PLASTIC STRAIN LOCALIZATION IN PERIODIC POROUS METAL SHEETS

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Introduction

Perforated metal sheets, Fig. 1, are found in a number of technologically important applications, including aircraft, building construction, electronic, naval and nuclear industries. They are typically fabricated with uniform perforation patterns of different hole shapes and arrangements characterized by a well-defined repeating unit cell that is the basic building block of the entire array, characteristic of materials with periodic microstructures. The perforation patterns include circular holes, hexagons, squares (rectangles) and slots arranged in square or hexagonal patterns. While fiber shape and fiber array effects on the elastic and post-yield response of metal matrix composites have been investigated extensively, little systematic data is available in the literature on the corresponding effects of hole shape and distribution in perforated thin metal sheets.

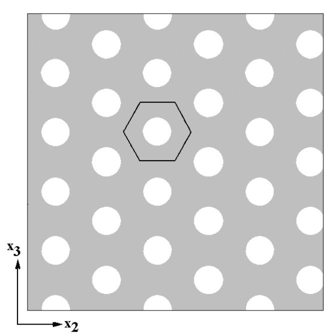

Fig. 1 Perforated sheet with circular holes in a hexagonal array.

Perforations reduce material's stiffness and load bearing capability through load transfer degradation and local stress concentrations. An effective and comprehensive methodology is essential in optimizing the design of perforated materials in a variety of applications, especially those related to structural safety issues. The micromechanics approach provides a systematic framework for analyzing the response of heterogeneous materials, including perforated thin sheets. For periodic materials, the fundamental problem is to determine the response of a unit cell that characterizes the material's microstructure under periodic boundary conditions. The homogenization theory has emerged as a dominant tool for this class of materials, with different versions of this technique continuously being proposed, the majority of them based on the finite-element method for the solution of the unit cell problem [1].

The FVDAM Homogenization Theory

An attractive alternative to the finite-element analysis of unit cell response is the finite-volume direct averaging micromechanics (FVDAM) theory [2]. The method employs elements of the homogenization theory within an approximate analysis framework of local displacement fields in the individual subvolumes of the discretized unit cell microstructure. The local/global stiffness matrix approach is used in the solution of the unit cell boundary-value problem based on satisfaction of traction and displacement interfacial continuity conditions and equilibrium equations in a surface-averaged sense. The incorporation of parametric mapping capability into the FVDAM theory [3] based on the original work reported in [4], and the recent implementation of thermal and plastic effects [5,6], has produced a robust tool for efficient analysis of periodic materials with complicated microstructures. Results with accuracy comparable to those of the finite-element method are now possible with much greater efficiency [7].

The above advancements have made FVDAM an excellent tool for the analysis of perforated metal sheets. Perforations of arbitrary shape arranged in various arrays can be rendered accurately, and parametric studies may be conducted efficiently to determine the response of such arrays in the elastic and elastic-plastic regions under inplane loading modes. Herein, we employ the FVDAM theory to investigate the effect of pore architecture on the plastic strain localization which limits the load-bearing capacity of perforated metal sheets fabricated with non-hardening structural steel.

Numerical Results

The investigated arrays include circular holes arranged in square and hexagonal arrays, hexagonal holes in hexagonal arrays, square holes in square arrays, and slots in hexagonal arrays. Figure 2 illustrates the effect of hole geometry and array type on the macroscopic response of perforated thin plates under normal transverse loading. As observed, both features play substantial roles in the plastic region. In particular, the array type influences the extent of plastic strain localization as seen in Fig. 3 for circular holes in square and hexagonal arrays under the considered loading. The results illustrated in the figures were generated using the elastic moduli of structural steel and the assumption of elastic-perfectly plastic response for the pore volume fraction of 0.40.

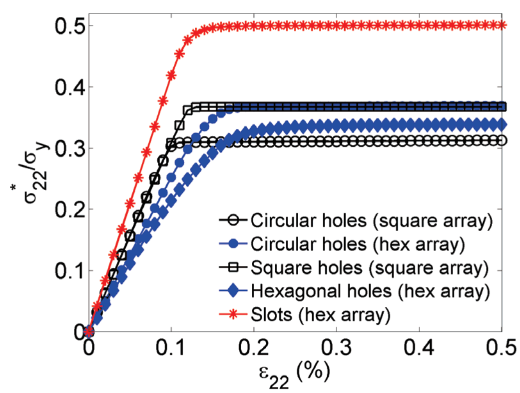

Fig. 2 Homogenized stress-strain response of steel sheets with different pore architectures.

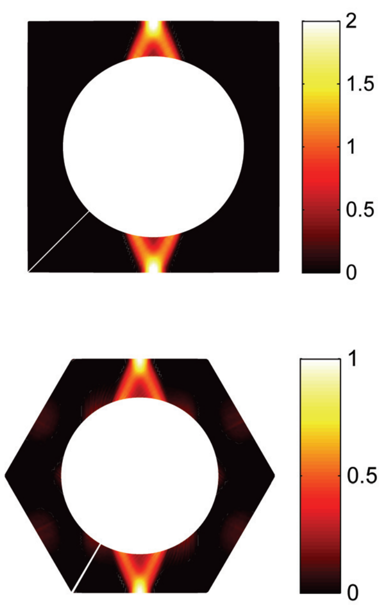

Fig. 3 Porosity array-dependent plastic strain localization under transverse loading at the applied strain of 0.3%.

The plastic strain localization phenomenon suggests the occurrence of plastic bifurcation at relatively small imposed homogenized strains. This depends on the loading mode, array and porosity shape, and the porosity content. For example, increasing the porosity content of circular holes arranged in a square array accelerates the plastic strain localization phenomenon and increases the magnitude of the maximum effective plastic strains in the localization regions. This imposes a constraint on the maximum homogenized strain that can be applied before the occurrence of failure by plastic bifurcation.

Summary and Conclusions

The differences in the local stress distributions amongst the investigated configurations produce large enough differences in the initiation of yielding to result in substantial differences in the asymptotic macroscopic stress-strain response. For instance, under normal loading by transverse stress, a square array of circular holes at sufficiently large porosity volume fractions attains a smaller asymptotic value of the macroscopic stress than a square array of square holes, despite the nearly identical elastic response. This is due to plastic strain localization across the critical load bearing cross section between the circular holes. The extent of this localization is smaller in a hexagonal array of circular holes under transverse normal loading, resulting in a higher asymptotic stress relative to the square array despite smaller transverse Young's modulus. Plastic strain localization observed in square arrays with circular holes propagates across the entire loading-bearing ligament under normal loading, imposing a limit on the extent of elongation that a perforated sheet may undergo before it fails due to plastic bifurcation. This localization increases with increasing porosity content.

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