Effect of Glass Fiber Content on the Flexural Modulus of Elasticity of Glass-Epoxy Sandwich Composites

Abdellatif Selmi

***Abstract*—**Mechanical properties of long glass fiber epoxy and syntactic foam are predicted for different reinforcement contents using mean field homogenization schemes then analytical investigations for the modulus of elasticity of composite sandwich composed of glass fiber epoxy and syntactic foam are demonstrated. Based on the analyses, new equations for the modulus of elasticity of the composite sandwich are developed. Four-point test is carried out using Ansys program to characterize the flexural behavior of the sandwich composite. Results obtained from the developed equations are compared to finite element results. The comparison indicates that there is a good agreement between the two approaches.

***Keywords*—**Syntactic foam, Epoxy, Flexural properties, Glass fiber, Sandwich composite, Homogenization

I. Introduction

SANDWICH composites are a special class of composite materials which have become very popular due to their high specific strength and bending stiffness[1].

Due to their lightweight, low density and high damage tolerance, sandwich composites are commonly used in various sectors. Some of the main areas of applications of sandwich composites are aircraft, submarine, ships and boats, surface transport vehicles, building materials, packaging materials, thermal and electrical insulation, storage tanks [2].

Innovativeness is essential in finding new combinations of core and skin materials and new ways to use them in various applications where conventional materials have already reached their performance limits.

In this paper, the epoxy resin used as matrix in the syntactic foam slabs which represents the core of the sandwich is also used to fabricate the skins.

The skins are made of glass fiber reinforced epoxy. Such materials have high specific strength and bending stiffness [3]. Syntactic foams have gained considerable importance as core materials in sandwich composites due to their broad range of mechanical properties coupled with vibration damping characteristics, fire performance and ability to be fabricated in functionally graded configurations [4].

Abdellatif Selmi is with the Civil Engineering Laboratory, Ecole Nationale d'Ingénieurs de Tunis (ENIT), B.P. 37, Le belvédère 1002 Tunis, Tunisia (corresponding author's phone: (00216)21509049 ; e-mail: selmifr2000@yahoo.fr).

Syntactic foams have two phases in their structure, namely matrix resin and hollow glass microspheres, HGM, [1]. Structure of syntactic foam can be observed in the scanning electron micrograph presented in Figure 1. HGM embedded in the matrix resin are visible in the structure. One of the major advantages of syntactic foams is their ability to be designed and fabricated according to the physical and mechanical property requirements of the application by adjusting the volume fractions of the matrix and HGM in the structure.

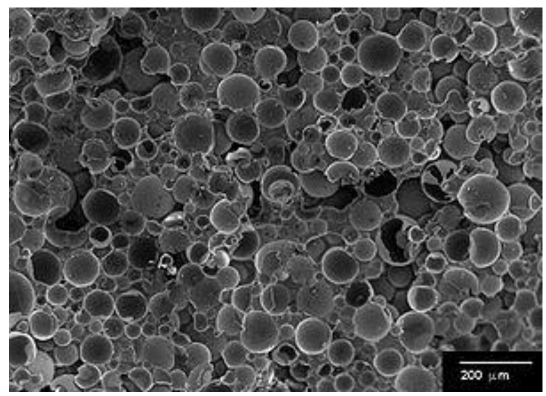

Fig. 1 Scanning electron micrograph showing structure of syntactic foam

For the analysis of the behavior of the heterogeneous sandwich composite, both the mechanical behavior of the sandwich components (syntactic foam, skins) and the global response of the assembled sandwich elements must be assessed.

Several experimental and analytical studies are available on compressive [5], impact [6] and hygrothermal [7] properties of syntactic foams. Syntactic foam core sandwich composites have also been studied by some researchers for compressive [4], impact [8] and flexural [9] properties.

None of these studies investigate the effect of the HGM and long glass fiber contents on the mechanical properties of the whole sandwich.

The objective of the present research is to develop an understanding for the effect of HGM and glass fiber volume fraction on the mechanical behavior of composite sandwich.

Accordingly, homogenization models have been used to predict the mechanical characteristics of syntactic foam and

http://dx.doi.org/10.15242/IIE.E0514619

glass fiber reinforced epoxy. Then, In order to investigate the mechanical properties of syntactic foam/glass fiber epoxy composite sandwich, a new design equation for flexural modulus of elasticity of sandwich composite is proposed in this paper.

The analytical results for the Young's modulus of the sandwich composite have been also simulated numerically by Finite Elements analyses through suitable engineering-oriented computational procedures, developed for the whole sandwich under four point bending test.

II. Mechanical properties of syntactic foam

Syntactic foam can be seen as reinforced materials made up of three phases: epoxy matrix, Glass layer and spheroid cavities. The Glass fibers used in this study called K37 present an average diameter of d=50 µm and a wall thickness of e=1.28µm [1]. The different material properties of both matrix and fiber are shown in the **Table 1**.

TABLE I
ELASTIC CONSTANTS OF EPOXY RESIN AND HGM K37 AFTER A. BRINI [10].

	Young's modulus E (MPa)	Poisson's ratio
HGM k37(glass layer)	72000	0.22
Epoxy resin	3700	0.40

In this section, the two level mean field homogenization procedure is explored to predict the overall elastic properties of syntactic foam. The main idea of the method is summarized hereafter.

A. The two-level procedure

It is based on the idea that the matrix sees reinforcements (HGM) which are themselves composites (Glass layer + void). Each HGM is seen (deep level) as a two-phase composite (glass layer with cavities) which, once homogenized, plays the role of a homogeneous reinforcement for the matrix material (high level). We recall that in classical continuum mechanics, the absolute sizes do not intervene, therefore in the first level of the two-level procedure, we consider a fictitious glass matrix containing many small ellipsoidal cavities (having the same shapes).

Homogenization schemes (e.g. Mori–Tanaka) are then used to obtain its overall properties. A two-level recursive application of two-phase homogenization schemes (e.g. M–T) is thus proposed. A particular scheme is identified by the schemes used to perform the levels. In this work, choosing M–T for both levels is labeled ''two-level (M–T/M–T)''. the title of this article).

B. Predictions of Glass fiber content effect on the syntactic foam

For different homogenized HGM volume fractions, the stiffness enhancement of epoxy matrix is investigated here using two-level procedure.

Figures 2a–2b contain respectively the effective and normalized Young's modulus (E/E_m) and the Poisson's ratio (nu) of epoxy reinforced with HGM as a function of homogenized HGM volume fraction. E_m is the epoxy Young's modulus.

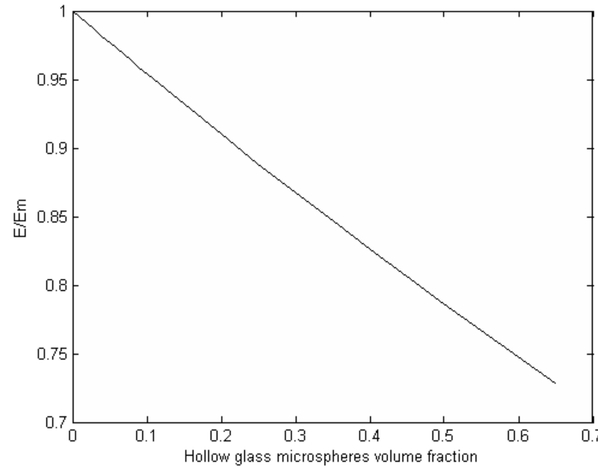

Fig. 2a. Normalized Young's modulus of HGM/Epoxy composite

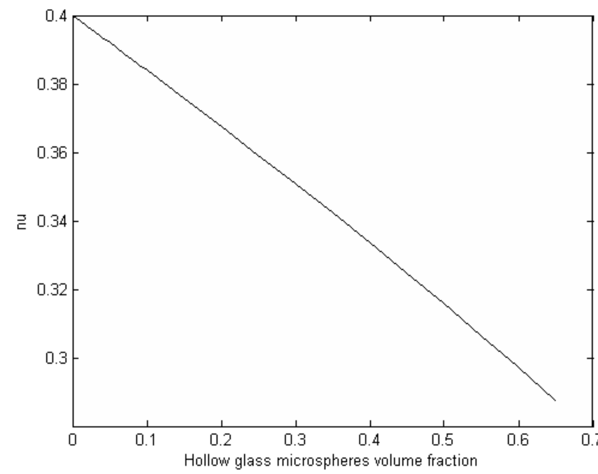

Fig. 2b. Poisson's ratio of HGM/Epoxy composite

***Interpretation*:** From Figures 2a–2b, it can be seen that increasing the homogenized HGM volume fraction leads to a decrease of Young's modulus of syntactic foam that is explained by the fact that the first level of the homogenization model results in a Young's modulus of the homogenized HGM equal to 2223.7MPa which less stiffer than that of epoxy (3700 MPa). For 65% 3D random oriented homogenized HGM, the normalized Young's modulus is decreased by a factor of 1.37 while the Poisson's ratio is decreased by a factor of 1.39. The negative effect of the HGM on the syntactic foam mechanical properties is negligible compared to its positive impact, in fact, the HGM play an important role in improving the thermal isolation of structures made of syntactic foam and are much appreciated in light structures and in delaying the hygroscopic spread for naval construction.

III. Mechanical properties of glass fiber/epoxy composites

The stiffness enhancement of the epoxy matrix comprising Glass fibers is investigated here for 3D randomly oriented morphology.

The Glass fibers used in this study are assumed to be perfect ellipsoids and infinitely long. The different material properties of both matrix and fiber are shown in the Table 1. In this section, the Mori-Tanaka homogenization procedure is used to predict the mechanical characteristics of randomly oriented long Glass fiber reinforced epoxy.

The predicted mechanical response of composites made of resin reinforced with Glass fibers, relative to the mechanical properties of epoxy is reported in Figures 3a–3b.

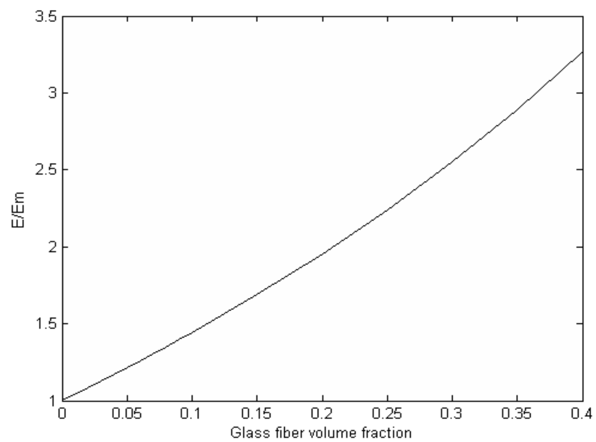

Fig. 3a. Normalized Young's modulus of long and randomly oriented glass fiber/Epoxy composite

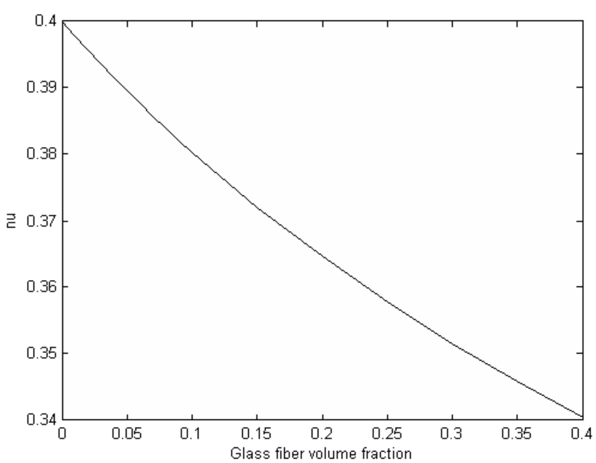

Fig. 3b. Poisson's ratio of long and randomly oriented glass fiber/Epoxy composite

Interpretation: Figures 3a–3b show respectively the effective and normalized Young's modulus, and the Poisson's ratio of random long Glass fiber reinforced resin.

We conclude that the effective Young's modulus increases with the Glass fiber volume fraction. For a composite comprising 40% of 3D randomly oriented Glass fiber (Fig. 3a) the Young's modulus E is raised by a factor of 3.3 while the Poisson's ratio (Fig. 3b) is decreased by a factor of 1.18.

IV. Longitudinal Young's modulus of sandwich composite

A. Introduction

This section presents an analytical study on the mechanical behavior of a syntactic foam/glass fiber epoxy composite sandwich. The external facings of the sandwich (*skins*) are made of glass fiber/epoxy matrix composites, whereas the central part of the sandwich (*core*) consists of syntactic foam made with an epoxy resin matrix embedding randomly-dispersed HGM. the title of this article).

B. Derivation of composite modulus of elasticity in flexure

For a flexural section of sandwich composite containing three layers as shown in Fig. 4, the equation of equilibrium in the elastic range can be written as follows:

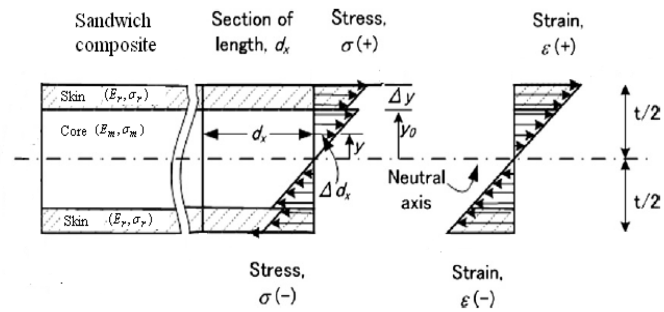

Fig. 4 Analysis of flexural cement composite section

$$M = 2\int_{0}^{y_0} y\sigma_m dA + 2\int_{y_0}^{y_0+\Delta y} y\sigma_r dA \tag{1}$$

where y_0 and Δy represent the syntactic foam and glass fiber/ epoxy portions, respectively; σ_m and σ_r are stresses developed in core made of syntactic foam and the skin made of glass fiber reinforced epoxy, and y is the distance from the neutral axis to the area dA. The dA can be expressed as bdy where b is the width of the flexural section and dy is the height of strip taken in the core and skin portion. The strain, ε, in any layer of length dx at distance y from the neutral axis can be written as follows:

$$\varepsilon = \frac{\Delta dx}{dx} = a.y \tag{2}$$

where Δdx is the deformation of the layer and a is the proportional constant. By using the Hook's law, the strain ε in any layer given in Eq. (2) can be written as follows:

$$\varepsilon = \frac{\sigma_m}{E_m} = \frac{\sigma_r}{E_r} \tag{3}$$

The strains in the core (ε_m) and skin (ε_r) layers are same, i.e. $\varepsilon_m = \varepsilon_r$ but the stresses in the core (σ_m) and skin (σ_r) layers are not same. (Fig. 4).

Substituting Eqs. (3) and (2) into Eq. (1), the following equation is obtained.

http://dx.doi.org/10.15242/IIE.E0514619

$$M = 2b\left[\int_0^{y_0} aE_m y^2 dy + \int_{y_0}^{y_0+\Delta y} aE_r y^2 dy\right] \quad (4)$$

where E_m and E_r are the moduli of elasticity of core and skin layers, respectively. After integration, the Eq. (4) with some calculations takes the following form:

$$M = 2ab\left[E_m \frac{y_0^3}{3} + E_r\left(\frac{(y_0+\Delta y)^3}{3} - \frac{y_0^3}{3}\right)\right] = ab\left[(E_m - E_r)\frac{\beta^3 t^3}{12} + E_r \frac{t^3}{12}\right] \quad (5)$$

where t is the thickness of the flexural section and β indicates the part of syntactic foam given as follows:

$$y_0 = \beta \frac{t}{2}, \quad \beta = 1 - V_r \quad (6)$$

Eq. (5) can be written in terms of moment of inertia as follows:

$$M = a\left[(E_m - E_r)\beta^3 + E_r\right]I_c \quad (7)$$

where I_c is the moment of inertia of the composite flexural section with respect to neutral axis which is given by: $I_c = \frac{t^3}{12}$

Substituting the value of a from Eq. (2) into Eq. (7) gives the composite modulus of elasticity of the whole section which is finally expressed as follows:

$$E_{com} = (E_m - E_r)\beta^3 + E_r \quad (8)$$

Which can be written as a function of the part of the skin , α :

$$E_{com} = (E_m - E_r)\left(\frac{\alpha}{1+\alpha}\right)^3 + E_r \quad (9)$$

the part of the skin is given by:

$$\alpha = \frac{y_0}{\frac{t}{2} - y_0} = \frac{\beta}{1-\beta} \quad (10)$$

C. Effect of glass fiber content on the longitudinal Young's modulus of sandwich composite

Effect of glass fiber content on the longitudinal Young's modulus of sandwich composite

Figs 5a shows the effect of homogenized HGM volume fraction on the Young's modulus of the sandwich composite, the long glass fiber volume fraction is taken equal to 40% which corresponds to a skin young's modulus of 12092.11 MPa.

Figs 5b shows the effect of long glass fiber volume fraction on the Young's modulus of the sandwich composite, the homogenized HGM volume fraction is taken equal to 65% which corresponds to a core young's modulus of 2695.5 MPa.

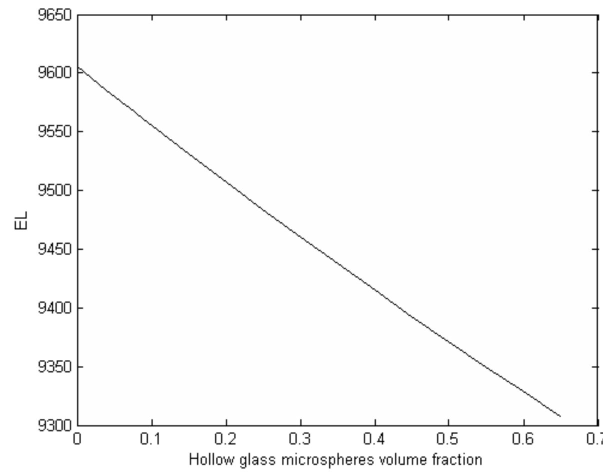

Fig. 5a. Longitudinal Young's modulus of sandwich composite as a function of homogenized HGM volume fraction

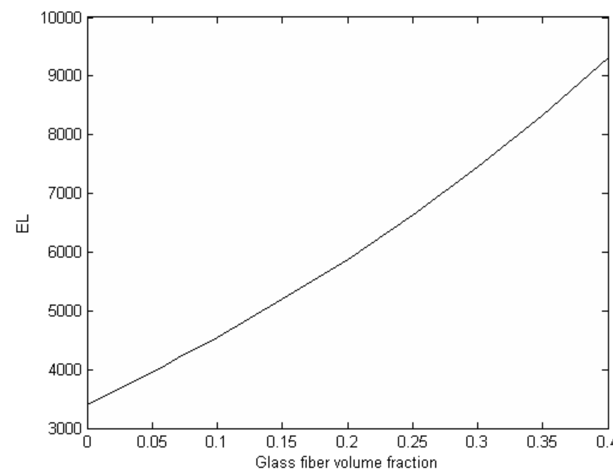

Fig. 5b. Longitudinal Young's modulus of sandwich composite as a function of long glass fiber volume fraction

Interpretation: We can see from fig 5a that the longitudinal sandwich Young's modulus decrease as the HGM volume fraction increased. That is due to the voids in the microspheres which influence the mechanical properties of the core and influence consequently the sandwich Young's modulus. For 65% volume fraction, the sandwich Young's modulus is decreased by 3% which indicates that the Young's modulus reduction factor is negligible. Voids are very important in terms of improving the thermal isolation of structures made of syntactic foam and are much appreciated in light structures and in delaying the hygroscopic spread for naval construction, hence reducing 3% in Young's modulus cannot be considered compared to the positive effect of voids.

The figure 5b proves that raising the long glass fiber volume fraction, improve the sandwich longitudinal Young's modulus. 40% of glass content leads to an enhancement of 300%.

D.Four point test simulation

ANSYS is used to carry out the 2D-finite element calculation to analyze a simply supported sandwich beam under four point loading. The dimension of the flexural specimens were 150*15*15mm. Plane 42 element type was used to mesh the model and the total number of elements was around 225000 with 226651 nodes. The mesh of the specimen is given respectively in figure 6.

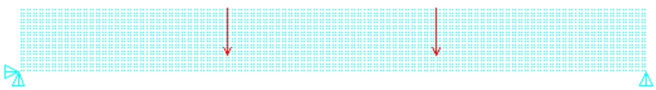

Fig. 6 2D view of FE mesh

The distance between the loading points is 50 mm with lever arms of 50 mm at both sides of the loading points. The load was applied in a vertically direction. In this study, the deflections were measured at the mid-section of a simply supported beam. In order to estimate the longitudinal Young's modulus, the equation for load–deflection relationship under fourth-point loadings is derived as:

$$\delta = \frac{PL^3}{56.35 E_{com} I_c} \tag{11}$$

where E_{com}. is the composite modulus of elasticity of the whole section, I_c is the moment of inertia of the flexural section with respect to neutral axis, L is the span length, P is the applied load and d is the deflection at mid-section. The modulus of elasticity of each specimen is, therefore, calculated by the following equation:

$$E_{com} = \frac{PL^3}{56.35 \delta I_c} \tag{12}$$

E. Results and discussion

The obtained deflection is $\delta = 0.0033984$. The sandwich longitudinal Young's modulus retrieved by finite element calculation is 8.377 GPa which is close to the result delivered by the developed method 9.3 GPa.

V. Conclusion

The effect of glass fiber content on the epoxy mechanical properties is investigated in this paper using homogenization models. It was demonstrated that HGM reduces the mechanical characteristics of syntactic foam and the long glass fiber improve the mechanical properties of epoxy. A flexural section of sandwich composite, which core is made with syntactic foam and its skin is made with long glass fiber reinforced epoxy, is theoretically analyzed and a simple design equation for flexural modulus of elasticity of the sandwich was derived. Finite element investigation was conducted to check the validity of the new equation. It was shown that the FE results and the mixture rule agree well with the results obtained by the proposed equations.

References

[1] E. Papa, A. Corigliano, "Mechanical behaviour of a syntactic foam/glass fibre composite sandwich: experimental results", Structural Engineering and Mechanics, 12(2001), 169-188. http://dx.doi.org/10.12989/sem.2001.12.2.169

[2] N. Gupta, E. Woldesenbet, "Characterization of Flexural Properties of Syntactic Foam Core Sandwich Composites and Effect of Density Variation", Journal of Composite Materials, 39(2005), 2197-2212. http://dx.doi.org/10.1177/0021998305052037

[3] A.K. Noor, W.S. Burton, C.W. Bert, "Computation Models for Sandwich Panels and Shells", Appl. Mech. Rev., 3(1996), 155–198. http://dx.doi.org/10.1115/1.3101923

[4] A. Corigliano,E. Rizzi, E. Papa, "Experimental characterization and numerical simulations of a syntactic foam/glass-fibre composite sandwich". Comp Sci Tech, 60(2000), 2169-2180. http://dx.doi.org/10.1016/S0266-3538(00)00118-4

[5] E. Rizzi, E. Papa, A. Corigliano, "Mechanical behavior of a syntactic foam: experiments and modeling". Intl J Solids Struct, 37(2000), 5773-5794. http://dx.doi.org/10.1016/S0020-7683(99)00264-4

[6] H.S. Kim, H.H. Oh, "Manufacturing and impact behavior of syntactic foam". J Appl Poly Sci, 76(2000), 1324-1328. http://dx.doi.org/10.1002/(SICI)1097-4628(20000523)76:8<1324::AID-APP13>3.0.CO;2-#

[7] N.R. Schott, T.K. Bhattacharjee, "New syntactic foams with polystyrene". J Cellu Plast, 29(1993), 556-568. http://dx.doi.org/10.1177/0021955X9302900604

[8] R. Olsson, "Engineering method for prediction of impact response and damage in sandwich panels". J Sand Str and Mater, 4(2002), 3-29. http://dx.doi.org/10.1177/1099636202004001192

[9] L. Bardella, F. Genna, "Elastic design of syntactic foamed sandwiches obtained by filling of three-dimensional sandwich fabric panels". Intl. J. Solids and Stru; 38(2001), 307-333. http://dx.doi.org/10.1016/S0020-7683(00)00025-1

[10] A. Brini. "Modélisation multi-échelle du comportement et du vieillissement des mousses syntactiques immergées", PhD Thesis, Pierre and Marie Curie university