Professor Wolfgang G. Knauss

See:
http://www.expertise.cardiff.ac.uk/staff.asp?details=217
http://mr.caltech.edu/experts_guide/3084
http://www2.galcit.caltech.edu/people/faculty/knauss.html
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Fields of Study:

Application of Scanning Tunneling Microscopy to Problems of Interfacial Strength Design in Composite Structures
The mechanical strength of interfaces is the basis of composite material strength. Because the region where the material properties of the two solids making up the interface is very small (micron and submicron scale),

mechanics related measurements are difficult to perform since optics can no longer serve for observation purposes. Accordingly, electron (tunneling) microscopy is being developed to perform observations at the submicron range. These developments are of interest in the evolution of high strength composite materials for aircraft/rocket designs as well as for microelectronic devices subjected to a variety of environmental influences in the manufacturing process.

Constitutive Behavior of Matrix Materials for High Temperature Composites

High-speed flight is the most important driver for aerospace engineering in the next decades. High-speed is invariably linked to the exposure of structures to high temperatures, and thus the rush is on for raising the temperature capabilities of structural composites. Polymer based composites are targeted for use in the 600/700=B0F range, with an important limitation set by creep and related viscoelastic failure behavior. Both structural creep as well as time-dependent fracture are governed by the high temperature viscoelastic behavior of the matrix material.

In order to make the development and use of such high temperature composites efficient requires the analytical characterization of the polymers in order to compute micromechanical characteristics and failure processes. This knowledge is particularly important for understanding the fracture behavior of these matrix materials and the composites into which they are incorporated. This (NASA) program is intended to develop such constitutive description for the next generation of polymer based aerospace materials.

Fracture Behavior of Non-Linearly Viscoelastic Solids Related to Adhesive Bonding in Solid Propellant Rockets (Shuttle Booster)

One of the areas of mechanics, which is currently attracting much interest, is that of interface separation between joined solids. For time-independent behavior, the motivation for this interest comes from a need to understand the fundamentals of internal cohesion in composites which exhibit a large amount of interfacial contact between its separate phases as well as from the failure mechanics of microelectronics, the increasing complexity of which call for a proportionately increasing need to understand their failure mechanics. The construction of solid propellant rocket motors depends similarly to a large degree on one's ability to bond the propellant charge to the rocket casing.

Fatigue of Thermoplastic Matrix Materials for Composites

Although thermoplastic matrix materials are hailed as being very tough in composite applications, we possess very little fundamental knowledge about their behavior under fatigue loading. To gain insight into the fatigue failure process, the development of microscopic energy absorption processes are studied at the tip of propagating cracks through the development of "crazes". Observations of this crack tip through a microscope are recorded and processed by computer in real time to measure crack growth with a resolution of 1 micron; simultaneously changes in the craze structure at the crack tip as observed by optical interferometry are monitored to assess the degradation of the craze material to examine how the material at the crack tip breaks down under repeated loading and with slow crack growth.

Time-Dependent Buckling of Structures Made of= Fiber-Composites

The introduction of thermoplastic, tough matrix materials into composite design brings with it an increased sensitivity to time-dependent or delayed failure. This phenomenon is heightened by the sensitivity of these materials to accelerated creep under even moderate temperature increases (100-150=B0C). This study is concerned with the gradual occurrence of buckling in composite structure because of the viscoelasticity of its matrix component. The delayed buckling may occur either in a gross structural mode or at the fiber level (compression crimping). Non-uniform temperature distributions through the skin of a high speed aircraft will be particularly detrimental because it not only accelerates the creep process in the hot part of the skin but also contributes to the out-of-plane deformation which strongly lowers the in-plane load needed to cause structural instability.

Failure of and Crack Propagation in (Particulate) Composites Incorporating Microdamage in High Deformation Gradients

There are many materials which fail through crack propagation, but in which the earlier stages of failure are identified by the evolution of many microfractures distributed spatially in high strain regions which ultimately become the failure regions. Failure is then the result of the coalescence of these microflaws into a macroscopic fracture. A basic problem is to characterize the behavior of the disintegrating and increasingly discontinuous material, riddled with microcracks, in terms of continuum concepts. It is the purpose of this study to deal with this discrete/continuous characterization on both the analytical and experimental basis.

Adhesion and Interfacial Fracture Mechanics

One of the most dominating issues for the strength of future high-strength/low weight materials is the characterization and performance of the interface between the two or more phases making up the composite. The toughness of the composite is most strongly influenced by the interface strength, though the highest value for the latter does not necessarily produce the best composite.

Similarly, the adhesive bonding of aerospace structures requires a markedly improved understanding of the interfacial fracture process before designs are to benefit from that very promising weight-saving technology. Issues to be examined relate to methods of characterizing interfacial strength, the development of fracture criteria to aid the structural designer. These developments are to emphasize time dependent processes (viscoelasticity and fatigue) in order to impact long term durability (tens of years) based on short term (laboratory) evaluations. The program anticipates drawing on the results from the Scanning Tunneling Microscopy to address questions of interfacial strength in composites at the submicron level.

Geometry-Induced Failure of Composite Structures for Future Aircraft

Besides inventing new and strong composite materials, their use in future aerospace designs requires new concepts of design that are different from those associated with metallic structures. For many structural problems the spanning of the size scale between the material microstructure and the macroscopic dimensions of a full scale structure requires a failure characterization at the macroscopic level but with a full understanding of the micromechanics of the failure process involved. Thus a new way of characterizing the failure behavior of these types of materials needs to be devised which, while recognizing the phenomena at the microscale, cast the failure behavior into more macroscopic concepts. This problem is known in the industry as the "Problem of

Scaling". It is particularly important in the class of geometries that involve sharp dimensional changes within structural components, e.g., stiffeners on skins, panel reinforcements, junctions of struts, etc.

A Few Selected Publications:

Chai, H., Babcock, C.D. and Knauss, W.G., “One-dimensional modeling of failure in laminated plates by delamination buckling”, Int. J. Solids Structures, Vol. 17, 1981, pp. 1069-1083

H.K. Muller and W.G. Knauss (1971) "Crack Propagation in a Linearly Viscoelastic Strip," Journal of Applied Mechanics 38 E 483.

K. Ravi-Chandar and W.G. Knauss (1984) "An Experimental Investigation Into Dynamic Fracture - IV. On the Interaction of Stress Waves with Propagating Cracks," International Journal of Fracture 26 189-200.

A.M. Waas, C.D. Babcock, Jr., and W.G. Knauss (1990) "An Experimental Study of Compression Failure of Fibrous Laminated Composites in the Presence of Stress Gradients," International Journal of Solids and Structures, (Charles Dwight Babcock, Jr. Memorial Issue) 26 (9/10) 1071-1098.

G.U. Losi and W.G. Knauss (1992) "Free Volume Theory and Nonlinear Thermoviscoelasticity," Polymer Science and Engineering 32 (8) 542-557.

Speech of Acceptance of the 2010 Timoshenko Medal by Wolfgang G. Knauss

Experimental Mechanics of History

It is a great honor to be selected to address you tonight on the occasion of receiving the Timoshenko Medal, the award notification of which caught me by total surprise. Selections for such honors are sometimes difficult and possibly contentious processes, and I thank the 15 or so colleagues making up the various committee groups for their forbearance and benevolence towards me. I am proud of this award, because it makes me only the fourth Caltech faculty recipient, with Theodore von Kármán, Eli Sternberg and Anatol Roshko the forerunners, and with two of these being heavily devoted to experimental work. I belong to a generation that no longer has a personal connection to Stepan Prokofievich Timoshenko, nor do I possess an academic genealogy which connects me to him, other than the assiduous studies of his “black books” as other Timoshenko awardees have called them. Instead, my history links me, in direct sequence, to Max Williams, Ernie Sechler, Theodore von Kármán, Ludwig Prandtl, August Föppel and Christian Otto Mohr, of Mohr’s circle fame: I owe a lot to these, my academic “forefathers”.

One of the intended purposes of the addresses following the Timoshenko award dinners is, if somewhat loosely, to preserve a history of (applied) mechanics. The choice of my title implies the reverse, namely that mechanics can and does describe or control history. That is indeed true if one thinks of the structural systems that contain viscoelastic materials which require the tracking of the deformation or loading histories to describe the system response. This may be a superficial twist of words, but the realistic implications are severe, as, I hope, you will see.

I owe personal and professional thanks to numerous individuals, and I cannot, with a clear conscience speak here without acknowledging and thanking them, and to let them participate in this honor. I will, therefore, divide the talk into two parts:

a) a brief recognition of at least two benefactors who got me to this podium followed by

b) the recounting of some mechanics-historical aspects, interlaced with remembering those who were involved in their developments. I do this primarily so that I can acknowledge the important role which my over 60 students and post docs played in my career and who have helped me over the years; I hope they will understand that there is not enough time allotted to mention them all here.

As the youngest in a German Methodist pastor's family with two brothers, my childhood was dominated by World War II, especially through the frightening air raids which leveled the small industrial town (Siegen) 60 miles east of Cologne where we lived then. After five years of reconstruction, my father was transferred to Heidelberg, so that my oldest brother could attend the University. Heidelberg, virtually untouched by war destruction, was a major tourist attraction for Americans. Among the visitors was a minister, Dr. Frank Williams, who at that time was the pastor at the Methodist Church closest to Caltech. When my father died during my final High School exams (Abitur), an advanced education was suddenly thrown into jeopardy. At that moment Frank Williams and his wife Margaret invited me to live with their family near Pasadena so I could attend college in the US. I lived with them for four years until I graduated with a BS in 1958 and married my wife Lydia, whom I had asked to come from Germany. Such magnanimity and generosity has shaped my experience and view of the United States to this day. While attending Pasadena City College, Dr. Williams suggested that I try the transfer examination to enter Caltech as a sophomore. My English, while good, was not sufficient to allow me to enter Caltech as a freshman because, besides it being a good college, that would greatly simplify the logistics to get me to and from school. I have been there ever since 1955.

Another Dr. Williams had a dominant influence on my career. Although I was interested initially in studying Jet Propulsion, Max L. Williams, Professor of Aeronautics at GALCIT and no relation to Pastor Frank S. Williams, offered me a summer job after the BS, which introduced me to solid mechanics, and more specifically, to fracture mechanics. Moreover, Max Williams' continual desire to combine theoretical endeavors with experimental evidence influenced my entire career by taking preponderance in virtually all of my studies. Besides bending my interest into solid mechanics, Max Williams provided for other professional starts for me. He had me appointed at Caltech as an assistant professor, and when he moved to the University of Utah as dean of engineering in 1966 he did another unbelievably good deed for me: he left me a lucrative NASA grant, in today's value close to 3/4 million dollars, not counting the follow-ons, with which I could perform all my early research on crack propagation in viscoelastic materials.

Let me move to part b).

In the late 1950s linearly viscoelastic theory and analysis in engineering revolved around the use of differential operators, and how Laplace or Fourier transforms reduced viscoelastic problems into elastic analogs through the correspondence principle. This type of formulation has today largely given way to the integral formulation for the constitutive laws, primarily coupled with computational means.

Before my graduate years chemical physicists were concerned primarily with studying the molecular structure and molecule interactions with little or at best secondary relation to structural problems. The major exception turned out to be the time-temperature trade-off principle, which started with Ferry (1950) and Tobolski (1952) and culminated in the phenomenally successful story of the Williams-Landel-Ferry (WLF, 1955) equation (and concept), which is still a major player in viscoelasticity today.

In 1957 Sputnik signaled a new era in aero-space developments including the need for a better understanding of the mechanical behavior of solid propellant rocket fuels. It now turned out that the chemists and chemical engineers, who formulated the compounds, lacked the understanding of how to incorporate their mixtures structurally and safely into a relatively rigid rocket motor case under sustained gravity and high acceleration loads. This new hardware required viscoelastic stress analysis which brought forth a number of capable, primarily academic, leaders: Max. L Williams dominated the field of physical properties and fracture, Erastus H. Lee originated the correspondence principle. He was another Timoshenko medalist. He was versed in the non-isothermal behavior. He and Harry Hilton addressed static and vibration analyses, while Karl Pister, Eric Becker and Charlie Parr, the latter of Rohm & Haas, were instrumental in developing and exploiting the new and growing field of (elastic) finite elements.

Early issues dealt with motor slump associated with the possible gas flow restriction in the central bore resulting from long time storage or acceleration during lift-off; this problem precipitated my first experiment presented at a national meeting. To demonstrate the deformation shape of a deformed, cylindrically perforated motor under axial acceleration, I cast grain shapes of Lemon-flavored Jell-O into a Plexiglas cylinder casing with a similarly clear bottom, from which a central, hollow brass mandrel could be removed after heating it with hot water. The deformations were literally very clear. The most memorable comment I received for this was, “Whether the experiment failed or succeeded, it could at least serve as desert on the dinner table of a graduate student living on a low stipend”

Solid propellant fuels are mostly highly loaded particulate composites. Ammonium perchlorate (oxygen supply, 80 to 90% by weight) is bonded together with a rubbery binder along with various additives such as aluminum powder for burning rate control. Not a simple homogeneous solid! A continual problem was that deformations could be accompanied by the binder pulling away from the particles, a process called “dewetting”, and associated softening. While this was being recognized, exploited notably by Rick Farris, later professor at the University of Massachusetts, it dominated the nonlinear character of these materials and impeded progress, because any nonlinear analysis was difficult in those days (the computers were used in the infancy of FE stress analysis). Dick Schapery derived his nonlinearly viscoelastic model on the basis of this behavior, and later Cate Brinson addressed the thermorheologically complex behavior of composites containing multiple viscoelastic phases.

A dominant issue concerned, however, fracture and grain cracking in the motor star valleys. To provide a nearly constant burning surface, the longitudinal perforation of a motor had the cross section of a typically five-point star. Under thermal shrinkage and/or pressurization upon ignition there existed thus the proclivity for cracks to form and propagate at the stress concentrations in the star valleys.

In place of the real but complex propellant I chose to model fracture with a homogenous polyurethane elastomer. Although the experimental equipment required was rather simple, the demonstration of repeatable and non-age related phenomena were important. I had the good fortune to have my first and capable graduate student, Hans-Karl Müller, work with me. To our surprise the data of crack speed was treatable by the time-temperature superpositioning principle usually associated with small deformation behavior, even though the strains at the crack tip were huge. From this followed the first theoretical, mechanics-based treatment of crack propagation in (linearly) viscoelastic materials (1971), succeeded by a more refined treatment of the cohesive forces at the crack tip (1973,1974) which was followed by Dick Schapery's power law-approximation (1975).

This development led to knowledge-transfer to the adhesion community for time-dependent disbonding, work that was carried on by Ken Liechti, who has had a very significant influence on fostering the use of mechanics in the community of chemists and physicists who then dominated adhesion research. In this discipline I was also fortunate to have G. Ravichandran (Caltech-Ravi). Later Philippe Geubelle provided analytical support to the adhesion community, along with John Bowen's experimental work.

It has always been a hope of mine that at least the rudiments of viscoelastic behavior be taught in virtually every undergraduate program. But that does not seem to have happened, even though by the mid 80s the weight of polymers produced in the US had surpassed that of steel. Thus a tremendous shift or change in the use of many materials in engineering occurred. The consequences of engineers not being properly informed on the time dependent issues are understandable in the early days but did and will have serious consequences. Though there are numerous and expensive examples, let me document here only two:

In the 1970s someone had the bright idea to simplify the delivery of drinking water, both through under-street as well as via in-home hot and coldwater plumbing. Compared to steel pipe (and even copper) the low weight and ease of assembly via gluing polymer tubing was very appealing and cost-efficient. This type of system was so efficient that large portions were, at times, assembled in a shop and then transported to the site for installation. The system consisted of polybutylene tubing and angle fittings of Celcon, an acetal copolymer, which were joined to the tubing via mechanical (compression) crimping employing copper rings. The underlying engineering consisted of testing the system under pressure for a few days to demonstrate that all was well. However, there were a number of problems with these systems many of which traced back to the time-dependent properties of the materials making up the system. Here is one example of where even minimal exposure to time-dependent material behavior in a school curriculum would have been helpful. While enough support points for the tubing were recommended to hold the water-filled tubing in place, apparently no one had worried about specifying that this support should be arranged along the tubing so as to prevent any significant bending moments from being transmitted to the fittings. One result was that after a number of years the fittings under bending could develop cracks and flood a home, a consequence that is obvious to any one who deals with polymers in engineering applications. The only answer to this poor design was re-plumbing the houses completely. Also, virtually all in-street water distribution in Puerto Rico was of this type, obviously not necessitating any other support than laying the pipes in a trench, but this happened without special care regarding bending moments. This application required vast and costly replacements. Another detrimental aspect was that both the Polybutylene tubing and the Celcon fittings were susceptible to attack by the trace amounts of chlorine in drinking water, which helped erode the wall thickness of the tubing and the fittings with time, thus accelerating the failure process sometimes even to the point where tubing split before the fittings failed. A costly affair!

Another example of missing educational exposure to the time-temperature sensitivity of polymer response was at the root of the Challenger explosion (1986). The launch took place after several days' delay during a cold spell with temperatures outside of the recommended launch envelope. Though Thiokol-Morton engineers were well aware of the fact that temperature had a strong effect on the response times of the sealant rubber in the boosters and advised against launch, they were overruled. Ultimately, this turned out to be the immediate (engineering) cause for the failure. As the story goes, Dick Feynman had a lot to do with steering the investigative Rogers commission in that direction.

There is an interesting vignette to this commission for me: The thought had leaked out that the seal may have been involved in the failure. Normally, an aeronautical engineer is not prone to educate a theoretical physicist of the Dick Feynman stature. But he, being a Caltech colleague of mine it seemed rational to talk to him. Besides, his daughter and our youngest son Stefan, who is in the audience here tonight, played in the Pasadena Young Musician's Orchestra, which orchestra my wife guided/chaperoned on tour through Germany in 1981. Dick also had been to our home repeatedly to arrange chairs for the annual garden festivities on behalf of that orchestra. So, when I called his office he had just left for Washington, which was not much of a problem because I was going there the next day. I reached him there at the Holiday Inn and told him what my purpose of calling was. I explained how temperature had an effect on changing the time scale of viscoelastic solids (rubber) so that their response time would be lengthened if the temperature was too low. I pointed out to him that if cold rubber is released from a prior constraint (stretched rubber band in a freezer), it will retract, but slowly so. He listened and after about 15 minutes of discussion he said, "Hey, you really do want to help me!?" Apparently he had heard from enough cranks. While I cannot claim that I was the one responsible for Dick Feynman's education on the Time-Temperature Superposition Principle, I do feel that I sensitized him to its importance. He later demonstrated it in the commission meeting by dunking the sealing O-ring rubber in ice water.

A significant detour from strictly viscoelastic fracture studies came about when the problems in solid rockets received diminished funding. Because of my continuing interest in fracture mechanics (after all, I was a Max Williams student) it had always bothered me that the unresolved issues in dynamic fracture, namely crack branching and fragmentation, were investigated with specimens too small to rule out multiple wave interactions between the crack tip and the boundaries. At that time the analysis of wave propagation in finite geometries was either very limited or non-existent. Several of the previous Timoshenko medalists talked of scientific epiphanies in their careers and I think this one qualifies. My colleague, Chuck Babcock, was a consultant to the McDonald Douglas Company. He told me of a set of nifty experiments there, involving an electro-magnetic Lorentz force generator rapidly to exert pressure to shell rings. That is when it struck me. What if one were to insert the conducting strip of such a device into the crack in a large plate so that during the time of interest no reflected waves would get back to the crack tip. This would be the ideal experimental geometry to parallel the dynamic crack analyses which did exist for infinite domains. A further fortunate ingredient was that Cliff Astill at NSF hinted that he was looking for supporting experimental work, and the final stroke of luck was the arrival of capable students, first Gordon Smith, then Ravi (K. Ravi-Chandar, aka. Austin-Ravi) and then Pete Washabaugh. We were able to demonstrate why the predictions of the linearized theory of elastodynamics, namely that the crack speed should reach the Rayleigh wave speed, did not materialize: Said simply, the linearized elasticity theory applied to materials possessing vanishing cohesive forces, but that situation is hardly matched in the real world.

Issues not resolved by this fracture work concerned the role of in the nonlinear viscoelasticity crack propagation in rigid plastics, where yield-like phenomena are important. As a consequence one could not readily formulate extensions of the linearized theory to behavior of the more common engineering plastics, as nonlinear (plastic) fracture mechanics had been extended from the Griffith concept. The nonlinearly viscoelastic constitutive theory paralleling plasticity simply did not exist, and still does not today. This recognition precipitated a continuing study of the role of dilatation and how that affects the viscoelastic time scale of a material. Consequently, work needed to be initiated that centered on the effect of time-dependent volume or bulk response on non-linear behavior. By then, no one had attempted experimentally to characterize viscoelastic bulk behavior for over thirty years because it was difficult. Besides, the earlier work was performed on a material that is a primary ingredient in chewing gum. Tony Deng and Sandeep Sane performed painstaking effort in carrying that work through, and Hongbin Lu and Weidong Zhu provided the experimental follow-on with respect to the role that this behavior has on the nonlinear response of rigid polymers (plastics), while Igor Emri and Giancarlo Losi provided the ground braking numerical analyses. Problems associated with this question still exist today and form major stumbling blocks to advancing the understanding of failure mechanics under high rate deformation and explosive loading conditions on elastomers, presently of concern to Roshdy Barsoum of ONR.

A topic of great interest to NASA's structures program pursued by its very influential manager of the structures division, Jim Starnes, was that of structural stability, and for me that meant time-dependent buckling. At the time Tim Minahen came to me as a student there was only the estimate of a time dependent buckling load by substituting the elastic Young's modulus by its viscoelastic (relaxation) counterpart. Experiments quickly showed that that was not a reliable approach, and Tim's work demonstrated that while a counterpart of the Euler treatment did not want to materialize, an initial imperfection approach made experiments and theory coalesce very well.

A final area of experimental work, initially motivated by polymer composites, centered on the smallest size scales. In mechanics it looked like microscopic domain work came of interest in the late 70s, so it seemed wise to get started. But agencies are not prone to let go of their money, unless there are enough people singing the same tune. At that time the digital image correlation method was under development and it seemed like combining submicroscopic imaging with solids deformation would be a wonderful tool to shed light on phenomena occurring at the smallest scale in composites. Although the tunneling electron microscope had been invented there were no instruments available (1981) with which one could interrogate a sample mechanically and deform it while on the microscope. This simply meant, that a mechanician had to build his/her own microscope. To achieve that goal it took us about 6 years to get, in 1976, $30,000 from NSF with the help of Lallit Anand. This just defrayed the cost of the hardware parts and construction, which Guillaume Vendroux did with excellent results. I still recall the wonder of the "first light" (first scan) experience. But before the great onslaught of micro- and nano-mechanics there was little interest in pursuing that work. The ultimate benefit accrued to my second-to-last graduate student Ioannis Chasiotis, who used our lab experience over the previous 15 years for his Ph.D. work.

Another illustration where being too early with experimental endeavors, is related to biomechanics. In the mid 70s Nick Panagiatopulos of JPL made me become interested in the mechanics of the human body and we developed a program directed at the viscoelastic behavior of the human intervertebral disc. Very few people worked in biomechanics at that time, but it seemed to be a promising field until one discovered that there were no jobs for the graduates in that discipline. After I found out from the celebrated biomechanician Y.C. (Bert) Fung, another Timoshenko medalist who was at UCSD by that time, that this was also a continuing problem for him, I decided to shut down that effort. It seemed unfair to get a student all hopped up about an exciting field and then find him relegated to pumping gas. What a difference two decades made in this regard. An outcrop during that early biomechanics study was that, with two masters class students, we examined the mechanics of radial keratotomy (near-sightedness correction via radial cuts in the cornea). Ophthalmology researchers at USC, concerned with the durability of the operation, did not wish to believe the then (Fyodorov's) prevailing theory that the cutting process disturbed an invisible tensile ligament around the eye's iris to lower the cornea's curvature. Through building a 15x scale and suitably pressurized rubber model and applying simple dimensional analysis to the results we could show that the keratotomy process was fully explained by the fact that the cutting merely changed the over-all compliance of the cornea under the influence of the intraocular pressure. Though ophthalmologists at large, not versed in mechanics, were rather skeptical, the USC colleagues confirmed these results successfully in their studies with Rabbits' eyes and used them until radial keratotomy was eventually replaced by various forms of the current laser treatments.

I need to come to a close. Let me again thank all those who have helped for this event to materialize for me, notably all my students and post docs, from whom I learned a lot, whether they were mentioned explicitly and are here tonight or not. Finally, I owe much to my wife Lydia and my sons Friedrich and Stefan for years of support and patience. Thank you all. **----from the post on iMechanica**