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A micromechanical model for quasi-brittle compressive failure of glass-microballoons/thermoset-matrix syntactic foams

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Abstract

We propose a micromechanical model for the quasi-brittle failure of syntactic foams subject to uniaxial compression. We focus on a failure characterised by shear bands inclined of about 45° with respect to the loading axis, often observed in thermoset polymers filled with glass microballoons. Our objective is to develop a three-dimensional Finite Element (FE) model for the effective compressive strength. Towards this aim, we extend our previous FE models, which include fifty randomly placed balloons and were developed to assess the accuracy of linear elastic homogenisation procedures for syntactic foams. Here, we account for the filler polydispersion and introduce a novel structural failure criterion for the glass microballoons. The proposed models are shown to be macroscopically isotropic with respect to the effective strength. We find good agreement with experimental results from the literature on syntactic foams with filler volume fraction of 60%, for which we assume the matrix to be linear elastic.

Keywords: Syntactic foam; Finite element method; Numerical homogenisation; Brittle failure; Failure criterion

1. Introduction

Syntactic foams are particulate composites whose filler consists of hollow spheres, also called balloons. Here, we study *glass-micro*balloons/*thermoset*-matrix syntactic foams,[c] which find applications in both aerospace and marine systems for their closed-cell microstructure. Such microstructure is indeed leveraged to obtain high effective stiffness per unit mass and to enhance stability under severe temperature and moisture conditions (see for example the review by Shutov[1]). In particular, the microballoons employed in this study are made of a soda-lime-borosilicate glass composition.[3] The main objective of this work is the development of a micromechanical model for the prediction of the effective strength of these syntactic foams. Specifically, we seek to investigate the quasi-brittle failure of syntactic foams subject to uniaxial compressive stress (henceforth simply referred to as uniaxial compression).

Several failure modalities have been observed in the literature for glass microballoons/thermoset matrix syntactic foams subject to compressive loading. Differences in experimental findings depend both on the many details of the constituent phases and on the precise boundary conditions. Among the observed failure modalities, we mention:

1. brittle failure with splitting along planes including the loading direction under uniaxial compression, experimentally observed by Bardella[4] and Gupta et al.[5];
2. quasi-brittle failure accompanied with shear bands inclined of about 45° with respect to the loading direction under uniaxial compression, observed by Rizzi et al.,[6] Adrien et al.,[7] and Gupta et al.[8];
3. crushing of a localised "weak layer" perpendicular to the loading direction, observed, for uniaxial compression, in the pioneering work of De Runtz and Hoffman[9];
4. large-scale breakage of microballoons with no macroscopic fracture and large inelastic deformations observed by De Runtz and Hoffman[9] for uniform volumetric loading or other loading conditions with prevalent compression.

Only a few investigations on the micromechanical phenomena underpinning the observed failure modalities can be

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[c] Syntactic foams may also be made of different materials,[1] such as ceramic microballoons and aluminum matrix.[2]

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found in the literature. Bardella and Genna[10] model the 1st collapse listed above through the Finite Element (FE) solution of a non-standard Eshelby-like problem in which a composite inclusion is surrounded by a nonlinear medium; therein, the composite inclusion consists of a flawed glass microballoon embedded in a nonlinear viscoelastic matrix. Tagliavia et al.[11,12] present micromechanical analyses that are relevant to the description of interfacial debonding of syntactic foams under tensile loading.

Here, we seek to model the 2nd collapse listed above, with 45°-inclined shear bands. As a first step towards the understanding of the micromechanics underlying this failure modality, we focus on the failure of the glass microballoons. Thus, we primarily consider syntactic foams with very high microballoons volume fraction, of about 60%. While such high filler content is useful to limit the viscoelastic behaviour of the composite, it may be responsible for a variety of undesired physical phenomena. For instance, the matrix stiffness may differ from that measured on plain matrix specimens because of differential curing within the composite, where the inclusions may act as heat sinks creating a non-negligible interphase region.[13,d] Also, the effect of imperfect interfaces is more likely to be relevant, since it is generally difficult for the matrix to completely wet the filler. In addition, the content of unreinforced voids[e] usually increases with the balloons' volume fraction f and its experimental determination may be hampered by the breakage of microballoons during manufacturing. We focus on syntactic foams with high filler concentration to formulate a simple and effective criterion for the failure of the glass microballoons. Hence, we establish a micromechanical modelling scheme which neglects the features discussed above, that will be dealt with in the near future.

In particular, we neglect the unreinforced voids, so that the matrix volume fraction is equal to $1-f$ and the void phase (exclusively enclosed within the balloons) has volume fraction equal to

$$f\eta^3$$

where η is the balloon radius ratio. The latter parameter is an average of the ratio between the inner and the outer radii of the inclusions computed from the filler effective density, ρ_f, and the density of the glass, $\rho_g = 2.6\ \mathrm{g/cm^3}$, through:

$$\eta = \left(1 - \frac{\rho_f}{\rho_g}\right)^{1/3}$$

In the cases of interest, η is always larger than 0.9 because the glass microballoons used in the synthesis of lightweight glass-polymer systems have $\rho_f \in (0.1\ \mathrm{g/cm^3}, 0.6\ \mathrm{g/cm^3})$.[1] In this work, we account for the polydispersion of various commercial batches of glass microballoons by considering, for each of them, varying radius ratios.

We study syntactic foams in which all the phases are isotropic along with the overall behaviour, the latter being a key feature we seek to model. The glass is assumed to have Young's modulus $E_g = 70,\ 110$ MPa and Poisson's ratio $\nu_g = 0.23$, while the thermoset matrix has Young's modulus $E_m \approx 3$ GPa and Poisson's ratio $\nu_m \approx 0.4$.

Our micromechanical modelling utilises the 50-balloons three-dimensional FE models (henceforth indicated with the acronym MPUC, for MultiParticles Unit Cell) presented by our group in Ref. 15 to assess the accuracy of available linear elastic homogenisation procedures for syntactic foams, including those proposed by Hervé and Pellegrini,[16] Bardella and Genna,[17] and Porfiri and Gupta.[18] The results of Ref. 15 indicate that, for a very wide range of phase moduli, volume fractions, and radius ratio, the MPUC provides estimates of the elastic moduli that are in very good agreement with the Composite Sphere-based Self-Consistent Scheme.[f] Since one of the main assumptions of the analytical homogenisation schemes for syntactic foams, and an effective real property of such composites, is the macroscopic isotropy, these results offer indirect evidence that the MPUC has well randomised distribution of inclusions. In this work, we test this feature in a failure study; to this purpose, the MPUCs developed in Ref. 15 are extended to account for the filler polydispersion in terms of radius ratio. This is accomplished by exploiting the filler characterisation of Aureli et al.[20] Modelling of the syntactic foam microstructure is thus central to this study and detailed in Section 3.

Inspired by the experimental observations of d'Almeida,[21] Adrien et al.,[7] and Gupta et al.,[8] we assume that the failure is governed by the collapse of the microballoons. In Section 2, we propose and discuss a novel structural failure criterion for the glass microballoons, in which we hypothesise that each microballoon fails in a brittle way when its average strain energy density reaches a critical value, independent of the microballoon radius ratio. The structural criterion has two main advantages, with respect to criteria based on pointwise local quantities (such as the Galileo–Rankine–Navier or the Beltrami criteria for brittle materials[22]): (i) the average strain energy density can be evaluated with good accuracy in a FE model with reasonable computational effort and (ii) the challenging evaluation of the material parameters related to the critical values of pointwise quantities (such as the maximum principal stress or the maximum strain energy density) at the microscale is avoided.

In Ref. 15, the MPUCs were implemented in Ansys, while, in this work, their extensions are re-implemented in ABAQUS, as detailed in Section 4, in order to exploit some amenable features of ABAQUS, to incorporate the proposed criterion for microballoon failure.

In Section 5, the micromechanical model is validated against the experimental results of Gupta et al.[8] on glass/vinyl ester

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[d] The interphase is a region of the matrix surrounding the inclusions with modified mechanical properties. This modification can be due to differential polymer curing in the proximity of the filler or to the presence of chemical agents on the microballoons' surface (such as silane, relevant for glass inclusions dispersed in epoxy matrix). The latter are often utilised to establish covalent bonds between the matrix and the filler, thereby affecting the matrix properties around the inclusions (see for example the work by Al-Moussawi et al.[14]).

[e] Such voids are also called interstitial or unwanted and are sometimes entrapped in the matrix during manufacturing.

[f] The Composite Sphere-based Self-Consistent Scheme is an extension of the "Generalized Self-Consistent Scheme" of Christensen and Lo[19] to the case of hollow inclusions.