J Mater Sci (2008) 43:6575–6577
DOI 10.1007/s10853-008-2849-x

Editorial: Targeting problems of composite failure

An International Conference co-sponsored by EPSRC and NSF: A Selection of Papers on Stretching the Endurance Boundary of Composite Materials: Pushing the Performance Limit of Composite Structures, 23rd–28th September 2007, Reid's Palace Hotel, Island of Madeira, Portugal

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Received: 13 May 2008 / Accepted: 1 July 2008 / Published online: 9 August 2008

This special issue of the Journal of Materials Science is dedicated to Professor Roger Morgan of Texas A & M, who died a few weeks after participating in the Madeira Meeting. He attended with his wife Anne in celebration of their 40th wedding anniversary.

> The point is, that as far as I can see, everything's cracking up.
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> "The Golden Notebook" by Doris Lessing, Nobel Laureate (2007)[1]

Predicting precisely about where a crack will develop in a material under stress and exactly when in time catastrophic fracture of the component will occur is one of the oldest unsolved mysteries in the design and building of large-scale engineering structures. Where human life depends upon engineering ingenuity, the burden of testing to prove a "fracture safe design" is immense. When human life depends upon structural integrity as an essential design requirement, it takes 10,000 material test coupons per composite laminate configuration to evaluate an airframe plus loading to ultimate failure tails, wing boxes, and fuselages to achieve a commercial aircraft airworthiness certification. Fitness considerations for long-life implementation of aerospace composites include understanding phenomena such as fatigue, creep, and stress corrosion cracking that affect reliability, life expectancy, and durability of structure. Structural integrity analysis treats the design, the materials used, and figures out how best components and parts can be joined; furthermore, SI takes into account service duty. However, there are conflicting aims in the complete design process: of designing simultaneously for high efficiency and safety assurance throughout an economically viable lifetime.

In the 20th century, modern mechanical design evolved with the development of the continuum theories of mechanics, (mathematical and continuum models of elasticity and plasticity), and later finite element modelling with the advent of computer power: a sort of "distilled empiricism". An empirical approach, however, without understanding the changes of internal structure of the material over time and awareness of the consequences of those mechanisms upon structural integrity would prove disastrous. In 1971, the jet engine manufacturer Rolls Royce came unstuck with their brand new RB 211 engine. Those Hyfil^R composite compressor blades, which exhibited a strong bond between carbon fibre and epoxy matrix (no unsticking on this size scale), and with foreign object impact failed to undergo innocuous cracking by local fibre-matrix de-bonding on the microscopic level. Consequently the material exhibited notch brittleness.

History is exhausted with structural failures where the crucial mechanism eluded the experimentalist. Successful prediction of mechanical behaviour of material and design performance of structure requires detailed information of all possible failure mechanisms across the widest spectrum of size scale under all sorts of operational conditions.

With respect to structural composite systems, oversight in design led to undesirable load paths in the matrix, at fibre-matrix interfaces, and at ply–ply interfaces. For composites under attack from stress and environment, this resulted in the activation of a complexity of atomistic

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[1] First published in Gt Britain by Michael Joseph Limited (1962), recently by Harper Perennial (2007).

defects and microscopic flaws and their accumulation over time was felt at the component level of size. Corrosion fatigue degradation of glass fibres in epoxy, for example, occurs by two rate-limiting phenomena. Hostile species penetrate the composite through matrix cracks. Reaction with the fibres reduces their strength and they fail at the matrix crack front. This is a reaction-controlled stress corrosion cracking process. On the other hand, for a narrow matrix crack opening, concentration gradients develop along the crack and the stress corrosion cracking process becomes diffusion-controlled.

In solving this particular problem, the difficulty is that pure atomistic models on their own break down because certain structural variables (diffusion-rates, jump frequencies, chemical activation energies, etc.) are not known, neither can they be easily measured. Whilst our understanding of the deformation and fracture behaviour of materials based on defect theory and crack mechanics has advanced considerably, failure prediction of composite structures on a macro-scale becomes problematic. And at the heart of the problem lies those failure mechanism(s) best identified by direct observation and that is not straightforward to undertake by any means.

Multi-scale problems of structural failure must be targeted by appropriate multi-scale modelling methods. A hierarchy of discrete methods of analysis in design from micro-mechanics to higher levels forms a framework, which spans several orders of magnitude from the very small to the very large, upon which can be labelled the various analytical methods for determining the endurance boundary of the composite on the one hand and performance limitation of the component on the other. Understanding structural behaviour at the various size levels requires dexterity in manipulating the designer's working tools: the tools of empirical analyses (mathematics and continuum modelling) or continuum mechanics, and mechanism models (micro-mechanical models), sometimes called physical modelling or micro-mechanics. Using these tools to determine constitutive equations relies on knowledge of the rules of material behaviour.

Of particular interest is how damage transfers from a lower scale to a higher scale. The idea is that the response at one level, as described by one (or more) parameter in a constitutive model, is passed to the next level up (the bottom-up approach). Ultimately, this requires the entire range of length scale be probed to understand issues to do with connecting failure of the material and fracture of the engineering structure. To devise a robust design methodology, preferably mechanism-based, successful implementation of a long-life structural failure prediction requires knowledge of structural failure over the entire range of size of structure.

By using experimental methods combined with appropriate analytical techniques including physical modelling, together with direct evidence of cracking and fracture processes, the aim is towards identifying permissible limits on the safe performance of the material on the one hand and the enduring component on the other. Such interplay of materials science and engineering is of crucial importance to key technologies such as the aerospace and energy industries. This provides us with scope for optimization, where composite material properties vary continuously with some internal parameter that relates to composite architecture in some way. Optimum material microstructure (and nanostructure) can be forecast and designed rather than found by trial and error, (with the possibility of calamity), whilst maximizing structural high performance and sustainable safe life. Then, when a set of properties is specified, it should be possible to select a particular lay-up or weave of an appropriate composite material system, and processing conditions, to meet that specification.

With the advent of powerful computers and software that can be purchased at reasonable cost, this means that many of the physical models and computer simulations, that would be cumbersome for design engineers to use, could be implemented as user-friendly computer applications or integrated within commercial finite element design systems. In this respect, mathematical challenges include hierarchical meshing strategies, which must be coarse enough at the largest scales (entire structure), whilst cascading down through finer and finer meshes to atomic scale (if necessary). The real challenge is to formulate design equations that combine continuum (spatially averaged) and discrete damage representations through physical (mechanism) models in a single calculation. But how much detail of failure mechanisms do we need to know to come up with a successful model for incorporating into a simulated virtual test to reproduce the outcome of a real test on an engineering structure? Successful implementation of physical models or simulations requires knowledge of appropriate phenomena.

Finally, there are two questions that require answers now: what do you do where the fatal flaw(s) in the structure is (are) smaller than the NDI detection limit? And second, what initial flaw (damage) content is acceptable in the starter material and in the final composite part as a result of the manufacturing process? It is essential to minimize initial flaw content through high-quality process-control including joining. And the structure requires though-life monitoring of damage growth. But what is an appropriate inspection period?

In organizing this Conference and in producing this issue of the Journal of Materials Science, Professor Young Kwon of the US Naval Postgraduate School and I have had the great pleasure of collaborating with many talented colleagues from around the world and we would like to thank all of them for their huge contribution to this synergistic effort.

A selection of papers from the Conference is presented here.

Acknowledgements The generous financial support of the Engineering and Physical Sciences Research Council (EPSRC), UK, and National Science Foundation (NSF), USA, is gratefully acknowledged. Also, the financial support of the European Office of Aerospace Research & Development (EOARD), London, is acknowledged.