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ORIGINAL PAPER

Modeling and analysis of K15 hollow glass microballoons filled epoxy syntactic foam for lightweight structures

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Abstract

Polymer matrix syntactic foams have received a lot of interest in recent years because of their advantages, such as their lightweight and energy-absorbing properties. The purpose of this study is to produce representative elementary volume of syntactic foams with a random filling of hollow glass microspheres from neat epoxy to 0.4 v/v filling in epoxy resin. Different forms of syntactic foams have been evaluated. ANSYS software (2020, R1) was used to investigate the numerical results. The impact of the microsphere volume fraction on the elastic mechanical properties of syntactic foams was investigated. The relative modulus, density and Poisson's ratio values of foams fall as the microsphere volume fraction rises but specific modulus values of composites increases, confirming that the weight of a component can be reduced. The relative modulus, Poisson's ratio and density of syntactic foam decreases with increasing volume fraction of microballoon, dropping to approximately 4.5, 8.9 and 30 percent respectively at 0.4 volume fraction compared to neat epoxy. Parameters for beam and plate design ensuring that with same bending and axial stiffness for beam and bending stiffness for plate, weight of a component could well be reduced. As a consequence, utilizing syntactic foams in structural applications may result in significant weight reductions.

Keywords Syntactic foam · Epoxy matrix · Glass microballoons · Modeling

1 Introduction

A combination of hollow-particle-filled polymers makes up syntactic foam with special properties such as reduced weight, minimal moisture absorption, stiffness and high specific strength and energy absorption characteristics. Syntactic foams have garnered a lot of attention from academics in recent years, and they've turned into a study hotspot [1–6]. In the equipment industry, aviation, spacecraft, automobiles, equipment for sports and deep-sea technology, syntactic foams with polyurethane, epoxy and other polymers as matrix phase and hollow glass microspheres of variable wall thicknesses, microspheres of ceramics and often hollow spheres of metals as fillers have been extensively utilized [7–9]. These investigations found that the features of syntactic foams are directly connected to volume percentage and type of microballoon loading in the syntactic foam matrix. Incorporation of microballoons offers significantly low density, which is advantageous for foams used in aircraft, vehicles and naval constructions. However, the incorporation of greater volume proportion of hollow counterparts also reduces the strength and stiffness of composites significantly [10, 11]. A few theoretical methods have already been developed to study the impact of volume fraction and wall-thickness of hollow fillers on modulus of syntactic foams [12, 13]. There has been significant research on the compressive, flexural, and hygrothermal characteristics of syntactic foams in the published literature [1, 14–16]. However, there are few researches on the tensile strength of these materials [2, 17, 18]. When it comes to applications, such as aircraft constructions and sport accessories, syntactic foams with the low density makes it essential to characterise such material for tension and to explore other factors affecting the properties. Existing research on the tensile characteristics of syntactic foams has focused on foams with low microballoon volume

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percentages (ϕ_g) [17–19]. Numerous automotive researchers have seized this chance to participate in chassis production and advancement of technology [20]. The frame construction was created in Creo, and further analysis, such as modal frequency, was performed in the Finite Element software ANSYS Workbench. Modal study indicate to be quite useful in the geometry optimization of the frame, which was one of the overall study's goals [21]. The advantages of utilising ANSYS were the ability to precisely display mode forms and greater precision for curves to optimise the size to 0.03–0.04 m simulation [22].

The current study analyzes syntactic foams with volume fraction (ϕ_g) 0–0.4 v/v. The microballoon selection criteria allows for a direct relationship between microballoon characteristics and the strength in tension and elastic modulus of syntactic foams. The current research investigates the impact of density of microballoon and volume fraction on the tensile strength and elastic modulus of syntactic foams in a targeted manner. Several uses of syntactic foams include sandwich composites used to make structural components or huge structures [23–25]. The wall-thickness of particles, size and ϕ_g has a direct influence on mechanical characteristics of composite and it is challenging to create a range of circumstances using experimental approaches.

Adopting the numerical simulation approach, on the other hand, is successful in taking into account numerous parameter changes [26–30]. Liang et al. [30] investigated the plastic characteristics of hollow, particle-filled epoxy resin composites, taking into account parameters such as volume fraction of microsphere,ratio of wall-thickness, which affected mechanical characteristics. RVEs (Representative elementary volume) are frequently used as a model, particularly microstructure based models in three-dimensions [31–34]. As indicated in prior literature, several researchers have embraced the experimental investigation of syntactic foams reinforced by hollow particles [35–38]. However, a study on the numerical modeling of hollow particle-filled polymers with varying volume fractions for constructing a light weight structure is scarce, even though numerical simulation may be utilised to examine numerous parameter modifications. Representative volume element method was never used to investigate such syntactic foams reinforced with K15 type hollow glass microspheres.

In this analysis, the representative volume element (RVE) of syntactic foams incorporating random hollow glass microspheres (K15, manufactured by 3M) filling in epoxy resin have been determined. The effect of microsphere volume fraction on the elastic characteristics of syntactic foams was studied. Elastic modulus was also computed, ensuring that with same bending stiffness, axial stiffness for beam, and bending stiffness for plate, the weight of a component could well be reduced. The major goal of this study is to compute the material properties of hollow glass microsphere reinforced composites using numerical analysis, such as density, modulus, and Poisson's ratio, and compare them to known experimental and analytical predictions. The use of syntactic foam in the design and production of discrete artefacts with lighter types of structures will be explained through current data.

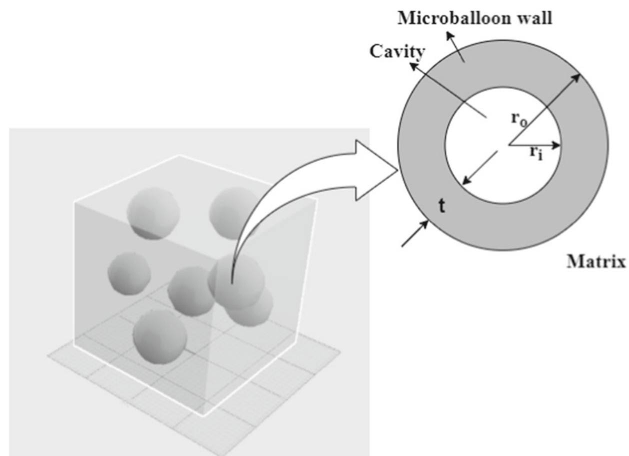

Fig. 1 Notations used to describe different physical characteristics for microballoons

2 Modeling

2.1 Notations used in analysis

The outer and inner radius of the hollow microballoon is taken as r_o and r_i respectively, the wall-thickness of filler is notified as t. The volume fractions are denoted with ϕ for all the analysis, as schematically represented in Fig. 1. The radius ratio $\eta = r_i/r_o$ and volume fraction have been used to describe the compositions in syntactic foams. $E, \upsilon,$ and ρ represents the syntactic foam's effective Young's modulus, Poisson's ratio and density respectively. Elastic characteristics and densities for matrix and microballoons are expressed using the same notation, along with the subscripts m and g.

2.2 The microstructure of syntactic foams

The micro-structure of syntactic foams are made up of two main components i.e. matrix material and random filling of hollow glass microspheres in epoxy resinto form binary syntactic foam. However, during processing, air is entrapped in the matrix and the resulting foams become three phase. For the purpose of modeling, it is assumed that the syntactic foam is purely binary without any voids. A representative scanning

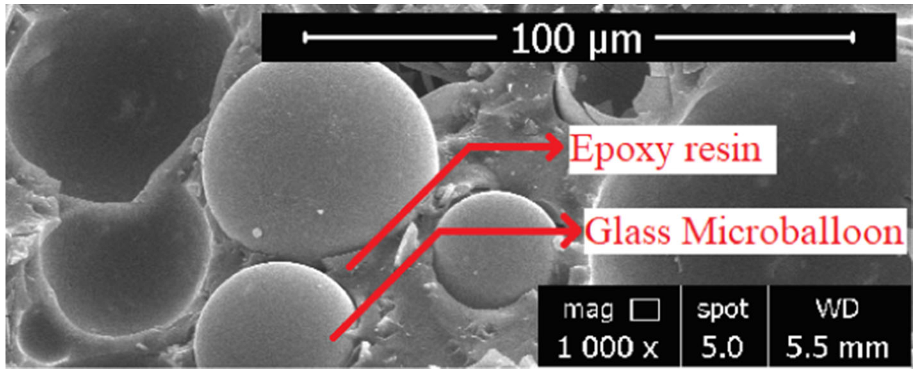

Fig. 2 A syntactic foam microstructure with a 40% glass microballoon content incorporated in an epoxy resin matrix

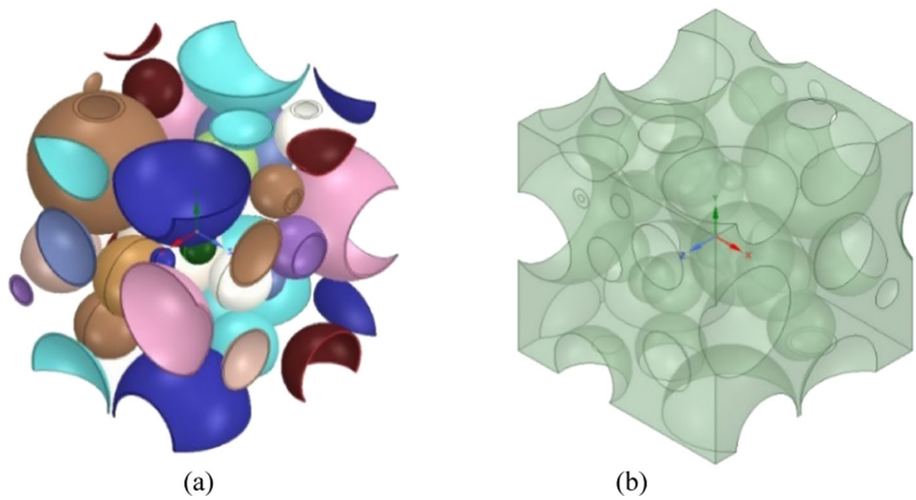

Fig. 3 **a** Distribution of microballoons; **b** Matrix phase

Table 1 Properties of epoxy used in syntactic foams [13]

	Material's Density (kg/m^3)	Young's modulus, E (GPa)	Poisson's ratio
Epoxy resin matrix	1160	3	0.35

electron microscopy (SEM) image of syntactic foam taken in our laboratory is presented in Fig. 2, where hollow glass microballoons (40 percent v/v) are distributed in an epoxy matrix. Numerical simulation was carried out assuming perfect adhesion between the two phases.

2.3 Finite element analysis and models

The smallest volume across which a measurement may be taken that will produce a value representative of the entire cell is defined as the Representative Volume Element (RVE) [39]. Figure 3 shows how the representative volume element model was created in a specific area using commercial software by ANSYS, Inc. The microspheres were created at random in the RVE. Finite element analysis (FEA) method has been widely used in the literature to make the model more realistic and hence has been used by us in this study as well [32–34, 40–42].

The properties of epoxy (used as matrix) and the physical properties of hollow glass microballoons, K15 (10–40% v/v) used for modeling purpose is presented in Tables 1 and 2 respectively.

2.4 Meshing of model and boundary conditions

Four meshed models were created corresponding to four different volume fractions of HGM (0.1–0.4). The same is presented in Fig. 4. The analysis made use of periodic and conformal meshing. In Fig. 4, there was 8,523,654, 95,632,517, 13,771,030 and 14,758,965 nodes in the meshed RVEs for glass filled syntactic foam with 0.1, 0.2, 0.3 and 0.4 v/v in epoxy matrix. RVE meshing was denser near the filler and less dense in the matrix further away from of the filler to confirm better adhesion and sufficient accuracy. For boundary conditions, periodic boundary conditions were used for simulation model (numerical) of particle filled composites.

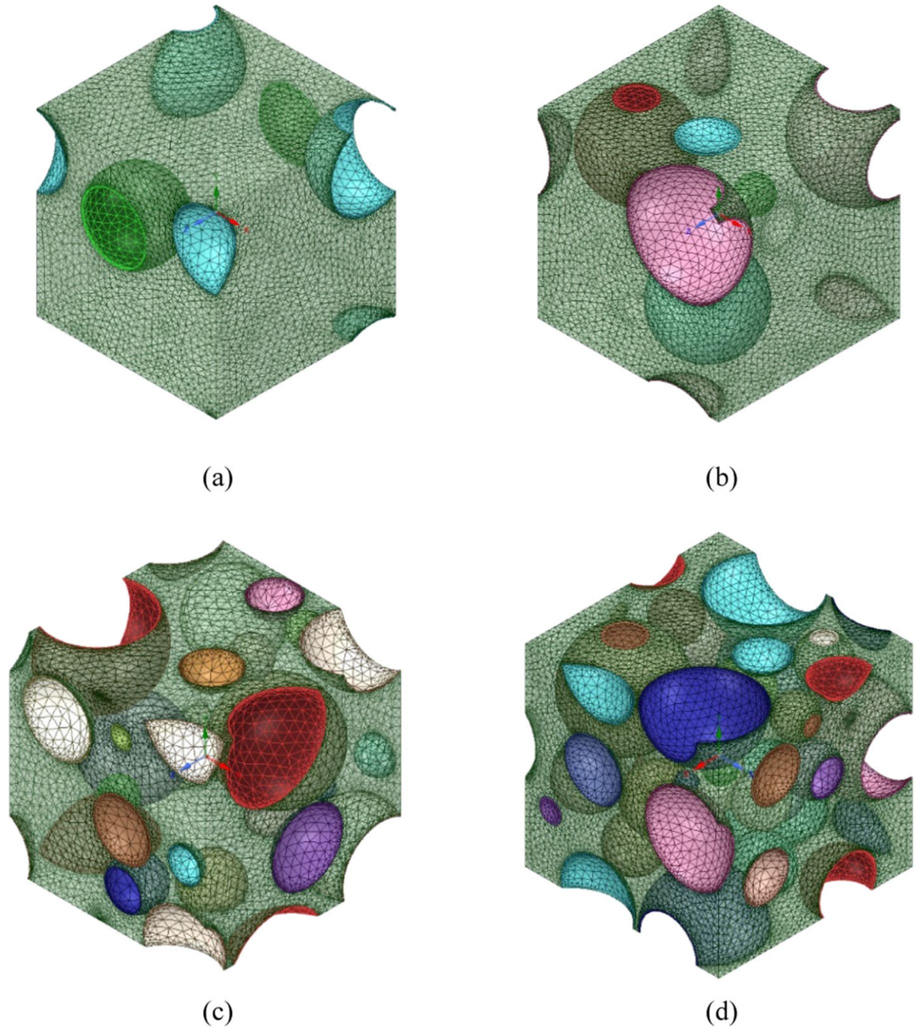

Fig. 4 RVE model with meshing for **a** 0.1; **b** 0.2; **c** 0.3; **d** 0.4 volume fraction of fillers

Table 2 Physical properties of hollow glass microballoons

Hollow Glass microballoons	Density, ρ (kg m^{-3})	Mean dia (µm)	Young's Modulus, E (GPa)	Poisson's Ratio	Wall Thickness, t (µm)	r_i (µm)	r_o (µm)	Radius ratio (η)
K 15	150	70	70	0.20	0.703	34.297	35	0.98

Since RVE is comparable to a material cube, periodic boundary conditions have been used to cut down on computation time.

2.5 Validation of models

The developed model was validated using existing data on tensile modulus, density of foams containing glass microballoons (K15) and Poisson's ratio in a variety of volume fractions.

3 Results and discussion

3.1 Density

In Fig. 5, density of foams reinforced by hollow glass microspheres obtained by RVE is compared to theoretical and experimental findings [44]. Experimental results with theoretical analyses for the K15 hollow glass microspheres reinforced syntactic foam was previously done by Ullas et al. [44]. It can be observed that there is a good match between previous outcomes and numerical findings from RVE analysis of current study. The density of syntactic foam drops

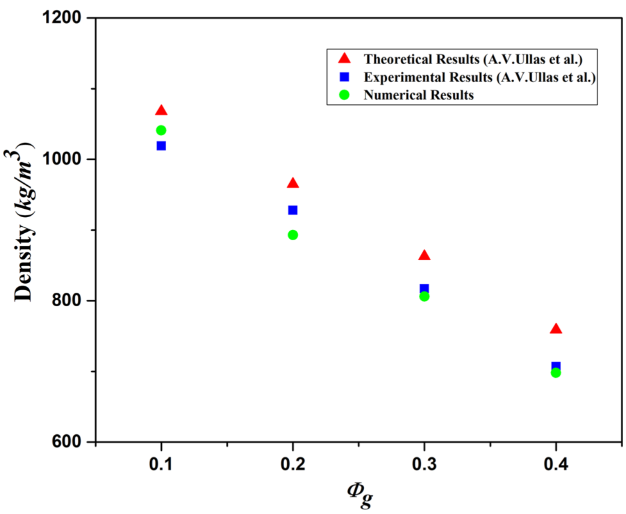

Fig. 5 Effect of increasing volume fraction of filler on density of syntactic foam

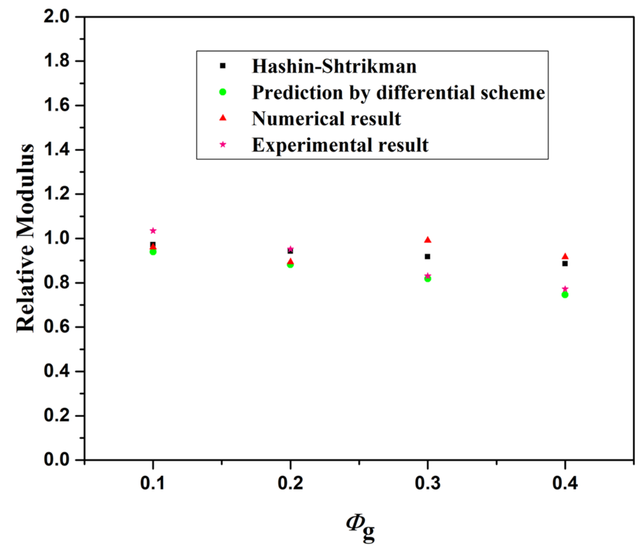

Fig. 6 Effect of volume fraction of microballoons on the relative modulus of syntactic foams

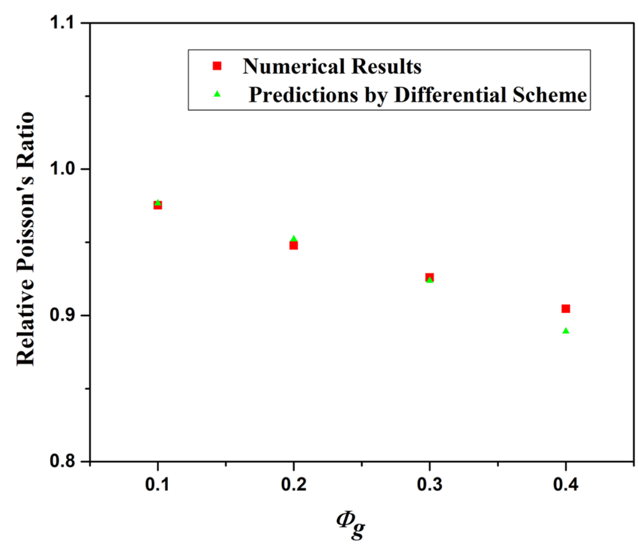

Fig. 7 Change in the Poisson's ratio in relation to microballoons volume fractions

significantly with increasing volume fraction of microballoons, reaching a loss of about 30% at 0.4 volume fraction. The change patterns of K15 microspheres were comparable with the published data on syntactic foams and the variation trends were identical with the other results on syntactic foams.

3.2 Mechanical properties evaluation

3.2.1 Relative modulus

The relative modulus (E/E_m) of syntactic foams including hollow glass microspheres derived by RVE in this research is compared to theoretical and experimental findings from the literature [13, 43] in Fig. 6. The notations, viz. circles and stars represent the theoretical prediction via differential scheme and experimental results respectively taken from the literature [13]. Figure also shows the Shtrikman-Hashin upper limit, which are calculated by a three-phase model [43]. The triangle symbols are the homogenised numerical results from our RVE analysis. The relative modulus in this research was calculated as the ratio between the modulus of the foams to the epoxy resin matrix. It can be seen that the relative modulus of syntactic foam decreases with increasing volume fraction of microballoons, dropping to 4.5% at 0.4 volume fraction.

3.2.2 Relative Poisson's ratio

The created model has been applied to calculate syntactic foam's relative Poisson's ratio and examine their relationship to the component's material and geometrical characteristics. As seen in Fig. 7, υ/υ_m (relative Poisson's ratio, calculated as the Poisson ratio of syntactic foam divided by neat epoxy) of foam falls with increasing volume fraction of microballoons, reaching a drop of ~ 8.9% at 0.4 volume fraction. Previously Porfiri et al. [13] had studies on the estimation of the relative Poisson's ratio of K15 reinforced epoxy matrix syntactic foam. It can observed from the Fig. 7 that there is an excellent agreement between the numerical results from RVE analysis and the results of Porfiri et al. [13]. It can be seen that there is negligible difference in the relative Poisson ratio values of syntactic foams prepared using varying microballoons volume fractions. It is worthwhile noting that the Poisson's ratio is a measure of the relative lateral strain

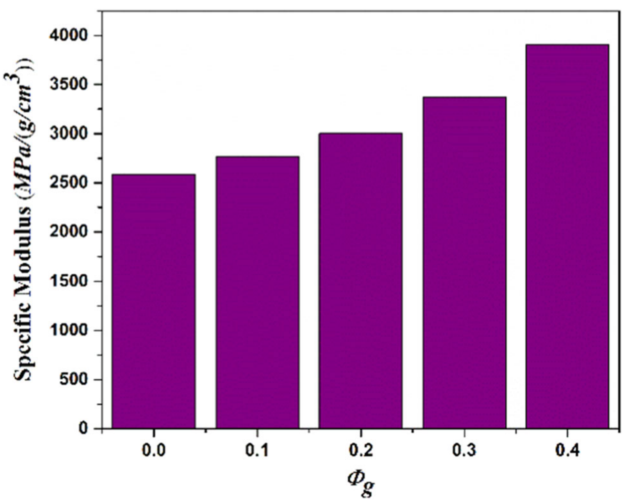

Fig. 8 Specific modulus (E/ρ) of syntactic foams containing microballoons (0.1–0.4 v/v)

to the axial strain and is an important consideration in the design of structures. So, incorporation of syntactic foams as a sandwich layer in structures will reduce the load on the building structures without affecting its integrity.

3.3 Parameters for beam and plate design

Several uses of syntactic foams include sandwich composites used to make structural components or massive structures [23–26]. To optimize the flexural stiffness for beams, it is usually necessary that material with high modulus must be positioned far from the neutral axis [17]. The component's mass with a certain axial stiffness could be reduced by choosing the material with the greatest value of specific modulus (E/ρ). Specific modulus is computed and shown in Fig. 8 for increasing the volume fraction of glass microballoon.

The mass of beam with span length, l and a specified flexural stiffness, S_b, expressed as

$$m = \frac{\rho}{\sqrt{E}}\sqrt{\left(\frac{4\pi S_b l^5}{\varnothing}\right)} \quad (1)$$

where $S_b, = E.I/l^3$, shape factor $(\phi) = (4.\pi.I)/A^2$, A and I are the area of cross section and moment of inertia, respectively [17].

The beam's mass with a particular bending stiffness may be reduced by choosing material with greatest value of E/ρ^2. Furthermore, it can be established that the plate's mass with a specific bending stiffness is reduced by choosing material with greatest value of E/ρ^3. [17] Both properties are computed and shown in Fig. 9 for increasing the volume fraction of glass microballoon.

As evidenced in these figures, the specific modulus, Young's modulus to square and cube of density, for all kinds of foams increases with increase in volume fraction of hollow glass microballoons. It is thus discovered that the ϕ_g in the material has a significant impact on these parameters. Parameters are likewise the greatest for the highest ϕ_g, giving birth to materials with low weight, examined in this research. As a result, the use of syntactic foams in structural applications may result in significant weight reductions.

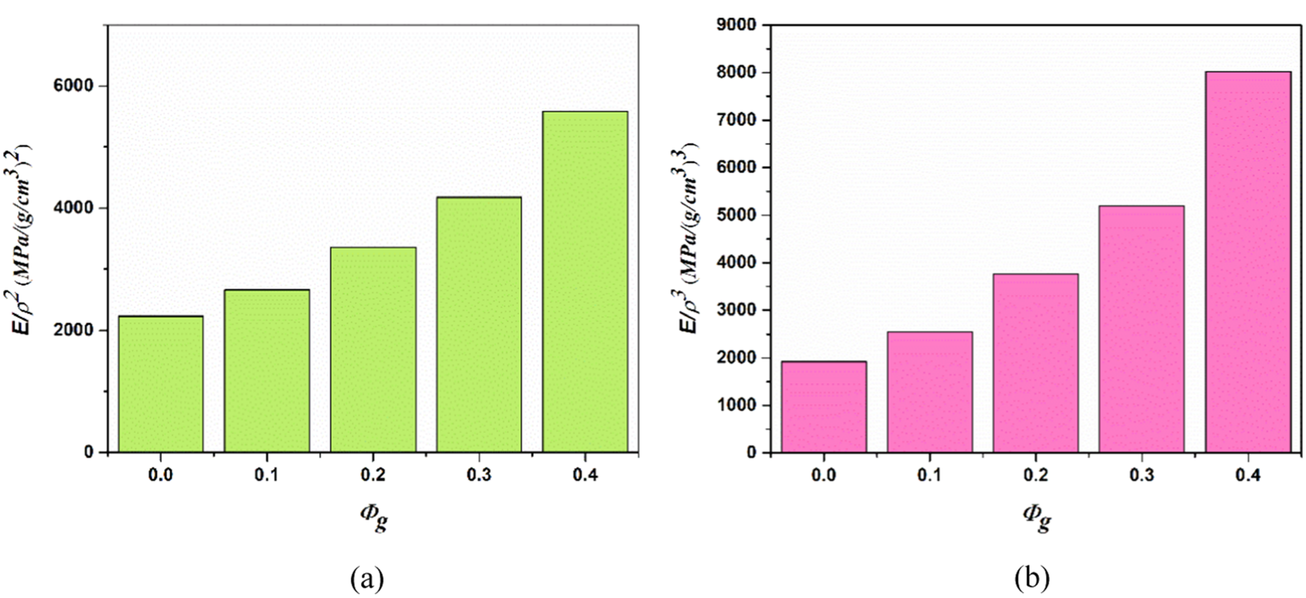

Fig. 9 For various volume percentages, **a** E/ρ^2; **b** E/ρ^3 for glass microballoons filled syntactic foam

4 Conclusions

The RVEs of syntactic foams with randomly filled hollow glass microspheres (K15) (0–0.4 v/v) in matrix of epoxy resin have been used to develop a model in ANSYS software (2020, R1) to investigate the numerical results. Modal study indicated to be quite useful in the evaluation of properties such as density, relative modulus and relative Poisson's ratio, which was one of the overall study's goals. The advantages of utilising ANSYS were the ability to precisely display mode forms and greater precision for curves. The model can evaluate elastic constants of the composites for higher volume fractions of microballoons. The impact of ϕ (volume fraction) on the elastic mechanical characteristics have been studied. The model is verified using experimental and theoretical data for syntactic foams. The relative modulus, density, and Poisson's ratio values of syntactic foams fall as the microsphere volume fraction rises, but specific modulus values of composites increases, confirming that component weight can be reduced. The relative modulus, relative Poisson's ratio and density of syntactic foam decreases with increasing volume of microballon, droping to ~ 4.5, ~ 8.9 and ~ 30 percent at 0.4 volume fraction. Results for the density, relative modulus and relative Poisson's ratio of K15 type hollow glass microspheres reinforced syntactic foam was compared with the previously studies by Porfiri et al. [13], Torquato [43], Ullas et al. [44]. There was considerable agreement between the numerical results and previous investigations. Parameters for beam and plate design are given ensuring that light weight materials for structural applications could be made by increasing and adjusting the volume fraction of hollow fillers which could permit the use of syntactic foams in structural applications. In further research, some different types of glass microbaloons reinforced syntactic foam will be analyzed using various other techniques that are now accessible and evaluated for many additional analyses. Validation of such foams was discovered to be challenging, however it may be done experimentally in future work.

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