Recent Advances in Experimental Mechanics

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In Honor of Isaac M. Daniel

Edited by

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Editor's Preface

This book contains 71 papers presented at the symposium on “Recent Advances in Experimental Mechanics” which was organized in honor of Professor Isaac M. Daniel. The symposium took place at Virginia Polytechnic Institute and State University on June 23-28, 2002, in conjunction with the 14th US National Congress of Applied Mechanics. The book is a tribute to Isaac Daniel, a pioneer of experimental mechanics and composite materials, in recognition of his continuous, original, diversified and outstanding contributions for half a century.

The book consists of invited papers written by leading experts in the field. It contains original contributions concerning the latest developments in experimental mechanics. It covers a wide range of subjects, including optical methods of stress analysis (photoelasticity, moiré, etc.), composite materials, sandwich construction, fracture mechanics, fatigue and damage, nondestructive evaluation, dynamic problems, fiber optic sensors, speckle metrology, digital image processing, nanotechnology, neutron diffraction and synchrotron radiation methods.

The papers are arranged in the following nine sections: Mechanical characterization of material behavior, composite materials, fracture and fatigue, optical methods, non-destructive evaluation, neutron diffraction and synchrotron radiation methods, hybrid methods, composite structures, and structural testing and analysis.

The first section on *mechanical characterization and material behavior* contains eight papers dealing with dynamic tests using Hopkinson bar techniques, gradient theory of micro-scale plasticity, time-dependent materials, foam materials, carbon nanotubes and nanostructured coatings. The second section on *composite materials* contains nine papers dealing with state variables, properties at high strain rates, metal matrix composites, particulate composites, hygric characterization, pneumatic behavior, compressive strength, interfacial strength and toughness, and residual strength after damage due to impact and erosion. The third section on *fracture and fatigue* contains ten papers dealing with a probabilistic model of fatigue, damage tolerance analysis, crack growth, failure initiation, crack paths in adhesive bonds, failure of spot welds, and dynamic and intersonic crack growth. The fourth section on *optical methods* contains seven papers dealing with moiré interferometry, optical fiber sensors, displacement measurements based on optoelectronics and photogrammetry, fracture processes using digital image correlation, determination of fringe order using different wavelengths, and heart mechanics problems by means of speckle metrology. The fifth section on *nondestructive evaluation* contains eight papers dealing with acoustic microscopy, acoustography, waves in elastic materials, shearography, laser-ultrasonics, scattering of flexural waves, and ultrasonic applications. The sixth section on *neutron diffraction*

and synchrotron radiation methods contains eight papers dealing with neutron diffraction techniques for strain scanning and measurement of residual stresses and synchrotron radiation analyses. The seventh section on *hybrid methods* contains eight papers dealing with combined numerical and experimental methods. The eighth section on *composite structures* contains six papers dealing with composite materials and sandwich structures. Finally, the ninth section on *structural testing and analysis* contains seven papers dealing with bridges, aircraft, stereolithography, sheet metal forming, and adhesive joints.

I consider it an honor and privilege to have had the opportunity to edit this volume. I wish to thank very sincerely the authors who have contributed to this volume and all those who participated in the symposium on "Recent Advances in Experimental Mechanics" to honor Isaac M. Daniel, a hero of experimental mechanics, a warm-hearted individual, a loyal friend, a colleague, whose work and ideas have and will be indelibly imprinted on the pages of solid mechanics history. Special thanks are due to my friend Dr. A. Youtsos of Joint Research Center of European Union at Petten, The Netherlands, who organized a special session on "Neutron diffraction and synchrotron radiation methods."

My deep appreciation and thanks go to Mrs Yolande Mallian for her many months of hard work and devotion and her dedicated, and competent support in the timely and meticulous editing of this work. Finally, a special word of thanks goes to Dr. Arno Schouwerburg of Kluwer Academic Publishers for his interest in publishing this work and his kind collaboration and support.

March 2002
Evanston, IL USA

Emmanuel E. Gdoutos
Editor

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ISAAC M. DANIEL

Biography of Isaac M. Daniel

Isaac M. Daniel was born on October 7, 1933 in Thessaloniki (Salonica), Greece, second of four children of Mordochai Daniel and Bella (Modiano) Daniel. Thessaloniki, the second largest city in Greece, is an ancient city named by Alexander the Great for his sister. It is also near Aristotle's birthplace. His family, for the most part, traces its origins to Spain from where they were expelled in 1492 for religious reasons, although it also has roots in a community that lived in the area for over 2000 years. His father was born and raised in the nearby town of Veria (Veroia) also an ancient city. His mother's family came from Livorno, Italy and is distantly related to the painter Amedeo Modigliani.

Thessaloniki, originally the center of Alexander's Macedonia became successively part of the Roman, Byzantine and Ottoman empires until 1912 when it was incorporated in Greece. Sometimes when talking about his family's background, Isaac says that his mother was born in Turkey, raised in Greece as an Italian citizen, attended an Italian school where she learned French, but at home she spoke Ladino (a medieval Spanish dialect with admixtures of Hebrew, Portuguese, Italian, Greek, French and Turkish).

Before the Second World War, Isaac's family moved to Veria (about 45 miles west of Thessaloniki) which at the time had a population of around 15,000. He entered the local Jewish school and attended the Synagogue that the apostle Paul visited some 2000 years ago. Isaac's father was a cabinet maker and occasionally worked as a grain dealer. His peaceful life came to a halt with the German invasion and its consequences. He still remembers all the horrible details of that period.

The roundup of the Jewish community came suddenly, but his family miraculously escaped and hid in their basement. They lived in that basement, just like Ann Frank, for about a month until they were found out, arrested and put in the Baron Hirsch transit camp in Thessaloniki. They were scheduled to be shipped within days to the death camps of Auschwitz, when another miracle occurred. They were put on somebody's list, the list of Guelfo Zamboni, the Italian consul in Thessaloniki. Through his intervention, 280 inmates, with direct or remote connection to Italian citizenship, out of more than 55,000 who passed through that camp, were released and taken to Athens which was then under Italian control. After Italy surrendered to the allies, life in Athens during the remaining war years became turbulent and full of dangerous adventures and more miraculous and narrow escapes. After the liberation on October 12, 1944, the troubles were not completely over, as they were caught in the middle of a brief but bloody civil war. Finally, they managed to return to their home in Veria and tried to start rebuilding their broken lives. They had lost over fifty of their relatives and most of their friends.

In 1945 Isaac Daniel enrolled in one of the public schools in Veria and then entered, after an entrance examination, the Gymnasium (High School). He has very

good memories of his high school years. He was very popular and had many friends. The school followed a classical curriculum which included among others, six years of ancient Greek, and four years of Latin and French. In the senior year the students put on a play and they raised enough funds for a class trip to southern Greece and the islands. It was Isaac's first and only attempt as a playwright. He had no favorite or less favorite subjects. He was equally at ease with Math and Science as with history and literature. He wrote poetry and had one poem published. He was selected to give the valedictory address at his graduation. He was told that a couple of his teachers had tears in their eyes during the speech.

Graduation from high school was the end of a care-free period and the beginning of a new phase of career planning and preparation. The high school principal who counseled all the graduating students individually told Isaac that he had no special advice to give him, that he would do well in whatever career he followed. It was a choice among Literature, Medicine and Engineering. He chose the latter because it seemed to be the most challenging at the time. The entrance exams for the National Technical University in Athens (the only technical school in the country at that time) were the toughest of all. The best graduating students from all high schools would take a year off and enter a preparatory school before attempting the entrance exams. Upon graduation from high school Isaac Daniel attended a preparatory school for less than a month and he spent the rest of the summer studying by himself. He took the exams in the fall and it was one of the greatest days of his life when he heard that he was successful.

He entered the School of Civil Engineering at the National Technical University (Metsovion Polytechnion). They had classes from 5 to 8 hours a day, six days a week. He finished two years and had enrolled for the third year when he immigrated with his family to the United States.

The family settled in Chicago in 1955 and Isaac transferred to the Illinois Institute of Technology. It was a bit of a cultural shock. He was more advanced in technical and math subjects, but he had to take English literature and other liberal arts courses. He was a straight A student and graduated with distinction, first in his class as well as the entire Engineering Division of IIT in 1957. He received a Fellowship from the Chicago Bridge and Iron Co. and entered graduate school at IIT.

IIT had an illustrious tradition in Mechanics with names like Enrico Volterra, Bill Ramberg, Eli Sternberg, Daniel Drucker and others associated with it before Isaac came. He had great teachers like August Durelli, Max Frocht, Lloyd Donnell and Phil Hodge. Durelli was his first mentor who introduced him to the field of Experimental Mechanics. Durelli was a scientist, philosopher and humanist. Frocht taught him precision and quality of presentation, especially in the case of photoelastic fringe patterns. Donnell impressed him by demonstrating the thought processes and approximations involved in developing complex relations. Hodge was clear and methodical in his lectures on continuum mechanics and plasticity. In addition to the technical knowledge, he learned one wise life guideline: "what is not worth doing is not worth doing well."

As he was finishing his Master's degree studies, Durelli offered Isaac a job at the Armour Research Foundation (later IIT Research Institute) the research affiliate of IIT, where he became deeply involved in Experimental Stress Analysis. At that time, the

late 50's and early 60's, the IIT campus was a hotbed of activity in experimental stress analysis. Albert Kobayashi and Pericles Theocaris had both worked in Durelli's laboratory. He was fortunate to have supervisors and colleagues like Jim Dally, Bill Riley, Cesar Sciammarella, Vince Parks, Bob Rowlands and Ted Liber. The biggest compliment that Durelli paid Isaac, when he ran the first dynamic photoelasticity test and showed him the results, was a quotation from El Cid: "leurs coups d'essai veulent des coups de maître" (their trial strokes are master strokes). His first technical presentation, based on his Master's thesis, was at the ASME meeting in New Orleans in 1960.

The work at Armour (IITRI) was exciting. Isaac Daniel worked on stress analysis problems using photoelastic, moiré and strain gage methods. He worked on fracture of brittle materials and published work on fracture probabilities with N. A. Weil. He worked on creep of rubberlike materials and was impressed to verify experimentally that the equilibrium modulus of these materials is proportional to the absolute temperature as predicted. He became interested in viscoelasticity and this led him to write a proposal to the Air Force for the development of dynamic photoviscoelasticity and application to the study of stress waves in earth media. This led him to his Ph.D. research which he did while working full-time at IITRI. The research was reviewed by a committee including K. H. Chu, Jim Dally, Phil Hodge and Frank Essenburg of IIT and IITRI. In the course of this research he received valuable advice from Y. H. Pao of Cornell who was visiting at IITRI for one summer. He developed a theory of photothermoviscoelasticity and applied it to wave propagation problems. In 1964, Isaac received his Ph.D. He continued research in the areas of wave propagation and rock mechanics and started applying experimental stress analysis methods to the emerging technology of composite materials. Initially, he studied the micromechanics of composites by means of photoelasticity.

In the middle 60's there was a government thrust to develop advanced composites. Texaco had developed a new boron prepreg tape, which was 1/8 in. wide. Isaac Daniel and his co-workers made their first advanced composite sample from this tape, the size of a postage stamp. The government announced a large program and encouraged the collaboration of universities, research institutes and industry. Isaac's director at IITRI wrapped the postage stamp sized specimen in his wallet and they both flew to Fort Worth to meet with General Dynamics. At a high level technical meeting they asked Isaac how much experience he had with advanced composites. Before he had a chance to say "not much" his boss kicked him under the table and said that they had expertise in fabricating composites and showed them the specimen. The General Dynamics people were impressed. It was proposed then that the first application be a flat part, namely the horizontal stabilizer of the F-111.

Isaac Daniel was appointed manager of the Experimental Stress Analysis Section at IITRI, a position previously held by Durelli and Riley. It was a heady time for research in composites and the funding was lavish. There were no established testing procedures for composites and the common practice was to adopt the same methods used for metals. For example, tensile testing was done by ultrasonically machining a narrowed section in a boron/epoxy coupon. This process, besides being very expensive and time consuming, did not work. It was then that Isaac tried a straight-sided coupon tabbed with glass/epoxy tapered tabs, a method that has become an ASTM standard. In the

following years his work with composites expanded in all directions including processing, development of test methods, micromechanics, material characterization, special test methods (torsion, impact, creep/relaxation, fracture toughness, hygrothermal effects, high rate testing, multi-axial testing, fatigue), stress and failure analysis (stress concentrations, joints, warpage), damage mechanics and nondestructive evaluation.

In the early 70's he worked with Bob Rowlands and Jim Whiteside of Grumman on the effects of stress concentrations in composite panels. They applied birefringent coatings and moiré techniques to study the deformation and failure around holes. This work was extended later to investigations of size effects and biaxial loading. He built a new biaxial testing system for flat plates. He had a chance to work on speckle interferometry with Mike Hung during his brief sojourn in his group at IITRI. In the 70's he also worked with Ted Liber on developing an embedded strain gage technique for determination of curing residual stresses, biaxial testing using tubular specimens, high strain rate testing and nondestructive evaluation of composites. He developed and built a fully controlled test system for multiaxial testing of thin wall tubular specimens. He also developed a new method for testing composites at very high strain rates using thin ring specimens subjected to an internal pressure pulse produced by an explosive inside a liquid container. This method did not have the limitations of other methods using test coupons such as the Hopkinson bar method, where stress wave propagation over the length of the specimen produces a nonuniform stress distribution. In the case of the thin ring specimen under internal pressure there are no end effects and the relevant dimension is the thickness of the ring. He also found out that they could determine dynamic compressive properties by loading thin wall cylinders under external pressure without producing buckling, if the pressure were applied at a sufficiently high rate.

Isaac Daniel received two best paper awards from the Society for Experimental Stress Analysis (SESA and later SEM). He became Fellow of SESA in 1981 and was invited to be the keynote speaker at the 7th International Conference on Experimental Mechanics in 1982 in Haifa. In the same year he coauthored with Jim Whitney and Byron Pipes a monograph on Experimental Mechanics of Composites.

In January 1982 he was invited to join IIT as Professor and Director of the Experimental Stress Analysis Laboratory (later Mechanics of Materials Laboratory). The first grant he received at IIT was from ONR (Yapa Rajapakse) which has continued its support to date. During this period he worked on damage mechanics of composites, including damage characterization, evolution and accumulation, accelerated testing and life prediction; dynamic fracture toughness, and nondestructive evaluation of composites.

In 1984 he received the B. J. Lazan Award for outstanding original contributions in Experimental Mechanics. In the same year he spent the summer in Poitiers, France, as a visiting Professor at the invitation of Professor Alexis Lagarde, and gave several seminars on composites.

In early 1986 he was invited to give a seminar at Northwestern University. During lunch, Toshio Mura, in his inimitable fashion, said to him: "After you join us in the fall, we will write a proposal together on solitons." That was the first hint he got of the offer from Northwestern that came later and he couldn't refuse. He joined Northwestern and he wrote the proposal with Toshio Mura to NSF. It received two "excellent" and one

“very good” rating, but it was not funded. He continued the work in damage mechanics and damage evolution in composites. This included development of models for stiffness and strength degradation and closed form expressions for constitutive behavior of cracked composite laminates with students Jae-Won Lee and Cho-Liang Tsai, now at Samsung Company in Korea and Yun Lin University in Taiwan, respectively. With Tsai he developed a unique method for determining all three shear moduli of an orthotropic composite. He developed advanced ultrasonic and acoustic emission techniques for flaw and damage detection and characterization with his student Shi-Chang Wooh, now Professor at MIT. This work included ultrasonic methods for three-dimensional imaging of internal damage, detecting porosity and for determination of elastic properties of composites. He worked with Tao-Ming Wang (now at Illinois Tool Works) on control of residual stresses and warpage in circuit boards, a problem of great interest in electronic packaging. One result of this work was a method for measuring the chemical cure shrinkage in composite laminates.

A multi-year program, started in the late 80’s, was the investigation of constitutive behavior of metal matrix composites sponsored by NASA-Lewis (Chris Chamis). He worked with his students Dimitri Karalekas and Heoung-Jae Chun, now Professors at the University of Piraeus, Greece and Yonsei University in Korea, respectively. They did a very extensive characterization of elastic and viscoelastic behavior of metal matrix composites at ambient and elevated temperatures.

Starting in the late 80’s and continuing into the 90’s he embarked on the study of micromechanics of failure and constitutive behavior of ceramic matrix composites with his students Jae-Won Lee, George Anastasopoulos and Jyi-Jiin Luo. Based on real time observations of microscopic failure modes and acoustic emission output, they proposed analytical constitutive models describing material response up to failure. The investigation was extended to elevated temperatures and determination of residual stresses. He worked with his former student and now research associate Jyi-Jiin Luo on the development of an analytical model and a general theory for characterizing deformation of damaged composites.

One of the most satisfying activities for Isaac Daniel in the early 90’s was writing the textbook “Engineering Mechanics of Composite Materials,” with Ori Ishai of the Technion in Israel. The book has been very well received by the community and is widely used as a textbook throughout the world. He is currently working with Ishai on the second edition.

In the early 90’s the composites thrust of ONR shifted to the compressive behavior of thick composites. With his student Hao-Ming Hsiao he developed methods for manufacturing thick composites of uniform quality and a new method for compressive testing of such composites using a specially designed fixture (NU fixture). They studied and recorded the failure mechanisms of kink band formation and its propagation. They investigated experimentally and modeled the behavior, both linear and nonlinear, of thick composites with fiber waviness. The above studies were followed by extensive investigations of the effects of high strain rate on the stress-strain behavior and properties of composites under tension, compression and shear.

This work was followed by research in the area of composite sandwich structures with the help of Emmanuel Gdoutos, visiting Professor from Democritus University of Thrace, Greece, and former student and now research associate Jandro Abot. They

developed methods for fabrication and testing of sandwich structures statically and under impact and studied experimentally and analytically the various failure modes and criteria for their occurrence.

A major expansion of his activity in composites occurred at the end of 1997 when Professor Daniel became Director of the new Center for Intelligent Processing of Composites. The objective of this center is to develop a comprehensive, commercially viable approach for fabrication of affordable, functional and reliable composite structures. This is an interdisciplinary program conducted by a team including University faculty, industrial firms and the government. Contributions of Daniel's group in this Center include the design and fabrication of an innovative computer controlled system for resin transfer molding (RTM); new methods for characterizing reinforcement preforms; flow and cure models; and a new noninvasive approach for on-line quality control of reinforcement quality, a method of great commercial potential.

Isaac Daniel received several recognitions and awards in the 90's. He became Fellow of the American Academy of Mechanics (1994); was invited to be a keynote speaker at the International Conference on Composites Engineering in New Orleans (1995); received the Distinguished Research Award of the American Society for Composites (1996); was elected Chairman of the Theoretical and Applied Mechanics program at Northwestern University (1996); received the William M. Murray Medal of the Society for Experimental Mechanics and gave the associated prestigious lecture to the society (1998); he was appointed the Walter P. Murphy Professor of Civil and Mechanical Engineering at Northwestern University (1998); became Fellow of the American Society of Mechanical Engineers (1999); received the Professional Achievement Award from his alma mater, the Illinois Institute of Technology (1999).

Besides all the research and professional activities, Isaac leads a busy and happy family life. His wife Elaine Krule Daniel of Chicago shares many interests with him. She studied at the Sorbonne and the University of Illinois. Elaine is a polyglot with degrees in French and teaching English as a second language and has taught at the University of Illinois in Champaign-Urbana and the University of Louisville in Kentucky. She is also a gourmet cook and a quilter. They have three children, Belinda, 13, Rebecca, 11, and Max 9. Isaac spends a lot of time with his family taking them along on trips to summer conferences in the United States and abroad. He attends and participates in the children's activities, such as concerts and Boy Scout projects. He is active in community affairs, reads, travels and is interested in photography. He has a sense of humor which Elaine appreciates by laughing at his jokes even when she hears them for the fifth time. He shares a special interest with Elaine in linguistics and their dream is to write a Ladino-English dictionary.

Isaac was very close to his father and mother who passed away in 1993 at the ages of 94 and 86. His older brother, Aaron, is an architect living in California. When he lived in Chicago he contributed to the design of the Sears Tower and the Civic Center plaza. His sister, Sarah Spector, has a degree in nutrition and lives in Chicago. His younger brother Sam, works for Motorola on artificial intelligence and lives in Arizona.

Isaac Daniel has no immediate plans for retirement. People say that his children keep him young and active. He hopes to continue working and help his children with their education and, maybe, have them in his class.

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