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13. ABSTRACT *(Maximum 200 words)*

The project delt with the in-plane crushing of aluminum honeycombs with hexagonal cells and polymeric honeycombs with circular cells. The relatively regular and periodic microstructure of these two-dimensional materials makes them excellent models for studying the mechanisms that govern the compressive response of cellular materials. Under displacement-controlled loading, the load-displacement response of such materials consists of a relatively sharp initial rise to a load maximum followed by an extended load plateau which is terminated by a sharp rise in load. It has been shown that these characteristics are associated with inelastic buckling and a localization process in which only a narrow zone of cells experiences collapse at any given time. The collapse spreads in a steady-state fashion until all the material is affected.

The crushing processes have been simulated numerically by modeling appropriately the underlying nonlinearities of geometry, material and contact. Aluminum was modeled as an elastic-plastic solid and the polycarbonate as an elastic-powerlaw viscoplastic solid. Results from analyses involving characteristic "cells" and from large scale simulations of cushing have been produced. Both are in very good agreement with the experimental results. The numerical models were also used to conduct parametric studies of the mechanical properties of these two types of honeycombs. The methods developed are currently being extended to the three-dimensional setting to enable similar parametric studies of foams.

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Project Final Report

THE ROLE OF INSTABILITIES ON THE MECHANICAL RESPONSE OF CELLULAR SOLIDS AND STRUCTURES

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THE ROLE OF INSTABILITIES ON THE MECHANICAL RESPONSE OF CELLULAR SOLIDS AND STRUCTURES

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Summary

Light-weight cellular materials are widely used for packaging, for impact mitigation purposes and as cores in sandwich structures for many applications. It is presently possible to tailor mechanical properties such as density, elastic modulus, crushing stress and energy absorption capacity to the needs of particular applications. In order for this to become models need to be developed which can predict these properties accurately. Honeycombs are two-dimensional cellular materials with relatively regular and periodic microstructures. These geometric characteristics make them good candidates for systematic analyses of the mechanisms governing the compressive behavior of cellular materials.

The project involved detailed studies of the compressive behavior of aluminum hexagonal cell honeycombs and polymeric honeycombs with circular cells. The work combined careful experiments with systematic analyses. Under displacement-controlled loading, the load-displacement response of such materials consists of a relatively sharp initial rise to a load maximum followed by an extended load plateau which is terminated by a sharp rise in load. It has been shown that these characteristics are associated with inelastic buckling and a localization process in which only a narrow zone of cells experiences collapse at any given time. The collapse spreads in a steady state fashion until all the material is affected. The first major accomplishments of the project was the proper identification of these mechanisms previously not well understood. The aluminum of the hexagonal honeycombs analyzed is elastic-plastic but relatively time independent. By contrast, the polycarbonate material of the circular honeycombs is rate-dependent and, as a result, the initiation and propagation loads of the governing instabilities depend on the rate at which the material is crushed.

The second major accomplishment of the project is the development of a systematic methodology for calculating the mechanical properties of cellular materials. The crushing processes have been simulated numerically using formulations which appropriately address the geometric nonlinearities of the problem, the nonlinearities due to contact between cell walls, and the nonlinearities of the two base materials. Aluminum was modeled as an elastic-plastic solid whereas the polycarbonate was modeled as an elastic-powerlaw viscoplastic solid. Both material models were calibrated through independent material characterization tests. Results from analyses involving characteristic "cells" and from full scale simulations of the experiments have been reported. Both are in very good agreement with the experimental results. The numerical models were also used to conduct parametric studies of the mechanical properties of these two types of honeycombs. The methods developed are currently being extended to the three-dimensional setting to enable similar parametric studies of foams.

Honeycombs have also been crushed under biaxial compression using a custom biaxial testing facility. Test specimens can be crushed in two perpendicular directions simultaneously at prescribed rates, to a maximum reduction in volume of 95%. For biaxial crushing the modes of collapse are different and more complex due to the higher degree of constraint.

1. Project Objectives

Materials with cellular microstructure are of growing importance in the development of high performance aerospace vehicles due to the benefits they provide resulting from their relatively high stiffness and strength-to-weight ratios. Recent advances in manufacturing processes enable the manufacturing of cellular materials (metallic, polymeric, ceramic, etc.) to chosen densities and cell sizes. This has made them very attractive in many applications either as the primary structural material or as constituents in composites. Because of their cellular and periodic construction, the extent to which they can be loaded or deformed is limited by instabilities. In compression, they usually exhibit an initial elastic response of relatively high stiffness which is terminated by an instability. The instability, which often is governed by interacting geometric and material nonlinearities, usually results in localization of deformation. The localized deformation subsequently tends to spread to the rest of the material at a nearly constant load. When all the material has been crushed, the response becomes stable and stiff again because of its densification.

The objective of this study, together with its companion study conducted by Professor Triantafyllidis of the University of Michigan, has been first to understand the underlying mechanisms of this behavior and second to develop continuum-type constitutive models which can be used in engineering design of and with such materials. The approach followed involves careful experimentation combined with various levels of consistent analyses.

2. Methodology

The first phase of the project has involved the study of the compressive response and crushing of honeycombs. Honeycombs lend themselves to systematic analyses of the mechanisms governing each of the three main deformation regimes because of the regularity and periodicity of their geometry. This is a prelude to similar studies, which will follow, of the more complex space filling foams.

Aluminum honeycombs with hexagonal cells and polymeric honeycombs with circular cells having a hexagonal close-packed arrangement have been studied to date. Each honeycomb analyzed through combined experimental and analytical efforts.

The experimental work involved the following: (a) Experiments in which the compressive quasi-static response of the materials is established and the mechanisms governing each deformation regime are identified; (b) measurement of the mechanical properties of the base material; and (c) analysis of imperfections, residual stresses and anisotropies induced by the manufacturing process. These have been established for each of the two materials for various cell sizes and material densities.

The theoretical work involves the following: (a) Development of models for full-scale simulations of the experiments; (b) development of simpler micromechanical models which provide accurate estimates of the three major mechanical properties of the material, that is, the initial elastic properties, the stress at the onset of the instability and the stress level and extent of the stress plateau; (c) development of homogenized models for predicting these properties (conducted by Triantafyllidis).

3. Accomplishments

(a) The study of the compressive behavior of hexagonal aluminum honeycombs under uniaxial loads has been completed [1,4]†. The behavior observed experimentally has been successfully simulated numerically using both full-scale numerical models which require extensive computation time, as well as simpler representative micromodels which are computationally efficient. The ability of the models to predict the three critical mechanical properties identified in the previous section was demonstrated in a parametric study of the problem.

(b) The compressive response and crushing of polycarbonate honeycombs has also been completed [2,3]. In this case, in addition to the complexity of the nonilinearities of geometry, contact and plasticity the problem is also rate-dependent. This rate-dependence has been found to enrich the instability mechanisms and to result in a more complex behavior. Honeycomb specimens have been crushed at different rates and the mechanisms carefully identified. Viscoplastic constitutive models have been developed, calibrated and used to analyze the problem. It is believed that this may be the first study of a propagating instability in a strongly rate-dependent material. Thus, the results should have repercussions in a broader field of problems and in particular in the study of polymeric foams.

(c) The third task of the study involved the compressive response and crushing of cellular materials under multiaxial loads. Because of technical challenges involved in such an undertaking, this had not been attempted experimentally by anyone in the past. To accomplish this task we designed and fabricated a novel testing facility capable of crushing such materials in two orthogonal directions simultaneously under controlled conditions. It is operated by two independent orthogonal actuators run by closed loop servo-controlled systems. In the first machine built each axis has a load capacity of

† Numbers in [•] refer to publications listed in § 6

10,000 lbs and an initial gage length of 5.25 inches. This can be reduced to 1.25 inches or about 75% of its original length. As a result, the area of the test section can be reduced down to nearly 5.5% of its original size. The crushing can be conducted either in load or displacement control. A patent is pending for this unique testing facility. The machine is currently being used to measure the properties of honeycombs and foams under biaxial loads applied at various displacement rates. The first body of results of this type are reported in [3].

4. Future Work

Future work will include two major tasks. First, the BICRUMA will be used to understand in detail the mechanisms which govern the crushing of cellular materials under biaxial loading. As was done in the previous tasks this will be accompanied with an analytical effort using the techniques developed suitably extended. The second new task will be to extend the techniques and knowledge base developed in two-dimensional cellular materials to the study to space-filling foams. Aluminum and polymeric foams with open and closed cells are being considered for this phase of the study which will involve characterization of their compressive response under uniaxial and multiaxial loadings.

5. Personnel

1. *Principal Investigator:* Stelios Kyriakides, Professor
2. *Graduate Research Assistant:* Scott D. Papka, M.S.

6. Publications

1. Papka, S. D. and Kyriakides, S., "In-plane Compressive Response and Crushing of Honeycomb." *Journal of the Mechanics and Physics of Solids* **41**, No. 3, 571-592, 1994.
2. Papka, S. D. and Kyriakides, S., "In-plane Crushing of a Polycarbonate Honeycomb." *Int'l Journal of Solids & Structures* (to appear in 1997).
3. Papka, S. D. and Kyriakides, S., "Compressive Response and Crushing of Polymeric Honeycombs." Proceeding, IUTAM Symposium Material Instabilities in Solids, Ed. R. De Borst and E. van der Giessen, Wiley, London (to appear in 1998).
4. Papka, S. D. and Kyriakides, S., "Full-Scale Simulations of In-Plane Crushing of Aluminum Honeycomb." In Preparation, to be submitted to Acta Meterialia 9/97.

7. Technical Presentations

1. Kyriakides, S., and Papka, S. D., "On the Crushing of Transversely Loaded Honeycomb," 12th US National Congress of Applied Mechanics, Seattle, Washington, June 21-July 1, 1994.

2. Kyriakides, S., "Localization and Propagation of Instabilities in Honeycomb under Compression." Applied Mechanics Colloquium, Division of Applied Sciences, Harvard University, May 8, 1996.

3. Papka, S. D. and Kyriakides, S., "Localization and Propagation of Instabilities in a Rate Dependent Honeycomb." ASME Mechanics and Materials Conference, June 12-14, 1996, Johns Hopkins University, Baltimore, MD.

4. Kyriakides, S. , "Compressive Behavior of Honeycombs." Workshop on Ultralight Metal Structures, Kenneunkport Maine, Sept. 16-19, 1996, Org. A. Evans, Harvard University (invited).

5. Kyriakides, S., "Mechanical Properties of Foams and Honeycombs." DOW Chemicals, Freeport, TX, March 20, 1997 (invited).

6. Papka, S. and Kyriakides, S., "Compressive Response and Crushing of Polymeric Honeycombs." IUTAM Specialty Conference, Material Instabilities in Solids, Technical University of Delft, Delft, The Netherlands, June 9-13, 1977 (invited).

8. Patents

Biaxial Crushing Machine (BICRUMA) Pending

9. Degrees Granted

- Papka, S. D., Ph.D. Degree in Engineering Mechanics
  Dissertation: In-Plane Crushing of Honeycomb (Expected Dec. 1997)

- Papka, S. D., Master of Science in Engineering Mechanics, Dec. 1994.
  Thesis: On the Crushing of Honeycomb Under In-plane Loads, Dec. 1994.

10. Awards During Period of Project

- S. Kyriakides, Elected Fellow of the American Society of Mechanical Engineers, July 1997.

- S. Kyriakides, Hayden Head Professorship in Engineering, UT-Austin, 9/96-present

- S. D. Papka, Ripperger Scholarship in Engineering Mechanics, UT-Austin, 1996-97

- S. D. Papka, Endowed Presidential Scholarship, UT-Austin, 1995-96

- S. D. Papka, Ripperger Scholarship in Engineering Mechanics, UT-Austin, 1994-95