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A selection of papers from an international meeting on: advances in multi-scale modelling of composite material systems & components

Development & application of predictive modelling in the arena of composite materials systems & technology

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Editorial comment

The driving force for composite materials in aerospace

The driving force to get new lightweight composite materials into the air comes from the increasing cost of fuel worldwide. An airline industry's response to higher fuel charges is to make aircraft lighter and fuel efficient. What appears to be a paradox is that as the cost of fuel is going up, so is the size of airframe; the new Airbus super-jumbo A380 is an example. New composite materials including those based on carbon fibre (CFRP) and the glass fibre-metal laminate called GLARE are replacing aluminium alloys, and modern civil airliners like Boeing's brand new Dreamliner 787 and the Airbus A350 may contain up to 50% by weight of composite material. The infrastructure required to support these new advances includes: fibre production and resin processing, manufacture of innovative fibre pre-preg architecture, new machine tools and assembly jigs, advanced fabrication processes and factory-of-the-future design, structure formulation of composite material systems, and revised test methods. In addition, is the need for improved design techniques to optimise airframe layout thereby maximising acceptable (safe) working loads. And at the same time, we must reduce fabrication costs through automation and low temperature curing matrix systems, and certify practical advanced inspection techniques for defect detection and repair.

Demands in modern aircraft include efficient aerodynamic design and lightweight materials combined with high efficiency engines to fly the aircraft, and providing electrical power for all the electrical systems. Keeping cost down is essential, which can only be achieved by using less fuel and reducing dramatically maintenance expense. The expectation is for materials to last longer and for structures to operate safely and reliably at increasingly higher stresses. In the case of engine components, we expect the material to work successfully at greater elevated temperature. The requirement is to push the performance of the structure to its limit thereby stretching composite materials to their boundary of strength and endurance.

Innovation in design and advancement in material ''know-how'' through discovery is no longer the single option. We see airframes made from composites, arriving at the probability of a successful outcome of a safe design by using intuition and our experience of circumstances that we have encountered before. But if we are to imagine the future differently, disaster as an act of God or of bad luck has to go. Predictive engineering design by intelligent-informed empiricism is the only ''show in town''.

There has been an invisible college of continuum mechanicians, scattered in universities, who have for decades studied the behaviour of composite materials based on an idealization of what behaviour is all about, and coming up with countless models without any reference whatsoever to microstructure; neither have they cared about mechanisms that act at the small end of the size-scale, nor structurally-based constitutive equations. Consequently, current design codes for composite material structures in critical loading situations do not take creep, fatigue and environmental-induced mechanisms into account. To predict a result, say lifetime or a stress

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response by a numerical method, there must be a self-evident truth that the mechanism regime in which the component is operating must be known. In other words, the important design issues must all be embedded in the same model of material and component behaviour that must also include the dominant mechanism(s) of structural change over orders of magnitude of size.

Furthermore, what makes for a successful and safe application varies from one material system to the next. Their diversity of failure characteristics stems from the differences between fibre-matrix systems and the nature of bonding between the constituent phases. It is not surprising then, that identifying the dominant process(es), meaning the one (or more) that has the most influence on the material’s or component’s limit of performance is not straightforward and sometimes the problem contains several sub-problems. To model each sub-problem separately and to combine the results later, if that is possible, requires a phenomenology—experience, ‘‘feel’’, ‘‘know-how’’ or ‘‘folklore’’—comprehensive collections of data, etc—a knowledge based on intelligent observations.

Predictive modelling of the behaviour of composite materials

Predictive engineering design by intelligent-informed empiricism has as its principal objective the identification and avoidance of all conceivable sources of weakness in the material and misfortune of structure. As always in science, advancement made brings a new set of great unknowns into sharper focus. Having discovered that we can grasp the basics of the origins of composite material behaviour, a myriad of other questions present themselves, questions about structural integrity and reliability of airframes, for instance, that we can realistically hope to answer.

For half a century, factors that influence the limits of performance of engineering composite materials and the capability of large structures and components to sustain high stresses without failure, have been the subject of many analytical and theoretical investigations, validated by observations and precise measurement of property data. Yet despite this acquisition of vast collections of information and compelling evidence, and an experienced designer’s intuition based on phenomenology, our ability to fully understand composite material behaviour remains restricted. Oversight in design across orders of magnitude of size of structure has led to undesirable matrix-dominated load paths. In composite structures under load, this has resulted in the cumulative evolution of a complexity of inter-acting small defects. This is material failing on the nanometre or micron size scale, and we notice its consequences at the component level.

There still remains the difficulty in connecting results at the different scale levels. Of particular interest is how damage transfers from a lower scale to a higher scale. Also required is the determination of their dependencies on stress, on temperature and environment, and time. And if there is no such phenomenology, then it will be necessary to generate one by conducting experiments. In other words, the constitutive equations of continuum design remain firmly based on direct experimental evidence. Difficulty arises, of course, when experimental conditions become so stringent, that even more properties are involved in the design process at all levels of size. What are needed, of course, are constitutive equations for design that encapsulate all of those intrinsic and extrinsic variables. Obviously, the experimental programme from which these constitutive laws are to be devised becomes formidable.

And if that is not enough, spatial variation appears when stress and temperature or other field variables are non-uniform. While simple geometries can be treated analytically, using, for example, the modelling tools of fracture mechanics, more complex geometries require discrete methods. The finite element method of modelling is an example. Internal material state variable formulations for constitutive laws are embedded in the finite element computations to give an accurate description of spatially varying behaviour.

Thus, the concept of multi-scaling has emerged where multi-function materials can be designed to satisfy several criteria simultaneously. Designers and engineers are freed from the bondage of having to apply technologies that are tied to material homogeneity. Advanced interpretation of reliability and durability for sub-micron size devices is being sought that no doubt will be the challenge of the 21st century.

Multi-scale problems have to be addressed by appropriate inter-disciplinary multi-scale modelling methods. The entire range of length scale has to be probed if we are to understand issues that limit the performance of the engineering structure. Understanding processes or mechanisms that operate in the material at all length scales and reconciling them with component durability and reliability is one of the ultimate challenges. The framework upon which the modelling processes can be placed, and the connections and continuity between them, is illustrated in Fig. 1.

We observe the hierarchy of structural scales from the nanometre to the micron to the metre (or greater) level of size. Also, the discrete methods of analysis ranging from micro-mechanical (mechanism) modelling to the continuum levels of mathematical prediction of the complete design process. Optimum material microstructure (and nanostructure) can be forecast and designed rather than found by trial and error, (with the possibility of calamity),

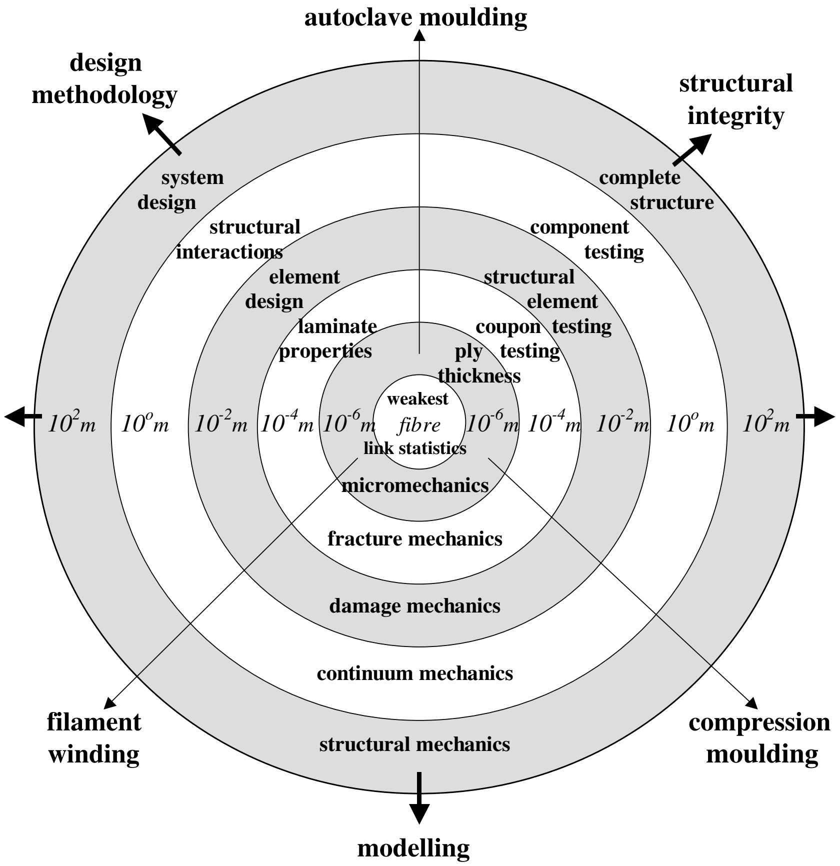

Fig. 1 Hierarchy of structural scales ranging from the micron to the metre (and greater) level of size, from the single fibre to the fully assembled structure, and discrete methods of analysis in design ranging from micromechanics to the higher structural levels of modelling

whilst maximising structural high performance and sustainable safe life. This is to follow the path of intelligent design in a functional direction.

By using the methods shown in Fig. 1, it is possible to identify permissible limits on the safe performance of the material on the one hand and the enduring component on the other. This will provide us with scope for optimisation, where composite material properties vary continuously with some internal parameter that relates to composite architecture in some way. 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.

Problem posing and solving are essential components of modelling studies, adding value to our current understanding of the application of predictive modelling of composite material behaviour. The style and level of modelling depends on the problem, and they must all have that right degree of sophistication for the task in hand. The model must be simple but not too simple (Albert Einstein). There is elegance in successful physical modeling.

Complementary to the unification of the multi-scale modelling methods, of the continuum and micro-mechanics approaches, more work is required into the development of the probabilistic approach. Not much has been done in this direction since Waloddi Weibull presented his work 50 years ago. As composite materials are stretched towards their limit, the statistical variation in their properties becomes more apparent. Always, one is working on the tail of the distribution, where the probability of failure is great. Predicting failure probabilities under extreme conditions is highly desirable.

The advent of powerful computers and soft ware that can be purchased at reasonable cost means that many of these models, 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. Physical-based damage and failure models can be incorporated into empirical or continuum methods of modelling that would lead to more efficient and reliable experimental programs and the safe design of composite structures.

Philosophy of this collection of invited papers

The philosophy of this collection of papers captures nano to micron to metre-sized phenomena; it broadens in scope by probing physical behaviour of these complex material systems under stress across the entire spectrum of size and time and environment. The invited writers of these papers are international leaders in their field, presenting engineering principals and new ideas in composite materials that evolve from classical materials science and mechanics; they discuss advanced concepts to identify and establish new disciplines to promote emerging technologies. A broad range of material and structural problems to solve are included from examining nano/micro phenomena, physics and mechanics of interfaces, observing phenomena and measuring experimental data, making links between compatible modelling techniques over the entire spectrum of size, and predicting behaviour. Hence, emphasis is placed on the accuracy of computation guided by the underlying physics of the problem to be solved. Attention is also directed towards new and innovative processing and fabrication methods, and the design of nano-composite materials and devices.

Bringing together key academics with partners in the related industries can unlock the timely opportunities for innovation in scientific achievement and new product introduction in composite materials technology.

In producing this special issue of the Journal of Materials Science, I have had the enormous pleasure of working and collaborating with talented colleagues from around the world and I would like to thank each of them for their huge contribution to this synergistic effort.

''The careful text books measure
(Let all who build beware!)
The load, the shock, the pressure
Material can bear.
So, when the buckled girder
Lets down the griding span,
The blame of loss, or murder,
Is laid upon the man.
Not on the stuff-the Man!''
Rudyard Kipling's ''Hymn of Breaking Strain''

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Courtesy of Peter W R Beaumont,
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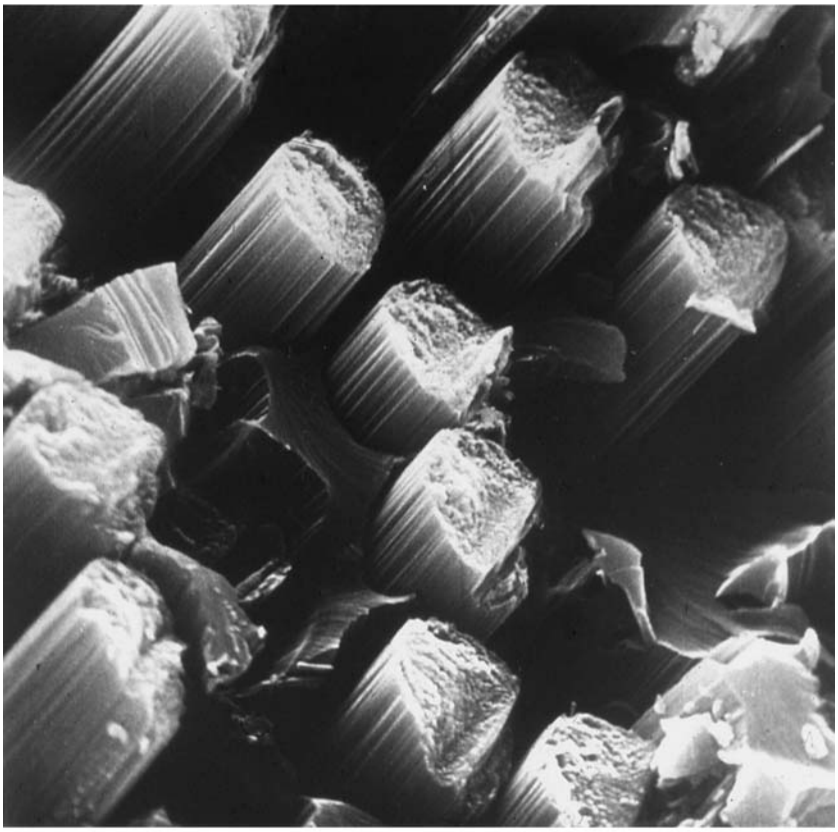

One of the earliest photomicrographs of the fracture surface of a composite material made from continuous type I (untreated, high modulus) carbon fibre in polyester resin. It was taken using a Cambridge Stereoscan scanning electron microscope in the School of Applied Sciences, University of Sussex. The fibre was supplied to Professor Bryan Harris and Dr Peter Beaumont in the autumn of 1967, courtesy of Mr Leslie Phillips OBE of the Royal Aircraft Establishment, Farnborough. This picture appeared on the front cover of the Journal of Materials Science in 1969.

Harris, B., Beaumont, P.W.R., Rosen, A., "Silane Coupling in Carbon Fibre-Reinforced Polyester Resin", J. Mater. Sci., 4 (1969) 432-438.