TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue II, June, 2024

SHEAR MODULUS ESTIMATION OF FIBER COMPOSITES USING FINITE ELEMENT METHOD

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Abstract: *Composite materials, in the general case, are made up of two or more components distributed in complex ways within the resulting material. It has global elastic properties, determined by the values of the elastic constants of the component materials and their geometry. Determining the characteristics of the homogenized material represents a main concern in a first phase of the design. To determine how the resulting, homogenized composite behaves, numerous calculation procedures were developed to predict the engineering material coefficients. In general, such a method is laborious and requires significant calculation time. Experimental measurements, presuppose the manufacture of the new material. Boundary methods, which assume the use of relatively simple relationships, lead to errors that can sometimes be significant. The research presents a fast method to estimate the shear modulus values for a new material with a reduced volume of calculations, via Finite Element Method(FEM). The torsion of a composite bar is studied for which the natural frequencies are determined using the FEM and the values thus determined are compared with the values obtained using the classical theory of the bar. The elastic constants of the material phases together with the arrangement in the composite are known. Based on these values, a good estimate of the shear modulus can be made. To verify the theory, an example is provided.*

Key words: composite; two phases composite; torsional vibrations; FEM ; shear modulus

1. INTRODUCTION

Determining the engineering constants of a composite is a main stage in any new design process. There is a rich literature presenting theoretical or experimental methods for doing this. For composite materials widely used at the moment, numerous calculation formulas or results in the form of inequalities are proposed. The field of determining the elastic constants of a composite material is very researched and numerous calculation methods are offered. This is due to the fact that any designer needs to know these values in order to create a design that corresponds from all points of view, including that of calculating the resistance to different loads. The paper presents a method to obtain the shear modulus using FEM for analyzing the composite and obtaining the eigenvalues and comparing the results with those obtained by applying the classical theory for the bar . Since the eigenmodes for axial, transverse and torsional vibrations are obtained through the FEM, the calculations made considering the bar-type composite element fixed at the ends provide a series of useless information. That is why the paper proposes the optimization of the calculation effort if only shear modulus is sought. This is done by introducing boundary conditions to eliminate unwanted vibrations. In the following, a brief presentation of the main ways to obtain the engineering coefficients for different two phase composite materials is given. For the composite materials that represent the subject of the work, the presentation will be wider.

At the moment, many procedures are elaborated to obtain the elastic coefficients if a two-phases composite is studied. These values need to be known with a certain approximation from the design and dimensioning phase. To do this, many of the works involve the prior determination of the stress and strain field if an arbitrary (usually particular) loading of the material is considered. Many such methods, which use particular load cases, ultimately

Received: 30.04.24; **Similaritie**s: 29.05.24: **Reviewed**: 10.06./10.06.24: **Accepted**:21.06.24.

provide only upper and lower bounds for these sought quantities. Obviously, for certain circumstances these limits offer totally unsatisfactory results [1]. In the mentioned paper, two cases are considered: first is an orthotropic material, second a transversally isotropic one. These values become disturbingly imprecise for certain ratios of the phases [2-5]. Another class of methods uses micromechanical models [6-8]. For the study of composites widely used today, those strengthen with cylindrical fibers, there are numerous researches [9-16]. These studies involve different and new aspects that must be taken into account [17-19]. Obviously, the most reliable are the experimental methods, but they are expensive and time-consuming. Modern calculation methods, widely verified and accepted in engineering such as FEM can present advantages for the study of particular phenomena such as the influence of temperature or moisture absorption [20-21]. The study of composites reinforced with graphite fibers is presented extensively in [22,29]. The model was adopted by other researchers [23,24] to determine the engineering constants. In the works I mentioned previously, the authors study composites with transverse isotropic behavior. In the paper [25], using system identification techniques, an experimental method for obtaining the Young's mode and its frequency dependence is determined. Some examples for materials as copper, brass, PVC or plexiglass illustrate the presentation. The method accepted almost unanimously by the studio is the consideration of a representative volume element (RVE) to determine the homogenized elastic coefficients. So, the material is considered a collection of such RVEs. At micro level, composite material is defined by individual structures and geometries, of great variety. A particular case is represented by the materials with short fibers [26,27] . Wood composite is a very special type of composite [28]. The study of the torsional vibration is made in [29]. If there is not enough data for the new and composite materials that we want to study, experimental vibration measurements become a n important way to determine the properties of the material [30-35]. There are a number of researches with more interesting applied results, such as concrete [36]. A study for a polymer composite, made up of a resin matrix is presented in [37].

In this work, the classical theory of bar vibrations is used, with FEM to determine the shear modulus. The novelty of the paper is the use of FEM to the eigenfrequencies of a straight beam, fixed at both ends. In our study this beam is manufactured by resin reinforced with cylindrical carbon fibers. Knowing the natural frequencies determined with the FEM, the shear modulus can be obtained using simple relationships. It can be considered too a composites composed of several phases. Several papers that present the methodology for determining these values using the vibrations of a bar clamped at both ends address this problem using FEM. However, the obtained results contain values for all types of vibrations. If it is desired to determine only certain elastic constants, the calculation effort is high and a series of useless information is obtained. As a result, it would be useful if only the information related to one of the elastic constants could be obtained directly. The aim of this paper is to obtain the shear modulus. As a result, boundary conditions are introduced that eliminate the possibility of vibration modes (transverse or longitudinal). in this way the required calculation effect decreases and the first vibration modes obtained are the pure torsion modes. A calculation obtained for a composite using a practice is presented in the paper.

In this way, with relatively little effort, that of modeling a bar with a very simple structure and geometry, the natural frequencies of the torsional vibrations of a bar can be obtained. With these determined values, shear modulus can be calculated with simple mathematical operations. This method therefore offers a quick estimate for the design needs of a new structure or machine. In the second phase of the design, when the solution has been established and more detailed studies are done, these determined properties can be obtained and experimented, obviously something that requires longer time and higher expenses.

Experimental results that prove the correctness of the results obtained by this method can be found in the previously cited references. Thus, the design engineer will have a quick and cheap method to obtain a sufficiently precise estimate for these materials.

2. MODELS AND METHODS

In what follows, some necessary results from the theory of torsional vibrations of straight beam will be briefly presented. Our beam is clamped at both ends (boundary conditions). The relationships that give the eigenfrequencies of this beam make it possible to determine the shear modulus, a size that appears in the formula of these eigenfrequencies. To determine the shear modulus for the homogenized material of the bar, the FEM is applied to this beam, if its real composition is taken into account. Then comparing with the values obtained for the homogenized bar, the shear modulus can be obtained.

Fig.1 shows this beam. The bar will be clamped at both ends. Using FEM, the eigenfrequencies can be obtained. As an application the calculations are performed and the numerical values obtained are presented in the Results section.

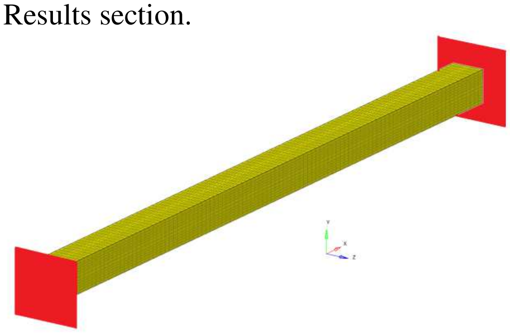


Fig.1. The clamped beam

Considereing a reference frame with the origin at the left end of the bar, then the free torsional vibrations are described by a second-order differential equation. At the distance *x* from the left end of the beam can be written [40-48]:

$$GI_p \frac{\partial^2 \varphi}{\partial x^2} = J \frac{\partial^2 \varphi}{\partial t^2} \quad , \tag{1}$$

Here G - shear modulus;
I_p - the inertia moment of the area;
J - the unitary mass moment of inertia;
φ - the rotation angle of the current area at the distance x.

Considering a homogeneous, continuous beam, it possible to write: $J = \rho I_p$ and the Eq. (1) has a simpler form:

$$\frac{\partial^2 \varphi}{\partial x^2} = \frac{\rho}{G} \frac{\partial^2 \varphi}{\partial t^2} \quad . \tag{2}$$

The solution can be obtained considering the initial and boundary conditions. The initial conditions at the moment $t = 0$ are:

$$\varphi(x,0) = f(x) \quad ; \qquad \left.\frac{\partial \varphi}{\partial t}\right|_{t=0} = g(x) \ . \tag{3}$$

These conditions define the liaison of the beam with the background. If it is considered a beam clamped at both ends we have:

$$\varphi(0,t) = 0 \quad ; \qquad \varphi(l,t) = 0 \quad . \tag{4}$$

The classic way to solve the Eq.(2) is to choose a solution having the form:

$$\varphi(x,t) = \Phi(x) \sin(pt + \theta) \quad . \tag{5}$$

Eq.(5) must verify the Eq.(2). It obtains a differential equation that offers the amplitude $\Phi(x)$ of the natural vibrations (eigenfunctions) of the torsion beam:

$$\frac{d^2 \Phi}{dx^2} + p^2 \frac{\rho}{G} \Phi = 0 \, . \tag{6}$$

The function $\Phi(x)$ represents the function amplitude to a moment *t*. It results:

$$\Phi(x) = C_1 \sin \alpha x + C_2 \cos \alpha x \, . \tag{7}$$

The notation:

$$\alpha^2 = p^2 \frac{\rho}{G} \, . \tag{8}$$

has been made. The boundary conditions (4) are, for a beam clamped at both ends:

$$\Phi(0) = 0 \quad ; \qquad \Phi(l) = 0 \quad . \tag{9}$$

and offer the conditions:

$$C_2 = 0 \quad ; \quad C_1 \sin \alpha l = 0 \, . \tag{10}$$

It obtains:

$$\alpha = \frac{n\pi}{l} \quad ; \quad n = 1,2,3,\ldots\ldots \tag{11}$$

Using the classic theory of beam, the natural frequencies can be written:

$$p_n = 2\pi\nu_n = \frac{n\pi}{l}\sqrt{\frac{G}{\rho}} \quad ; \quad n = 1,2,3,...... \qquad (12)$$

Knowing an natural frequency, it is possible to obtain the shear in this case:

$$G = \frac{p_n^2\, l^2 \rho}{n^2 \pi^2} = \frac{4\nu_n^2\, l^2 \rho}{n^2} \quad ; \quad n = 1,2,3,...... \qquad (13)$$

From Eq.(12), the different eigenfrequencies can be expressed in term of the lower eigenfrequency:

$$\nu_1 = \frac{\nu_2}{2} = \frac{\nu_3}{3} = ... = \frac{\nu_n}{n} \quad ; \quad n = 1,2,3,...... \qquad (14)$$

The Eq.(14) represents a verification relation for the obtained values.

3. RESULTS

In this study, the eigenfrequencies of a straight beam clamped at the two ends, were determined, manufactured from a resin reinforced with cylindrical carbon fibers. In order to separate and calculate with precision the natural frequencies due to the torsional vibrations, the symmetry axis of the beam is fixed. In this way, the possibilities of bending and the possibilities of tension/compression of the bar as a whole are eliminated.

In section 2, the classic beam model was briefly subjected to torsion and the eigenfrequencies of a beam clamped at the ends were determined. Using FEM, the torsional vibrations of the respective beam were considered based on a complex model, in which the real structure of the fiber composite is considered. The eigenfrequencies were thus calculated and the values obtained were compared with those determined with the classic model, if the bar is considered to be made of a homogenized material. By comparing the values calculated on the complex model, with the values obtained analytically on the beam model made of the considered phases, it was possible to determine the shear modulus for the resulting material. This way of calculating the shear modulus facilitates the calculation of this engineering constant, avoiding laborious calculations and procedures to obtain it [49].

For the studied bar, the eigenfrequencies were calculated and the eigenmodes were determined. The pure torsional vibrations of the bar were analyzed. FEM offered numerical results and comparing with the values obtained from the exact formulas, the shear modulus was determined [50-52]. For the calculation with finite elements, the beam with three-dimensional hexahedral finite elements was discretized. Each node of this type of element has 3 degrees of freedom (DOF) represented by the displacements along the X, Y and Z directions (in the considered global coordinate system). A finite element will thus have 24 DOF. For such an element, details can be found in references [51].

To remove unwanted vibration modes, the axis of symmetry of the bar is fixed. Thus we remove the pure axial and transverse modes of vibration. We analyze the torsional vibration modes in order to determine the shear modulus. Figure 2 shows the bar specimen that we took into account to analyze with FEM. It is a simplified epoxy matrix beam reinforced with four carbon parallel fibers The dimensions of this material specimen are shown in Figure 3. For the carbon fiber used we have: Young's modulus= 86.960 GPa. For the matrix there is Young's modulus= 4.140 GPa. The density of is 1850 kg/m^3 for the matrix and 2000 kg/m^3 for the carbon fiber, respectively. Poisson's ratio will be for matrix and carbon, respectively 0.22 and 0.34. These material properties will define the specimen shown in Figure 2. Analyzing the results of the calculations, the torsional vibration modes can be easily identified. Six modes of vibration are presented in our paper..

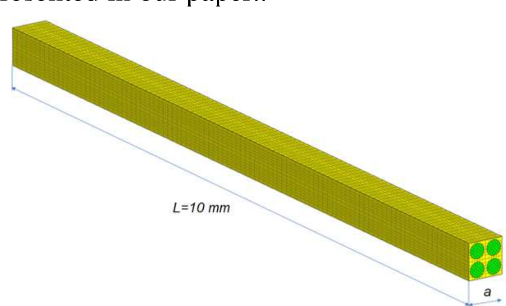


Fig. 2. The composite material

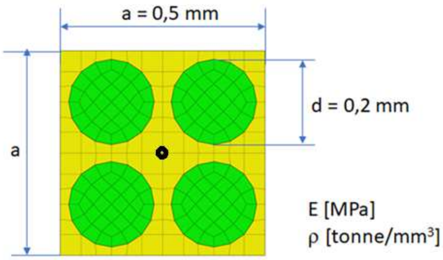


Fig.3. A section through beam

Name	Matrice_MAT
ID	1
Color	
Include	[Master Model]
Defined	☑
Card Image	MAT1
User Comments	Hide In Menu/Export
E	4140.0
G	
NU	0.22
RHO	1.85e-09

Fig.4. Properties of the matrix

Name	Fiber_MAT
ID	2
Color	
Include	[Master Model]
Defined	☑
Card Image	MAT1
User Comments	Hide In Menu/Export
E	86960.0
G	
NU	0.34
RHO	2e-09

Fig.5. Properties of the fiber

The first 6 eigenmodes are torsional modes of vibration. Table 1 shows l eigenfrequencies ν_n ($p_n = 2\pi\nu_n$) and the corresponding eigenmodes. Based on Eq. (13) presented before, the shear modulus can be now obtained. Eq.(13) give us:

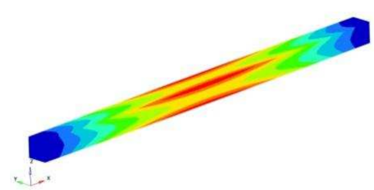
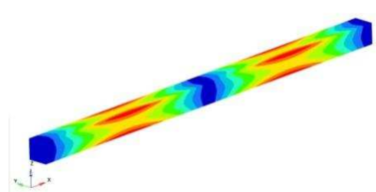
$$G = \frac{4\nu_n^2 l^2 \rho}{n^2\pi^2} \quad ; \quad n = 1,2,3,\ldots\ldots \qquad (15)$$

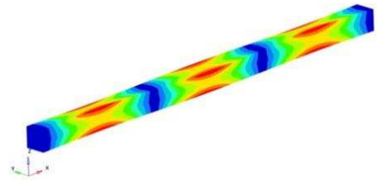
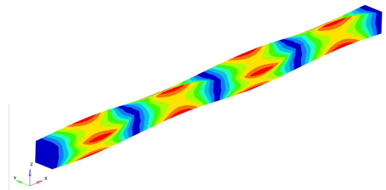
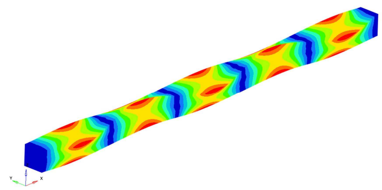
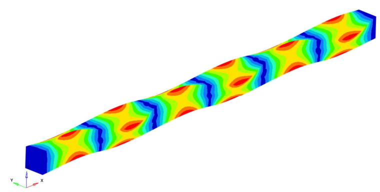
So, if we know eigenfrequency, and the properties of the homogenized material (the length and the density in our case), it is possible to obtain the shear modulus. The density of the homogenized material is:

$$\rho = v_f \rho_f + v_m \rho_m \,. \qquad (16)$$

useful in the following.

Table 1. Eigenfrequencies

Mode No.	Eigen frequency ν_n [Hz]	Representation	$\frac{\nu_n}{\nu_1}$ $n = 1,2,3,..$	Transverse shear modulus $G = \frac{4\nu_n^2 l^2 \rho}{n^2}$ [GPa]
1	82,288.62		1.0000	5.1463
2	16,475.72		2.0022	5.1575

3	247,584.1		3.0087	5.1763
4	330,944.5		4.0218	5.2024
5	415.008.4		5.0433	5.2359
6	499,938.3		6.0754	5.2765
Average shear modulus [GPa]				5.226834

4. DISCUSSION

To determine the engineering coefficients of a composite material, developed calculation procedures are proposed in the specialized literature. They generally require the determination of the stress and strain field for a certain state of loading of the considered specimen. Experimental methods give reliable values but with high costs and time. In this paper, the natural frequencies are determined using a FEM model, then using simple formulas provided by the classical theory of the bar, the shear modulus is determined. This method has the advantage of simplicity and the possibility of obtaining quick and accurate estimates within a current design process [40-42]. The method described in the work is accurate if we are in the assumptions made for the right beam. Any errors can be mainly due to the usual errors in the FEM. It can be considered that the method is precise enough to satisfy the needs of engineering design. The continuous increase in the use of polymer composite materials in most industries has required the development of methods for calculating elastic constants. Different methods have been developed, using different approaches such as homogenization theory (applied in the case of materials with a periodic structure), micromechanical methods or variational methods. There are various results of analytical relationships for determining the elastic constants of the material, which, however, involve a rather important calculation effort. All methods involve the knowledge of the field of stresses and deformations, which is generally difficult to do. If a particular state of stress is considered, upper and lower bounds are obtained for the elastic constants, which can sometimes lead to significant errors [7-13]. As a result, the proposed method can be considered as an acceptable method for determining the shear modulus, which is done relatively quickly and with minimal costs. In the design phase of a material, the estimates given by the method can be relatively accurate.

5. CONCLUSIONS

With the help of the described method, a precise estimate of the shear modulus is obtained. For this, the FEM is used to calculate the natural frequencies of a beam fixed at both ends, made of a polymeric material reinforced with cylindrical carbon fibers. For the calculation of these natural frequencies, the mechanical properties of the constituent phases and their distribution and geometry are considered known. Using the classical theory of the beam, the natural frequencies can be expressed as a function of the shear modulus of the homogenized material. Using the two formulas to determine the natural frequencies, it is easy to obtain the shear modulus from simple calculations. It is a relatively simple and easy to apply method, and the time required to apply the procedure is reduced. The estimator can only be affected by the approximations that are made in the classic beam theory and by the errors inherent in the FEM application. The described procedure can be a very good solution in the design phase of a composite, when homogenization, variational or micromechanical methods involve a large volume of calculation and long necessary time. Obviously, the method can be adapted to more complex situations. The use of the FEM must be adapted to take into account these additional factors.

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ESTIMAREA MODULULUI DE FORFECARE A COMPOZITELOR DE FIBRE FOLOSIND METODA ELEMENTULUI FINIT

Rezumat. *Materialele compozite, in cazul general, sunt alcatuite din doua sau mai multe componente distribuite in moduri complexe in cadrul materialului rezultant. Acesta are proprietati globale, determinate de proprietatile fazelor componente si de distributia lor. Determinarea proprietăților materialului omogenizat reprezinta o preocupare principala in faza de proiectare a materialului. Pentru a determina cum se comporta materialul rezultant, omogenizat, au fost dezvoltate numeroase metode de calcul pentru predictia constantele elastice. In general o astfel de metoda este laborioase și necesită timp de calcul semnificativ. Măsurători experimentale, metoda cea sigura pentru a determina proprietatile mecanice, presupun fabricarea compozitului. Metodele de marginile, care presupun utilizarea unor relatii relativ simple duc la erori care pot fi uneori insemnate. Lucrarea propune o metoda rapidă pentru a estima valorile omogenizate ale shear modulus pentru un material nou cu un volum redus de calcule, utilizand Finite Element Method. Este studiata torsiunea unei bare compozite pentru care utilizand FEM se determina frecventele proprii iar valorile astfel determinate se compara cu valorile obtinute utilizand teoria clasica a barei. Proprietățile mecanice ale fazelor materiale si modul de dispunere in compozit sunt cunoscute. Pe baza acestor valori se poate face o estimarea rapidă a valorii modulului de forfecare. Un exemplu pentru un material compozit polimer ranforsat cu fibre este prezentat în lucrare.*

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