ZVI HASHIN

1929–2017

Elected in 1998

"For contributions to the theory and technology of advanced composite materials."

BY J.N. REDDY

ZVI HASHIN passed away October 29, 2017, in his hometown of Haifa at the age of 88. He was one of the world's leading experts on micromechanics of composite materials and a pioneer in the exploration and application of materials across many fields of engineering—from marine vehicles to space and aerospace structures like the Boeing 787 Dreamliner. His collaboration with physicist and classmate Shmuel Shtrikman on calculating the tightest bounds on the elastic moduli for two-phase composites, known in the literature as the "Hashin-Shtrikman bounds," was hailed as one of the 100 most important mechanics projects of the 20th century.

Zvi was born June 24, 1929, in the Free City of Danzig (today Gdańsk, Poland). In 1936 he emigrated with his family to British Mandatory Palestine and settled in Haifa. After his military service, he wanted to study mathematics and physics, but his father persuaded him to take up engineering, telling him that it was a good way to make a living. He earned a BS degree in civil engineering in 1953 and MS degree in mechanics (under Markus Reiner) in 1955 from the Technion, and completed his studies as a *docteur ès sciences* from the Sorbonne in 1957. His dissertation was on development techniques for strengthening bridges.

His career began with positions as a lecturer (1957–58) and senior lecturer (1958–59) at the Technion, after which he was hired as a research fellow at Harvard University (1959–60) and then as an associate professor (1960–65) and professor (1965–71) at the University of Pennsylvania. He returned to Haifa to take a position as a professor at the Technion (1971–73) before joining the faculty at Tel Aviv University, where he was a professor and founding chair of the Department of Solid Mechanics (1973–77; he again chaired the department in 1979–81). He held the Nathan Cummings Chair in Mechanics of Solids until his retirement in 1981.

He was also a visiting professor at the University of Pennsylvania, Harvard University, University of California at Berkeley, University of Cambridge, and École Polytechnique (outside Paris). And he worked as a consultant for companies all over the world, including General Electric and Scott Paper, and held research contracts with NASA as well as the US Army, Air Force, and Navy.

By definition, composite materials are made up of two or more constituents; for example, fiber-reinforced composites are made of fibers and a matrix material, which can be a polymer or metal. They vary greatly in their physical characteristics (e.g., modulus, thermal conductivity, permeability, electrical and magnetic properties) at both the macro- and microscopic scales. To create a composite that has the desired properties, the constituents have to be combined in such a way that their differing properties will complement each other. A good understanding of how each constituent responds to stress and strain loads is essential for the prediction of damage and failure modes in a composite material.

Zvi Hashin was recognized for five decades as the world's preeminent authority in the micromechanics of composite materials. He pioneered contributions in two broad areas related to such materials: (1) estimation of properties and (2) damage and failure.

His most celebrated publication (when he was at the University of Pennsylvania), coauthored with Shtrikman, describes the application of variational principles in the linear theory of elasticity to the derivation of upper and lower bounds for the effective elastic moduli of quasi-isotropic and quasi-homogeneous multiphase materials of arbitrary phase geometry.[1] The work has been cited nearly 5800 times. In his own words,

> At that time the literature on the subject was already considerable, but only a small number of rigorous results were available. These consisted of solutions for properties of composites described as matrix containing dilute concentration of spherical particles, effective bulk modulus for a special geometry—composite spheres assemblage—for all volume concentrations of spherical particles, and bounds for effective properties based on the classical variational principles. Many workers in the field did not recognize the fact that phase volume fractions are totally insufficient information for determination of effective properties, although W.F. Brown Jr. of the University of Minnesota had shown in 1954 that effective electric properties of a two-phase medium depend on the entire statistics of the phase geometry.
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> Since, however, the statistics of phase geometry are never known in detail, a logical approach is to bound effective properties in terms of available geometrical information. This we did in terms of the simplest such information: phase volume fractions. The bounding procedure was based on new variational principles in elasticity, in terms of the stress polarization, which we had established.[2]

Hashin's first monograph on the subject of composite materials was published as a NASA report, *Theory of Fiber Reinforced Materials* (NASA CR-1974; 1972), when there were no authoritative books available on the subject. He presented a unified and rational treatment of the theory of fiber-reinforced composite materials along with detailed derivations of the effective elastic moduli, considering viscoelastic and thermoelastic properties. In a 1991 article he outlined a rigorous solution of

[1] Hashin Z, Shtrikman S. 1963. A variational approach to the theory of the elastic behavior of multiphase materials. *Journal of the Mechanics and Physics of Solids* 11(2):127–40.

[2] From *This Week's Citation Classic*, CC/NUMBER 6 (A1980JC93400001), University of Pennsylvania, February 11, 1980.

the spherical inclusion problem with remote uniform strain or stress and imperfect elastic spring-type interface conditions.[3] In the case of a thin elastic interphase, the interface spring constants were expressed in terms of interphase elastic properties and thickness.

In the field of damage and failure of composite materials, his first major contribution was in a 1980 paper in which he properly accounted, for the first time, for physically observed failure modes and presented three-dimensional failure criteria of unidirectional fiber composites in the form of quadratic stress polynomials, expressed in terms of the transversely isotropic invariants of the homogenized unidirectional composite.[4] Four distinct failure modes—tensile and compressive fiber and matrix modes—were modeled separately, resulting in a piecewise smooth failure surface.

In 1985 he made another significant contribution to damage mechanics when he applied variational methods to cross-ply laminates with an array of transverse cracks for estimating rigorous lower bounds of the elastic properties.[5] This work was extended to orthogonally cracked cross-ply laminates in a paper 2 years later and subsequently to angle-ply laminates, as reported in a 2010 paper.[6] In this paper, stiffness reduction of the laminates with intralaminar cracks in the middle layers was studied and lower bounds to stiffness coefficients were derived using the principle of minimum complementary energy.

Zvi Hashin's lasting contributions to micromechanics and damage and failure in fiber-reinforced composites earned him several significant awards. He was elected a foreign member of the NAE in 1998. In 2007 he was awarded the Israel Prize for

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[3] Hashin Z. 1991. The spherical inclusion with imperfect interface. *Journal of Applied Mechanics* 58(2):444–49.

[4] Hashin Z. 1980. Failure criteria for unidirectional fiber composites. *Journal of Applied Mechanics* 47(2):329–34.

[5] Hashin Z. 1985. Analysis of cracked laminates: A variational approach. *Mechanics of Materials* 4:121–36.

[6] Vinogradov V, Hashin Z. 2010. Variational analysis of cracked angle-ply laminates. *Composites Science and Technology* 70:638–46.

his research in engineering. In 2012 he received the Benjamin Franklin Medal from the Franklin Institute "For ground-breaking contributions to the accurate analysis of composite materials, which have enabled practical engineering designs of lightweight composite structures, commonly used today in aerospace, marine, automotive and civil infrastructure."

Composite materials are now an indispensable part of multifunctional materials for modern technologies. Many researchers and engineers have contributed to the field of micromechanics, but Zvi Hashin stands out for his extensive fundamental and impactful contributions. His damage and failure theories and bounds on material properties for fiber composites raised the level of scientific rigor and physical understanding in the field. His contributions will continue to help researchers and engineers reach new levels of understanding of interfaces and interphases and associated failures in multiphase composites in the 21st century and beyond.

Hashin is survived by his wife Tamar, three children, and five grandchildren.