COMPOSITES
THE DYNAMIC CONTRIBUTION TO VEHICLE PERFORMANCE

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In the past 40 years lightweight structures in motor racing have seen change from the first monocoque through the first aluminium honeycomb to the first carbon fibre structures. But over the recent past, the rate of change has slowed; perhaps the most innovative recent changes were Jaguar Formula One's adoption of new fibres (Zylon) and the successful introduction of carbon fibre gearboxes. Meanwhile civilian and defence projects have encompassed every fibre so far contemplated, virtually every matrix from thermosets through thermoplastic to metals and ceramics and now to molecular composites.

The design and manufacture of composite structures for both ground and air vehicles has tended to centre on the search for lightness, torsional and beam rigidity and, to some extent, resistance to impact.

To follow this path ignores the key role that a composite structure of any sort plays in the dynamics of the vehicle as a whole, and of its parts. A composite structure can influence dynamic behaviour, from aero loads to fundamental ride/handling/traction aspects of a race car. To take full advantage of the opportunities and to avoid the undoubted pitfalls demands a considerable shift in the techniques of design, analysis and manufacture from the "black aluminium" approach that is still employed. To apply design technology optimised for metals to materials that behave in entirely different ways militates against efficiency.

The approach we adopt starts from an understanding of what a composite structure is, whether it be a crude and complex metal and timber bridge or the most sophisticate molecular composite.

A composite is a structure where an optimised specialised element handles tensile loads and a second, different material handles compressive loads. In terms of carbon fibre structures for example, the carbon fibre can handle tensile loads whilst the matrix material is loaded in compression to provide load distribution between the individual fibres, as well as fulfilling some compressive stability requirements. Despite the simplicity of the definition, the effects of the interaction between tensile and compressive members, and the influence on the overall performance of manufacturing techniques present an enormous range of design solutions.

Advanced materials allow a composite structure to be designed to meet a need with minimal compromise. The proper use of these materials provides a new series of engineering solutions that integrate the design of materials, of the composite combination of materials, of tooling and of manufacturing process.

In contrast to manufacturing in conventional materials, the system is closely coupled and failure to complete or integrate any stage seriously damages the functional and economic efficiency of the result.

A major objective of the design process is to engineer the material solution. Rather than qualifying a material for general use, the appropriate route in composites is to design a qualified part using a composite materials solution uniquely appropriate to that part. The material solution can be arrived at one of a number of levels that range from describing orientation and structure at a molecular level to grosser parameters related to fibre orientation or laminate descriptions.

In any solution however, the main load-bearing element is normally based on a highly oriented macromolecule, and for convenience and handling converted into a fibre or whisker.

As far as is possible, load bearing fibres in composites must be arranged in straight lines, parallel to the load path. Thus, the design process starts with a determination of loads, considered in abstract.

The load paths that result from this consideration determine both the directions and the dimensions of the fibre bundles that make up the load-bearing element of the composite.

This information ultimately determines the shape of the structure: it also determines the information needed to create a pre-form. From the information of the magnitude of the load cases and from the environmental conditions in which the fibre will operate, a rational choice of load carrying material can be made. Similarly, from information as to the operating environment, as to load cycling and as to ultimate performance, a sensible decision as to a matrix material can be made.

Analysis of the performance of a part is complex. In molecular materials, a polymer will orientate along lines of applied force, changing from an amorphous state to a crystalline state over time and, consequently exhibiting some degree of creep. However, the ability of the fibre structure to absorb work cycles is effectively infinite provided that the inter-molecular cohesive forces are not exceeded.

To repeat myself: the mechanism by which the matrix transfers load is complex. Essentially, the matrix is always under compressive load and therefore fails in buckling; the resistance to buckling is proportional to the square of the effective column length. It is therefore clear that matrix performance is monotonically related to the square of fibre volumes, reinforcing the importance in all composites of maximising fibre volumes.

The design process is obviously very different from that prevailing in metals regimes. At a macro level, loads must be analysed in the abstract - in a way much more akin to an analysis of a pin jointed structure - in order to create the fibre runs and quantities necessary. Discontinuities in fibre structures must be avoided and, as far as is possible, unidirectional fibres utilised.

At a micro level, the actual performance of the matrix can be analysed. In the case of polymeric matrices, analysis of the molecular behaviour is advantageous so that manufacturing technology and tooling can be designed to minimise creep or other alterations under load. In metal matrix components in particular, the ductility of the matrix and the differential thermal expansion between the matrix and the fibre require careful consideration.

The most important design discipline is to integrate initial load analysis with part design, with material choice and with tooling and process design. Increasingly specialised mathematical modelling is required that can integrate analysis of loads and performance at a micro-level with pre-form toolpathing, with tool design and that can handle the complex orientation and flow influences that extend from the inherent material property to the achieved part property. The part property is the sum of materials, tooling, method and shape considerations where the number of variables is infinitely greater that it is with metal solutions.

Any composite structure has a significant impact on its dynamic performance. A tree is a classical composite structure: the fibre/matrix relationship is adapted to meet the dynamic requirement of the species. The wing structure of the proposed NASP aircraft is a classical, complex composite that is designed to react to changing aircraft dynamics so that the wing can alter from a negatively stable device to a positively stable device when wing loadings reach certain levels. Composite structures in nuclear powered submarines have dynamic reactions that would be impossible in homogenous structures and where the black aluminium approach would fail.

But because a composite structure does perform entirely differently from a homogenous material it demands fundamentally different design protocols and approaches.

The goal is to optimise the material properties by design. Working in composites, that means a change from the accepted norm of describing a shape as a solution and then optimising that shape to meet material objectives. The composites route is to define the load cases for the structure or part and to construct an un-restrained pin-jointed model of the load case within the overall size constraints. The resulting model is then optimised in terms of ensuring that the elements carry tensile loads and that their arrangement produces as little instability as possible.

Constraints are then applied to the nodes to ensure that the system is stable within all load conditions.

At that stage, the tensile members represent the fibre performs and the selection of the appropriate fibre can be made based on this information. In the same way, the matrix selection is made based on the compressive values required to ensure nodal stability. The matrix selection and the extent of the constraint volumes can be best selected with a view to the other parameters imposed by temperature in use, by manufacturing constraints

What is very clear is that the optimum structure demands the use of highly oriented uni-directional fibres, regardless of the composite and regardless of the materials. That does not necessarily mean that broad goods cannot be used: inter-laced materials, multi-ply unidirectionals with surface plies of bi-axial cloth and even three dimensionally braided pre-forms all play a role and all have been used efficiently.

What we have come to mean in composites is an arrangement where one element of performance is predominant and for our purposes that means a structure where the principal loads are taken in tension in specialised high tensile materials.

It also means that structures where fibres are used to improve performance...fibre reinforced metals, glass reinforced plastics...aren't really composites in our definition.

The key objectives remain to maximize structural efficiency in strength to weight ratios, in strength to size ratios and in strength to cost ratios.

Inevitably, this must lead to the adoption of design methods, manufacturing systems and material solutions intended to reduce the load distributive matrix material to a minimum and maximise the load bearing materials.

In composite materials this search for structural and economic efficiency implies fibre proportions of the order of 70% by volume at a minimum.

[In molecular composites, genuinely advanced materials, it implies high proportions of oriented molecules and a lower proportion of amorphous molecules.]

The load distributive matrix of any composite is only loaded in compression and it fails as if it were a column in buckling (Euler) mode. That means that the effective column length of the matrix that is, the distance between fibres governs the performance of a composite. Since resistance to buckling is inversely proportional to the square of the length of the column, any divergence from idealized fibre packing rations reduces the performance, increases the overall size and adds to cost. If the geometric packing ideal is 90% fibres, then making a part with a fibre volume of 80% means that the part has roughly one quarter of the strength of the more densely packed variant. That is, your part is now four times as big, more than four times as expensive and much more prone to micro-cracking.

The portfolio of materials (of fibres, whiskers, matrices) that is available is extremely wide. However, the ability to produce usable parts with high levels of efficiency, repeatability and quality control requires urgent development if the economic and engineering potential of these materials development are to be met.

The most rewarding approach is to seek a better understanding of the behaviour of structures at a molecular level so that the real load carrying capability can be determined, processing and tooling regimes designed to maximise performance and a consistent result obtained.

Composites, by and large, are made up of macro-molecules and, as such, have peculiar performance characteristics not shared by, for example, metals. Generally, a macro-molecule will change its shape when it is subjected to energy inputs. For example, protein macromolecules effectively uncoil when they are heated...changing from amorphous towards crystalline...which is why custard can be made. In polymers, this behaviour results in changes in structural performance and in the phenomenon of creep, where the shape of a structure can and will change over time. However, composites share with natural materials the benefits of longevity. Oak, for instance, which is a high performance composite if there ever was one, has an almost infinite structural life and a performance which improves with age as the fibre volume increases.

A composite structure can have an almost infinite fatigue life if properly designed and if it is stressed within limits. Composites can exhibit characteristics of fatigue, but these reflect poor manufacturing techniques rather than an inherent character of the material and the conventional fatigue life calculations (Tsai etc.) relate to poor manufacturing methods not to inherent fatigue within the structures.

However, the reverse of the coin is that failure in a composite structure is catastrophic in its nature and where a structure has been designed with maximum economy, that failure will be more delineated.

The methods of failure are not widely understood. As stated, the accepted failure life predictions (Tsai-Chin etc) are based on Hill’s progression which postulates a ‘sequence of events’ assuming an original locus of failure. That is acceptable in predicting failure based on poor manufacturing process and was entirely appropriate thirty years ago. However, our manufacturing and materials techniques should now allow us to avoid these manufacturing pitfalls, whilst improving non-destructive testing improves quality and repeatability.

The single most common and critical cause of failure is too high a matrix proportion. That cannot be over-emphasised. However, the causes of failure start in the design process. Composite structures do not resist compressive loads. They can be designed so that, for example, a tubular structure can, as a structure, be loaded in compression whilst the material is loaded in tension, but where compressive loads predominate, composites are inherently unsuitable. For example, where a connecting rod is designed for an engine, the correct approach is to use fibre composites to handle the tensile loads and ceramics such as silicon carbide to handle the compressive load.

However well designed the load inputs may be, it is impossible to ensure that the load is equally spread over all of the fibres. As a result, the load distributive matrix is always but unevenly loaded in compression and where the effective length of the matrix column is excessive progressive failure occurs. This is normally characterized as micro-cracking, but it is in fact localised buckling failure.

Minimizing effective column length obviously minimizes the effects of creep. Creep occurs where there is a gradual change in the conformation of a molecule. Where the molecules are fully orientated and fully crystalline [that is, in their longest form and with minimum rotational frequency] they are dimensionally stable in tension. However, matrices do not exhibit those characteristics and will change their dimensional characteristics under load.

Where a composite part is well designed and well made, it will suffer non-progressive, catastrophic failure if the tensile capacity of the fibres is exceed. Where woven or knitted fibre forms are used this failure is exaggerated because of the stress raisers inherent in the points where the fibres cross over. Multi-axial forms (for example, MASS) where the layers of uni-directional material are stitched together are a preferable form. Alternatively uni-directional tapes can be used but the formatting problems in thermosets are formidable. Perhaps the best solution is the adoption of interlace formats, although these are not widely available. Interlacing lends itself to integrated manufacturing however.

Incidentally, there is no automatic benefit in a balanced lay-up; indeed, very often a balanced lay-up is not desirable especially where a neutral axis replacement such as foam or honeycomb is used.

It is, as we all know, entirely within our theoretical technical capability to produce components of outstanding performance. In doing so we must take into account very real differences in material performance. For instance, a considerable increase in stiffness may well mean that compliance in mounts elsewhere in the machine may have to be closely re-examined. Changes in inherent sound and vibration damping exhibited in composite, high fibre volume structures produce other problems. Reduction in structure weight has serious dynamic and control consequences demanding new ride/handling solutions and fresh approaches to traction controls.

The inherent damping characteristics can be valuable: the acoustic tiles for US nuclear submarines are complex thermoplastic matrix constructions with good broadband dynamic damping.

Lightweight airframes, capable of high speed, have serious control issues. The vehicle has reduced inertia and is almost inevitably dynamically unstable at certain points within the envelope. One solution is to stress the flying surfaces so that as wing loadings exceed the design envelope, the wing shape changes to restore dynamic stability: an old, old solution lost with the move from wooden wing spars to metals, rediscovered to solve a modern problem.

The automotive industry has special problems. As platforms become lighter, the relation of laden to unlade weights covers a far greater span, to the point where conventional suspension, however sophisticated, is unacceptable towards the extremes. One solution is to move from displacement related suspension to velocity related, where wheel rates rise with wheel velocity.

The adoption of composites, especially where there is an established benchmark for the artefact, requires an overall vision. The solutions can be complex…or simple. The requirement for compliance can be achieved by judicious use of highly amorphous, elastomeric matrices at critical points in the load path.

The choice of toughened thermoset resins for safety critical structures can and frequently does have a seriously damaging influence on overall vehicle dynamics. Most toughening systems rely on the introduction of micro- or nano-speheres of a thermoplastic to provide greater resistance both to the micro-cracking induced by column buckling of the matrix and to grosser impact or excessive compressive load damage. However, all thermoplastics have the property of reducing viscosity as a result of high shear loads and some of the more common toughening agents derived from poly-sulfones exhibit this characteristic to a very considerable extent.

The result is that when high loads are applied very sharply, the load travels through the structure creating a high shear front which in turn can significantly reduce the stiffness along the shear plane. The consequences on a vehicle's dynamics are, of course, considerable quite apart from the dangerous possibility of catastrophic or even progressive failure as a result of this phenomenon.

It also points up the issues of the ways in which loads are fed into the structure. A common practice has arisen whereby adhesively bonded joints are used. Joints of this nature introduce loads into the top laminate and as a direct result introduce inter-laminar shear. The joint is inherently unstable and the concentrated load case that results increases the matrix instability in the case of sudden loadings. The use of these joints in aerospace is far more acceptable; aerospace applications with very few exceptions do not experience the sudden loadings characteristic of race and rally cars. (Bouncing the ATF tail first across the desert may be seen as an exception, but the material used was a thermoplastic matrix carbon composite where the matrix material is polyetheretherketone. As a result of the processing technology used, the matrix is almost entirely crystalline and has much greater resistance to viscosity (which are only conformational) changes).

Where high transient and instantaneous loads can be expected the preferable method to minimise transient instability is to use compressive, large area joints: typically, where the load bearing composite is sandwiched between the load input member and a clamping plate.

Whilst the relatively minor geometric changes that can result from the share behaviour of the matrix may be of less importance, the inherent damping performance of a composite structure is more critical. The vertical vibration induced in a tyre especially under braking or acceleration loads is considerable.

Spring/damping systems are not normally capable of damping this small amplitude (up to 5mm of vertical movement) and the relatively high frequencies. The frequency is dependent on the sidewall depth as well as the sidewall construction. As a result, the vehicle structure is required to provide a degree of inherent damping. The damping of the structure has been investigated exhaustively and over many years with particular reference to submarine vibrational and acoustic damping. The inherent damping is proportional to the density of the matrix/fibre interface.

The impact of a very stiff, undamped structure on vehicle dynamics is fairly obvious. If the vertical movement is transmitted, undamped, to an aerosurface, at the typical frequencies of around 1 kilohertz, downforce will be significantly reduced. Since the front tyres generate the largest vertical displacement under braking, and the rear tyres under acceleration, the result in extreme circumstances can be understeer into a corner and oversteer through and out of it. Unfortunately trying to tune that characteristic out of the aero-package tends to be a pointless and sometimes self-defeating exercise whereas the problem and the solution need to be addressed at the structure design stage.