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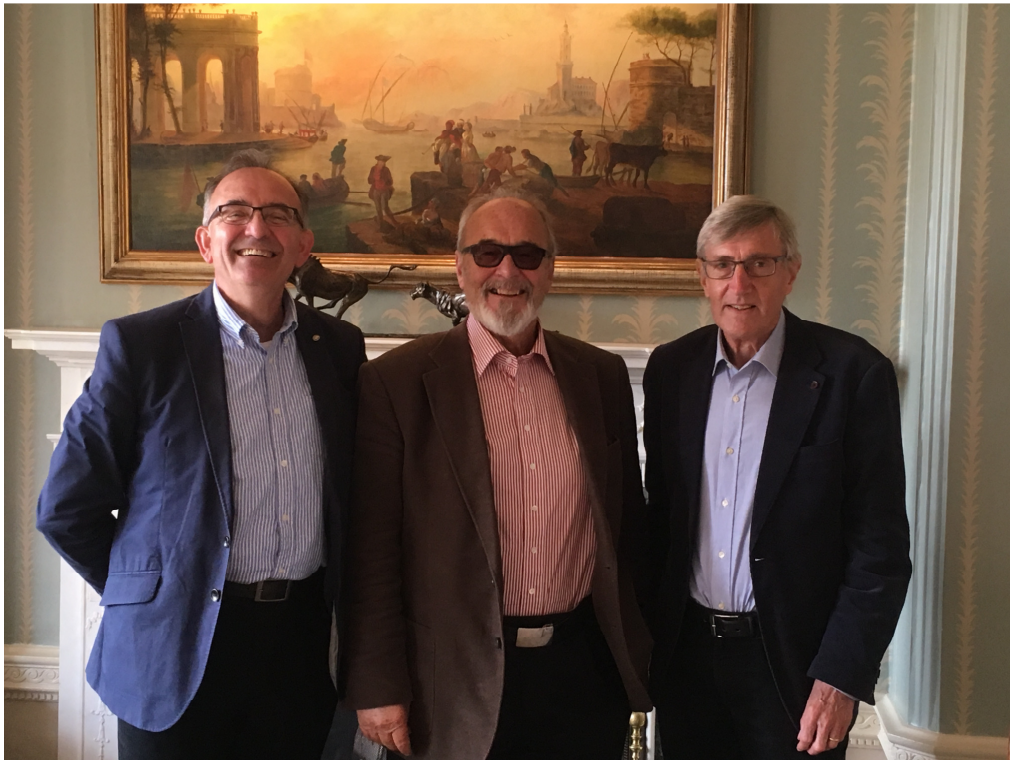


Fitness considerations for contemporary composite materials: (Who's afraid of the composite micro-crack?)

Peter W R Beaumont¹, Costas Soutis², Alastair Johnson³

Abstract

Avoiding the catastrophic failure of a large structure demands the material's microstructure be designed in such a way as to render any crack present innocuous thereby raising the integrity of that structure. Structural integrity (*S*) of a composite material embraces contributions from: materials science and engineering; processing science; design and fabrication technology. It combines a number of interacting factors: the criticality of the application; the accessibility for and ability to inspect vital parts and components; the intended use including load spectrum and time; the consequences of impact, fatigue, temperature and hostile environment; the nature of inherent flaws; the constituent properties of the material system utilized; and it takes into account *human factors*.



The authors (editorial board members of *Applied Composite Materials* journal, pictured left to right: Soutis, Beaumont, Johnson) at a recent meeting at Hambleton Hall, UK, to discuss the future directions of composite materials research and scientific publication.

¹Cambridge University Engineering Department
Trumpington Street, Cambridge, UK
webmail: pwb1000@hermes.cam.ac.uk

²Professor of Aerospace Engineering, Head, Aerospace Research Institute, Director, NW Composites Centre & NCCEF, Director, Sino-British Advanced Control Laboratory, University of Manchester (UK)

³Composite consultant, Stuttgart, Germany, (previously at the German Aerospace Center (DLR), Stuttgart, Germany)

1 A pointillistic portrait of the discipline of composites

The discovery 50 years ago of high strength, high stiffness carbon fiber that could be woven into fine fabrics and textiles returned us to those factories of northern British towns of the 18th and 19th century. With fiber in and product out through the factory front door, we arrived where material processing and manufacture, design and fabrication of the final product can now take place under one roof. We arrived back to the *factory of the future*.

In the *blink of an eye* we have in composite materials discovered a clearly defined and distinct discipline, which in practice doubles up as a multi-discipline with a substantial number of independent *branches*, each one with its associated multifarious journals and textbooks, read by materials scientists and practising engineers alike who communicate with each other on that basis.

In *Applied Composite Materials* journal, authors of papers collectively produce an impressionistic map of the present state of the science and mechanics of composite materials, seen as a pointillistic portrait of the discipline of composites, to be viewed from a slight distance. But what defines composite materials science and links it to traditional engineering disciplines? Perhaps the way to address this question is by means of what philosophers call an *ostensive definition*, relying on analogical or case-based reasoning. In other words, those published papers in *ACMa* over several decades are an essay in ostensive definition albeit a lengthy and comprehensive one.

Throughout the pages of successive issues of this Journal, we observe the materials scientist and materials engineer working at several levels of organization, each of which is underpinned by the next level. This feature is central to the subject of composite materials – the concept of “architecture” as the defining theme that connects composite materials science to engineering across orders of magnitude of size. At some point on this scale can be defined the concept of *meso-structure*, a term frequently used by modellers and simulators of composites alike, that level between the microscopic level observed by the materials scientist and the macroscopic appearance from the viewpoint of the engineer.

Over decades, writers of *ACMa* papers have delved into the natural characteristics and behaviour of particular classes of engineering material reinforced in some way by fiber of high strength and stiffness, probing and examining such concepts and relationships as structural architecture and design from the very small to the very large. What emerges is the evolution of a number of neighbouring disciplines in mechanical design and processing: experimentation and analysis; mathematical and continuum modelling; constitutive and physical modelling (or micro-mechanics or damage mechanics); computational mechanics and virtual simulation aided by computer power.

Fine-scale phenomena become embedded in calculations representing larger-scale behaviour, arriving at intelligent predictive design based upon the application of the principles of integrated multi-scale mechanics and hierarchical models and analyses. They all share certain characteristics in terms of hierarchy in which material constitutive properties are passed on from one model to the next via inheritance throughout the complete manufacture and design process of the engineered composite.

Major themes range from descriptions and analyses of micro-scale phenomena that affect composite material behaviour at the metre level of size and above. And at the microscopic level of size, they include the nature of cracks that nucleate and grow stably to threaten eventually the safety of large engineering composite structures. Fundamental material issues are probed that affect composite weakness and compromise composite strength; and solutions proposed to challenging material problems that hinder the safe exploitation of large composite structures. This requires an in-depth knowledge and

understanding of the deformation and failure processes in the composite best detected and monitored directly, if possible, tracing damaging mechanisms, and generally the slow progression of structural change over time.

But that which draws the threads of *ACMa* papers together is an understanding of what is meant by the structural integrity of the composite. By means of careful experimentation and sound analysis, this ultimately leads to successful forecasting of the limits of material performance on the one hand and defining the conditions for safe operation of composite structure on the other from *cradle to grave*.

2 Contemporary composite materials in service

In spite of early failures where high stiffness, low weight composites lacked corrosion resistance and poor resistance against impact and fatigue, carbon and other fiber composites are becoming common place. Examples of applications are: legion micro-light (man powered) aircraft, Formula 1 car chassis, un-stayed masts, high performance racing sails, vaulting poles, squash and tennis racquets, skis and golf clubs, (each of which has raised the modern standards of the game and sport to new heights), helicopter rotor blades, light weight construction and repair in civil engineering. There are many others including the Northrop Grumman B-2 Spirit Stealth Bomber and Lockheed's F-117 Nighthawk Stealth aircraft, and fast naval boats.

While military aircraft have incorporated composite components for many years, civil aircraft are beginning to do so in increasing quantity. Boeing manufactures the large civil airliner, the Dreamliner 787 with more than 50% of the airplane made of composite. However, in January 2016, an engine on the Japan Airlines 787 flight from Vancouver to Tokyo had to shut down an engine due the accumulation of ice on the fan blade in GE's most advanced GEnx engine. It was found that the tips of blades rubbed against the engine casing with possible damage and in-flight non-restartable power loss. Likewise, the Dreamliner was dogged by a series of problems during development and production since its first commercial flight in late 2011.

It is interesting that Boeing is aiming to take the lead over Airbus who may legitimately claim to have pioneered the use of advanced composite materials with the A300B incorporating them in secondary structures such as tail fin leading edges. The A340-600 saw the first use of composites in crucial primary structures such as the rear pressure bulkhead and the keel beam. Other components made from composites on this aircraft include the fin and rudder, horizontal tail plane and wing trailing edge moving surfaces as well as the floor panels in the passenger deck.

The airframe materials by weight of Boeing's 787 are 50% composite, 20% aluminium, 15% titanium, 10% steel and 5% other materials. This might be contrasted with the same breakdown for the Airbus A380, the world's largest civil airliner now flying in service since the beginning of 2008; 22% composite (or 25% if the 3% of Glare is included), 10% steel and titanium, and 61% aluminium. In contrast, Boeing's 777 includes 50% aluminium and only 12% composite. By volume, the 787 will comprise 80% composite. Each 787 contains 35 tonnes of CFRP made from 23 tonnes of carbon fiber. The lighter weight provides greatly reduced fuel burn and a side advantage is that high humidity in the passenger cabin is possible because composites do not corrode like aluminium. Other innovations are an automatic active gust alleviation system developed for the B-2 bomber.

The most striking innovation of the Boeing 787 is its all-composite fuselage made by filament winding 4 barrel sections joined end to end. This eliminates the use of 50,000 fasteners and allows a higher cabin pressure during flight compared to that attainable using aluminium. The Airbus riposte, the A350 as a direct competitor, is constructed of an airframe of 52% composite, 20% Al-Li alloy, 14% titanium, 7% steel and 7% miscellaneous; 50% composite wing, and an all-composite fuselage but with the fuselage made of curved longitudinal sections. A composite fuselage offers advantages for highly integrated design concepts and reduction in production costs. Much potential is seen in thin walled sandwich structures leading to higher bending stiffness than single skin designs.

The A380 is the first commercial airliner with a central wing box been made of carbon fiber-epoxy and the first to have a wing cross section smoothly contoured – which allows maximum aerodynamic efficiency – where thermoplastics are used in the leading edges of the slats. Glare is used in the upper fuselage and in the stabilizers leading edges. Glare has better fatigue, corrosion and impact resistance than conventional aluminium alloys and can be repaired using conventional repair techniques. Furthermore, Laser beam welding is used to eliminate riveting in much of the Glare construction.

Avoidance of the failure of large composite structured assemblies such as these and their complexity of design presents a major challenge. Anticipating possible material and structural problems are just too complicated and too interactive to admit a solution by practical testing and in any case the structures are too large. It follows that judicious testing coupled with well-substantiated computer modelling is the only way forward at present. Bird strike, the fatal nemesis of the RB211 Rolls-Royce fan project can now be adequately modelled so that the EASA (European Aviation Safety Agency) will accept bird strike simulation. And some forms of virtual testing have been accepted.

Virtual testing procedure for drop weight impact tests have been developed using finite element methods. Recent advances allow the inclusion of complex constitutive equations and their manipulation with fast computers. But the difference in designing and testing composites compared with metal structures is still vast. Data sheets used for metal structures in the certification process are not suitable for composites because there is simply too little data.

A feature of modern composite materials engineering with large or critical new structures is the manner in which university groups and research institutes, ex-house to the main contractor, are involved both in design, particularly for the last stages, and in testing activities. As an illustration, the production project for the end section of the A350 involves the following specific requests for work.

On the production side:

- Getting it right first time and quality control of the manufacturing process.

On the sustainable damage side:

- Effects of impact damage – with composites impact due to falling or struck by flying objects (at up to 900km/hr) may not immediately give visual evidence of the event on the exterior surface – but delamination (or peeling) could have resulted at the inner surface. It turns out that curved sections appear to be more susceptible to damage than are planar ones.
- Damage tolerance is an important concept and consideration must be given to defining a reliable quantitative statement of damage tolerance as a “design allowable” without compromising safety.
- For the last two, the *NDI* method for checking the adhesive bond failure is important.

3 In search of structural integrity

Since the *First International Conference on Carbon Fibre*¹ held in the splendid Connaught Rooms, London (1971), organised by the Plastics and Rubber Institute (PRI), there has been a plethora of papers published in a growing number of journals and books on a variety of aspects of composite materials behaviour and design methods of composite structures. However, remarkably few (in percentage terms) have provided in-depth understanding of why composite materials fail and structures collapse over a range of industrial applications and variety of public sectors. In scientific terms, there has not been a thorough quantitative formulation of the relationships that connect processing and design of composite material on the one hand and durability and reliability of composite structure on the other. As a result, there lacks an appreciation of what structural integrity of a composite actually means. Structural integrity is the optimisation of microstructure by intelligent processing of material in order to maximise safe mechanical performance of structure, thereby overcoming calamity and misfortune.

Consider airframes made from a composite. The overall stress field of fuselage components during flight is two-dimensional; engine thrust works against drag, and lift works against payload. Hence, for normal flight of aircraft with engines mounted on wings below the fuselage, the fuselage is subjected to bi-dimensional compression force, and to shear aft of the wings. Even when subjected to bi-dimensional compression, pre-existing cracks can be expected to propagate if and when the principal stresses become strongly unequal as happens to airframes during both air turbulence and “heavy” landing.

At the moment we arrive at the probability of a successful outcome of a safe design by using intuition and our experience of circumstances that we have encountered before. Our comprehension of structural changes in composite materials, however, which take place continuously and cumulatively, is lacking in detail. More often than not, these simultaneously acting microscopic (or even atomistic) processes are simply not known. Consequently, recent design codes both for material and structure have had to resort to flexible numerical modelling tools to simulate the conditions of creep, fatigue, and environmental failure. Thus, failure criteria (stress or fracture based) are not universally acceptable in practice so leaving further unresolved issues. This is of particular importance for modern manufacturing challenges in the aerospace industry where the aircraft production speed dominates the global demand, and machining of composites plays a major role in defining quality of the finished structures and consequently aircraft performance.

To predict a result, say lifetime or a stress response by a numerical method, there should 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 should 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 and time. And there still remains the difficulty in connecting results at the different scale levels and how damage transfers from a lower scale to a higher scale. To imagine the future differently, then composite material and engineering disaster as an *act of God* or of bad luck has to go. Total safety is the *only show in town*.

¹It is interesting to note that the Conference was well attended by many scientists and engineers from Rolls-Royce who, on leaving the Connaught Rooms at the end of day, learned from the London newspaper vendors that they no longer had jobs to return to. Many left the UK; some moved to the USA, Canada, or Australia.

If we begin design at the micron level of size (or below), basic research seeks a detailed understanding of the problem of structural failure through elegant modelling or experimentation with conspicuous absence of immediate need for solution or time constraints. At the other end of the size scale, solutions to applied structural problems need not necessarily be complete; in fact a full understanding of the situation is rarely required. These solutions require synthesis, optimisation, approximation and *feel*, and they generally have a time constraint. Undoubtedly, progress has been made in the past decade in bringing together the basic concepts of physical modelling, mathematical, and continuum models and in reconciling them with each other. But the rate of progress has been slow and the burden of cost so enormous that industry can reasonably be expected to ask now for a condensation of all this work to a set of effective design codes applied by those who understand and recognise likely dangers and limitations of large scale structure.

It is time to apply existing knowledge and *know-how* to the development and exploitation of design methods for safe life prediction of large structures; to reappraise current design practice and future design strategies; and to develop and validate risk-based assessment methodologies. This requires an integration of scientific disciplines, skills and understanding across a broad spectrum of size-scale. And this must come from the condensation of a wealth of knowledge of experimental information and applied analytical procedures, and from the successful application of modelling of various kinds including computer-based hi-fidelity simulation. We need to reconcile the irregularities of microstructure with the assumed continua of computational methods of modelling through an integrated multi-scale approach to design. The benefits include shortening of the design-cycle time (reducing costs), optimisation of safe performance of structure, and raising confidence levels in life prediction of highly-stressed structures.

There is another set of issues that cannot be ignored and runs through the papers of *Applied Composite Materials* journal like a leitmotif: what is a scientific discipline; how do disciplines emerge and differentiate; can a discipline also be interdisciplinary or multi-disciplinary? Perhaps it is the last of these questions which gives the editors of *ACMa* the impetus to embark on the publication of papers having such a wide range of themes and disciplines.

So why do we still encounter materials that crack and structures that fail? It is because our knowledge is based (almost) entirely on this store of information being empirical in nature. Basic human instincts, thinking, perceptions and judgements were misdirected and became the compulsory basis of creative endeavours in building large structures: quite simply, empirical understanding of structural behaviour became representations of a distorted reality.

4 An alternative route to traditional engineering design

Whilst some ancient temples and cathedrals have stood the test of time, many others have collapsed prematurely without warning leaving the builder not knowing why. History is littered with structural disasters where the crucial failure event eluded the experimentalist. Yet despite an acquisition of vast collections of experimental data, information and compelling evidence, and an engineer's intuition based on *feel*, - experience coupled with intelligent observation - a phenomenology - our ability to fully understand that longstanding problem of structural failure remains unresolved. Traditional empirical design formulations have not done well dealing with these challenges.

For decades, an *invisible* college of continuum mechanicians studied mechanical behaviour based on an idealization of what behaviour is, without any reference to microstructure. In many cases, they did not even care. The route less travelled by some practitioners but becoming more familiar today to solving this dilemma has led to the development of the principles of damage mechanics (constitutive equations of material behaviour based on physical models of structural change including deformation and cracking processes). A requirement is that extensive (but time-consuming and expensive) test programmes must reveal all those failure mechanisms likely to operate in service. But for composite materials, the components of damage are complex and yet, ideally, they must be observed directly and not inferred by chance. Unfortunately, damaging processes feed off one another; there is synergistic interaction.

So empirical *laws* have serious limitations; quite simply, they do not have the power of prediction. Successful prediction of mechanical behaviour of material under stress and design life of a structure in service requires detailed information of all possible failure mechanisms across the widest spectrum of size-scale under all sorts of operational conditions. To set up an experimental programme that covers all eventualities, the scope of the test programme would be immense and unaffordable. Not only would the findings be complicated to sort out because of the many different test and material variables, and the complicated mechanisms of fracture and fatigue involved, the question of their interaction would have to be resolved. And material characterization over one range of temperature, for instance, could not safely be extrapolated into another thermal regime: a new characterization would be needed for every set of composite lay-up, selection of fiber and matrix system, operating conditions, and environment.

To follow the traditional route of engineering design is merely an attempt to ensure that a highly stressed critical component could not possibly fail within its design life time. This exercise involves deriving over the entire life of the structure, the spectrum of loads experienced in service and to compare with materials test data; strength, fatigue and creep data, stress corrosion cracking-rate, etc., - - that phenomenology mentioned above. The next step would be to determine the component's dimensions to maintain the design loads and to guarantee the design life within a margin of safety, allowing for some acceptable risk of disaster. And what is an acceptable degree of risk? What danger level are we prepared to accept? In this way, we build up to testing larger and larger items until the complete structure undergoes that *multi-million dollar test* to destruction. Nevertheless, determining the ultimate strength of the completed structure experimentally has its benefits; it helps verify the new analytical methods used to calculate the loads and deformations the structure will have to carry in service. In reality, there are still many tests to complete from elements to components to sub-structures where internal stress fields are too intricate to evaluate by analysis.

Eventually, the method of extended empiricism simply breaks down under such an unmanageable load of variables. Not surprisingly, the design and development of large structures based on full scale testing is slow and expensive. Furthermore, the burden of testing to prove absolute safety of structure would be impossible to manage in practice. This experimental challenge is based upon two extreme forms of testing: either test thousands of coupon specimens to establish basic laminate properties, or have the knowledge (and wisdom) to be able to make confidently prediction based on just 1 or 2 tests on the complete aircraft or major components to ultimate load or fatigue life.

Traditionally, then, practical design methods followed time-consuming, expensive test programmes to establish damage tolerance certification of the large structure. The consequences of changing laminate design (fiber orientation, stacking sequence, weave pattern, or ply thickness) or material system along the way would undoubtedly prove disastrous. A heavy price is paid for making mistakes using this approach. Unfortunately, the entire test matrix for material qualification must be repeated. Furthermore, there are complications as the result of laminates being heterogeneous elastic bodies containing sites of stress singularity; and secondly, the mechanisms controlling damage initiation and propagation are non-linear. The likelihood is these mechanisms would not be known. As said before, directly observing them is best. Sleepless nights, however, continue to haunt the specialist in non-destructive inspection for fear of *missing* a large crack in a critical location.

In contrast, for a metal undergoing fatigue, we know that cracks grow and we can control life by monitoring the growth of the longest crack. The behaviour under multi-axial stresses can be quantified by the use of Goodman diagrams. These diagrams, however, are not feasible for a composite structure but some still try to use them, and although it can be said that composite structures are more resistant to fatigue than are metal ones, this is only strictly the case in a tensile stress – tensile strain situation.

Metallurgists fear small cracks that can easily be missed during routine inspection. Small cracks grow in fatigue resulting in time-dependent structural failure accelerated by stress corrosion effects. In contrast to metals, progressive damage in composites under load takes the form of a multiplicity of nucleating micro-cracks predominantly in the matrix material, at the fiber-matrix interface, and by interply de-lamination. Energy is absorbed in this complex process of coalescing micro-cracks leading to the instantaneous fracture of cascading fiber breakage and catastrophic structural failure.

For resin-based composites, matrix micro-cracks, transverse ply cracks in laminates and local delaminations in the vicinity of a notch tip, hole or cut-out are *desirable*, since for elastic composite systems these micro-cracks absorb energy (called *energy sinks*) and provide *ductility*, thereby reducing the local stress intensity. The net result is a *benign* structural failure. Unfortunately, these energy sinks cannot be monitored easily, and therefore this complex process of interacting micro-cracks cannot be applied extensively. Real time structural health monitoring becomes critical.

The key for designers is to understand and control this initial phase of micro-cracking and for ultimate failure to concentrate on large scale delamination, which propagates rapidly (similar to fatigue cracks in metals) and leads to ply splitting and fracture. This is best illustrated by crash energy absorption in composite structural elements which happens in F1 crash cones and aircraft subfloors. They are *triggered* to initiate ply micro-crushing in compression, followed by delamination and ply splaying at the crush front. These elastic composite systems absorb specific energies (by mass) several times higher than aluminium tubes, which buckle then fold under plastic hinge formation.

To begin with, damage can be sustained but it spreads over time through significant parts of the bulk material and structure. Since there is no dominant crack (at least to begin with), it is not feasible with preset knowledge to access the nature of the damage simply by microscopic examination. Detection by acoustic emission may be possible but sorting out the different cracking mechanisms is not straightforward. Some suggestions include the use of measurements of Poisson's ratio of the fatigued structure as a monitor of damage progression. To overcome this uncertainty the designer reduces the allowable stress on the material so that the structure then becomes overweight or over-cost.

By the end of the 20th century, modern mechanical design had evolved with the development of the continuum theories of mechanics (mathematical and continuum models of elasticity and plasticity), diffusion and reaction-rates. With the advent of computer power this resulted in finite element (FE) modelling, numerical analyses, and high-fidelity simulation, the result of which led to an optimisation of structure to minimise cost or to maximise performance or safety.

Thus, the modern designer had to show dexterity in the application of two boxes of working tools: mathematics and continuum modelling, from which those continuum theories and constitutive modelling evolved, (a sort of *distilled empiricism*); and secondly, micro-mechanics modelling (or physical modelling). Successful use of these tools to determine constitutive equations depends upon knowledge of the rules of material behaviour. The idea is that the response of the material to a stress at one level of structural size can be described by one (or more) parameters and then passed to the next size level up (or down). Hierarchy of structural scale and discrete methods of analysis in design ranges from micro-mechanics to the higher structural levels of modelling, continuum mechanics, etc.

Combining information obtained at the different levels on this size scale leads to the development of the principles of *damage mechanics*; constitutive equations of material behaviour based on physical models of deformation and fracture. One problem is that constitutive equations of continuum design are once again based on experiment. This is where micro-mechanics helps by identifying those mechanisms responsible for cracking and an understanding derived from the theory of reaction-rates (for example) to model them. But micro-mechanical models have something else to offer, they point to rules that the constitutive equations must obey. Although micro-mechanical models cannot by themselves lead to precise constitutive laws, the result is a constitutive equation that contains the predictive power of physical modelling combined with the precision of ordinary curve fitting methods of experimental data (called *model-informed empiricism*).

A key role in failure prediction, from empirical methods to high-fidelity simulations of damage evolution, is played by certain physical length scales in the damaging processes, which provide a rationale for making modelling decisions. A length-scale arises because of the complexity of the nature of cracks; de-lamination and splitting (shear) cracks (and associated interfacial sliding friction between fiber and matrix socket), fiber rupture, fiber micro-buckling or kink formation, and diffuse micro-cracking or shear damage.

Corresponding physical models and mathematical theories describe those mechanisms on a micro-scale and crack growth in the large engineering structure. Boundaries on this length-scale define the point of breakdown in the model and assumptions implicit to a particular size. Thus, we can define points on that scale by phenomena that are treated discretely from phenomena treated collectively. The two exceptions are the end points of the length-scale. (Everything at the electronic level is treated discretely whereas everything at the macro size is treated collectively).

Our confusion over how damage is interpreted along this length-scale is causing difficulty as progress is made from one design stage to the next; from the size of an architectural feature of the laminate to that of structural element, and from component to the fully assembled large scale structure. Lack of mastery in combining architectural design of the material at the micron (or less) size with the design of elements of the engineering structure metres in length, has led to the opening of a gap in our knowledge of composite failure. This weakness can be traced to the changing nature of cracks and the fracture event as structural size increases. If we consider coming to terms with all sorts of material behavioural complexities at the (sub-) microscopic end of the scale, we might say that we

have characterized the properties of the composite by reference to the fiber only. There has been no real consideration of the *make up* of the material or macroscopic geometry of the laminate or shape of part or component. Any notch, hole or cut-out is but a geometrical aberration. Conversely, at the size level of component design, we have tended to look at the overall geometric shape and thought of the material properties as being set (in a geometric sense) at global level.

Coming to terms with these differences of scale appears to be a key source of design difficulty because it is precisely at that size where the material problem becomes a structural one where this gap in understanding of composite failure has opened up. This gap has been partially filled using fracture (and damage) mechanics, where quantitative relationships between microscopic and macroscopic parameters have been developed. But, as before, damage tolerance certification of a material and structure requires time-consuming, expensive testing. Fortunately, with the development of computer power and appropriate software, this has led to a reduction in number of tests by substituting with high-fidelity damage simulations that serve as virtual tests of structural integrity.

Unfortunately, understanding damage by experimentation and modelling across orders of magnitude of structural dimension and linking analyses systematically to provide a total predictive design strategy is lacking with respect to absolute reliability and guaranteed safety. This is particularly critical regarding two design issues: (1) a structure capable of sustaining a potential damaging event (*damage resistance*) and (2) a structure's ability to perform satisfactorily and safely with damage present (*damage tolerance*). Even with the exponential growth of computational power, which has resulted in an abundance of numerical analytical models, there still exists fundamental barriers to overcome as progress is made by connecting one damage analysis to the next, from the time the smallest undetectable defect forms in the solid to the point where a visible crack is found in a full-scale engineering structure *down the road*.

5 Considerations for long-life implementation: how much danger can we live with?

For half a century or longer, those factors that influence the endurance boundary of the composite material on the one hand and performance limit of the composite structure on the other has been the subject of a great number of analytical investigations, validated by precise measurement of critical property data. But our comprehension of the sustainable damage of a composite material and the mechanical stability of a composite structure over a wide range of operating conditions remains restricted.

Selecting the right material system at the very beginning of the design process is a sensitive issue and requires careful material properties profiling. *Dimensions* must be consistent with the overall function including *minimum weight* and there are data bases for materials properties to which designers can refer; The *Cambridge Materials Selector* is an example [1]. When it comes to material property profiling, frequently Young's modulus E and density ρ are the *performance drivers* in which case the materials engineer consults a chart having the axes E - ρ with superimposed lines of *constant design* or *merit indices*: a) E/ρ for a strut; b) $E^{1/2}/\rho$ for a beam, and c) $E^{1/3}/\rho$ for a plate, where the index is maximised for optimum design.

Additional input in selecting the correct combination of fiber and matrix might include *thermal conductivity* and *thermal expansion coefficient*. For thermal properties profiling, an expansion coefficient mismatch between ceramic constituents leads to *thermal fatigue cracking* or ratchetting in metal-matrix composites (MMC). This requirement constrains selection of fibre reinforcement and protective coatings for high-temperature application; Ti

requires Al_2O_3 fibres, not SiC fibres. Ceramic-ceramic composites (CMC) preference is for SiC/SiC or mullite (alumino-silicate ceramic)/ Al_2O_3 over SiC/Al_2O_3

Where toughness is a critical requirement of a material, experience indicates a practical minimum level of plain strain fracture toughness (K_{IC}) of $10-15MPa.m^{1/2}$ (in fracture mechanics units). Toughness, however, is not a unique property of composites, which complicates things. For example, crack tip *blunting* mechanisms stabilize damage at notches: multiple matrix cracking, fiber bridging of de-lamination cracks, fiber buckling zones around notches or holes in compression, etc. Furthermore, the stress concentration factor around holes diminishes under increasing (and repeated) load because inelastic (damage) zones develop, corresponding in an elevation in local tensile strength.

Multiple fiber fracture and matrix-dominated cracking below ultimate strength allows other inelastic mechanisms to activate in the matrix and stabilize the effect of damage. The failure probability distribution is dramatically modified. Crack tip processes and mechanisms acting in the crack wake behave in synergistic fashion. Since notch strength scales with fracture toughness, notch sensitivity is a more robust, useful measure of material performance.

In service, composites may undergo combined attack from stress and environment. The result is the activation of a complexity of atomistic defects and microscopic flaws and their accumulation over time will be felt at the component level of size. Corrosion fatigue degradation of glass fiber in epoxy is an example where there are two rate-limiting phenomena. Hostile species penetrate the composite through matrix cracks; reaction with the fiber reduces its strength; and fibers snap 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 fine crack and the stress corrosion process at the crack tip thus becomes diffusion-controlled. The chemically activated kinetics of the process is thermally sensitive, so models based on statistical mechanics will lead to a rate that depends upon temperature. 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 or neither easily measured.

The main damage mechanisms known by experiment involve intra-laminar and inter-laminar cracking, and they must explicitly be taken into account. Behaviour of the interface elements may be controlled using a simple cohesive crack model and the maximum load at failure and absorbed energy can be accurately predicted. But life is just not that simple. Damage by cracking involves complex non-linear processes: at the micro scale; it includes micro-cracking of the matrix and fiber breakage, and at the macro level of size we see the appearance of *joined up* cracks in large components. There are just too many possible interacting mechanisms of damage to understand let alone to build into a single realistic predictive model of the point of catastrophic structural failure. Prediction really is a problem.

To formulate a life-prediction methodology where conditions of stress corrosion cracking exist, for example, three principal phenomena have to be addressed: reduced strength of reinforcement; fiber stress at the tip of a crack; and concentration of hostile species within the crack, all issues related to the *chemistry* and the *kinetics of reactions*. But there is another complication: structure evolves with time and ageing weakens. Furthermore, when cracks form they in turn increase the *rate* of damage progression. There is positive feedback. The difficulty is that we simply do not know what happens once damage begins.

How, therefore, can we deal with the *nucleation* of damage and then the multiplicity of *interacting*, competing, complex cracks? Understanding this life-long dilemma requires knowledge of the following phenomena: impact; fatigue; creep; and stress corrosion cracking, etc. All affect the reliability, life expectancy, and durability of structure; the structural integrity. *SI* analysis treats simultaneously design and materials used; it figures out how best components and parts are joined; it takes service duty into account; and it accepts a level of danger. But what is an acceptable level of danger? It depends to what level of excitement you are prepared to go: driving a F1 car or flying in a brand new composite aircraft. An engine blows up on a new Airbus A380 (Qantas Airlines, 4th November 2010, London to Sydney). A turbine disc in the Rolls-Royce Trent 900 engine disintegrated resulting in damage to the nacelle, wing, fuel system, landing gear, flight controls, and undetected fire in an inner wing fuel tank. It seems that loss of aircraft avoided was but by the *Grace of God*.

There are, then, conflicting aims of designing a structure simultaneously for high efficiency and safety assurance throughout an economically viable lifetime and it comes down to the price of safety but with an acceptable level of risk *as decided by society's experts*. Quite simply, how close to potential disaster are we prepared to go? The short response is that it is the *design life* that determines the answer. Absolute safety is determined by structural integrity, which defines design life. In a *nut shell*, design life is that point in time when a structure suffers loss of function for which it was intended. An important feature of *SI* analysis is that it provides quantitative input to the formulation of an appropriately balanced response to that question above. Where human life depends upon structural integrity, it takes 10⁴ material test coupons per laminate configuration to evaluate an airframe for a given set of operating conditions.

Various design methodologies exist, all dealing with critical issues of structure and all common to the overall design process of production, maintenance, and repair. Superimposed are two items – assessment by non-destructive inspection (*NDI*) and safety. Is safety compromised where the fatal flaw(s) in the structure is (are) smaller than the *NDI* detection limit? What initial flaw (damage) size (content) is acceptable in the final structure as a result of the manufacturing process, and then the service conditions? And what is an appropriate inspection period? Just how far are we prepared to go? Fitness considerations of large structures require though-life monitoring of damage growth.

Materials have to be processed, components shaped, and structures assembled. Lack of attention to detail leads to premature failure after shorter service duty because of the introduction at some stage of fatal flaws (voids, de-laminations, fiber waviness, contamination at joints, etc) and they all impact on structural performance. Predicting damage initiation followed by damage evolution and specifying accurately the safe operating limits is a major challenge. The problem is especially difficult if the damage is severe. Difficulties in prediction arise because composites modelled as heterogeneous elastic bodies contain sites of stress singularity; secondly, because the mechanisms controlling damage initiation and growth are non-linear. Multi-scale problems of structural failure that occur at the micro, meso, and the macro size of scale must be targeted by appropriate multi-scale modelling methods. Testing and analysis across a size spectrum reflect responses at all structural levels, which we call *multi-scale modelling*.

6 Multi-scale modelling and failure prediction

The macroscopic response of a composite material system and component reflects responses at all levels beneath. The idea is that the response at one level is passed to the next level up (or down). Hierarchical and multi-scale modelling link *top-down and bottom-up*

methods when designing against fracture. Almost always, behaviour at one level can be passed to the next level up (or down) as a simple mathematical function. Of particular interest is how damage transfers from a lower scale to a higher scale. This requires the entire range of length scale be probed in order to connect failure of the material and fracture of the engineering structure. Regrettably, distinct communities have pursued either top-down (TD) or bottom up (BU) methods of design only occasionally transferring information from one to the other.

The TD method begins with a macroscopic engineering model, a procedure that depends only on knowledge of straightforward *macroscopically* measurable properties, like hardness or yield stress or ultimate tensile strength, which an engineer can handle. The BU approach on the other hand, seeks to model (or simulate) failure by building upon events that initially take place at the atomistic (or microscopic) level, which in engineering terms are difficult to determine, let alone quantify.

Based on the TD strategy, component testing can be carried out through structural analysis using micro-mechanical models for the homogenized laminate behavior (3D continuum shell and cohesive elements). These virtual experiments open revolutionary opportunities to reduce the number of costly tests to certify safety, to develop new materials configurations and to improve the accuracy of failure criteria. However, the problem still remains that it is difficult to model first damage (matrix cracking perhaps) and progression into a delamination crack and final rupture of the component by fiber breakage.

Whilst physical modelling as described by one (or more) parameters in a constitutive model, for example, can help rationalise those microscopic processes responsible for yield stress, toughness (notch sensitivity), fatigue, stress corrosion cracking etc, generally, these models are too imprecise for an exact engineering solution. In fatigue, for example, life expectancy based on a physical model only might give a prediction within a factor of 10. That is because the material parameters of the physical model are not known with any certainty and they are too difficult to determine or measure with any confidence. They can be estimated only by empirical means. Knowledge of matrix crack density or size and proximity of clusters of fiber breaks, for instance, would characterise the state of damage in a composite under fatigue but there is no straightforward way of quantifying it in a large structure.

Such interplay of materials science and engineering is of crucial importance where composite material properties vary continuously with some internal parameter that relates to composite architecture in some way. The aim is to forecast and design optimum material microstructure (and nanostructure) rather than found by trial and error, (with the possibility of calamity), whilst maximising 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 set of processing conditions, to meet that specification and provide structural integrity. We require mathematical formulations that link TD and BU approaches in single design codes that represent fine-scale phenomena embedded in calculations representing larger-scale phenomena, tracing damage mechanisms through all size scales.

Beware of fraudulent claims of success: those Top-Downers who fit engineering data with a large number of material and experimental parameters and infer their model is unique; and those Bottom-Uppers who project their mechanism as the dominant one amongst all others in order to control engineering behaviour. In reality is there a mechanism that has not been observed; is there a significant crack that has gone undetected?

7 Computer simulation and multi-scale modelling

Simulation is a study of the dynamic response of a modelled system by subjecting the model to inputs that simulate real events, ways in which complex structures evolve without the need to perform expensive, time consuming experiments. This path leads to a quantitative prediction that represents the actual behaviour of the material under stress or performance of full-size structure across a broad spectrum of size (or multi-scale) without the cost, time, accident risk, effort and repeatability, and problems normally associated with real testing. But how much detail of failure mechanisms do we need to know in order that a successful physical model can be incorporated into a simulated virtual test that reproduces the outcome of a real structural situation? Creating physically sound damage simulations is difficult because damage initiation must first be predicted for parts containing no cracks.

Computer power makes it possible to describe the motion of atoms in materials, rather than making the approximation that matter is continuous. Most simulations of cracks, however, ignore the quantum-mechanical nature of the bonds between atoms. This limitation is overcome by using a new technique called *Learn-on-the-fly*. It is based on a quantum-mechanical description of bonding near to the crack tip where essentially it is coupled seamlessly to a large (on the atomic scale) region described with an inter-atomic potential.

Developments in non-linear elements in computational mechanics have led to damage simulations of sufficient fidelity in engineering design. A key feature is the incorporation of elements into a finite element formulation that can explicitly represent displacement discontinuities associated with cracks – so-called *cohesive elements*. These elements relate the displacement discontinuity across a crack to tractions that act across that crack. Examples include: fibrils in polymer craze zones; bridging fibers; or ductile particles stretched across a matrix crack, or fiber-matrix slippage following de-bonding (friction at interfaces). Cohesive elements can be formulated that admit cracks crossing a surface within the finite element. The developing crack path in a damage simulation need not be specified *a priori*; it can simply follow any locus that the mechanics of the evolving failure process has determined.

A composite can be modelled by layered elements (homogeneous and orthotropic) whose properties (for example, stiffness) degrade by micro-cracking according to a continuum damage model. The co-existence (*coupling*) of a discrete de-lamination crack and continuum damage (matrix crack) can be captured via a cohesive interface model. Micro-cracking is modelled by a non-linear constitutive law to the individual ply that causes material degradation (*softening*) according to the continuum damage model. The ply degradation parameters in the model are the internal state variables governed by the damage evolution equations. An idealization of a cohesive zone based on the finite element approach computes the stress distributions for the generic geometry and applied load. A realistic model or simulation then predicts the effect of load, fiber orientation, and stress concentrator upon damage and strength. Strain energy concentrations suggest correctly that ply junctions are sites that initiate de-lamination cracks.

Simulating crack propagation needs an accurate representation of the stress field ahead of the crack front known as the *process zone*, which may be small. The need for finite elements smaller than the process zone at a crack tip means less than 1mm for typical resins. A mesh this fine is unrealistic for a true structure. Most codes contain a local/global strategy whereby an existing coarse (global) finite element model has embedded a refined (local) region. However, a number of minor difficulties still exist before damage simulations of sufficient fidelity can replace qualification tests: (1) the implications of length scales associated with non-linear cohesive processes for correct mesh refinement; (2) the calibration of cohesive traction-displacement laws in order to confirm a physically-sound model of the particular crack wake mechanism; and (3) the problem of instability in

numerical iteration of non-linear damage problems, which may have physical (not algorithmic) origins.

Those damage growth mechanisms that have been observed in laminates include: delamination and splitting (shear) cracks, which grow in various orientations and change in shape with time; fiber rupture; fiber micro-buckling or kink formation; global buckling of delaminated plies; and diffuse micro-cracking or shear damage within individual plies. Those mechanisms (with the exception of global buckling) can be represented by cohesive elements, by collapsing the non-linear processes onto surfaces with the physics embedded in traction-displacement constitutive behaviour (rather than stress-strain behaviour).

Solving the problem of suitable mesh refinement might be achievable in terms of length scales associated with cohesive laws. Calibration of traction-displacement laws requires a successful physical model and appropriate set of experiments. This is not straightforward because different cohesive mechanisms often act simultaneously in a single crack, with their relative magnitudes depending on interaction effects with other cracks. Defining experiments is also challenged because traction laws must be deduced from experiments via inverse problem methods, which are vulnerable to numerical noise. Instability can be dealt with in one of two ways: (1) run the complete simulation as a dynamic model; or (2) invent algorithms that stabilize the model by controlling local displacements.

Modelling and hi-fidelity simulation methods are becoming more and more ambitious. On the one hand, there are calculations that aim at increasingly precise and detailed description of material behaviour. The number of assumptions is minimised and empirical elements are replaced wherever possible. Improvements in detail yield improvements in accuracy and provide the potential tool to resolve previously intractable problems. On the other hand, increasingly large complex systems are being investigated. These have different challenges. The methods, which are best for studies at the atomistic size scale are unlikely to be efficient for larger structures. This is because atomistic models for service performance are too firmly rooted in the underlying atomistic processes, and although understood, can be characterized only by microscopic measurements, which are impractical for an engineer.

Furthermore, interpretation itself is difficult without other aids. There is a need to link experience at levels between the macroscopic size level with understanding at the micro-structural scale of the material. One way forward is to identify the broad rules governing material behaviour and the rules governing the magnitudes of material properties, which are contained in the microscopic models, and to use them as the basis of *model-informed empiricism*.

The details of microstructure at either the fiber-matrix or tow architectural scales, however, are too complex to analyse. Instead, micro-mechanical models are used to obtain the effective properties at the micron scale to obtain effective fibre tow properties. Then, a model or representative of a volume element is used to obtain the effective properties of the textile architecture at this size scale. Inserting these values into a structural model identifies the *hot spots*. These hot spots are interrogated by reversing the process in order to determine whether the structure has to be re-designed or an alternative material system selected. Examples of challenges include dealing with large macroscopic gradients, non-periodic loads including transient loads, non-periodic microstructure, mesh generation, and data management.

The structural model is synthesized from the basic textile microstructure. The difference is the degree of repetition of the basic unit; also, how closely the material has to be modelled (for example, in the presence of large macroscopic strain gradients, a higher magnification is required). For coarse and fine microstructures the analyses involve discrete and

homogenized modelling, respectively. What is not so clear is how to handle the *transitional microstructure*, for which there is too much detail for discrete modelling, but too little repetition of representative behaviour to use homogenisation. One way is to use homogenisation, selective homogenisation, macro elements (finite elements that allow complex variation of properties within an element), and global to local interfacing techniques, including one technique based on modal analysis.

An aspect of multi-scale analysis often overlooked is the integration of different models. A common characteristic of many analytical studies is the need to construct and manipulate related models, related in the sense that they share some characteristics. In other words, there is a clear hierarchy in which many properties are *passed on* via inheritance. The hierarchical analysis environment can be used in parametric studies of structures or situations in which the constitutive behaviour is defined in a hierarchical sense.

Recent developments in simulation based on multi-scale modelling strategies have led to the virtual mechanical testing of composite structures right up to the point of failure. In the virtual testing of realistic aerospace composite structures, the validation of finite element (FE) predictions has been mostly proven for simple coupon and benchmark test specimens. The difficulty is simulating the correct failure mechanisms of realistic aerospace structures: for example, post-buckled compression panels, impact-damaged shells, major joints or any component with geometrical discontinuities. Commercial FE codes are powerful enough to capture the correct physics of the failure process. Some codes model the initiation of material failure followed by propagation to full structural failure.

Having a FE code is just the beginning: the modeller has to create a FE model, which is capable of capturing the internal stress fields with the required accuracy. Assessing damage in sandwich structures under hard and soft impacts, for example, requires validated FE design tools together with structural impact test data in order to validate FE codes and airworthiness certification.

8 At the heart of structural integrity

Component failure is normally due to instability of one kind or other and it is irrevocable. When a crack extends in a solid, energy is irreversibly lost. Load on the structural part is not indefinitely sustainable and it eventually fails. Basically, we require in the design of a damage-tolerant composite material the presence of a *microscopically weak* structure built into a *macroscopically strong* solid that ensures any crack present becomes innocuous. This was most cogently argued in discourses by Professor Alan Cottrell to The Royal Society more than 50 years ago [2]. Cottrell presented a novel treatment of a long-standing problem, namely the crack with a force between its faces. His direct approach to finding a solution was to obtain general expressions for the force and displacement between the crack surfaces. In the case of the fibrous composite under tensile loading, carbon fibers in epoxy, for example, all the fibers in the fracture plane do not snap at once; they do so in a sequential manner because of the variability in flaw size and flaw distribution along the fiber length. By careful manipulation of fiber-matrix bonding, the fiber-matrix interface is *allowed* to fail by de-cohesion and, in so doing, blunts the tip of any small propagating matrix crack present, whilst fibers bridging that crack remain intact and carry the traction. At the heart of the matter, then, is the question whether the matrix or interfacial (de-bond) crack between layers is stabilised by fiber bridging in preference to fiber fracture?

In the absence of de-bonding or when the sliding (shear) resistance along the de-bonded interface is high, crack tip stresses are concentrated in the fiber and they decay rapidly with distance from the matrix crack plane. Consequently, fibers are more likely to snap at or near to the crack plane rather than pulling out, thus diminishing their vital role in bridging

matrix cracks and de-lamination cracks. Under these circumstances, the composite would exhibit notch sensitivity (brittleness). Re-call the fate of the original carbon fiber compressor blades of the RB211 jet engine where de-bonding and fiber pullout of bridged fibers was more or less absent. The toughness (resistance to cracking) of the material was, therefore, somewhere between that of the resin matrix and the brittle carbon fiber, some 2 orders of magnitude less than found when controlled de-bonding is permitted.

Thus, the critical issue concerning structural integrity of the composite centres on the extent of this de-bonding mechanism and its dependence on interface properties, and its effect on crack opening and fiber fracture. These contributions on the dissipation of energy in a stable manner can be derived in terms of the constituent properties of the fiber and the shear resistance or shear toughness of the interface. Furthermore, the question of structural integrity concerns the definition of optimum surface treatment of fiber and optimum properties of any coating or inter-phase between the fibre and matrix.

Vital, then, is the nature of the bond and integrity of the interface, and knowledge of any thermal stresses and shrinkage effects of the matrix during processing and ageing in wet and dry environments. Thus, questions surrounding the mechanisms of *mixed-modes* of splitting and de-lamination cracking require resolution. Another consideration is how to include in a physical model the probabilistic nature of the failure behaviour of composite materials.

So, while 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. At the heart of the problem lies those failure mechanism(s) best identified by direct observation. But that's not straightforward to undertake by any means. It is dangerous to assume a mechanism without direct evidence or that it is dominant. The next best thing is by indirect observations; mechanisms can be inferred by C-scan or by changes in modulus or Poisson's ratio.

The value of Poisson's ratio is a more sensitive indicator of the presence of cracks than is a direct measure of the other elastic constants. It has been argued against this in that the principal Poisson's ratio of an aligned carbon fiber composite is very small and hence changes in its value difficult to detect. One answer to this objection is that a composite has a number of Poisson's ratios and so while a very small one may occur between one particular pair of directions, it will be accompanied by a much larger value shown when another pair of directions is taken for the measurements. The latter pair should be chosen. An angle ply laminate has a very large value of the principal Poisson's ratio.

9 Think physical modelling

Consider a physical model as a gross simplification of the essentials of the problem. An example is a topographical map of a mountain in winter displaying lines of different colour indicating the degree of difficulty of a ski run. All successful models capture features that really matter. With the snow-covered pistes colour coded (the skiers map), the blue run indicates the easiest way down the mountain to safety (hopefully). ("An artistic skill helps in coming up with a physical picture or map"; M. F. Ashby, private communication).

For the composite containing a flaw or microscopic crack, first identify the problem. Understand the nature of the problem (the mechanism(s)) such as matrix cracking, de-lamination, etc. Next, model each mechanism separately (coupling is the real challenge); then compare with data. Remember what the model is for: to gain physical insight; to capture the material's response in an equation or code; to predict material response under conditions not easily reproduced; and to allow extrapolation in time or temperature. What

do you want from the model? Identify the desired inputs and outputs of the model. A physical model is a transfer function. It transforms those inputs into outputs. When models couple the outputs of one become the inputs to the next. What are the macroscopic variables and boundary conditions - - *temperature, time, loads, etc.*? And at the heart of the model lie the physical mechanisms of structural change.

To construct the model use standard, familiar techniques using the modelling tools of engineering and materials science: equations of fracture mechanics, kinetics, dynamics. Exploit previously validated models of the problem using those tools. If parts of the process cannot be modelled introduce an empirical fit to the data (e.g., a power law) that can be replaced later by a better model when it becomes available.

The point is this: the physical model suggests the form for a constitutive equation (law), and for the significant groupings of the variables that enters it. Empirical methods can then be used to establish the precise functional relations between these groups. Finally, we arrive at a constitutive equation that contains the predictive power of micro-mechanical modelling with the precision of ordinary curve fitting of experimental data. In other words, input variables like maximum stress, stress range or stress amplitude, frequency, etc, and temperature, concentration of chemical species, damage-state, are all embedded in the physical model.

However, the model points to something else, and it is of the greatest value; it suggests the proper form that the constitutive equation should take. This physical model-informed empiricism has led to the development of a new branch of mechanics called *damage mechanics*. It is possible to add later complexity: 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 (damage) mechanics, more complex geometries require discrete methods.

The finite element method of modelling is an example. Here the material is divided into cells, which respond to temperature, body forces, and stress via constitutive equations, with the constraints of equilibrium, compatibility and continuity imposed at their boundaries. Internal material state variable formulations for constitutive laws are embedded in the finite element computations to give an accurate description of spatially varying behaviour. Ultimately, the aim is to develop a design tool that incorporates an initial material variability and operating environment to provide a *knock-down* factor that corresponds to a specified probability of failure.

Critical aspects include:

- 1) understanding of the expected load and environment for a particular structure based on a statistical description via a Monte Carlo simulation; and
- 2) development of a database of initial strength based on a Weibull distribution and residual (fatigue) strength evolution curves (the input) based on a stress analysis and structure evolution to support the “informed empiricism” of a residual strength model.

10 Final remarks

Composite materials are used increasingly in aerospace applications and designs and analysis methods are based on well-established design practices. Fifty years on from the discovery of the high performance carbon fibre, regrettably *black metal design* seems still to be the common word. Material and geometric non-linearity is not accepted as a common analysis method of composite structures. No-growth damage criteria are still applied, while post-buckling design has not yet been explored in composite wings. Bolted patch repair has become accepted as common practise for military and civil platforms.

And there remains a limitation on operational strains. The dilemma is that conventional analysis methods developed for metallic structures might be too conservative for composite structures.

A major difficulty in designing composite structures is how to predict damage initiation and damage evolution, and safe operating limits to ensure structural integrity. It is worth reminding ourselves that our comprehension of structural changes in composite materials, which take place continuously and cumulatively, is simply lacking in detail. That to predict a result, say lifetime or a stress response by a numerical method, there must be self-evident truth that the mechanism regime in which the component is operating must have been identified. In other words, the important design issues must all be embedded in the same model of material and component behaviour that also include the dominant mechanism(s) of structural change over orders of magnitude of size and time. This remains a difficulty.

Critical design issues that relate to anisotropy effects should take into account toughness and its manifestation in notch sensitivity. Weaknesses caused by anisotropy should be identified, such as de-lamination and transverse ply cracking, and de-bonding at interfaces. Mechanisms that govern inelastic strains and re-distribute stresses and diminish peak stress magnitudes should be understood.

Damage tolerance certification requires time-consuming, expensive testing. The consequences of changing composite lay-up and textile architecture are unpredictable and the complete test matrix for materials qualification would have to be repeated at the coupon level. In the design process, a key role has to be played by certain physical length scales in the failure process, which arises from de-lamination and splitting (shear) cracks, fiber rupture and fiber micro-buckling or kink formation, and diffuse micro-cracking or shear damage. All provide a rationale for making modelling decisions.

With the advent of powerful computers and software that can be purchased at reasonable cost, many of the physical models and computer simulations that would be cumbersome for design engineers to use, can now 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. And at the heart of the model lies those mechanism(s) best identified by direct observation. Ignore them at your peril.

Successful implementation of physical models or simulations requires knowledge of appropriate phenomena such as impact. Multi-scale modelling will arise because impact damage is localised and requires fine scale modelling of failure processes at the micro level, whilst the structural length scales are much larger. The solution is to use meso-scale models based on continuum damage mechanics in explicit FE codes that provide a framework within which failure processes can be modelled. Key issues currently under investigation include the development and implementation of: constitutive laws for modelling failures mechanisms; models for folding and collapse in composite sandwich cores; and materials models into FE codes.

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 in order to reproduce the outcome of a real test on an engineering structure? How frequently do we need to use NDT or NDE to inspect critical components for cracks? And then, what decision do we

make should we find a crack that might, after all, has turned out to be innocuous or sub-critical? How do we incorporate into the overall design process real time structural health monitoring that could be implemented in composite engineering applications and the possibility of a large crack being missed during inspection?

It is envisaged that new strategies for designing damage resistant and damage tolerant composite materials and structures may become available if we first develop and then synergistically combine new capabilities enabling in-service damage detection and characterisation, health monitoring and structural prognosis. The rapid development of numerical codes and experimental techniques make possible not only the robust modelling behind the design of advanced composites with improved behaviour in critical operational conditions but also for establishing sound, reliable SHM methods and strategies. The challenges include an integration of modelling the design of composite structures, as well as process modelling, together with SHM and repair strategies. Moreover, SHM may also promote a *self-healing* reaction in case of a particular damage event, maintaining structural integrity at least for a known period of time. The assurance of structural reliability of aircraft systems, for example, will greatly enhance confidence in their safety, reduce the probability of premature failures, and diminish the costs of operation and maintenance (see Further reading: ACMA Vol. 24 No. 2 April (2017)).

A word of warning: while carbon fiber is strong, stiff and light-weight, it does have an *Achilles heel* (re-call the RB211 story). Fairly recently, Professor Nicola Pugno of the *Laboratory of Bio-Inspired & Graphene Nanomechanics*, University of Trento, Italy fractured his right shoulder due to the sudden breakage of the carbon fiber frame of his bicycle due to poor material toughness. “In principle you can negate poor toughness of the carbon composite with hybrid composites like carbon/Kevlar”, said Pugno. However, Kevlar is not as strong as carbon fiber, so if Kevlar replaces some of the carbon to increase toughness then strength becomes compromised.

Frequently, compromise is the price paid by engineers (and politicians too!).

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This paper raises some important issues and ideas on *structural integrity of composite materials and structures* discussed most recently at The Royal Society’s Theo Murphy special *Research Discussion meeting* at Chicheley Hall, Buckinghamshire, England (see Further Reading: Phil. Trans. Part A (2016)). This was the latest of many *Research Discussion* meetings supported by the Universities of Cambridge, Sheffield and Manchester in the UK, and the Naval Postgraduate School and US Air Force Academy in the USA under the auspices of EPSRC, NSF, and EOARD London for which the authors are grateful.

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