlation of the numerical results with analytic and experimetnal ones for 65% fibre volume ratio specimen from reference [7] are shown in Figures 7 and 8.

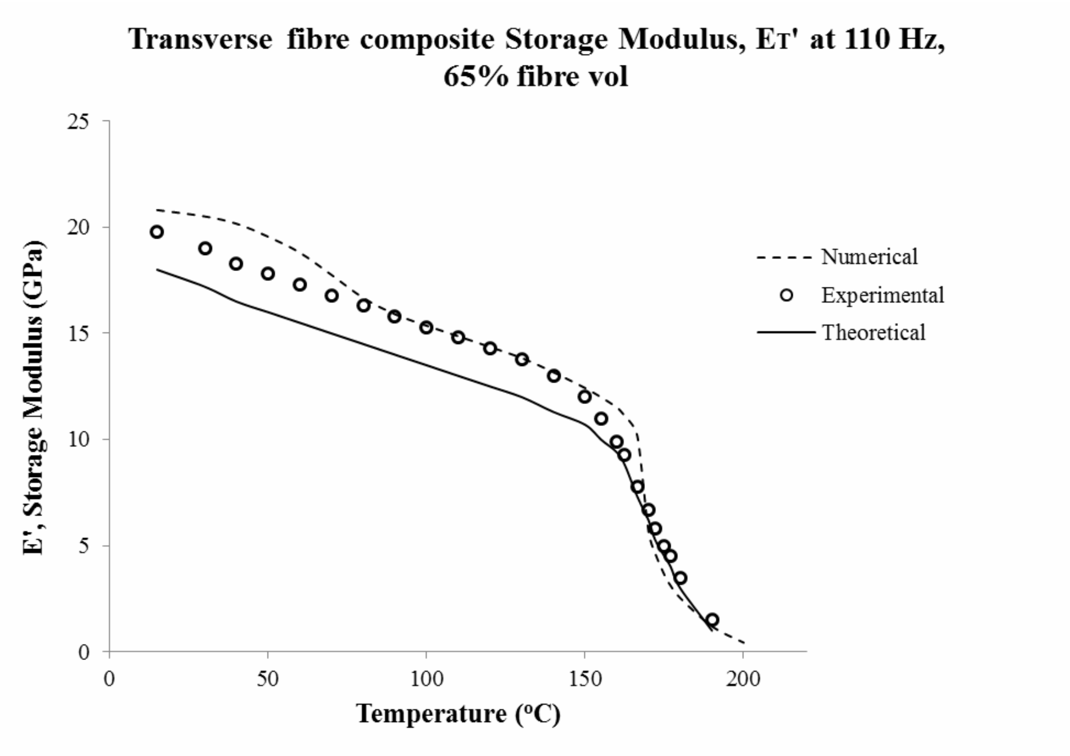

Figure 7: Correlated Storage Modulus curves

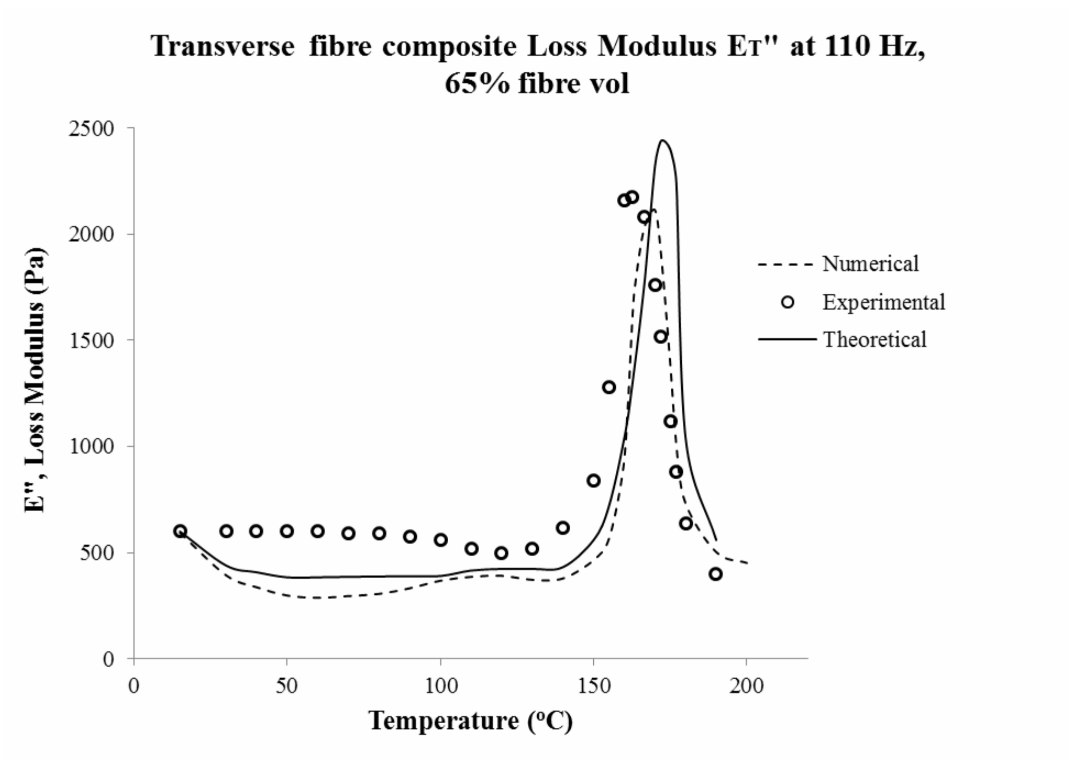

Figure 8: Correlated Loss Modulus curves

B. FREQUENCY SWEEP DMA

Numerical results of the composite material response versus temperature for a constant frequency and for various fibre volume contents are shown in Fig. 5. As it has already explained in Section 2, since there were no available data on the variation of the epoxy mechanical properties according to frequency, they were assumed to be constant. The study provided with an insight into the material response and the type of data that could be extracted for a numerical simulation in the case that actual frequency dependant data were available.

The results drawn for the frequency sweep through test are not displayed in terms of storage and loss moduli, but in terms of radial displacement, r direction shown in Fig.1, versus frequency. The reason for that was that in the case of temperature sweep, the actual changes on the graphs indicate the glass transition temperature. For a frequency sweep test, it was considered more important to show the effect of the matrix structural damping and the fibre volume content of the material on the global dynamic response of the composite, in order to draw conclusions on the structural damping of the composite. In Figs 9 and 10, the numerical frequency sweep through test engulfed the first modal response for each fibre volume fraction. The aim was to draw a pictorial representation of the height and sharpness of the curves close to the first resonant frequency, for observing the possible dynamic behaviour of the material.

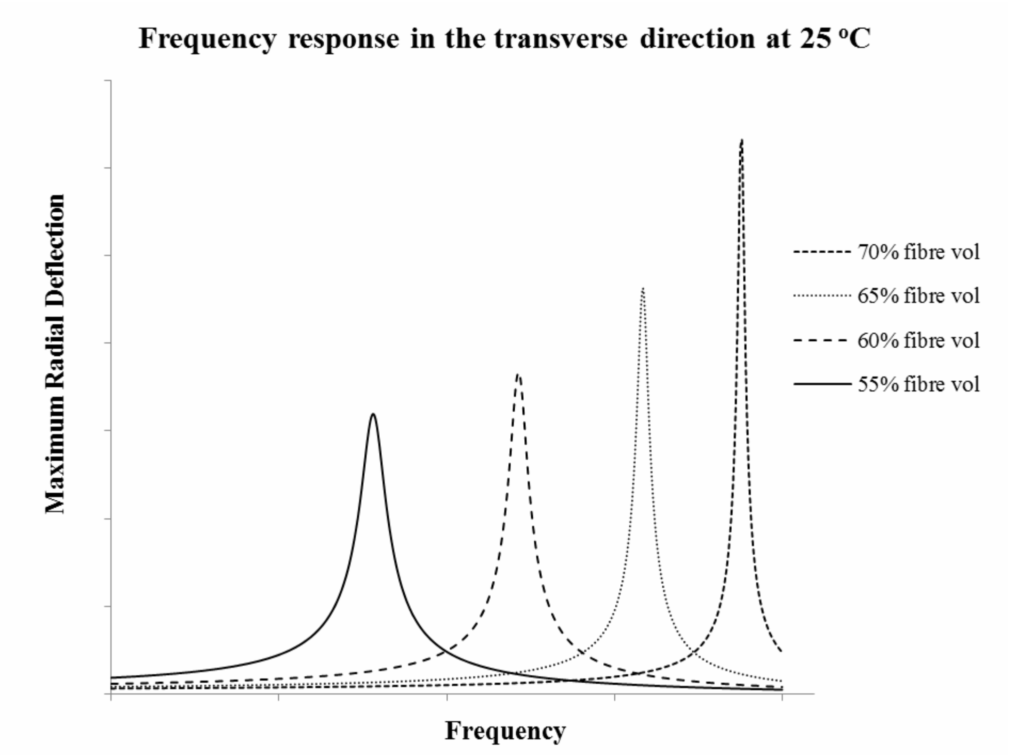

Figure 9: Frequency response of the radial displacement for various percentages in fibre volume content, at room temperture

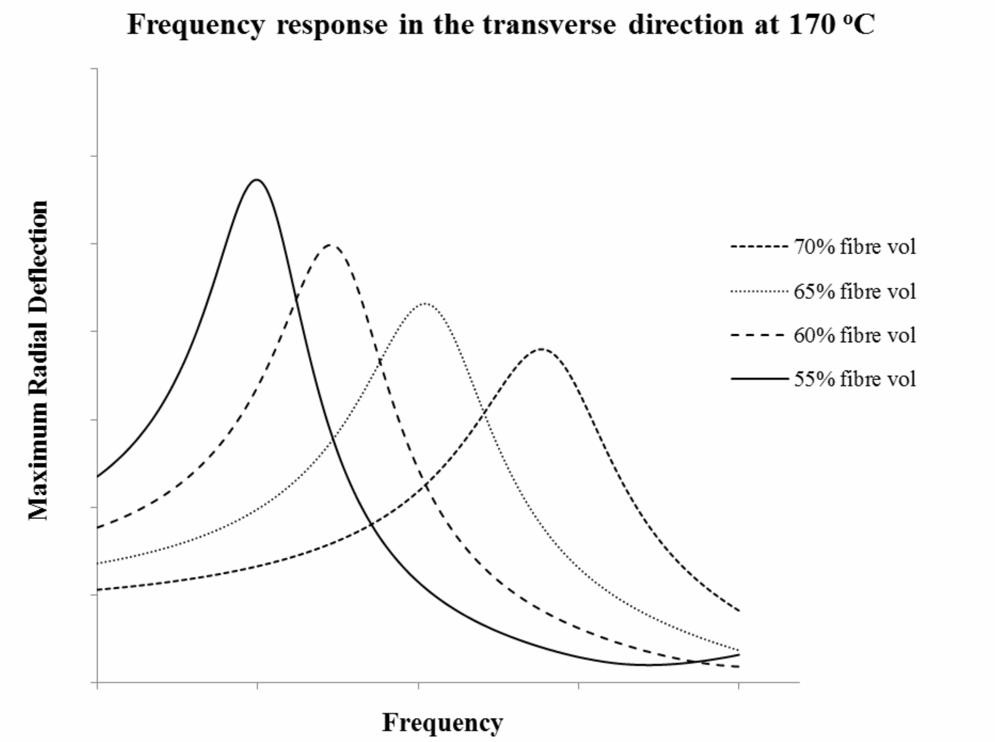

Figure 10: Frequency response of the radial displacement for various percentages in fibre volume content, at maximum loss temperature

4 DISCUSSION

Numerical analysis results from the temperature sweep DMA showed that for higher fibre volume content, the composite material was proportionally stiffer (Fig.5). Similarly, the loss modulus of the composite material exhibits higher values (Fig.6). These results were anticipated since the tanδ of the epoxy material, where δ represents the phase difference between load and response is constant. The levels of the storage and loss moduli at various temperatures were approximated.

Figures 7 and 8 show the correlation between the numerical results of the current study, to the experimental and analytic results proposed in the study of Theocharis et al. [7]. The differences between these results can be attributed to the approximation efficiency of the numerical model, to variations in values from the actual testing set up [9] and to the approximating assumptions that led to the analytic study of the problem [7]. The difference in the peak value of the loss modulus in terms of actual loss modulus value as well as the temperature of occurrence indicates the dependance of the tested epoxy material properties to other factors and processes within the test that simple finite element procedure was not able to capture with great accuracy.

Figures 9 and 10, display the frequency response of the composite at various levels of matrix damping and for various fibre volume contents. Further analysis of the results and sharpness of the curves near the vicinity of the resonance, can lead to approximations of the modal structural damping of the material which in turn can generate results on global structural damping behaviour [10, 11]. It is worthwhile noting that while for small values of damping, the first modal eigen frequencies are higher for small fibre volume fraction, the opposite occurs for large values of material damping, Fig.10.

The additional effect of numerically modelling the interphase region as a separate domain in between the fibre and the matrix was investigated separately [4, 5]. It was hard to make any assumption for the domain size where the interphase region resides, since there was no information in the literature on the domain's variance according to temperature, especially in the vicinity of the glass transition temperature of the epoxy. As a rough approximation, the existence of an interphase domain to our two phase material, would give rise to a stiffer composite material, thus its response could be approximated and bounded by simulations of a slightly larger in fibre volume content composite.

5 CONCLUSIONS

Micromechanical modelling and numerical analysis could be used to generate rough approximations to the dynamic response of unidirectional fibrous composites, assuming that the dynamic reponse of the matrix and the fibre material are known. Fibre and matrix materials and properties could be mixed along with the assorted fibre volume ratios in the composite and their dynamic response to be calibrated accordingly. Such an investigation could potentially provide insights to the designing of suitable materials specifically tailored to certain applications were specific dynamic response characteristics are expected. Numerical results that can be utilized for the designing purposes are the storage and loss moduli, their mapped variations with temperature as well as the material modal damping at various frequency levels.

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