References Cited

[1] RO Ritchie. The conflicts between strength and toughness. *Nature materials*, 10(11):817–822, 2011.

[2] F Barthelat and R Rabiei. Toughness amplification in natural composites. *Journal of the Mechanics and Physics of Solids*, 59(4):829–840, 2011.

[3] R Rabiei, S Bekah, and F Barthelat. Nacre from mollusk shells: Inspiration for high-performance nanocomposites. In MJ John and S Thomas, editors, *Natural Polymers*, volume 2 of *Green Chemistry*, pages 113–146. Royal Society of Chemistry, 2012.

[4] JD Currey. How well are bones designed to resist fracture? *Journal of Bone and Mineral Research*, 18(4):591–598, 2003.

[5] RZ Wang, Z Suo, AG Evans, N Yao, and IA Aksay. Deformation mechanisms in nacre. *Journal of Materials Research*, 16(09):2485–2493, 2001.

[6] JD Currey. Further studies on the mechanical properties of mollusc shell material. *Journal of Zoology*, 180(4):445–453, 1976.

[7] JD Currey. Mechanical properties of mother of pearl in tension. *Proceedings of the Royal Society B: Biological Sciences*, 196(1125):443–463, 1977.

[8] UGK Wegst, H Bai, E Saiz, AP Tomsia, and RO Ritchie. Bioinspired structural materials. *Nature materials*, 14(1):23–36, 2015.

[9] MA Monn, JC Weaver, T Zhang, J Aizenberg, and H Kesari. New functional insights into the internal architecture of the laminated anchor spicules of euplectella aspergillum. *Proceedings of the National Academy of Sciences*, 112(16):4976–4981, 2015.

[10] S Baskaran, SD Nunn, S Popovic, and JW Halloran. Fibrous monolithic ceramics: I, fabrication, microstructure, and indentation behavior. *Journal of the American Ceramic Society*, 76(9):2209–2216, 1993.

[11] G Mayer. Rigid biological systems as models for synthetic composites. *Science*, 310(5751):1144–1147, 2005.

[12] MA Meyers, J McKittrick, and PY Chen. Structural biological materials: critical mechanics-materials connections. *Science*, 339(6121):773–779, 2013.

[13] H Gao and JR Rice. A first-order perturbation analysis of crack trapping by arrays of obstacles. *Journal of applied mechanics*, 56(4):828–836, 1989.

[14] D Dalmas, E Barthel, and D Vandembroucq. Crack front pinning by design in planar heterogeneous interfaces. *Journal of the Mechanics and Physics of Solids*, 57(3):446–457, 2009.

[15] P Gu and RJ Asaro. Crack deflection in functionally graded materials. *International Journal of Solids and Structures*, 34(24):3085–3098, 1997.

[16] JC Weaver, GW Milliron, P Allen, A Miserez, A Rawal, J Garay, PJ Thurner, J Seto, B Mayzel, LJ Friesen, BF Chmelka, P Fratzl, J Aizenberg, Y Dauphin, D Kisailus, and DE Morse. Unifying Design Strategies in Demosponge and Hexactinellid Skeletal Systems. *The Journal of Adhesion*, 86(1):72–95, 2010.

[17] J Cook, JE Gordon, CC Evans, and DM Marsh. A mechanism for the control of crack propagation in all-brittle systems. 282(1391):508–520, 1964.

[18] F Barthelat and HD Espinosa. An experimental investigation of deformation and fracture of nacre–mother of pearl. *Experimental mechanics*, 47(3):311–324, 2007.

[19] J Poissant and F Barthelat. A novel "subset splitting" procedure for digital image correlation on discontinuous displacement fields. *Experimental mechanics*, 50(3):353–364, 2010.

[20] H Kesari, JC Doll, BL Pruitt, W Cai, and AJ Lew. Role of surface roughness in hysteresis during adhesive elastic contact. *Philosophical Magazine Letters*, 90(12):891–902, 2010.

[21] H Kesari. *Mechanics of Hysteretic Adhesive Elastic Mechanical Contact Between Rough Surfaces*. PhD thesis, Stanford University, 2011.

[22] Haneesh Kesari and Adrian J Lew. Effective macroscopic adhesive contact behavior induced by small surface roughness. *Journal of the Mechanics and Physics of Solids*, 59(12):2488–2510, 2011.

[23] WJ Clegg, K Kendall, N McN Alford, TW Button, and JD Birchall. A simple way to make tough ceramics. *Nature*, 347(6292):455–457, 1990.

[24] N Lee, MF Horstemeyer, H Rhee, B Nabors, J Liao, and LN Williams. Hierarchical multiscale structure–property relationships of the red-bellied woodpecker (melanerpes carolinus) beak. *Journal of The Royal Society Interface*, 11(96):20140274, 2014.

[25] CR Jaslow. Mechanical properties of cranial sutures. *Journal of biomechanics*, 23(4):313–321, 1990.

[26] K Thomas. Red-bellied woodpecker (male). http://kenthomas.us/?page_id=140&px=%2FRed-bellied_Woodpecker-male.jpg&px=%2FRed-bellied_Woodpecker-male.jpg. Online; accessed 10-March-2016.

[27] F Barthelat, H Tang, PD Zavattieri, C-M Li, and HD Espinosa. On the mechanics of mother-of-pearl: a key feature in the material hierarchical structure. *Journal of the Mechanics and Physics of Solids*, 55(2):306–337, 2007.

[28] BL Smith, TE Schäffer, M Viani, JB Thompson, NA Frederick, J Kindt, A Belcher, GD Stucky, DE Morse, and PK Hansma. Molecular mechanistic origin of the toughness of natural adhesives, fibres and composites. *Nature*, 399(6738):761–763, 1999.

[29] MA Meyers, AYM Lin, PY Chen, and J Muyco. Mechanical strength of abalone nacre: role of the soft organic layer. *Journal of the Mechanical behavior of biomedical materials*, 1(1):76–85, 2008.

[30] X Li, WC Chang, YJ Chao, R Wang, and M Chang. Nanoscale structural and mechanical characterization of a natural nanocomposite material: the shell of red abalone. *Nano Letters*, 4(4):613–617, 2004.

[31] AYM Lin, MA Meyers, and KS Vecchio. Mechanical properties and structure of strombus gigas, tridacna gigas, and haliotis rufescens sea shells: a comparative study. *Materials Science and Engineering: C*, 26(8):1380–1389, 2006.

[32] Q Chen and NM Pugno. Bio-mimetic mechanisms of natural hierarchical materials: a review. *Journal of the mechanical behavior of biomedical materials*, 19:3–33, 2013.

[33] AG Evans. Perspective on the development of high-toughness ceramics. *Journal of the American Ceramic society*, 73(2):187–206, 1990.

[34] HL Cox. The elasticity and strength of paper and other fibrous materials. *British journal of applied physics*, 3(3):72, 1952.

[35] AP Jackson, JFV Vincent, and RM Turner. The mechanical design of nacre. *Proceedings of the Royal society of London. Series B. Biological sciences*, 234(1277):415–440, 1988.

[36] H Gao, B Ji, IL Jäger, E Arzt, and P Fratzl. Materials become insensitive to flaws at nanoscale: lessons from nature. *Proceedings of the national Academy of Sciences*, 100(10):5597–5600, 2003.

[37] DR Bloyer, RO Ritchie, and KT Venkateswara Rao. Fracture toughness and R-curve behavior of laminated brittle-matrix composites. *Metallurgical and Materials Transactions A*, 29(10):2483–2496, 1998.

[38] R Wang and HS Gupta. Deformation and fracture mechanisms of bone and nacre. *Annual Review of Materials Research*, 41:41–73, 2011.

[39] RK Nalla, JJ Kruzic, JH Kinney, and RO Ritchie. Mechanistic aspects of fracture and R-curve behavior in human cortical bone. *Biomaterials*, 26(2):217–231, 2005.

[40] A Hillerborg, M Modéer, and P-E Petersson. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. *Cement and concrete research*, 6(6):773–781, 1976.

[41] XP Xu and A Needleman. Numerical simulations of fast crack growth in brittle solids. *Journal of the Mechanics and Physics of Solids*, 42(9):1397–1434, 1994.

[42] MGA Tijssens, BLJ Sluys, and E van der Giessen. Numerical simulation of quasi-brittle fracture using damaging cohesive surfaces. *European Journal of Mechanics-A/Solids*, 19(5):761–779, 2000.

[43] RHJ Peerlings, R De Borst, WAM Brekelmans, and MGD Geers. Gradient-enhanced damage modelling of concrete fracture. *Mechanics of Cohesive-frictional Materials*, 3(4):323–342, 1998.

[44] T Belytschko, N Moës, S Usui, and Ch Parimi. Arbitrary discontinuities in finite elements. *International Journal for Numerical Methods in Engineering*, 50(4):993–1013, 2001.

[45] C Daux, N Moës, J Dolbow, N Sukumar, and T Belytschko. Arbitrary branched and intersecting cracks with the extended finite element method. *International Journal for Numerical Methods in Engineering*, 48(12):1741–1760, 2000.

[46] MJ Borden, CV Verhoosel, MA Scott, TJR Hughes, and CM Landis. A phase-field description of dynamic brittle fracture. *Computer Methods in Applied Mechanics and Engineering*, 217:77–95, 2012.

[47] R De Borst. Numerical aspects of cohesive-zone models. *Engineering fracture mechanics*, 70(14):1743–1757, 2003.

[48] R De Borst, JJC Remmers, and A Needleman. Computational aspects of cohesive-zone models. *Advanced Fracture Mechanics for Life and Safety Assesments-Stockholm (Sweden)*, pages 1–18, 2004.

[49] J-H Song, H Wang, and T Belytschko. A comparative study on finite element methods for dynamic fracture. *Computational Mechanics*, 42(2):239–250, 2008.

[50] É Béchet, H Minnebo, N Moës, and B Burgardt. Improved implementation and robustness study of the x-fem for stress analysis around cracks. *International Journal for Numerical Methods in Engineering*, 64(8):1033–1056, 2005.

[51] JHP De Vree, WAM Brekelmans, and MAJ Van Gils. Comparison of nonlocal approaches in continuum damage mechanics. *Computers & Structures*, 55(4):581–588, 1995.

[52] J-H Song and T Belytschko. Cracking node method for dynamic fracture with finite elements. *International Journal for Numerical Methods in Engineering*, 77(3):360–385, 2009.

[53] N Moës, J Dolbow, and T Belytschko. A finite element method for crack growth without remeshing. *International Journal for Numerical Methods in Engineering*, 46(1):131–150, 1999.

[54] C Miehe, F Welschinger, and M Hofacker. Thermodynamically consistent phase-field models of fracture: Variational principles and multi-field fe implementations. *International Journal for Numerical Methods in Engineering*, 83(10):1273–1311, 2010.

[55] B Bourdin, GA Francfort, and JJ Marigo. Numerical experiments in revisited brittle fracture. *Journal of the Mechanics and Physics of Solids*, 48(4):797–826, 2000.

[56] RA Day and DM Potts. Zero thickness interface elements–numerical stability and application. *International Journal for numerical and analytical methods in geomechanics*, 18(10):689–708, 1994.

[57] E Benvenuti. A regularized xfem framework for embedded cohesive interfaces. *Computer Methods in Applied Mechanics and Engineering*, 197(49):4367–4378, 2008.

[58] B Bourdin, GA Francfort, and JJ Marigo. The variational approach to fracture. *Journal of elasticity*, 91(1-3):5–148, 2008.

[59] C Miehe, M Hofacker, and F Welschinger. A phase field model for rate-independent crack propagation: Robust algorithmic implementation based on operator splits. *Computer Methods in Applied Mechanics and Engineering*, 199(45):2765–2778, 2010.

[60] GA Francfort and JJ Marigo. Revisiting brittle fracture as an energy minimization problem. *Journal of the Mechanics and Physics of Solids*, 46(8):1319–1342, 1998.

[61] AA Griffith. The phenomena of rupture and flow in solids. *Philosophical transactions of the royal society of london. Series A, containing papers of a mathematical or physical character*, 221:163–198, 1921.

[62] T Belytschko, WK Liu, B Moran, and K Elkhodary. *Nonlinear finite elements for continua and structures*. John wiley & sons, 2013.

[63] T Dally and K Weinberg. The phase-field approach as a tool for experimental validations in fracture mechanics. *Continuum Mechanics and Thermodynamics*, pages 1–10, 2015.

[64] TN Bittencourt, PA Wawrzynek, AR Ingraffea, and JL Sousa. Quasi-automatic simulation of crack propagation for 2d lefm problems. *Engineering Fracture Mechanics*, 55(2):321–334, 1996.

[65] F Amiri, D Millán, Y Shen, T Rabczuk, and M Arroyo. Phase-field modeling of fracture in linear thin shells. *Theoretical and Applied Fracture Mechanics*, 69:102–109, 2014.

[66] A Braides. *Gamma-convergence for Beginners*, volume 22. Clarendon Press, 2002.

[67] A Chambolle. Addendum to "an approximation result for special functions with bounded deformation." [j. math. pures appl.(9) 83 (7)(2004) 929–954]: the n-dimensional case. *Journal de mathématiques pures et appliquées*, 84(1):137–145, 2005.

[68] L Ambrosio and VM Tortorelli. Approximation of functional depending on jumps by elliptic functional via Γ-convergence. *Communications on Pure and Applied Mathematics*, 43(8):999–1036, 1990.

[69] G Mayer, R Trejo, E Lara-Curzio, M Rodriguez, K Tran, H Song, and WH Ma. Lessons for new classes of inorganic/organic composites from the spicules and skeleton of the sea sponge euplectella aspergillum. In *MRS Proceedings*, volume 844, pages Y4–2. Cambridge Univ Press, 2004.

[70] M Sarikaya, H Fong, N Sunderland, BD Flinn, G Mayer, A Mescher, and E Gaino. Biomimetic model of a sponge-spicular optical fiber–mechanical properties and structure. *Journal of Materials Research*, 16(05):1420–1428, 2001.

[71] MA Monn and H Kesari. Enhanced bending failure strain in biological glass fibers due to internal lamellar architecture. *Journal of the Mechanical Behavior of Biomedical Materials*, 2017. In press.

[72] MA Monn and H Kesari. A new structure-property connection in the skeletal elements of the marine sponge tethya aurantia that guards against buckling instability. *Scientific reports*, 7:1–10, 2017.

[73] X Wang, M Wiens, HC Schröder, S Hu, E Mugnaioli, U Kolb, W Tremel, D Pisignano, and WEG Müller. Morphology of sponge spicules: Silicatein a structural protein for bio-silica formation. *Advanced Engineering Materials*, 12(9):B422–B437, 2010.

[74] JC Weaver, LI Pietrasanta, N Hedin, BF Chmelka, PK Hansma, and DE Morse. Nanostructural features of demosponge biosilica. *Journal of structural biology*, 144(3):271–281, 2003.

[75] A Woesz, JC Weaver, M Kazanci, Y Dauphin, J Aizenberg, DE Morse, and P Fratzl. Micromechanical properties of biological silica in skeletons of deep-sea sponges. *Journal of materials research*, 21(8):2068–2078, 2006.

[76] A Miserez, JC Weaver, and PJ Thurner. Effects of laminate architecture on fracture resistance of sponge biosilica: lessons from nature. *Advanced Functional Materials*, 18(8):1241–1248, 2008.

[77] B Lawn and R Wilshaw. Indentation fracture: principles and applications. *Journal of materials science*, 10(6):1049–1081, 1975.

[78] AG Evans and EA Charles. Fracture toughness determinations by indentation. *Journal of the American Ceramic Society*, 59(7-8):371–372, 1976.

[79] WC Oliver and GM Pharr. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *Journal of materials research*, 7(06):1564–1583, 1992.

[80] DB Marshall. An indentation method for measuring matrix-fiber frictional stresses in ceramic composites. *Journal of the American Ceramic Society*, 67(12), 1984.

[81] JD Bright, DK Shetty, CW Griffin, and SY Limaye. Interfacial bonding and friction in silicon carbide [filament]-reinforced ceramic-and glass-matrix composites. *Journal of the American Ceramic Society*, 72(10):1891–1898, 1989.

[82] JO Outwater and MC Murphy. Fracture energy of unidirectional laminates. *Modern Plastics*, 47(9):160, 1970.

[83] RJ Kerans and TA Parthasarathy. Theoretical analysis of the fiber pullout and pushout tests. *Journal of the American Ceramic Society*, 74(7):1585–1596, 1991.

[84] C Liang and JW Hutchinson. Mechanics of the fiber pushout test. *Mechanics of materials*, 14(3):207–221, 1993.

[85] B Moran and CF Shih. Crack tip and associated domain integrals from momentum and energy balance. *Engineering fracture mechanics*, 27(6):615–642, 1987.

[86] MA Monn, J Ferreira, J Yang, and H Kesari. A millimeter scale flexural testing system for measuring the mechanical properties of marine sponge spicules. *Journal of Visualized Experiments*, pages 1–11, 2017. In Press.

[87] Brown Science Center SciToons. Design Inspired by Nature. https://www.youtube.com/watch?v=Ezd4AcC3uZ4&t=13s, 2017. [Online; accessed 11-September-2017].

[88] Weilin Deng and Haneesh Kesari. Molecular statics study of depth-dependent hysteresis in nano-scale adhesive elastic contacts. *Modelling and Simulation in Materials Science and Engineering*, 25(5):055002, 2017.

[89] DS Dugdale. Yielding of steel sheets containing slits. *Journal of the Mechanics and Physics of Solids*, 8(2):100–104, 1960.

[90] GI Barenblatt. The mathematical theory of equilibrium cracks in brittle fracture. *Advances in applied mechanics*, 7:55–129, 1962.

[91] GT Camacho and M Ortiz. Computational modelling of impact damage in brittle materials. *International Journal of solids and structures*, 33(20-22):2899–2938, 1996.

[92] HEJG Schlangen. Experimental and numerical analysis of fracture processes in concrete. *HERON, 38 (2)*, 1993.

[93] JC Gálvez, M Elices, and DA Cendón. Fracture of double-edge notched specimens under compression loading. *Construction Materials: Theory and Application*, pages 95–105, 1999.

[94] T Belytschko and T Black. Elastic crack growth in finite elements with minimal remeshing. *International journal for numerical methods in engineering*, 45(5):601–620, 1999.

[95] S Bordas, PV Nguyen, C Dunant, A Guidoum, and H Nguyen-Dang. An extended finite element library. *International Journal for Numerical Methods in Engineering*, 71(6):703–732, 2007.

[96] J Dolbow and T Belytschko. A finite element method for crack growth without remeshing. *International journal for numerical methods in engineering*, 46(1):131–150, 1999.

[97] N Sukumar, N Moës, B Moran, and T Belytschko. Extended finite element method for three-dimensional crack modelling. *International Journal for Numerical Methods in Engineering*, 48(11):1549–1570, 2000.

[98] N Moës, A Gravouil, and T Belytschko. Non-planar 3d crack growth by the extended finite element and level sets–part i: Mechanical model. *International Journal for Numerical Methods in Engineering*, 53(11):2549–2568, 2002.

[99] A Gravouil, N Moës, and T Belytschko. Non-planar 3d crack growth by the extended finite element and level sets–part ii: Level set update. *International Journal for Numerical Methods in Engineering*, 53(11):2569–2586, 2002.

[100] T Belytschko, H Chen, J Xu, and G Zi. Dynamic crack propagation based on loss of hyperbolicity and a new discontinuous enrichment. *International journal for numerical methods in engineering*, 58(12):1873–1905, 2003.

[101] J-H Song, P Areias, and T Belytschko. A method for dynamic crack and shear band propagation with phantom nodes. *International Journal for Numerical Methods in Engineering*, 67(6):868–893, 2006.

[102] GL Golewski, P Golewski, and T Sadowski. Numerical modelling crack propagation under mode ii fracture in plain concretes containing siliceous fly-ash additive using xfem method. *Computational Materials Science*, 62:75–78, 2012.

[103] O Barkai, T Menouillard, J-H Song, T Belytschko, and D Sherman. Crack initiation and path selection in brittle specimens: A novel experimental method and computations. *Engineering Fracture Mechanics*, 89:65–74, 2012.

[104] X Peng, S Kulasegaram, SC Wu, and SPA Bordas. An extended finite element method (xfem) for linear elastic fracture with smooth nodal stress. *Computers & Structures*, 179:48–63, 2017.

[105] Dassault Systèmes Simulia Corp. Simulia (2014) abaqus analysis user guide 6th edn. 2014.

[106] JM Melenk and I Babuška. The partition of unity finite element method: basic theory and applications. *Computer methods in applied mechanics and engineering*, 139(1-4):289–314, 1996.

[107] N Sukumar, ZY Huang, J-H Prévost, and Z Suo. Partition of unity enrichment for bimaterial interface cracks. *International Journal for Numerical Methods in Engineering*, 59(8):1075–1102, 2004.

[108] T Elguedj, A Gravouil, and A Combescure. Appropriate extended functions for x-fem simulation of elastic-plastic crack growth with frictional contact. *European Journal of Computational Mechanics/Revue Européenne de Mécanique Numérique*, 15(1-3):155–166, 2006.

[109] GN Wells and LJ Sluys. A new method for modelling cohesive cracks using finite elements. *International Journal for Numerical Methods in Engineering*, 50(12):2667–2682, 2001.

[110] N Moës and T Belytschko. Extended finite element method for cohesive crack growth. *Engineering fracture mechanics*, 69(7):813–833, 2002.

[111] S Mariani and U Perego. Extended finite element method for quasi-brittle fracture. *International Journal for numerical methods in engineering*, 58(1):103–126, 2003.