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Size effects in cellular solids

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References

Adachi, T., Tomita, Y. and Tanaka, M. [1998], “*Computational simulation of deformation behaviour of 2D-lattice continuum*”, Int. J. Mech. Sci. 40, 857-866.

Aero, E. L. and Kuvshinskii, E. V. [1961], “*Fundamental equations of the theory of elastic media with rotationally interacting particles*”, Soviet Physics Solid State 2, 1272-1281.

Aifantis, E. [1987], “*The physics of plastic deformation*”, Int. J. Plasticity 3, 211-248.

Anderson, W. B. and Lakes, R. S. [1994], “*Size effects due to Cosserat elasticity and surface damage in closed-cell polymethacrylimide foam*”, J. Mat. Sci 29, 6413-6419.

Anderson, W. B., Chen, C. P. and Lakes, R. S. [1994], “*Experimental study of size effects and surface damage of polymethacrylimide closed-cell foam*”, Cellular Polymers 13, 1-15.

Andrews, E., Sanders, W, Gibson, L.J [1999], “*Compressive and tensile behaviour of aluminum foams*”, Mater. Sci. Eng. A 270, 113-124.

Andrews, E.W., Gioux, G., Onck, P., Gibson, L.J [2001], “*Size effects in ductile cellular solids. II. Experimental results*”, Int. J. Mech. Sci. 43, 701-713.

Antoniou, A., Onck, P. R. and Bastawros, A. F. [2004], “*Experimental analysis of compressive notch strengthening in closed-cell aluminum alloy foam*”, Acta Mater. 52, 2377-2386.

Ashby, M. F., Evans, A., Fleck, A. N., Gibson, L. J., Hutchinson, J. W., Wadley, H. N. G.[2000], “*Metal Foams: A Design Guide*”, Butterworth-Heinemann, Oxford.

Aşkar, A., and Çakmak, A. S. [1968], “*A structural model of a micropolar continuum*”, Int. J. Engrg. Sci. 6, 583-589.

- Banks, C. B. and Sokolowski, M. [1968], "*On certain two-dimensional applications of the couple stress theory*", Int. J. Solids Structures 4, 15-29.
- Bart-Smith, H., Bastawros, A. F., Mumm, D. R., Evans, A. G., Sypeck, D. J., Wadley, H. N. G. [1998], "*Compressive deformation and yielding mechanisms in cellular Al alloys determined using X-ray tomography and surface strain mapping*", Acta Mater. 46, 3583-3592.
- Bastawros, A. F., Bart-Smith, H., Evans, A.G. [1999], "*Experimental analysis of deformation mechanisms in a closed cell aluminium foam*", J. Mech. Phys. Solids 48, 301-322.
- Bazant, Z. P. and Christensen, M. [1972], "*Analogy between micropolar continuum and grid frameworks under initial stress*", Int. J. Solids Structures 8, 327-346.
- Brezny, R. and Green, D. J. [1990], "*Characterization of edge effects in cellular materials*", J. Mat. Sci. 25, 4571-4578.
- Chen, C. and Fleck, N. A. [2002], "*Size effects in the constrained deformation of metallic foams*", J. Mech. Phys. Solids 50, 955-977.
- Chen, C., Lu, T. J., Fleck, N. A. [1999], "*Effect of imperfections on the yielding of two-dimensional foams*", J. Mech. Phys. Solids 47, 2235-2272.
- Chen, J.Y., Huang, Y., Ortiz, M. [1998], "*Fracture analysis of cellular materials: a strain gradient model*", J. Mech. Phys. Solids 46, 789-828.
- Christensen, R. M. [1995], "*The hierarchy of microstructures for low density materials*", Z. Angew. Math. Phys. 46, 506-521.
- Cosserat, E. and Cosserat, F. [1909], "*Theorie des Corps Deformables*", Hermann, Paris
- De Boor, R [1998], "*Theory of porous media – Past and present*", Z. Angew. Math. Mech. 78, 441-446.
- Delaunay, B. [1934], "*Sur la sphère vide*", Izvestia Akademii Nauk SSSR, Otdelenie Matematicheskikh i Estestvennykh Nauk 7, 793-800.

- Dendievel, R., Forest, S., Canova, G. [1998], "*An estimation of overall properties of heterogeneous Cosserat materials*", J. Phys. IV (Proceedings) 8, 111-118.
- Deshpande, V. S. and Fleck, N. A. [2000], "*Isotropic constitutive models for metallic foams*", J. Mech. Phys. Solids 48, 1253-1283.
- Deshpande, V. S., Ashby, M. F. and Fleck, N. A. [2001a], "*Foam topology bending versus stretching dominated architectures*", Acta Mater. 49, 1035-1040.
- Deshpande, V. S., Ashby, M. F. and Fleck, N. A. [2001b], "*Effective properties of the octet-truss lattice material*", J. Mech. Phys. Solids 49, 1747-1769.
- Diebels, S. and Steeb, H. [2002], "*The size effect in foams and its theoretical and numerical investigation*", Proc. R. Soc. Lond. A 458, 2869-2883.
- Dillard, T., Forest, S., Ienny, P. [2006] "*Micromorphic continuum modelling of deformation and fracture behaviour of nickel foams*", Eur. J. Mech. A/Solids 25, 526-549.
- Doyoyo, M and Wierzbicki, T [2003], "*Experimental studies on the yield behaviour of ductile and brittle aluminum foams*", Int. J. Plasticity 19, 1195-1214.
- Ellis, R. W. and Smith, C. W. [1967], "*A thin plate analysis and experimental evaluation of couple stress effects*", Exp. Mech. 7, 372-380.
- Engel, G., Garikipati, K., Hughes, T. J. R., Larson, M. G., Mazzei, L., Taylor, R. L. [2002], "*Continuous/discontinuous finite element approximations of fourth-order elliptic problems in structural and continuum mechanics with applications to thin beams and plates, and strain gradient elasticity*", Comput. Methods Appl. Mech. Engrg. 191, 3669-3750.
- Eringen, A. C. [1962], "*Nonlinear theory of continuous media*", McGraw-Hill, New York.
- Eringen, A. C. [1965], "*Theory of micropolar elasticity*", Proc. 9'th Midwestern Mech. Conf., 23-40.
- Eringen, A. C. [1966], "*Linear theory of micropolar elasticity*", J. Math. Mech. 15, 909-923.

- Eringen, A. C. [1968], "*Theory of micropolar elasticity*", in: "*Fracture: An advanced treatise*", Vol. II: Mathematical fundamentals, Ed.: Liebowitz, H., Academic Press, New York and London.
- Eringen, A. C. [1971], "*Micropolar elastic solids with stretch*", in: "*Prof Dr. Mustafa Inan Anisina*", Ari Kitabevi Matbaasi, Istanbul.
- Eringen, A. C. [1990], "*Theory of thermo microstretch elastic solids*", Int. J. Engng. Sci. 28, 1291-1301.
- Eringen, A. C. [1999], "*Microcontinuum Field Theories I: Foundations and Solids*". Springer-Verlag, New York.
- Eringen, A. C. and Şuhubi, E. S. [1964], "*Nonlinear theory of simple micro-elastic solids*" Int. J. Engng. Sci. 2, 189-203.
- Eshel, N. N. and Rosenfeld, G. [1970], "*Effects of strain-gradient on the stress concentration at a cylindrical hole in a field of uniaxial tension*", J. Eng. Math. 4, 97-111.
- Fazekas, A., Dendievel, R., Salvo, L., Brechet, Y. [2002], "*Effect of microstructural topology upon the stiffness and strength of 2D cellular structures*", Int. J. Mech. Sci. 44, 2047-2066.
- Fleck, N. A. and Hutchinson, J. W. [1993], "*A phenomenological theory for strain gradient effects in plasticity*", J. Mech. Phys. Solids 41, 1825-1857.
- Fleck, N. A. and Hutchinson, J. W. [1997], "*Strain gradient plasticity*", Adv. Appl. Mech. 33, 295-361.
- Fleck, N. A. and Hutchinson, J. W. [2001], "*A reformulation of strain gradient plasticity*", J. Mech. Phys. Solids 49, 2245-2271.
- Fleck, N. A., Olurin, O. B., Chen, C., Ashby, M. F. [2001], "*The effect of hole size upon the strength of metallic and polymeric foams*", J. Mech. Phys. Solids 49, 2015-2030.
- Forest, S. and Sievert, R. [2006], "*Nonlinear microstrain theories*", Int. J. Solids Structures, in press.

- Gauthier, R. D. [1982], “*Experimental investigation on micropolar media,*” in: *Mechanics of Micropolar Media*, Ed.: Brulin, O. and Hsieh, R.K.T (CISM Lecture Notes) World Scientific, Singapore.
- Gauthier, R. D. and Jahsman, W. E. [1975], “*A quest for micropolar elastic constants*”, J. Appl. Mech. 42, 369-374.
- Gibson, L. G. and Ashby, M. F. [1997], “*Cellular solids: structure and properties*”, 2nd edition, Cambridge University Press, Cambridge.
- Gibson, L. J., Ashby, M. F., Schajer, G. S., Robertson, C. I. [1982], “*The mechanics of two-dimensional cellular solids*”, Proc. R. Soc. Lond. A 382, 25-42
- Gioux, G., McCormack, T. M., Gibson, L. J. [2000], “*Failure of aluminum foams under multiaxial loads*”, Int. J. Mech. Sci. 42, 1097-1117.
- Green, A. E. and Rivlin, R. S. [1964], “*Simple force and stress multipoles*”, Arch. Rat. Mech. Anal. 16, 325-353.
- Grenestedt, J. L. [1997], “*Effective yield behavior of some models for 'perfect' cellular solids*”, CUED Report, Cambridge University, Cambridge.
- Grenestedt, J.L. [1998], “*Influence of wavy Imperfections in cell walls on elastic stiffness of cellular solids*”, J. Mech. Phys. Solids 46, 29-50
- Grenestedt, J. L. [1999], “*Effective elastic behavior of some models for 'perfect' cellular solids*”, Int. J. Solids Structures 36, 1471-1501.
- Grioli, G. [1960], “*Elasticita asimmetrica*”, Ann. di. Mat. Pura ed appl., Ser. IV 50, 389-417.
- Gurtin, M. E. and Murdoch, A. [1975], “*A continuum theory of elastic material surfaces*”, Arch. Rat. Mech. Anal. 57, 291-323.
- Hartranft, R. J. and Sih, G. C. [1965], “*The effect of couple-stresses on the stress concentration of a circular inclusion*”, J. Appl. Mech. 32, 429-431.
- Hibbitt, Karlsson and Sorensen [2001], “*Abaqus standard user manual*”, U.S.A.

Kesler, O and Gibson, L. J. [2002], "*Size effects in the metallic foam core sandwich beams*", Mat. Sci. Eng. A326, 228-234.

Koiter, W. T. [1964], "*Couple stress in the theory of elasticity I, II*", Proc. Kon. Nederl. Akad. Wetensch. B 67, 17-44.

Kouznetsova, V. G. [2002], "*Computational homogenization for the multi-scale analysis of multi-phase materials*", PhD Thesis, Technische Universiteit Eindhoven, Eindhoven.

Lakes, R. S. [1983], "*Size effects and micromechanics of a porous solid*", J. Mat. Sci. 18, 2572-2580.

Lakes, R. S. [1985] "*A pathological situation in micropolar elasticity*", J. Appl. Mech. 52, 234-235.

Lakes, R. S. [1986], "*Experimental microelasticity of two porous solids*", Int. J. Solids Structures 22, 55-63.

Lakes, R. S. [1995], "*Experimental methods for study of Cosserat elastic solids and other generalized elastic continua*", in: "*Continuum models for materials with microstructure*", Ed.: Mühlhaus, H., J. Wiley, New York.

Lam, D. C. C., Yang, F., Chong, A. C. M., Wang, J., Tong, P. [2003], "*Experiments and theory in strain gradient elasticity*", J. Mech. Phys. Solids 51, 1477-1508.

Malvern, L. E. [1969], "*Introduction to the mechanics of a continuous medium*", Prentice-Hall: Upper Saddle River, NJ, USA.

Miller, R. E. and Shenoy V. B. [2000], "*Size-dependent elastic properties of nanosized structural elements*", Nanotechnology 11, 139-147.

Mindlin, R.D. [1963], "*Influence of couple stress on stress concentrations*", Experimental Mechanics 3, 1-7.

Mindlin, R.D. [1964], "*Microstructure in linear elasticity*", Arch. Rat. Mech. Anal. 16, 51-78.

Mindlin, R.D. [1965], "*Second gradient of strain and surface tension in linear elasticity*", Int. J. Solids Structures 1, 417-438.

- Mindlin, R.D. and Eshel, N. N. [1968], “*On first strain-gradient theories in linear elasticity*” Int. J. Solids Structures 4,109-124.
- Mindlin, R.D. and Tiersten, H. F. [1962], “*Effects of couple stresses in linear elasticity*”, Arch. Rat. Mech. Anal. 11, 415-448.
- Mora, R. and Waas, A. M. [2000], “*Measurement of the Cosserat constant of circular-cell polycarbonate foam*”, Phil. Mag. A 80, 1699-1713.
- Nowacki, W. [1986], “*Theory of Asymmetric Elasticity*”, Pergamon Press, Oxford.
- Onck, P. R. [2002], “*Cosserat modeling of cellular solids*”, C. R. Mechanique 330, 717-722.
- Onck, P. R., Andrews, E., Gibson, L.J [2001], “*Size effects in ductile cellular solids. Part I: modeling*”, Int. J. Mech. Sci. 43, 681-699.
- Ostojca-Starzewski, M., Sheng, P. Y., Alzebdeh, K. [1996], “*Spring network models in elasticity and fracture of composites and polycrystals*”, Computational Materials Science 7, 82-93.
- Padovani, C. [2002], “*Strong ellipticity of transversely isotropic elasticity tensors*”, Meccanica 37, 515-525.
- Paul, A., Seshacharyulu, T., Ramamurty, U. [1999], “*Tensile strength of a closed-cell Al foam in the presence of notches and holes*”, Scripta Mater. 40, 808-814.
- Pradel, F. and Sab, K. [1998], “*Cosserat modelling of elastic periodic lattice structures*”, C. R. Acad. Sci., Serie II B, 326, 699-704.
- Rajagopal, E. S. [1960], “*The existence of interracial couples in infinitesimal elasticity*”, Ann. der Physik 6, 192-201.
- Schijve, J. [1966], “*Note on couple stresses*”, J. Mech. Phys. Solids 14, 113-120.
- Shu, J. Y., King, W. E. and Fleck, N. A. [1999], “*Finite elements for materials with strain gradient effects*”, Int. J. Numer. Meth. Engng. 44, 373-391.

- Silva, M. J., Wilson, C. H. and Gibson, L. J. [1995], "*The effects of non-periodic microstructure on the elastic properties of two-dimensional cellular solids*", Int. J. Mech. Sci. 37, 1161-1177.
- Simone, A. E. and Gibson, L. J. [1998a], "*Effects of solid distribution on the stiffness and strength of metallic foams*", Acta Mater. 46, 2139-2150.
- Simone, A. E. and Gibson, L. J. [1998b], "*Aluminum foams produced by liquid-state processes*", Acta Mater. 46, 3109-3123.
- Sugimura, Y., Meyer, J., He, M. Y., Bart-Smith, H., Grenestedt, J. and Evans, A. G. [1997], "*On the mechanical performance of closed cell Al alloy foams*", Acta Mater. 45, 5245-5259.
- Tekoğlu, C. and Onck, P. R. [2003a], "*A comparison of discrete and Cosserat continuum analyses for cellular materials*", Proc. Int. Conf. Cellular Metals and Metal Foaming Technology, 23rd -25th June 2003, Ed.: J. Banhart, N. A. Fleck, A. Mortensen, Verl. MIT Publ., Berlin.
- Tekoğlu, C. and Onck, P. R. [2003b], "*Identification of Cosserat constant for cellular materials*", Proc. 9th Int. Conf. Mechanical Behaviour of Materials (ICM9), Geneva, Switzerland [CD_ROM].
- Tekoğlu, C. and Onck, P. R. [2005], "*Size effects in the mechanical behavior of cellular materials*", J. Mat. Sci. 40, 5911-5917.
- Timoshenko, S. P. and Goodier, J. N. [1970], "*Theory of elasticity*", 3rd edition, McGraw-Hill, New York.
- Toupin, R. A. [1962], "*Elastic materials with couple-stresses*", Arch. Rat. Mech. Anal. 11, 385-414.
- Toupin, R. A. [1964], "*Theories of elasticity with couple-stress*", Arch. Rat. Mech. Anal. 17, 85-112.
- Triantafyllidis, N. and Schraad, W. [1998], "*Onset of failure in aluminum honeycombs under general in-plane loading*", J. Mech. Phys. Solids 46, 1089-1124.
- Truesdell, C. A. and Toupin, R. A. [1960], "*The classical field theories*", Encyclopedia of Physics, III/1, Springer, Berlin.

Van der Burg, M. V. D., Shulmeister, V., Van der Giessen, E., Marissen, R. [1997], “*On the linear elastic properties of regular and random open-cell foam models*”, J. Cellular Plastics 33, 31-54.

Voronoi, M. G. [1908], “*Nouvelles applications des parametres continus a la theorie des formes quadratiques*”, J. Reine Angew. Math. 134,198-287.

Wang, X. and Stronge, W.J. [1999], “*Micropolar theory for two-dimensional stresses in elastic honeycomb*”, Proc. R. Soc. Lond. A 455, 2091, 2116.

Warren, W. E. and Byskov, E. [1997], “*Micropolar and nonlocal effects in spatially periodic, two-dimensional structures*”, Report R 37, Technical University of Denmark.

Warren, W. E. and Byskov, E. [2002], “*Three-Fold Symmetry Restrictions on Two-Dimensional Micropolar Materials*”, European J. Mech. A/Solids 21, 779–792.

Weitsman, Y. [1965], “*Couple stress effects on stress concentration around a cylindrical inclusion in a field of uniaxial tension*”, J. Appl. Mech. 2, 424-428.

Yang, J. F. C. and Lakes, R. S. [1981], “*Transient study of couple stress in compact bone: torsion*”, J. Biomech. Eng. 103, 275-279.

Zhang, X. and Sharma, P. [2005], “*Inclusions and inhomogeneities in strain gradient elasticity with couple stresses and related problems*” Int. J. Solids Structures 42, 3833–3851.

Zhu, H. X., Hobdell, J. R. and Windle, A. H [2000], “*Effects of cell irregularity on the elastic properties of open-cell foams*”, Acta mater. 48, 4893-4900.

Zhu, H. X., Thorpe, S. M. and Windle, A. H. [2001a], “*The geometrical properties of irregular two-dimensional Voronoi tessellations*”, Phil. Mag. A 81, 2765-2783.

Zhu, H. X., Hobdell, J. R., Windle, A. H [2001b], “*Effects of cell irregularity on the elastic properties of 2D Voronoi honeycombs*”, J. Mech. Phys. Solids 49, 857-870.

Zienkiewicz, O. C. and Taylor, R. L. [2000], “*The Finite Element Method*” Vol. 1: “*The Basis*”, 5th edition, Butterworth-Heinemann, Oxford.

