Use of numerical approaches to predict mechanical properties of brittle bodies containing controlled porosity

V. CANNILLO, T. MANFREDINI, M. MONTORSI
Department of Materials and Environmental Engineering, University of Modena and Reggio Emilia, Via Vignolese 905, 41100 Modena, Italy
E-mail: valeria@unimore.it

A. R. BOCCACCINI
Department of Materials, Imperial College London, Prince Consort Rd., London SW7 2BP, UK

Considerable research efforts have been devoted to the investigation of porous materials due to their interesting features. In particular, porous materials with closed, isolated porosity can be exploited for several applications, for example to reduce the dielectric constant of glasses and ceramics used as high performance substrates in electronic packaging [1, 2] or to increase the thermal shock resistance of brittle solids [3]. Although the presence of pores usually decreases the mechanical properties of the materials [4], in same cases even the fracture toughness may be enhanced by addition of porosity [5]. Therefore, it is crucial to design the porous microstructure in order to achieve best possible combination of macroscopic properties. To this aim, it is essential to correlate the effect of the porosity characteristics with the resulting behavior of the material. In a recent study, the effect of pore size, aspect ratio and volume fraction on mechanical properties of model porous glasses has been thoroughly investigated by means of a

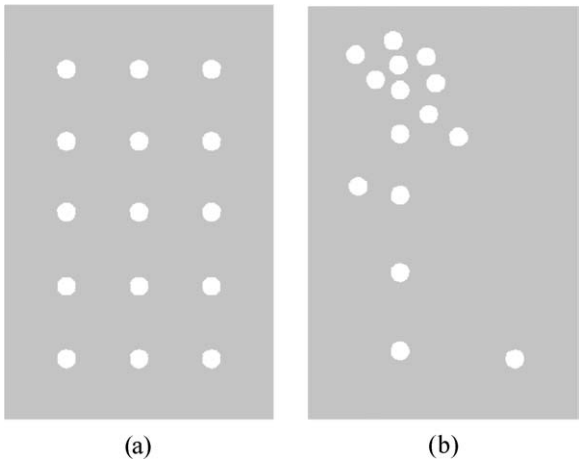

Figure 1 The 2-D porous microstructures analyzed, exhibiting the same concentration of circular pores but different arrangement: (a) regular distribution of pores and (b) inhomogeneous pore distribution.

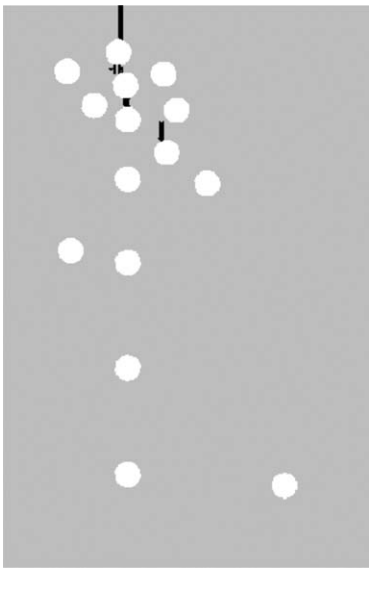

Figure 2 Fracture initiation in the microstructure with pore clustering under tensile load, as determined by OOF calculations.

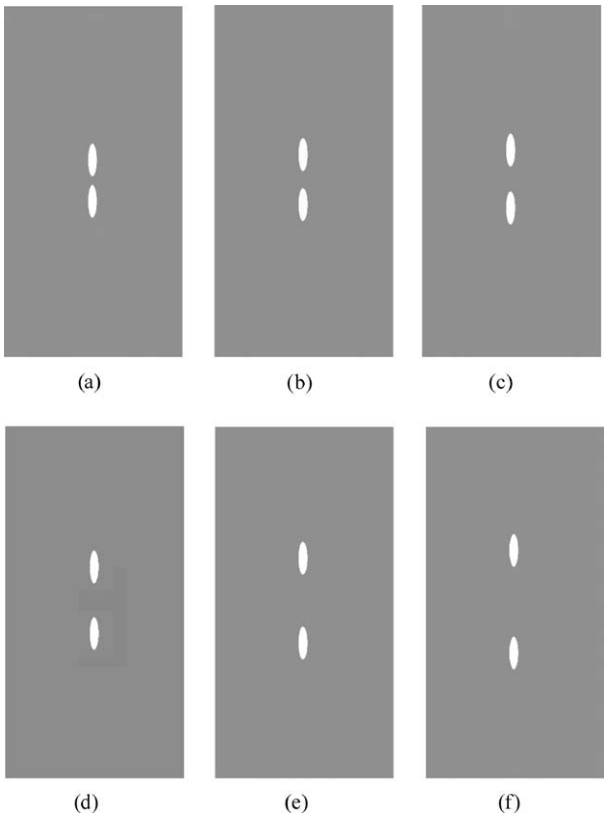

Figure 3 2-D microstructures characterized by an increasing distance between elliptical pores: (a) 25 μm, (b) 50 μm, (c) 75 μm, (d) 100 μm, (e) 150 μm, and (f) 200 μm.

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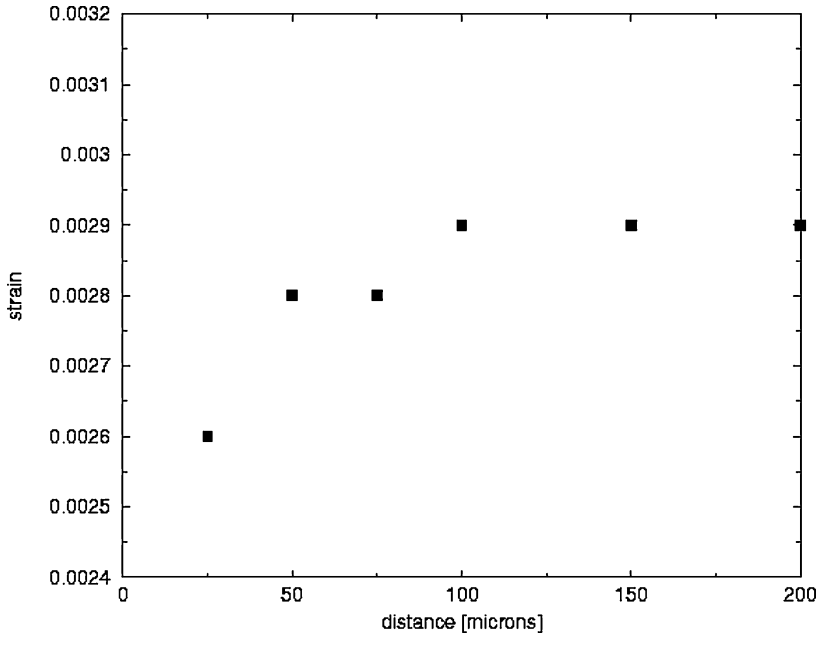

Figure 4 Strain at which microcracking occurs vs. mean distance between pores for the microstructures of Fig. 3.

numerical approach [6]. The strong correlation between the microstructural features and the resulting properties was confirmed; in particular, the critical stress for crack initiation was shown to scale with pore dimension and aspect ratio, i.e. oblate and larger pores oriented perpendicularly to the stress direction cause a higher reduction of strength of the specimen. However, in the aforementioned numerical study the effect of spatial distribution of pores was not analyzed in detail. Other authors emphasized that the decrease in strength of porous materials can be correlated with the average distance between pores [7]. The objective of this paper is to determine if pore clustering at some locations within the porous body may have a detrimental effect on the fracture resistance. In particular, we aim at assessing the influence of the distance between neighboring pores on the resulting mechanical behavior by using a numerical finite element approach.

FEM methods have been successfully employed to characterize the mechanical behavior of porous brittle bodies in previous works [6–8]. In this study, the OOF code [9] is considered in order to map different porous microstructures onto finite element meshes. Griffith's elements are chosen from the OOF library to study the fracture response, as in a previous paper [8]. These elements presume that the material behaves elastically up to failure, which occurs following the Griffith's criterion. In fact, such elements are designed to fail when the total surface energy required to propagate the crack can be supplied by the elastic energy stored; if such condition holds, the element breaks.

Model 2-D microstructures of glass plates containing closed and isolated circular porosity are analyzed. The microstructures have the same volume fraction of pores but different arrangements: a microstructure with a regular distribution of pores (Fig. 1a) and a microstructure exhibiting pore clustering (Fig. 1b) are examined. The corresponding finite element meshes are constructed and the samples are placed under tension in order to simulate a tensile test, under plane stress conditions. The stress at which the specimen begins to break is recorded for both samples. The microstructure of Fig. 1a, with a regular arrangement of pores, begins to fracture at a strain equal to 0.0034, whilst in microstructure of Fig. 1b crack initiates at a strain of 0.0027. As shown in Fig. 2, fracture occurs in areas of high pore concentration. This is due to pore clustering and consequent stress concentrations superposition as well as due to the local reduction of the load-bearing cross-section of the material.

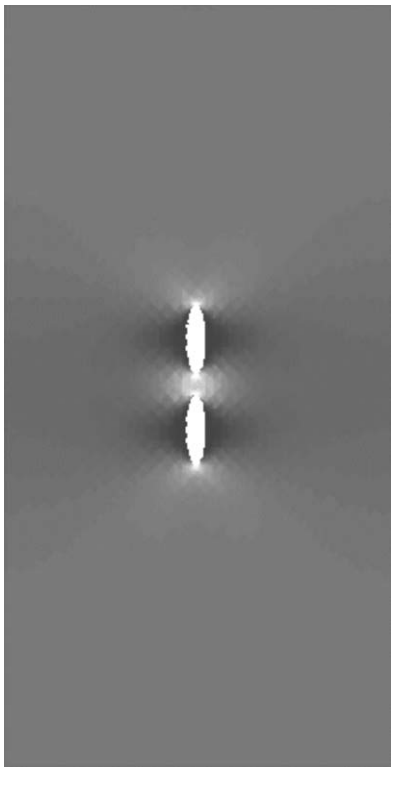

Figure 5 Stress concentration at the pore tips, as determined by the finite element code. If the pores are close the two stress fields are superimposed.

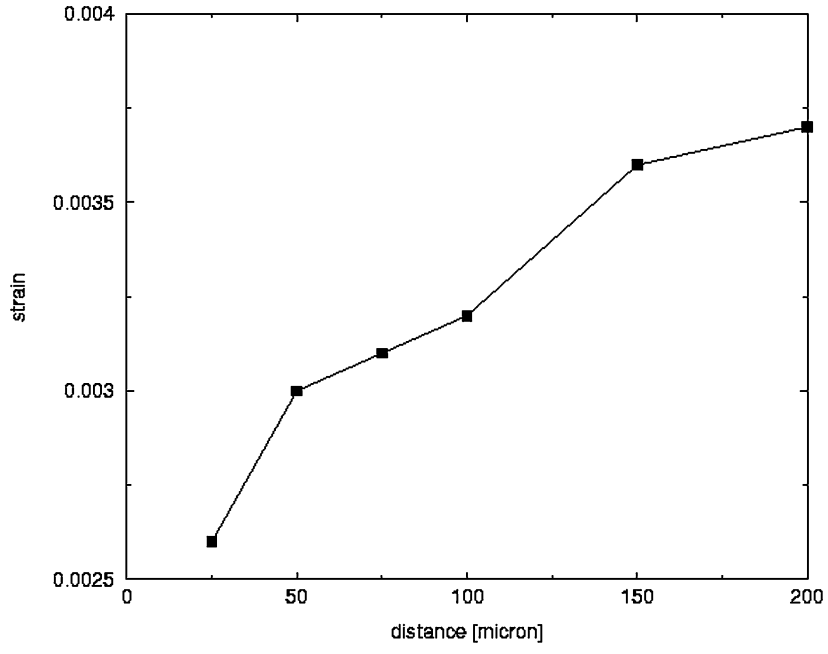

Figure 6 Strain at which the crack connects the two pores vs. the distance between the pores for the microstructures of Fig. 3.

In order to systematically investigate the effect of interpore distance on the strength of the porous sample, a simple 2-D microstructure constituted of a plate of glass with only two elliptical pores is considered. The relative position of the pores is varied, i.e., the distance between the two pores is decreased progressively in order to detect the interaction between pores. Six different microstructures are considered, characterized by a distance between the two pore tips ranging from 25 to 200 microns (the major axis of the pore is about 80 microns), as illustrated in Fig. 3. The microstructures are subjected to a tensile load perpendicular to the major axis of the elliptical pores and the strain at which fracture appears at the pore tip is recorded. Fig. 4 shows that decreasing the distance between pores causes the crack to appear at lower strains, i.e., there is a detrimental effect on the strength if the inter-pore distance is reduced. Similar results were found by other authors [7]. Fig. 5 illustrates the stress concentration at the pore tip as calculated by the finite element model, showing that if the pores are close enough, the two stress fields interact.

Moreover the strain for which the crack connects the two pores, i.e., the condition for crack and pore coalescence, is reported in Fig. 6. As can be noted, an increasing applied strain is required as the distance between pores increases.

Thus, it can be concluded from the numerical results that porous structures with regions of very dense pore concentration potentially lead to a decrease in strength, which is well known from experiments [4]. The aim of the paper was thus to emphasize the use of numerical methods for investigating mechanical properties of porous structures. In fact, it was shown that the application of the finite-element method and in particular of innovative approaches, able to consider microstructural features, such as the OOF code [9], is a useful tool in order to determine microstructure-property correlations and consequently crucial design parameters in porous materials. This paper completes the results of [6], demonstrating that even if pore size, shape and volume fraction are controlled, also the spatial distribution is critical in determining the mechanical behavior of the porous body. Therefore, when designing a porous material, it is important to control not only the porosity and pore morphology, but also the pore spatial positioning, if the mechanical properties, in particular fracture strength, are to be optimized. To this aim, suitable production techniques should be developed in order to guarantee an homogeneous dispersion of pores. For example, the addition of hollow glass (or ceramic) microspheres to glass (or ceramic) powders may enable the preparation of porous bodies with such requirements by hot-pressing methods [10]. The final goal is to produce a porous material with optimal pore structure in order to obtain the best possible combination of macroscopic properties.

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