Design of New Materials and Structures to Maximize Strength at Probability Tail: A Neglected Challenge for Quasibrittle and Biomimetic Materials

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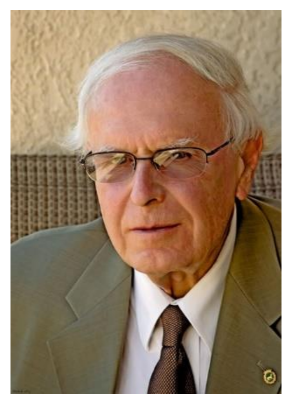
In developing new materials, the research objective has been to maximize the mean strength (or fracture energy) of material or structure and minimize the coefficient of variation. However, for engineering structures such as airframes, bridges of microelectronic devices, the objective should be to maximize the tail probability strength, which is defined as the strength corresponding to failure probability 10^{-6} per lifetime. Optimizing the strength and coefficient of variation does not guarantee it. The ratio of the distance of the tail point from the mean strength to the standard deviation depends on the architecture and microstructure of the material (governing the safety factor) is what should also be minimized. For the Gaussian and Weibull distributions of strength, the only ones known up to the 1980s, this ratio differs by almost 2:1. For the strength distributions of quasibrittle materials, it can be anywhere in between, depending on material architecture and structure size. These materials, characterized by a nonnegligible size of the fracture process zone, include concretes, rocks, tough ceramics, fiber composites, stiff soils, sea ice, snow slabs, rigid foams, bone, dental materials, many bio-materials and most materials on the micrometer scale. A theory to deduce the strength distribution tail from atomistic crack jumps and Kramer's rule of transition rate theory, and determine analytically the multiscale transition to the representative volume element (RVE) of material, is briefly reviewed. The strength distribution of quasibrittle particulate or fibrous materials, whose size is proportional to the number of RVEs, is obtained from the weakest-link chain with a finite number of links, and is characterized by a Gauss-Weibull grafted distribution. Close agreement with the observed strength histograms and size effect curves are demonstrated. Discussion then turns to new results on biomimetic imbricated (or scattered) lamellar systems, exemplified by nacre, whose mean strength exceeds the strength of constituents by an order of magnitude. The nacreous quasibrittle material is simplified as a fishnet pulled diagonally, which is shown to be amenable to an analytical solution of the strength probability distribution. The solution is verified by million Monte-Carlo simulations for each of fishnets of various shapes and sizes. In addition to the weakest-link model and the fiber-bundle model, the fishnet is shown to be the third strength probability model that is amenable to an analytical solution. It is found that, aside from its well-known benefit for the mean strength, the nacreous microstructure provides a significant additional strengthening at the strength probability tail. Finally it is emphasized that the most important consequence of the quasibrittleness, and also the most effective way of calibrating the tail, is the size effect on mean structural strength.



Bio-Sketch: Born and educated in Prague (Ph.D. 1963), Bažant joined Northwestern in 1969, where he has been W.P. Murphy Professor since 1990 and simultaneously McCormick Institute Professor since 2002, and Director of Center for Geomaterials (1981-87). He was inducted to NAS, NAE, Am. Acad. of Arts & Sci., Royal Soc. London; to the academies of Italy (lincei), Austria, Spain, Czech Rep., India.and Lombardy; to Academia Europaea, Eur. Acad. of Sci. & Arts. Honorary Member of: ASCE, ASME, ACI, RILEM; received 7 honorary doctorates (Prague, Karlsruhe, Colorado, Milan, Lyon, Vienna, Ohio State); Austrian Cross of Honor for Science and Art 1st Class from President of Austria; ASME Medal, ASME Timoshenko, Nadai and Warner Medals; ASCE von Karman, Freudenthal, Newmark, Biot, Mindlin and Croes Medals and Lifetime Achievement Award; SES Prager Medal; RILEM L'Hermite Medal; Exner Medal (Austria); Torroja Medal (Madrid); etc. He authored seven books: Scaling of Structural Strength, Inelastic Analysis, Fracture & Size Effect, Stability of Structures, Concrete at High Temperatures, Concrete Creep and Probabilistic Quasibrittle Srength. H-index: 121, citations: 66,000 (on Google, incl. self-cit.), i10 index: 605. In 2015, ASCE established ZP Bažant Medal for Failure and Damage Prevention. He is one of the original top 100 ISI Highly Cited Scientists in Engrg. (www.ISIhighlycited.com). His 1959 mass-produced patent of safety ski binding is exhibited in New England Ski Museum. Home: http://cee.northwestern.edu/people/bazant/

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