BIOGRAPHICAL MEMOIRS

Anthony James Merrill Spencer. 23 August 1929 — 26 January 2008

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ANTHONY JAMES MERRILL SPENCER

23 August 1929 — 26 January 2008
Anthony J. M. Spencer, known to all as Tony, was one of the most outstanding British applied mathematicians of his generation. His main field of research was in understanding and predicting the mechanical behaviour of advanced materials. His insight and skill in formulating constitutive equations enabled him to develop new models of materials and then solve physically significant problems in the fields of composites, granular materials and laminates. He studied at Cambridge, Birmingham and Keele and, after postdoctoral research in the acclaimed Division of Applied Mathematics at Brown University in the USA and a short period of employment in government service, moved to Nottingham University and spent the rest of his career there. He soon became Head of the Department of Theoretical Mechanics, which had been formed in 1960 and given responsibility for teaching mathematics to students in the Faculty of Applied Science. Under Tony’s guidance and inspirational leadership it gained an unrivalled reputation, by virtue of its productivity in research, the quality of its staff and its innovative approach to undergraduate teaching and graduate training. Although firmly rooted in Nottingham, Tony travelled widely and was very well known. He was an astute and highly proficient research worker whose views were prized by his many collaborators and friends in the solid mechanics community. It is a measure of his intellectual strength and dedication that he published 40 research papers in his 13 years of retirement.
Anthony James Merrill Spencer, Emeritus Professor of Theoretical Mechanics in the University of Nottingham, was born in Edgbaston, Birmingham, on 23 August 1929. His grandfather, Isaac Spencer, had been a colliery engineer who rose to become a deputy in the Derbyshire coalfield and lived at Beighton in northeast Derbyshire. He is remembered by the family as being a strict Methodist. His mother’s father, Frederick Merrill, was a grocer who ran a small shop in the village of Swallownest, east of Sheffield. Tony’s father, James Lawrence (Jim) Spencer, was born in 1902 and was academically very gifted. He won a scholarship to Staveley Grammar School, and received several prizes while there. He entered Sheffield University at the age of 17 years, graduated in chemistry and stayed on for an extra year to gain an MSc. He then moved to the Birmingham area and joined the firm of Accles and Pollock, who were the leading British metal tube manufacturers. Their products included tubes for bicycle frames, furniture and bus seats, box spanners and aircraft. They developed a process for the cold drawing of the world’s first stainless steel tube and also produced seamless tapered golf club shafts. Jim Spencer conducted research into steel tubing, and during World War II managed the factory that produced components for aircraft. He was also a very talented footballer, playing professionally for West Bromwich Albion for the three seasons 1922–25 in the outside right position, while employed by Accles and Pollock. In fact, in the season 1924–25 West Bromwich Albion were runners-up in the First Division of the Football League. Jim Spencer played for them until a torn cartilage ended his professional career. He died suddenly at the age of 59 years in 1961.

Jim Spencer married Gladys Merrill in August 1928, and Tony, their first child, was born in August 1929. Initially, the family lived in Smethwick, but they moved to Streetly in Staffordshire in 1934, shortly after Tony’s sister Rosemary was born. Tony attended a local private junior school at which his mother became a teacher after Tony and Rosemary had left. At the outbreak of World War II he was evacuated to Anglesey, but soon returned to Streetly. He won a scholarship to Queen Mary’s Grammar School in Walsall in 1940. Queen Mary’s is an ancient foundation, dating from 1554. In the 1940s it was a medium-sized selective boys’ school, classed as a public school on account of its Head being a member of the Headmasters’ Conference. Teaching resources were depleted by the call-up of male staff for war service but, among those who remained, William A. Burn taught mathematics and physics and stimulated in Tony, as in many of his contemporaries, a deep interest and enthusiasm for both subjects. Mr Burn was also the Commandant of the Local Home Guard Unit. Among Tony’s friends at school were Steve Hunter, later a Professor of Mathematics at Sheffield University, and Neill Dennison, later His Honour Judge Dennison QC and Common Sergeant of the City of London, and Tony’s best man. The family recall that Tony and Steve Hunter often cycled the five miles to the school in Walsall over Bar Beacon on Steve’s tandem.

On leaving school in 1947 Tony had the choice of going to Birmingham University or of joining the armed forces and going to Cambridge University with a deferred entry two years later. He opted for the Army and then Cambridge. He was called up under the wartime regulations ‘for the duration of the Emergency’ and joined the West Yorkshire Regiment in January 1948, serving in a Signals Section. He was sent to Austria and stationed in Vienna and Klagenfurt. Mrs Margaret Spencer recalls that on their 40th wedding anniversary in January 1995 they went to Vienna to stand on the frozen Danube to view Tony’s old yellow-painted barracks. He was very proud to have served in the Army. Later he recalled that the Carol Reed
The film *The Third Man* of 1949, which was written and had a screenplay by Graham Greene, and the ‘Harry Lime’ theme played on the zither by Anton Karas, accurately evoked the somewhat ‘seedy’ atmosphere of Vienna in those postwar days. After some 20 months of service, during which he was promoted to the rank of lance corporal, Tony secured an early discharge and an ex-service grant to enter Queens’ College, Cambridge, in October 1949.

**CAMBRIDGE, BIRMINGHAM AND KEELE**

Tony’s Director of Studies at Queens’ College was the geometer Dr E. A. Maxwell, and among his mathematics lecturers were many who later became distinguished professors: George Batchelor (FRS 1957), Hermann (later Sir Hermann) Bondi (FRS 1959), John Burkhill (FRS 1953), Fred (later Sir Fred) Hoyle (FRS 1957), who lectured on elasticity, Raymond Lyttleton (FRS 1955) and Robert Rankine. He was a member of the cricket, table-tennis and film clubs and the Agnostics. After graduating in mathematics in 1952, he decided he wanted to undertake research in materials; whether his knowledge of his father’s field of work influenced this decision is not known. He joined the Department of Metallurgy in Birmingham University to work with F. R. N. Nabarro (FRS 1971) on the brittle fracture of elastic–plastic materials. He said later that there were several reasons for this: his friend from school, Steve Hunter, was in that department, he saw an advertisement for a research studentship on an Admiralty contract, and his future wife, Margaret, was based in Birmingham. Unfortunately, after about 10 months, Frank Nabarro left to take up a chair of physics at the University of Witwatersrand. It was arranged for Tony to transfer to the recently established University College of North Staffordshire (now Keele University) to work with the young and dynamic mathematician Ian Sneddon (FRS 1983). Professor Sneddon remembered Tony’s arrival at Keele, with his own problem, which he considered too tough to be solved analytically and so advised Tony to tackle it numerically. His fellow research students at Keele, George Eason and Denis Berry, recalled Tony spending long hours working with an electric desk calculator applying relaxation methods to find the stress fields near holes and cracks in elastic–plastic plates. His PhD was awarded by the University of Birmingham in 1955.

Tony had met his future wife, Margaret Bosker, before entering the Army and they met again just before his demobilization. They married in January 1955 and lived in Newcastle-under-Lyme during the last eight months of his PhD study at Keele University.

Tony was an enthusiastic cyclist, cycling from his home at Streetly to Cambridge University. He and Margaret enjoyed cycling holidays during their student days. They explored the southwest of Ireland during one vacation and on another cycled up the Rhine from Cologne to Lake Constance, and then over the Arlberg Pass into Austria, finally reaching Salzburg. He continued to be a keen cyclist, occasionally cycling into his office at Nottingham University, until an accident and later a knee operation curtailed this activity.

**BROWN UNIVERSITY**

In 1955 Tony was awarded a two-year Fulbright Travel Grant to study in the Division of Applied Mathematics at Brown University in Providence, Rhode Island. The Division of Applied Mathematics in Brown was set up in 1941 to train applied mathematicians for
industry. By 1955 it was the foremost centre for research in theoretical solid mechanics in the Western world, numbering among its staff William Prager, D. C. Drucker, Ronald Rivlin, Eli Sternberg, E. H. Lee, Harry Kolsky, R. T. Shield and Turan Onat. Topics studied included continuum mechanics, plasticity, viscoelasticity, finite and linear elasticity; as this list of names indicates, all of the senior Faculty became leaders in their fields. Brown also attracted distinguished visitors, including Albert Green (FRS 1958), on leave from King’s College, Newcastle upon Tyne. Tony was to work with Rivlin and Green, and, as he later remarked (Hill & Selvadurai 2000, p. 2), ‘My debt to Rivlin in particular is huge, and I also owe a great deal to Albert Green, from whom I learned much.’ Also, later (Chadwick 2001, p. 261):

Albert and Ronald were completely different personalities, but I thought they complemented each other perfectly; Ronald had the ideas and very deep physical insight, while Albert was also pretty good at the physics but in addition was an excellent technical mathematician. Ronald would always tackle a problem head on, whereas Albert tended to be more subtle. Neither of them could be easily persuaded to accept an argument, but they normally agreed in the end.

Tony worked with Albert Green on the stability of an elastic cylinder subject to finite extension and torsion, which led to his first published paper (1)* and introduced him to perturbation methods in finite elasticity, a theme he was to return to several times in his career.

After wartime work on radar, Ronald Rivlin had joined the British Rubber Producers Research Association in 1944, becoming its Superintendent of Research in 1950. In this period he performed fundamental experiments on rubber elasticity and developed the (nonlinear) theory of finite elastic deformations. Rivlin spent a year in the USA as a consultant in the Naval Research Laboratory in Washington in 1952 and then decided to stay permanently in the USA, moving to Brown University in 1953. Tony Spencer, in a paper written in 2007 as a tribute to Ronald Rivlin, but not published until after his death (74), described how, in a series of papers published between 1948 and 1952 entitled ‘Large deformations of isotropic elastic materials’, Rivlin had established the basis of the modern theory of finite elasticity and thereby initiated several decades of advances in nonlinear continuum mechanics. Rivlin, in part IV of this series, explicitly stated that the strain–energy function for an isotropic elastic solid can be expressed as a function of the three strain invariants of the right Cauchy–Green deformation tensor, and consequently was able to solve several non-trivial problems for incompressible isotropic elastic materials. It was found that when the stress depends on a single kinematic variable, the analysis relies on classical matrix theory; however, some materials have a more complex behaviour. Rivlin & Ericksen (1955) derived properly invariant higher-order kinematic tensors and formulated the invariance requirements for the situation in which the stress depends on several kinematic tensors. To obtain explicit results in this case requires additional mathematical apparatus, based in part on Rivlin’s generalization of the Cayley–Hamilton theorem. Tony Spencer became much involved in this research, thus initiating a collaboration with Rivlin on the theory of algebraic invariants, which represents a milestone in the development of continuum mechanics. For materials of various crystal classes and for materials exhibiting invariance under some subgroup of the full orthogonal group, Tony developed techniques for identifying sets of tensor invariants of minimal size. In the following five years, in collaboration with Rivlin, he published further papers (2–4, 8), which are standard citations in modern continuum mechanics. He found this field fascinating

* Numbers in this form refer to the bibliography at the end of the text.
and worked on invariant and tensor function theory throughout his career, as described below. In fact his last paper (74), referenced above, illustrates how these ideas have recently been applied to the modelling of materials reinforced by fibres with bending stiffness.

ALDERMASTON

The Spencers returned to England in 1957 and Tony became a Scientific Officer at the Atomic Weapons Research Establishment (AWRE) at Aldermaston, Berkshire. His later colleagues presumed that his work involved studying the effects of underground nuclear explosions, but Tony was very circumspect; he had signed the Official Secrets Act, and to our knowledge he refrained from discussing his Aldermaston work. However, it can now be recorded that he joined a small group directed by Ernest P. Hicks, concerned with ground effects of explosions. One of us (P.C.) had been a member of Hicks’s group since 1955, and a collaboration had been established with a group of applied mathematicians in the Royal Armament Research and Development Establishment (RARDE) at Fort Halstead in Kent. The RARDE group included Tony’s friends Steve Hunter and George Eason and was led by Geoffrey Hopkins, later Professor of Mathematics at the University of Manchester Institute of Science and Technology. The main results of this collaboration are presented in Chadwick et al. (1964), and the book by Lorna Arnold (Arnold 2001) contains an account of the achievements of the Theoretical Physics Division at AWRE up to 1960. The Spencers’ first few months at Aldermaston were a little fraught because they could not find suitable accommodation. They were expecting their first child, so Tony lived in a hostel near Aldermaston and Margaret lived in her parents’ house in Sutton Coldfield, where their son John was born. They eventually moved into a house in Newbury in April 1958. One of Margaret’s recollections of that house is that it used to shake when large aircraft were taking off from the Greenham Common US Air Force base.

Tony worked at Aldermaston for three years, during which he developed his interests in plasticity, with particular reference to the application of perturbation methods as described below. The decisive move in his career came at the end of this period, in 1960, when he accepted a lectureship in the newly created Department of Theoretical Mechanics in the University of Nottingham. This was the department in which he was to spend the next three decades. Tony Green, who also was appointed to the department in 1960, had worked at Aldermaston in the late 1950s before joining the National Engineering Laboratory at East Kilbride, near Glasgow.

NOTTINGHAM UNIVERSITY IN THE 1950S

Nottingham University engaged in a period of rapid expansion in the 1950s under Bertrand Hallward, its first and visionary Vice-Chancellor. The University Park was expanded to its present size by the purchase of some large houses and their grounds, adjacent to the prewar campus of the University College on the Highfields Estate. It was envisaged that the area at the eastern edge of the campus, adjoining Clifton Boulevard, would eventually house the new Science and Engineering Buildings. The site was occupied by the Ministry of Works in temporary single-storey wartime buildings, and these occupants were somewhat reluctant to move. A new Chemistry and a new Mathematics and Physics building were planned, together
with the Engineering buildings described below. The whole complex eventually acquired the name ‘Science City’! Tolley (2001) has described the growth of the university in great detail.

During this period the Applied Science Faculty consisted of a joint Department of Mechanical and Civil Engineering, a Department of Electrical Engineering and a Department of Mining and Fuels. Joseph Pope was appointed head of the joint Mechanical and Civil Engineering Department in 1949. His great strengths were his organizing ability and his vision for the education of engineers. The Faculty expanded with Metallurgy being set up in 1954 and Chemical Engineering in 1960. Mechanical and Civil Engineering separated in 1958, with Rex Coates becoming the first Head of Civil Engineering. Production Engineering was set up in 1962. Pope believed that all engineering students should follow a common first-year course, with time set aside for a departmental option. This course was instituted in the early 1950s. The desire of the various engineering departments to determine and control the mathematical content of the courses offered to their students led, in 1960, to the creation of a new Department of Theoretical Mechanics to be based in the Faculty of Applied Science.

The university appointed the Basil Spence Partnership as architects for the new Engineering Buildings. The buildings planned were the First Year Teaching Building (T1, later renamed the Pope Building) and the Second Year Teaching Building (T2, later renamed the Coates Building), linked by a three-storey glass-walled Exhibition Hall. Four spur laboratory blocks for Mining Engineering, Civil Engineering, Chemical Engineering and Mechanical Engineering were planned. In addition a 17-storey Tower Block for Electrical Engineering and the Department of Architecture, and the (George Green) Science Library were designed for later construction. A Faculty committee under the chairmanship of Pope had a major influence on the design and equipment of these buildings. By 1960, when Tony joined the university, the T1 Building was on the point of completion, with T2 being occupied in 1962, and the Tower Block and the Science Library late in 1964.

DEPARTMENT OF THEORETICAL MECHANICS

The Department of Theoretical Mechanics was set up in 1960 as part of the Applied Science Faculty. Its remit was to provide all the mathematics instruction for engineering students, to set up its own degree course and to offer a range of short courses in this field for industry. The first Head of Department was Dr John Adkins, who had been a Reader in the Department of Mathematics at Nottingham. Adkins had been a colleague of Ronald Rivlin at the British Rubber Producers Research Association before joining Nottingham University, and he had worked on finite elasticity with Rivlin and Albert Green. In 1960 Adkins published with Green a seminal book, *Large elastic deformations and nonlinear continuum mechanics* (Green & Adkins 1960), a comprehensive study of this field.

Tony Spencer and Tony Green were also appointed to the department at its inception in 1960 and, when Adkins departed almost immediately for a prearranged sabbatical at Brown University to work with Rivlin, they were left as the sole staff of the department. Later, Tony Spencer acknowledged that this experience was beneficial, because he was forced to learn quickly about university politics, in which the engineers, especially Rex Coates, ably assisted him. The Department of Theoretical Mechanics moved into the T1 (Pope) Building as soon as it was completed; in fact the two Tonys shared a desk until the new furniture arrived. It was to remain there until well after Tony Spencer’s retirement.
The opening of the new buildings enabled the Applied Science Faculty to expand in both staff and undergraduate numbers. Initially the teaching emphasis in the department was on reorganizing the Engineering Mathematics course. However, the Theoretical Mechanics (later renamed Mathematics with Engineering) degree was also designed in this period. In 1963, Tony Spencer was promoted to a Readership and John Adkins was promoted to the Chair of Theoretical Mechanics. Tragically, John Adkins suffered a recurrence of a chronic illness and he died in October 1964 at the early age of 45 years, shortly after heroically coming in a wheelchair to welcome the new undergraduates. Tony Spencer immediately became the acting Head of Department and, after public advertisement of the post, he was appointed Professor and Head of Department, taking up this post on 1 April 1965. He always maintained that this was a significant choice of day for the start of his appointment.

Engineering Mathematics

The teaching of mathematics to the Engineering students and the different requirements of the Engineering Departments, in terms of both the content of the syllabus and its timing, were matters of fundamental importance to Theoretical Mechanics. The Engineering Departments valued the close contacts with Theoretical Mechanics, and, in its turn, Theoretical Mechanics always felt the need and took pride in ‘delivering the goods’. A unit scheme was set up in the mid-1960s that covered not only the conventional calculus course for first-year and second-year engineers, but also some linear algebra, numerical analysis and statistics. Third-year engineers were offered a wide choice of optional courses. These developments became firmly established under Tony’s guidance and have proved remarkably resilient and adaptable to changing circumstances. Staff meetings could be interesting with strong-minded individuals in the department, but Tony took care to ensure that each had their say and that a consensus was reached with which he could agree! Teaching was shared as evenly as possible across the department, and Tony always insisted on teaching at least one Engineering Mathematics course or module per year. An indication of the spirit of mutual cooperation that Tony had built up within the department and his ability to enthuse is that, when he was approached in 1974 to write an undergraduate textbook on Engineering Mathematics, he immediately put the proposal to all nine members of the current staff with the suggestion that it should be a joint project. This was duly agreed and, after an equitable split of the writing duties and a reasonably amicable internal reviewing and revision process, a two-volume textbook appeared (28). Some aspects of the courses covered in that publication were adapted to form a one-week Mathematics for Industry course, which was offered for several years in the mid-1970s.

Mathematics with Engineering

The Department of Theoretical Mechanics set up its own honours degree course in 1964. The intention was to train mathematicians to understand engineering principles and to apply their mathematics to the solution of engineering and industrial problems. Originally the degree title was Theoretical Mechanics, but this was changed in 1968 to Mathematics with Engineering to emphasize the major–minor nature of the course. In the first year the students largely followed the Common First Year course, with the departmental option and the engineering mathematics course replaced by specialist pure and applied mathematics courses. In later years students could take one engineering option. Tony gave a detailed description of the philosophy behind this course and its implementation in ‘The education of mathematicians for industry’ (15). He emphasized that as well as providing a firm grounding in mathematical techniques,
numerical analysis and computing, ‘it should be made clear to students that not all fluids are incompressible and non-viscous, and not all solids are perfectly elastic’. This structure allowed the department to offer final-year courses in fluid mechanics, elasticity, electromagnetic waves and mathematical methods. Tony’s 1980 monograph Continuum mechanics (31), which grew out of the second-year introductory course, was very well received and had several reprints. One notable feature of the course was that each student completed a final-year project working with a member of staff on a substantial problem of engineering interest. For several years this was the only degree course of its type in the UK. Later, in 1982, the joint-honours degree course Electronic Engineering and Mathematics was set up. Apart from the intrinsic merits of these courses, they provided a good basis for postgraduate studies, and the department found a ready source of research students among these graduates. Recently, colleagues in the Engineering Faculty have commented on how many of their younger colleagues have first degrees in mathematics, indicating an ongoing need for this type of training.

An early catalyst for departmental esprit de corps was Tony’s full involvement over lunchtime, initially in the staff restaurant but later in the student buttery, in which staff were joined by the research students. After two or three hours of lecturing in the morning, the chance to recuperate before an afternoon of tutorials, preparation and research was enlivened by anecdotes from colleagues Tony Green and Tryfan Rogers, with Tony Spencer restricting himself to the occasional deep, but perceptive, interjection. More importantly, Tony was the driving spirit behind the research colloquia. These happened just three or four times per term, but each was eagerly anticipated, both because the topics of the visiting speakers related well to the interests of many of the staff and because each was followed by an evening’s visit to a Nottingham pub, followed by a meal, often at a Berni Inn—in the 1960s and early 1970s the height of sophistication and gastronomic experience! The group photograph in figure 1 shows the staff, research students and some of the undergraduates in 1967.

For almost 30 years Tony ran an unusually harmonious department, inspiring and encouraging by example. Throughout, while having considerable administrative and research commitments, he carried a teaching load as great as that of any of his colleagues. He served...
on university and national committees, including the Mathematics Committee of both the Science and Engineering Research Council and the University Grants Committee, and the Conference of Professors of Applied Mathematics. He was a keen supporter of the British Theoretical Mechanics Colloquium, attending as many of the annual meetings as he could, and was chairman when the Colloquium came to Nottingham in 1969, and again in 1987, the year of his election as a Fellow of the Royal Society. He was Britain’s Euromech correspondent for 10 years. He also organized the SERC Undergraduate Solid Mechanics Conference held at Nottingham in 1989. He undertook external examining for both departments and individuals, feeling that it was part of his job. He chaired and served on committees for numerous international conferences. Tony’s own publication record demonstrates that, during this period, both his research supervision and publication carried on apace. On stepping down as Head of Department in 1991, he was presented with an engraved silver tankard by his staff (figure 2).

Tony was interested in the history of George Green (1793–1841), the Nottingham miller’s son, who apparently received only a rudimentary education in Nottingham and yet went on to publish scientific papers (including his ground-breaking work on electricity and magnetism) privately from 1828 before entering Gonville and Caius College, Cambridge, in 1833. Green introduced potential functions, and what are now known as Green’s Theorem and Green’s functions, into mathematical physics in his paper of 1828. Tony had a correspondence with H. G. Green (no relation), a retired Reader in Geometry at Nottingham University, who had done some painstaking historical research on George Green in the prewar period. This led to a paper by a Nottingham graduate student (Edge 1978). Later, under the chairmanship of Lawrie Challis, a Professor of Physics at Nottingham, the George Green Memorial Fund was set up. Tony served on that committee, and Green’s Mill was restored. This brick tower windmill, in which George Green worked, was built and operated by his father. It now incorporates a Science Centre.
Tony was chairman of the conference ‘George Green, a Bicentennial Celebration’, at the Royal Society in 1993, during which a commemorative plaque was placed in Westminster Abbey. A book by Mary Cannell (Cannell 2001) brings our knowledge of George Green up to date and gives a record of the proceedings of the conference and the dedication of the memorial plaque.

Tony remained Head of the Department of Theoretical Mechanics until 1991, then being succeeded by his colleague of nearly 30 years and frequent research collaborator Tryfan Rogers, whose untimely death in 1993 led to Tony’s resuming the headship for the final 15 months of his employment. After his retirement in 1994, the university appointed him Emeritus Professor of Theoretical Mechanics. A joint Symposium of the International Union of Theoretical and Applied Mechanics (IUTAM) and the International Society for the Interaction of Mechanics and Mathematics (ISIMM) was held in his honour (Parker & England 1995). A special volume of the Journal of Engineering Mathematics (Hill & Selvadurai 2000) was published to celebrate his 70th birthday, and in 2004 he was elected a Foreign Honorary Member of the American Academy of Arts and Sciences. In 2007 the University of Nottingham established the Spencer Institute of Theoretical and Computational Mechanics. The Spencer Institute was created to bring together and add critical mass to the existing activities in solid mechanics, fluid mechanics and the mechanics of multiphase media that existed in individual schools within the university. Since its inauguration, seminars, meetings and courses have been organized under its auspices.

On 25 January 2008 Tony received news that he had been awarded the 2008 Engineering Science Medal of the Society of Engineering Science, to which he immediately replied by e-mail that he was delighted to accept both the award and the invitation to deliver a plenary lecture at the 45th Annual Meeting of the Society, to be held at the University of Illinois, in Urbana-Champaign. Tragically, the very next morning he died completely unexpectedly at home. Professor John Willis FRS recalls that on 24 January Tony had attended a lecture at the Royal Society by Professor Jean-Baptiste Leblond (given through an arrangement with the Academie Français) and the dinner following it and that he had interacted very happily with Leblond and the others present, before staying overnight in London. Professor Willis adds: ‘In part this is sad but I have always found it something of an inspiration: he died at the very top of his game, and was doing what he loved until the last.’ The medal was awarded posthumously and his wife Margaret received it at the Symposium. A special issue of the International Journal of Engineering Science had been planned by Patrick Selvadurai, K. R. Rajagopal and Kostas Soldatos to celebrate Tony’s 80th birthday in August 2009. Unfortunately it had to become a Memorial Issue (Selvadurai et al. 2009) in which his achievements were celebrated by his research collaborators and friends. It contains a complete list of his scientific publications.

Research

As described in greater detail below, Tony Spencer’s research work covered many different topics and ranged from fundamental theoretical contributions to practical applications. He supervised about 30 students, either individually or jointly, and assisted numerous other students and colleagues with sound advice. In particular, his 30-year collaboration with his colleague Tryfan Rogers and their research students was stimulating for all concerned, as their discussions invariably continued into a communal lunch with other staff and students.
This fruitful cooperation, modelling fibre-reinforced materials and laminated plates, ended only with Tryfan’s death in 1993. Many of these students received support from industry either directly, as in the case of Shell Research BV, or via Science and Engineering Research Council (SERC) Collaborative Awards in Science and Engineering (CASE) studentships with Rolls Royce, British Gas, ICI, Molins and Nuclear Electric. The work on flow processes in composite materials was supported by a consortium involving ICI, British Aerospace, Westland Helicopters and the Ministry of Defence. It ran in conjunction with University of Wales Aberystwyth, University College Galway, Limerick University and Nottingham University.

In addition, the department attracted a steady stream of distinguished postdoctoral research fellows and overseas visitors, including David Clements, James Hill and Vincent Hart from Australia, David Owen, Steve Cowin, Jack Pipkin and Alan Wineman from the USA, Q.-S. Zheng from Tsinghau University, China, and Patrick Selvadurai from Montreal, most of whom worked with Tony and valued his insight into their research. David Owen of Carnegie-Mellon University has commented:

To this day I have not encountered a more friendly, personable, convivial and hospitable group within Academia that also maintained such a high level of quality both in instruction and research. In his own unobtrusive way, Tony was at the centre of this group.

A characteristic of Tony’s research work was that once a topic entered his portfolio of interests he continued to work at it throughout his career. His early involvement with finite elasticity, invariant theory and plasticity enabled him to develop theories modelling granular materials, fibre-reinforced materials, inhomogeneous plates and fibre-reinforced fluids. All these studies have a common pattern: formulation of a theory followed by applications, usually involving exact solutions, extensions to the theory, and further applications. His skills in constitutive modelling and problem solving enabled him to establish and explore these fields. Regarded as a whole, his work represents a very substantial contribution to the advancement of theoretical solid mechanics.

He was a frequent participant in international conferences and was in much demand as a keynote speaker, giving clear and stimulating accounts of his work. His publications show clarity and succinctness, and generally his contributions were highly regarded in the mechanics community. He enjoyed periods of study leave, both before and after his retirement, in the USA, Canada, France, Australia and New Zealand. He was a member of the editorial boards of several journals.

**Contributions to theoretical mechanics**

*Nonlinear elasticity*

With one exception, Tony’s papers in nonlinear elasticity concerned approximations to the exact equations of elastostatics for isotropic materials. They included the stability and bifurcation of incremental deformations of a twisted and extended circular cylinder (1), a second-order theory for axially symmetric deformations, perturbation of the strain–energy function, and a treatment of materials that are almost incompressible (10). Solutions for a thick-walled torus, for a toroidal membrane (13) and for axially symmetric deformations of initially cylindrical elastic membranes (16, 41) were obtained. The review (18) also included...
an exposition of nonlinear isotropic elasticity. The paper that involves no approximations presented a family of exact solutions for combined torsional and shearing motions of a slab of Mooney–Rivlin material (51).

**Invariant and tensor function theory**

Tony played a leading part in the development of invariant and tensor function theory and he applied it successfully to the formulation of constitutive equations in continuum mechanics. Initially, he worked in collaboration with Ronald Rivlin, who was the co-author of four of his early papers (2–4, 8), and he celebrated this collaboration in a lecture published posthumously (74). Tony added a wealth of results of his own (12), which brought to completion an exhaustive study of the theory of matrix polynomials and its use in determining polynomial invariants of sets of vectors and second-order tensors under transformations belonging to the full and proper orthogonal groups. Later, in 1971, he published a long and comprehensive review article (20) in which tables were drawn up of complete and irreducible sets of polynomial invariants and tensor functions of vectors and second-order tensors; these have been widely used to reduce constitutive equations to their simplest and most explicit form. A later, more concise, account (42, 43) incorporated extensions to the theory.

He also considered invariance under the groups of transformations that characterize transverse isotropy and the crystal classes. He returned to these topics in the 1990s; later, in collaboration with Q.-S. Zheng, he derived the reduced form of the constitutive equation for micropolar elasticity both isotropy and for all possible types of anisotropy (49). This paper earned its authors the 1994 *International Journal of Engineering Science* Distinguished Paper Award. In a later paper (50) they devised a simple method of determining structural tensors under the transformations of any given symmetry group.

**Theory of plastic deformation**

The theory of plastic deformation was the subject of Tony’s PhD thesis. It informed and influenced much of his work on granular materials and on continuum theories of fibre-reinforced solids, considered in the following two subsections, so attention is here confined to publications dealing with isotropic rigid–plastic and elastic–plastic materials.

As in his work on nonlinear elasticity, Tony’s interest centred on the development of approximate methods of solution when there is a slight material inhomogeneity (6), a small surface irregularity (7) or a distribution of small body forces (9). As illustrative examples, approximate solutions were derived for problems of indentation, by stationary and moving loads (5), by a punch (6, 9) and by the curved surface of a rigid cylinder (7). Later, an exact solution was obtained for the axially symmetric flow of a rigid–plastic material past a smooth cone (35). Other work in this field concerned constitutive theory. The effects of introducing different measures of stress rate into the constitutive equations of elastic–plastic materials were examined (21), with particular reference to simple shear and torsion, and a nonlinear theory of viscoplasticity for transversely isotropic materials was presented (66, 67).

**Mechanics of granular materials**

The constitutive modelling of the deformation and flow of granular materials remains a subject of some controversy. Tony Spencer’s rationale was to develop a particular theory with plausible features and to perform a detailed investigation of its consequences, enabling the predictive value of the theory to be assessed and comparisons made with alternative approaches. In his
two-dimensional analysis (11) he constructed a model incorporating incompressibility with pressure-dependent yield so that the resultant flow was represented as the superposition of two simultaneous shearing motions along the two families of characteristic curves of the stress equations, the two directions in the plane most likely to yield. This formulation has come to be known as the non-dilatant double-shearing theory; it has gained wide, but by no means universal, acceptance and applies both to dry granular materials and to soils. In the years after its publication, under Tony’s guidance, doctoral and postdoctoral workers solved important practical problems such as compression between parallel plates, flow in a converging channel and an extension of the theory to allow for compressibility (23); however, after 1973 he did not publish on granular materials until contributing a review article in 1982 to the Rodney Hill 60th birthday volume (34). (His attention in this period seems to have been focused on fibre-reinforced materials.) Besides reviewing papers already published, that article presents a major contribution to the subject by extending the double-shearing theory from planar to three-dimensional flows of Mohr–Coulomb materials.

Writing the review (34) seemed to excite Tony’s imagination, because he subsequently published many papers on the double-shearing and other models for granular materials from the early 1980s onwards. In private conversations and in seminars Tony would make it clear that, among all his research interests, the double-shearing model had a special place in his affections. A recurring theme was what Tony did best—the striving to obtain exact solutions to initial and boundary value problems. The papers usually exploited some special geometric feature of the problem at hand, for example axial symmetry (38), gravity flows in a variety of channel, funnel and hopper configurations (see (63)) and combined compression and shear of a layer (70). Nevertheless, he still found the time to develop a theory for rectilinear flows (37) for which the double-shearing model was not applicable. A second recurring theme involved the instability of solutions, the study of which was initiated with (39) and continued subsequently with results of practical interest, particularly those for dynamic shear flow (see (55) and (61)), which have possible relevance to landslides and earthquakes. One paper showed how the double-shearing model related to the conventional coaxial model with a view to demonstrating the superior properties of the solution for the former (57), and another developed a hybrid theory in which some features of the critical state theory for soils were incorporated into the double-shearing framework (60). Finally, in a little known paper (71), with the potential to have a significant impact in the future, the double-shearing theory is extended to a viscoplastic material, via the introduction of rate dependence (that is, viscosity) to supplement the rate-independent contribution of solid friction.

Continuum theories of fibre-reinforced materials

In a series of papers written in the late 1950s, Adkins and Rivlin considered rubber-like materials reinforced by layers of inextensible and perfectly flexible cords (Green & Adkins 1960, ch. 7). In developing a continuum theory of fibre reinforcement, Tony Spencer and Tryfan Rogers assumed that a fibre (perhaps more than one) is present at each material point of the body and deforms with the material. This concept was designed to model contemporaneous developments in the aerospace and automotive industries. Initially, it was also assumed that each fibre is inextensible and the matrix incompressible. Tony Spencer referred to such materials as ideal fibre-reinforced materials. Theories using these assumptions were developed by Spencer and Rogers for rigid–plastic (14) and elastic–plastic materials (17) for a single family of fibres (with Mulhern) and for rigid–plastic materials for two
families of fibres (19), with Smith. Tony Spencer then examined the dynamical behaviour of rigid plastic beams and plates in a series of nine papers, mainly co-authored with Linda Shaw. In particular, the energy-absorbing properties of metal-matrix fibre-reinforced beams were evaluated (24–27, 29, 30). Soon after the completion of (14) it was realized jointly by Jack Pipkin, Tryfan Rogers and Tony that it is possible to construct kinematically admissible deformations that satisfy the constraints of fibre inextensibility and material incompressibility, independently of a constitutive equation. Because a constraint such as inextensibility has an arbitrary reaction stress associated with it, and incompressibility gives rise to an unknown pressure field, many problems can be solved kinematically with the reaction stresses being found from the equilibrium equations. This theory and many of these results were succinctly described by Tony in his 1972 monograph (22). There followed a very active period in which the theory was extended and various special problems were considered, such as the bending of a laminated plate, the deformation of a cylinder under pressure and axial loading, the stress intensity factor for a crack in a fibre-reinforced plate, and the reinforcement of a hole in a plate by concentric circular fibres (40). At about the same time, helically wound cross-ply ideal elastic and elastic–plastic fibre-reinforced tubes were modelled (32). In the case of a uniform axial extension, or of pure bending, or of inflation of the tube by a uniform internal pressure, the corresponding stress fields were found to have zero shear stresses only when the winding angle had the value \( \tan^{-1}(\sqrt{2}) \). For this special angle (which is used in practice), because there are no shear stress discontinuities across the internal and external surfaces of the tube, these basic deformations do not give rise to singular stress layers on the surfaces of the tube.

The occurrence of singular stress layers in ideal fibre-reinforced materials leads naturally to a boundary-layer analysis in the neighbourhood of such a surface, and several problems of this type were considered (33). In the construction of the ideal theory, a key step was the inclusion of a vector defining the fibre direction among the constitutive variables. Tony realized that this principle could be applied generally to anisotropic materials, particularly to materials with nonlinear response, and to fibre-reinforced materials without introducing kinematic constraints. The resulting theory (36) provided a means of studying finite deformations of structured solids in which the directions characterizing the anisotropy could vary in space and time. His Nottingham colleague Tryfan Rogers was very active in these investigations and was a joint author of eight of the papers, as well as being a joint supervisor of nine of their doctoral students. Much of this material formed the basis of an International Centre for Mechanical Sciences (CISM) course given by Tony and his collaborators in Udine in 1981 (36). Further work was done on plasticity (47), and thermoelastic problems were also considered (54).

Later these techniques were used to examine the bending and flexure of helically reinforced cables and cylindrically monoclinic elastic cylinders (68), and also to extend the theory to reinforced elastic materials in which the fibres have a non-zero bending stiffness (73).

**Laminated, inhomogeneous and functionally graded plates**

In a paper published in 1988 (44), Kaprielian, Rogers and Spencer devised an exact solution for a laminated elastic plate that was a generalization of Michell’s solution (Michell 1900) for a uniform elastic plate with zero tractions on its upper and lower surfaces. This fundamental solution relates to a laminated plate that is symmetric about the midplane of the plate and enables the inter-lamina stresses to be calculated. We well remember Tryfan Rogers saying, ‘it’s unbelievable, the series truncate’. The plate is deformed by tractions applied around its...
periphery, so that the problem reduces to an equivalent-plate problem. This solution also applies to the case of an isotropic inhomogeneous (or functionally graded) plate in which the elastic constants are functions of the through-thickness coordinate of the plate. Both the stretching and the bending of a laminated plate containing a circular hole were examined in that paper. This work for symmetric plates was extended to thermoelasticity (46); an Airy stress function formulation was derived (58), which was then applied to an inhomogeneous plate containing a semi-infinite crack. Mian and Spencer (59) then generalized the analysis to yield exact solutions for inhomogeneous plates that are not symmetrical about their midplanes. For this important problem the extensional and bending behaviours of the plate are coupled, so that even under simple tension the plate bends. Again, the three-dimensional displacement field in the plate was expressed in terms of the displacement field on (say) the midplane of the plate, multiplied by weight functions that depend on the through-thickness coordinate. These weight functions are found to satisfy a system of differential equations that can be integrated. In the special case of a uniform plate the weight functions reduce to polynomials. Concentrated force solutions for an infinite plate and on the boundary of a semi-infinite plate were obtained, and a half-space problem and the case of a thick elastic plate with a thin surface layer (72) were also considered. Finally, a complex-variable formulation (69) was derived that linked the solutions of these inhomogeneous plate problems to the Kolosov–Muskhelishvili solutions (Muskhelishvili 1963) of two-dimensional elasticity.

The aforementioned analysis only applied to isotropic inhomogeneous plates and did not immediately extend to anisotropic plates or to shells. These problems were tackled by using a transfer-matrix approach, and solutions were obtained as series expansions in powers of the aspect ratio. These methods were applied to anisotropic plates and to anisotropic circular cylinders. In addition, exact three-dimensional bending solutions were found for an anisotropic and inhomogeneous elliptical plate bent under normal pressure and clamped around its edge (48) and for strips under normal pressure. A total of 24 papers were written in this field, several with Rogers and Watson as co-authors. A summary of the main results was given in (64).

Fibre-reinforced fluids

In collaboration with Tryfan Rogers and Ken Walters FRS and some industrial partners, the high-temperature forming of fibre-reinforced thermoplastic laminated sheets was investigated. At the forming temperature these materials are essentially incompressible viscous fluids constrained by inextensible fibres. Much of the ideal theory described above could therefore be applied to these problems. A considerable body of work was done in this field, leading to 22 papers; some of the work was described in a review article (52) in conjunction with an exposition of the continuum theory of fibre-reinforced viscous fluids. Aspects of the forming process such as fibre placement, fibre wrinkling resulting from shear-flow instability, controllable flows and fibre-streamline flows, in which the streamlines are aligned with the fibres, were discussed (56). The forming of resin-impregnated fabrics was also modelled (62).

A major manufacturing problem in this field is that formed parts often undergo distortion on cooling, as a result of the thermal contraction of an anisotropic material varying from direction to direction, an effect known as springback. A formula was proposed (45) to predict the springback in orthotropic channel sections, which has proved robust. Further analysis of the thermally induced distortion that occurs in thermoplastic laminates applied to thermoelastic–plastic and thermoviscoelastic channel sections (65). The effect of the rate of
cooling on the corresponding residual stress field was also examined. In further developments
the theory was extended to nonlinear fibre-reinforced fluids, equivalent to isotropic Rivlin–
Ericksen fluids (53).

RETIREMENT

Tony Spencer enjoyed a very active retirement. He was awarded a three-year Leverhulme
Emeritus Fellowship in 1995 and spent part of that year in Canterbury, New Zealand. He paid
two extended visits to the University of Wollongong to work with James Hill and two to McGill
University in Montreal to work with Patrick Selvadurai. He attended numerous international
conferences and was a keynote speaker at many of them. The following titles exemplify the
wide variety of topics covered: ‘Flow processes for composite materials’, ‘Dynamic analysis
of shear flow of granular materials’, ‘The thermoelastic springback problem’ and ‘Three-
dimensional elasticity solutions for anisotropic and inhomogeneous plates and shells’. In the
meantime he had a knee replacement, followed by an infection and a second replacement. In
2007, just before Nottingham University inaugurated the Spencer Institute, he slipped and
had to have a hip replacement. These adversities seemed to have little effect on his research
productivity. He was active until his sudden death at the age of 78 years, and wrote almost
40 research papers in his retirement. It takes exceptional dedication and intellectual strength
to maintain a high-quality research career for more than 50 years. Tony Spencer had these
qualities in abundance.

THE MAN AND THE MATHEMATICIAN

Tony was an admirable head of department. Despite appearing reserved, he was always
approachable for his staff; his office door was closed only when the occasion really demanded
it. He could be reticent; you sometimes had to know which was the most appropriate question
to ask, but when you did his replies were full and frank, laced with his dry humour and
observations. A measure of his calm disposition is that the department was a very pleasant
place in which to work and that he fostered, by his example, a culture of mutual cooperation.
He was, however, a determined individual who knew what he wanted.

He was happily married to Margaret for 53 years and they had three sons: John, Timothy
and Richard. They entertained regularly at their home, making the staff and their partners,
visitors and research students most welcome, so that even the shyest newcomer felt part of the
team. These were always enjoyable and convivial evenings in which everyone could savour
Margaret’s cooking and admire her artwork, which adorns the walls of their house. Just as
Margaret was very supportive of Tony, he was supportive of her as an artist. She remains, to
this day, a prominent member of the Nottingham Society of Artists. Their three sons have all
followed scientific careers: John also read mathematics at Queens’ College and now works at
the Hydraulics Research Station at Wallingford, Tim is a land surveyor working in the field of
oil exploration, and although Richard trained as an architect he is now a software developer.

Perhaps his birth in Edgbaston as the son of a (semi-)professional footballer accounts for
his enthusiasm for both cricket and football. He was a member of Nottinghamshire County
Cricket Club, sometimes allowing himself to visit Trent Bridge in the late afternoon on his
Anthony James Merrill Spencer

way home from work. He tried to attend Test Matches when he could. He followed the Cricket World Cup, no matter which continent he was on. Patrick Selvadurai recalls attending a Sri Lanka–England match at Trent Bridge with Tony in 2006. On that occasion Sri Lanka beat England and after the match he thanked Tony for inviting him to watch the match. Tony’s reply was ‘I meant to be hospitable, but not that hospitable!’ He took a very active part in the annual staff–student cricket matches, both as a batsman and as a bowler. This match was always followed by a gathering at a local hostelry, eagerly anticipated even when rain intervened, as a post-exam highlight of the year. He was a regular on the terraces at Nottingham Forest Football Club, especially during its glory days under Brian Clough and Peter Taylor. When in the early 1970s the university acquired its large indoor Sports Centre, he also sometimes took part in the Theoretical Mechanics five-a-side football team ‘The Retarded Potentials’. He was a keen participant in the pre-Christmas five-a-side football competition, which involved teams from each year of the undergraduates, the research students and the staff. Inevitably this was followed by a social gathering at a local pub. Dating from his time at Brown, he followed the fortunes of the Boston Red Sox baseball team. He was also a keen walker.

He enjoyed a certain amount of DIY, including adding insulation to his new house at Stanton-on-the-Wolds, creating a new garden and laying a block-paved patio. Shortly after this he had to have a major operation on his jaw that resulted in his having his upper and lower teeth wired together for a period of some weeks. He bore this ordeal with great fortitude, much to the admiration of his colleagues. His only relief was Guinness, taken through a straw and paid for by the National Health Service!

Patrick Selvadurai of McGill University, Montreal, comments: ‘his style of research supervision was non-intimidating; he always made the effort to meet with the students to discuss their problems and accomplishments. I got the impression that he did not need postgraduate students in order to do research, but we all needed his help and guidance.’

George Dvorak of Rensselaer Polytechnic Institute, Troy, comments: ‘Tony consistently made numerous important contributions to the mechanics of solids. The sheer number and wide scope of these topics would suffice to support not one but several parallel careers of major prominence in different fields of mechanics.’

Steve Cowin of the City University of New York said that the advice he received from Tony was ‘always concise and to the point and often made me reconsider what I was doing.’

Rob Davis of the University of Canterbury, New Zealand, at which Tony was an Erskine Visiting Fellow in the year after his retirement, writes: ‘His lectures were models of clarity punctuated with clever examples and dry humour. Tony was a true English gentleman as well as a scholar. Yet he was totally down to earth, easy to talk to, fun to be with.’

Robin Knops of Heriot-Watt University writes: ‘Despite an outwardly quiet personality, Tony was an inspirational leader in science, academic administration, and social affability. He always exercised an independent but balanced judgment complemented by incisive observation, and became widely admired as someone who would unfailingly provide support, encouragement, and information.’

Leslie Morland of the University of East Anglia observes that over the years of shared interests in the flow of plastic and granular materials he had much to learn from Tony, ‘who could gently alert you to misunderstandings in a nice non-critical manner’, and that he was ‘a man who could always be approached for advice, knowing it would be given generously.’

His Nottingham colleague Kostas Soldatos, who first visited as a young lecturer from Ioannina, Greece, found that ‘Tony had the ability to inspire and keep together valuable
friends and colleagues, through his modesty, simplicity, hard work and well known research and administrative qualities. The fact that Tony led such a harmonious internationally reputable department for more than a quarter of a century is therefore no surprise to those of us who knew him well.'

Tony had a great admiration for Ronald Rivlin. Figure 3 shows Tryfan Rogers, Ronald Rivlin and Tony in a relaxed mood at a conference in Greece. Patrick Selvadurai recalls that when Tony was due to give a talk at the Ronald Rivlin Memorial Conference in Penn State, he arrived at Heathrow Airport to discover that all transatlantic flights had been cancelled because of an ‘on-board liquids’ terrorist threat. He returned home, managed to book a flight online to New York. He took it and then drove late into the night from New York to Penn State to arrive at the conference in time to deliver his paper.

When Tony died, British theoretical mechanics lost a most versatile research worker who made very substantial contributions to the advancement of mechanics over the past half century. Many of us here and around the world have reason to be grateful for his legacy.

**Honours and awards**

1980  ScD, University of Cambridge
1987  Fellow of the Royal Society
1993  Honorary Doctorate, Aristotle University of Thessaloniki
1994  IUTAM/ISIMM Symposium in his honour
(With Zheng Quan-Shui) Distinguished Paper Award for paper (49)
Anthony James Merrill Spencer

1995–98 Leverhulme Emeritus Fellow
2000 Special Issue of the Journal of Engineering Mathematics
2004 Foreign Honorary Member of the American Academy of Arts and Sciences
2007 Nottingham University established the Spencer Institute of Theoretical and Computational Mechanics
2008 Engineering Science Medal of the Society of Engineering Science
2009 Special issue of the International Journal of Engineering Science

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Biographical Memoirs


Anthony James Merrill Spencer


