A DAMAGE MICROMECHANICS APPROACH OF A HETEROGENEOUS MATERIAL

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A damage micromechanics modelisation of a syntactic foam is purposed. A damage criterion based on the components caracteristics such as microspheres size distribution, volume fraction, mechanical behavior parameters of the glass and the resin, is established for a tensile load. The stresses redistribution due to the microspheres local failures is taken into account to determine the damage rate evolution and modelize the instability of the failure.

INTRODUCTION

The incorporation of hollow glass microspheres in a resin matrix increases the specific failure strength. The excellent compressive strength for a low density allows to use this syntactic foam for submarine or aeronautic applications but, in tension, the mechanical behavior is brittle and the tensile strength is twice less important than in compression (1). The aim of this study is to purpose a micromechanic approach of the damage resulting from a tensile load. The damage micromechanics modelisation starts from the failure of one hollow glass microspheres family depending on its size, volume fraction and the stress redistribution due to the failure of bigger microspheres. A relation between the microstresses at the microsphere scale and the macrostresses at the homogeneous volume

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element scale, can be given. It shows the influence of the microstructure parameters on the failure macrostress. This can be used in order to ameliorate the material by changing the components. In the case of structure, this model allows to know the damage state of the material for any tensile load. It also gives the evolution of the damage rate occurring at different stress levels. An instability phenomenon due to the successive failures of large families of microspheres appears without changing too much the load. This can be dangerous in the case of structure use and can be prevented by the model.
The damage effect on the elastic behavior was taken into account with the replace of a broken microspheres family by the corresponding microvoids family.It can then be calculated, using the Hashin's model (2), a decrease of the elastic Young's modulus.This modelisation gave the expected relation between the local stresses in a microsphere and the macroscopic stress applied on the reference volume element (3).

2 Material

The studied material is a syntactic foam FM280 composed of hollow glass microspheres in a resin matrix. The microspheres diameters d oscillate between 20 and 200 µm, the thickness e between 1 and 2 µm. The total volume fraction F_V is about 0.64. The microspheres repartition is given by a statistical Log-normal law.
The syntactic foam behavior is completely elastic. The addition of microspheres in a resin matrix induces a decrease of the Young s modulus and the failure strength. The resin behavior is also elastic .

3 Experimental results

During a tensile test, replicas have been applied on the specimen surface. It can then be observed the different states of damage when the load increases. For a load of about one third of the failure strength, the biggest microspheres break along the median plane, perpendicularly to the load direction. The number of broken microspheres increases and the size of these decreases, when the tensile load increases.The failure surface (fig 1) shows that some of the microspheres are broken, some not (the smallest ones). It can be deduced from this figure that under a critical value of the microsphere diameter d_r, the matrix breaks around the microspheres.

The stress-strain curve depends on the way of mesuring strains. A strain gauge has been adapted on the specimen geometry where the section is minimal in order to localise the damage. It can be seen on the figure 2 the non linear evolution of the stress-strain curve. This nonlinearity is only due to the damage effect. Some periodic relieves of the tensile stress show a decrease of the Young's modulus (4) . Only the failure of microspheres induces this phenomenon.

4 Damage micromechanic modelisation.

4.1 Plan of the modelisation .

This modelisation has been done with finite elements method calculation, in order to correlate the local microstresses field to the macrostress applied to the volume element.

This approach can be described as follows:

Young's modulus evolution, E_{eff}, function of the volume fraction of broken microspheres, F_{vr}
↓
Stresses field calculation in the glass microspheres, function of the ratio e/d, E_{eff} and the macroscopic tensile stress Σ
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Failure criterion of the glass
↓
For a given mean thickness e_m, determination of the critical failure diameter d_r as a function of Σ and F_{vr}.
↓
Use of the statistical repartition of microspheres sizes. Relation between F_{vr} and d_r.
↓

Damage criteria:
relation between d_r and Σ
relation between f_{vr} and Σ
relation between E_{eff} and Σ

↓

Analysis of the microstresses field in the matrix around a cavity created by a microsphere failure, function of Σ and E_{eff}.

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Evolution of microstresses in the resin matrix induced by the stresses redistribution due to damage, as a function of Σ.

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local failure criterion of the resin matrix.

↓

final failure of the syntactic foam.

4.2. Microstresses field calculation.

To predict the damage evolution with the microspheres failure, a basic cell for finite elements calculation has been chosen. The figure (3) shows the basic cell composed with an hollow glass microsphere (thickness e, diameter d) surrounded by the resin matrix with an external spherical dimension d_l given by the volume fraction F_V.

$$Fv = d^3 / d_l^3$$

A cylinder (diameter d) of the equivalent homogeneous material surrounds the two previous microspheres. Its dimensions are large enough, $D > 3d$, to not disturb the stresses field in the glass microspheres.

When the first volume fraction of a given microspheres size breaks, a stress redistribution, inside the syntactic foam, occurs. Then the smallest microspheres are more stressed than previously.

To take into account this effect, finite elements calculations have been made with different effective Young's modulus of the equivalent homogeneous material, correlated with the damage process.

From a known tensile macrostress Σ applied to the basic cell, the maximum principal microstress located in the glass microsphere, has been calculated as a function of the size ratio (e/d) and the effective Young's modulus E_{ff} (fig4)
The curves of the figure 4 show the stress concentration in the glass hollow microspheres increases when the microspheres size becomes bigger.

$$\sigma_{Ib} / \Sigma = (25.24-3.94\, E_{eff})\, \exp(\,0.005\, d/e)$$

It can be noticed that the decrease of the effective Young's modulus E_{eff}, due the damage process, induces an increase of the principal microstress in the glass for a given macrostress Σ and microsphere size e/d. It means that a stresses redistribution occurs when the failure of a microspheres volume fraction appears.

The glass is a brittle material. To describe its failure we chose a Lame's criterion which is based on the maximum principal stress. The microspheres are broken along the median plane perpendicularly to the tensile stress. The failure in torsion occurs along an helix at 45°. So a glass microsphere breaks when the maximum principal stress reaches the glass failure strength . The dispersion of the glass failure strength is very large. For that material we choose σ_{rv}= 700 MPa. A Weibull's statistic can easily be used to give a glass microspheres failure probability(5).
Remaining that

$$E_{eff} = E_0\,(1 - F_{VR})^{1.732}$$

we get:

$$\Sigma = \frac{\sigma_{Rb}}{(\,25.24 - 10.46\,(1 - F_{VR}(d_R))^{1.732})\, \exp(0.005\, d_R/e)}$$

Where d_r is the critical failure diameter of the glass microspheres. The volume fraction of broken microspheres is not independent of the critical failure diameter repartition in the syntactic foam.

For the FM280, this diameter repartition is given by the log-normal following law:

$$f(d)=\begin{cases} 0 & \text{if } d=0 \\ \dfrac{1}{\sigma\sqrt{2\pi}d} \exp\left(\dfrac{-(\ln d - m)^2}{2\sigma^2}\right) & \text{if } d>0 \end{cases}$$

with m= 3,810 and τ= 0,4921

Mathematical expectation : E (d) = 56,7 Variance V(d) =859

The volume fraction of broken microspheres F_{vr} is then given by the equation:

$$F_{vr}(d_R) = F_v.\left(1 - \frac{\int_{-\infty}^{d_r} d^3 f(d) d(d)}{\int_{-\infty}^{+\infty} d^3 f(d)\, d(d)}\right),$$

since all the microspheres with a diameter bigger than d_r have been broken.

Assuming e_m= 1,5 μm, the mean value of the microsphere thickness, a damage criterion correlating the critical microsphere diameter d_r to the macroscopic stress Σ , can be established. The figure 5 shows an instability of the damage process (curve 1). For a given macrostress Σ (25 MPa), the successive failure of smaller and smaller microspheres occurs. The curve 2 shows this instability phenomenon disappears when the Young's modulus E_{eff} is considered as constant and equal to E_0.

The evolution of volume fraction of broken microspheres F_{vr} as a function of the macroscopic stress Σ is obtained with:

$$F_{VR}(\Sigma) - F_V \left(1 - \frac{\int_{-\infty}^{d_R(\Sigma)} d^3 f(d)\, d(d)}{\int_{-\infty}^{+\infty} d^3 f(d)\, d(d)}\right)$$

The evolution of the syntactic foam Young's modulus E_{eff} can then be deduced:

$$E_{eff} = 2.70\,(1 - F_{vr}(\Sigma))^{1.732}$$

The comparison with the experiment is in good agreement.

6 Conclusion

This micromechanic approach, based on the three phases homogenization technique, allowed us to describe the damage state of a syntactic foam from the characteristics of the components. This modelisation showed the influence of every characteristic of the material on the physical damage. It has been correlated with many microscopic observations and experiments with a good agreement. Applied to a syntactic foam, this approach can be generalized to other heterogeneous materials where the geometry of the components can be simply modelized.

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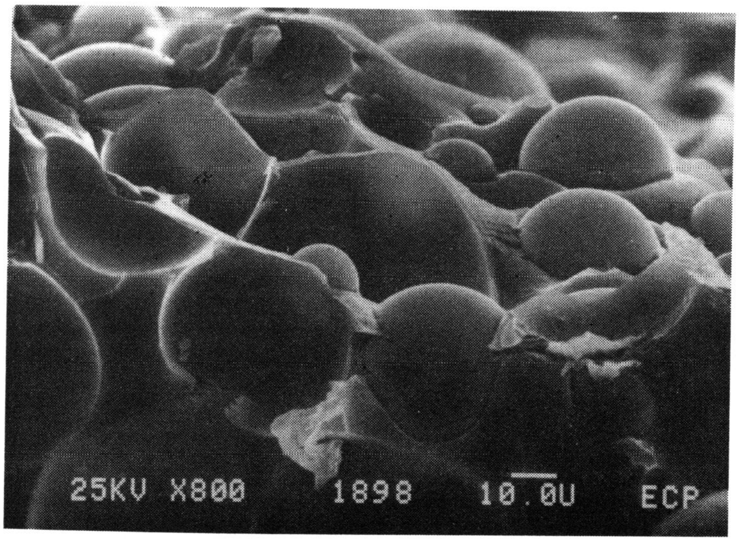
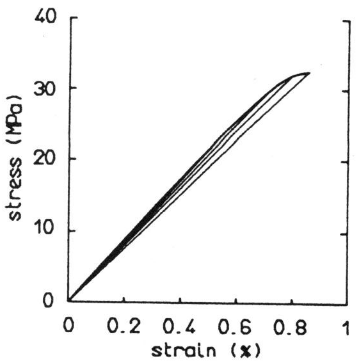


Figure 1 Failure surface of a syntactic foam



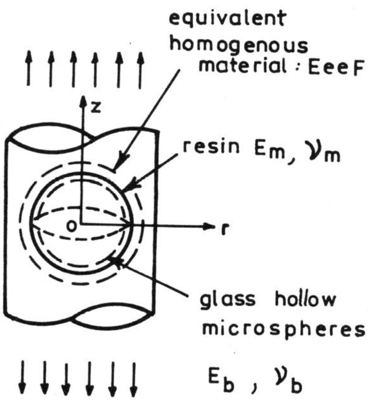


Figure 2 Damage effect on the stress-strain curve

Figure 3 Basic cell

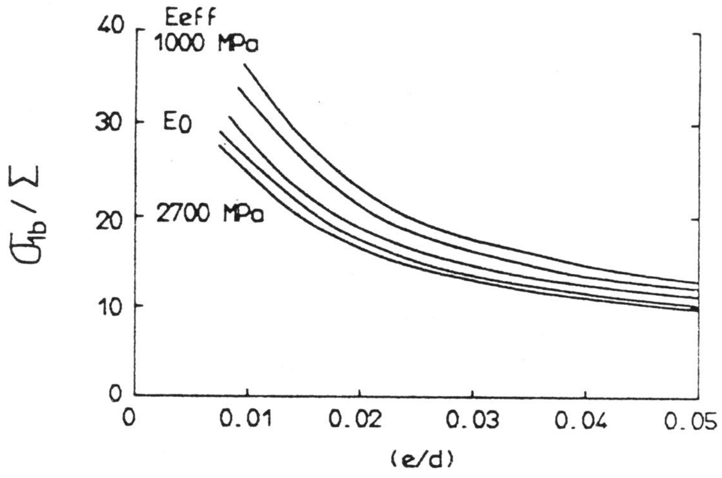


Figure 4 Stress concentration factor function of the ratio thickness diameter, for different Young's modulus

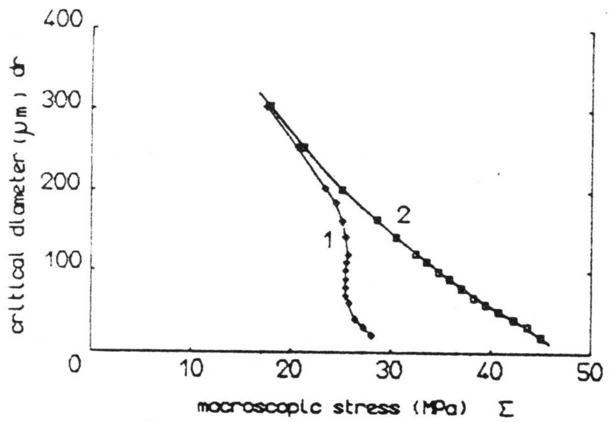


Figure 5 Microspheres failure diameters function of the macroscopic stress