What new analysts should know about COMPOSITES

Recent additions to FEA software make it easier to find stresses and strains in composites.

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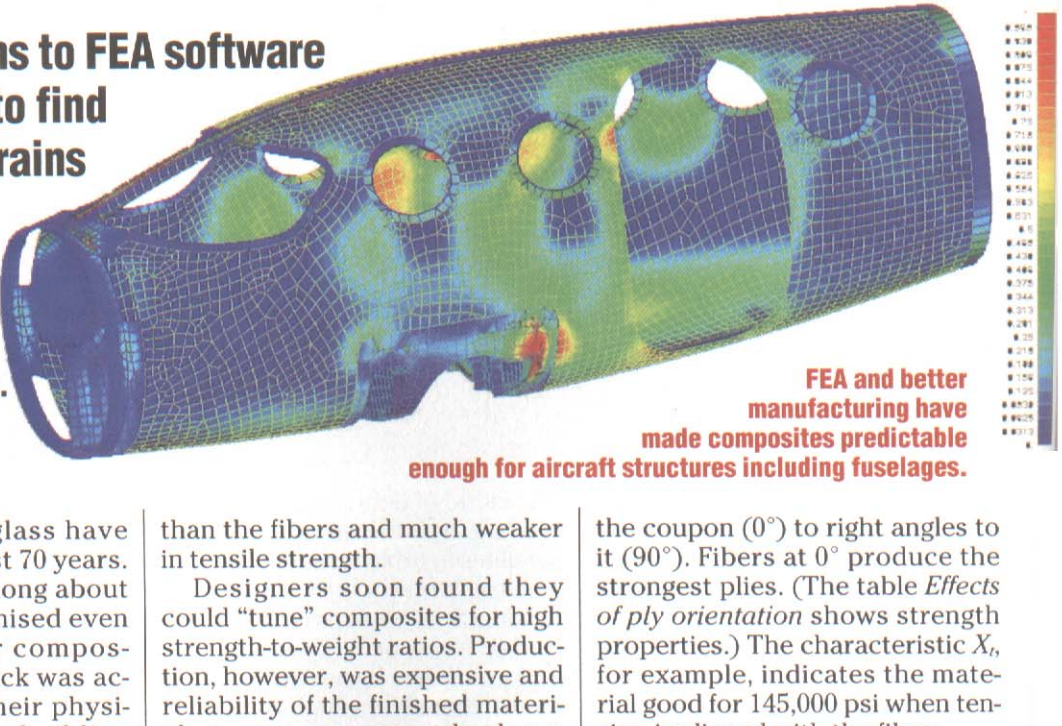


FEA and better manufacturing have made composites predictable enough for aircraft structures including fuselages.

Composites of fiberglass have been around for almost 70 years. Carbon fibers came along about 20 years ago and promised even lighter and stronger composites. The only drawback was accurately predicting their physical properties before building and testing prototypes. Analyzing them once amounted to just running through closed form solutions.

Today's FEA does a better job. But before getting into simulations, it's useful to review how the materials are made, and see why accurate analyses have been slow in coming.

COMPOSITE PRIMER

Aerospace engineers were the first to use carbon and boron-fiber-reinforced materials. They are a mixture of brittle but strong fibers imbedded in a resin or binder. The resin is more ductile than the fibers and much weaker in tensile strength.

Edited by Paul Dvorak

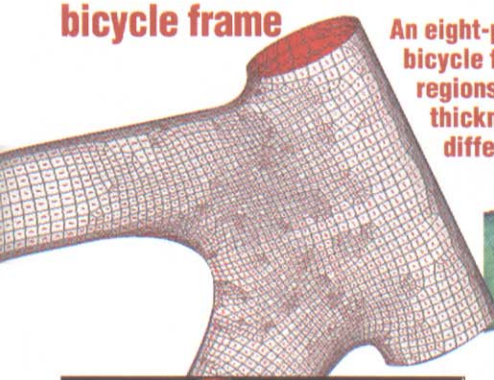
Designers soon found they could "tune" composites for high strength-to-weight ratios. Production, however, was expensive and reliability of the finished materials was unproven under long-term loading, environmental damage, and handling. The early promise of radically stronger materials was broken because outside the lab, fiber and resin matrices could not maintain the strength of the fibers. It took a further period of test, analysis, and development before composites were accepted and understood.

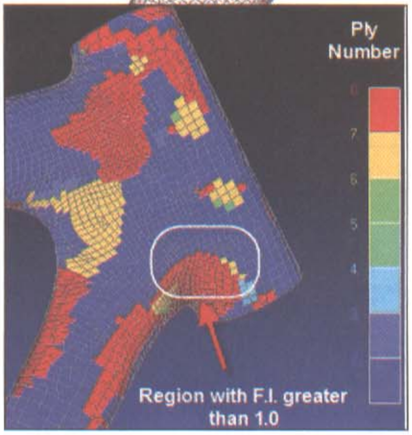
One thing that has not changed: experimental strength data comes still from testing coupons. These samples have fiber orientations defined relative to a coupon's long axis. Testing loads it on this axis. To show effects of fiber orientation, a series of FE simulations were run on computer models of designs with fibers varying from aligned with the coupon (0°) to right angles to it (90°). Fibers at 0° produce the strongest plies. (The table *Effects of ply orientation* shows strength properties.) The characteristic X_1, for example, indicates the material good for 145,000 psi when tension is aligned with the fiber.

The curve in *Load versus ply angle* shows the full allowable stress (X_1) is obtained up to the failure load. This is because the fibers are carrying the load in the most favorable manner — along the axis. The resin stabilizes the fibers without carrying significant load. Stress at right angles to the fiber direction, X_2, tends to pull fibers apart. But because everything is symmetric at this orientation, transverse stress, X_2, and shear stress, X_{12}, are zero.

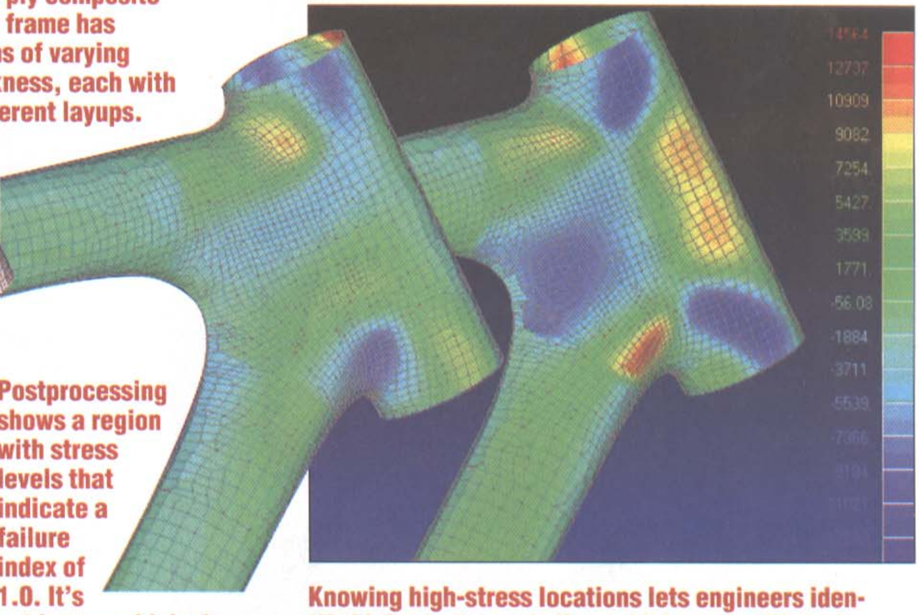
The plot shows strength drops rapidly after turning the ply even a few degrees from zero. At 10°, for example, stress at failure is down to just over 40,000 psi. That's because at 10°, fibers are subjected to transverse stresses.

Stresses in a bicycle frame


An eight-ply composite bicycle frame has regions of varying thickness, each with different layups.



Postprocessing shows a region with stress levels that indicate a failure index of 1.0. It's not known which ply failed or the failure mode, but their locations on the structure are evident.



Knowing high-stress locations lets engineers identify highest-stressed plies, which are in either ply 1 or 8. The layup is symmetric, and these locations represent the outer 0° plies, top and bottom surfaces. The third image shows X_t stresses. The right frame shows transverse stresses

The resin and fibers have to balance applied stresses. The weaker transverse strength of the resin reduces material strength. The table shows an allowable transverse tension of only 4,500 psi, Y_t, which is mostly resin strength.

At intermediate angles, loads generate longitudinal, transverse, and shear stresses. The first two can be in tension or compression. A failure theory analogous to Von Mises stresses for isotropic materials can predict failure.

Engineers would seldom use unidirectional layups unless loading was guaranteed to be along the fiber axis. More likely, a composite would be made of several layers with the fibers at different angles to handle a variety of loads. So a six-layer material could be defined with sequence of angles:

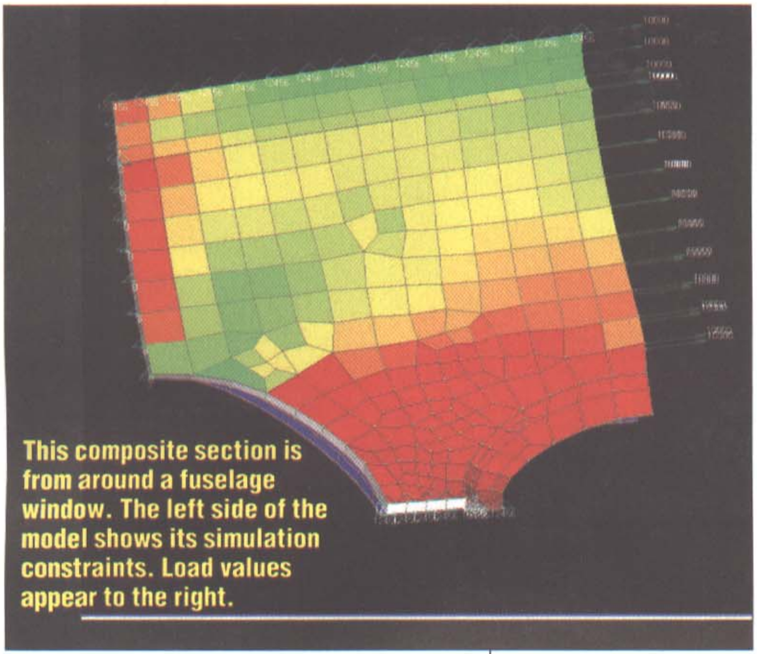
[0/90/–45/45/90/0]

This says the top and bottom layers would be at 0° or aligned with the axis, and the middle two layers would be at ±45°, and so on. The thickness of each ply would also be defined. Such a layup would handle transverse loading because of the 90° fibers, as well as shear loads because of the ±45° fibers. The actual mix of layers and angles depends on the anticipated loading. The layup would couple in-plane and out-of-plane loads because it is not symmetric about the central thickness plane. There is a 45° layer on one side and a –45° on the other

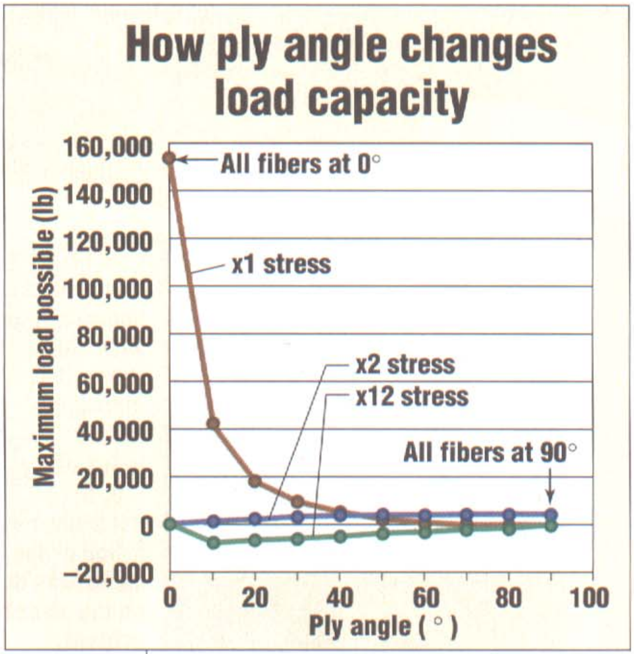
Material properties for a glass-epoxy laminate

Characteristic	Name	Value
Modulus in the fiber direction	E_1	5.6×10^6 psi
Modulus 90° across the fibers	E_2	1.2×10^6 psi
	G_{12}	0.6×10^6 psi
Poisson's ratio	Nu_{12}	0.26
Allowable stresses		
Maximum stress along the fibers	X_t	154×10^3 psi
	X_c	88.5×10^3 psi
	Y_t	4.5×10^3 psi
	Y_c	17.1×10^3 psi
Shear	S	10.4×10^3 psi
Allowable strain along fibers	e_1	0.008 in.
Allowable strain across fibers	e_2	0.004 in.
	g_1	0.008 in.


Single-ply coupons with varying orientations could have the characteristics shown. The coupon is 30 × 10 × 0.1 in.



This composite section is from around a fuselage window. The left side of the model shows its simulation constraints. Load values appear to the right.



How ply angle changes load capacity

side. So pulling on a beam of this design would bend and twist it, a phenomena called extensional loading. Extensional coupling also produces an axial response from a bending load.

To avoid this, symmetric layups are often used. For example:

[0/90/–45/45/45/–45/90/0]

This symmetric layup avoids bending and extensional coupling. The design is a special class because it has a balanced layup. Each 0° has a 90° mate and every –45° has a 45° mate. The layup also avoids in-plane coupling and doesn't distort from shearing modes generated by axial loads.

Conversely, engineers may *want* coupling in the structural design. Forward-swept wings, for example, can be designed so that bending twists the wing tips up to avoiding structural coupling that may induce flutter.

MANUFACTURING METHODS

Examples so far are simple layups that could be made from prepreg sheets. These are sheets of fibers preimpregnated with resin. Manufacturers cut the sheets to shape and assemble them on a mold. They are put in an autoclave and heated under pressure. Resin fills voids between sheets and flows to form a continuous matrix of resin and fiber.

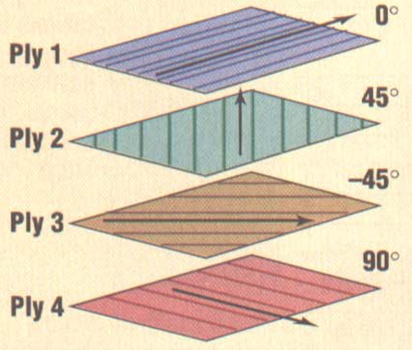
Other fabrication techniques include:

- Hand layup of fiber in a cloth or weave over a mold, which then has resin manually applied.
- Filament winding wraps material around a mandrel with individual fibers bathed in resin. This can be a simple cylindrical linear winding or a complex, tapered, and nonlinear shape.
- Manually or machine laid tapes form overlays and joints.
- Resin-transfer molding uses high pressure and temperature to make complex parts.

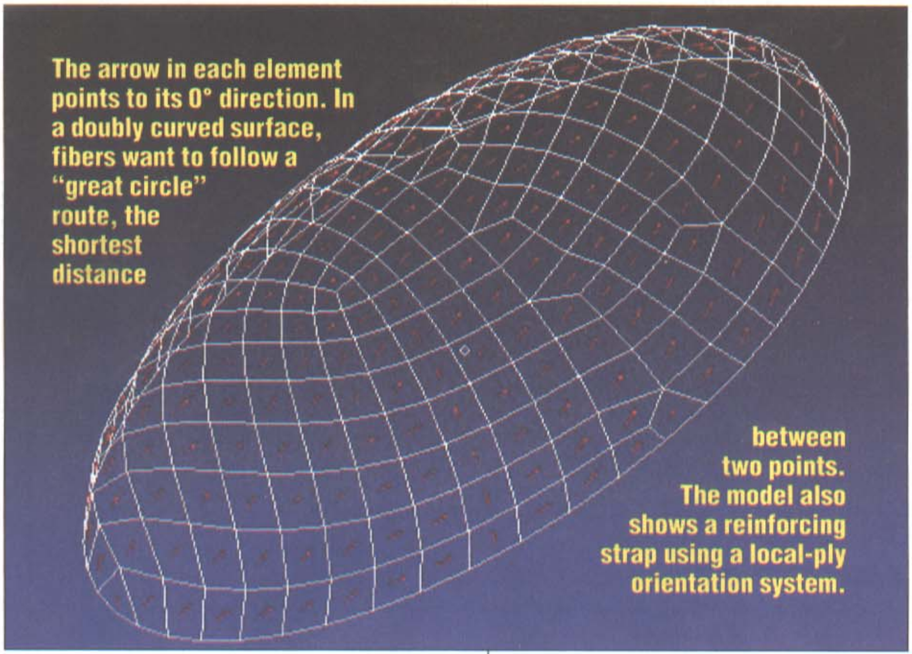
PUTTING FEA TO WORK

A sample analysis shows how FEA works on composites and illustrates a few recently developed features.

A four-ply laminate



A typical laminate, or layup, is made up of individual plies. Each has fibers laid in a specific orientation and held in place by a resin matrix. The 0° angle is aligned with the coupon and 90° is transverse to it.



The arrow in each element points to its 0° direction. In a doubly curved surface, fibers want to follow a "great circle" route, the shortest distance between two points. The model also shows a reinforcing strap using a local-ply orientation system.

An intro to the "tropics"

Engineers should familiarize themselves with a few terms that characterize composites. For instance, *isotropic* structures such as steel have the same material properties in all directions. A material referred to as *anisotropic* has different material properties in all directions. A chunk of volcanic rock is one example. And *orthotropic* materials have almost uniform but different properties along its three axes. Composites are usually orthotropic. Properties come from the fiber and resin matrix, which differs in long, transverse, and through-thickness axis. A further simplification is *2D orthotropic*, which ignores through-thickness variations.

First, define the material properties. These are more complex for orthotropic materials such as composites. The *FEA input form* shows how it groups stiffness and strength properties.

Define ply layup. It is important to describe the ply stacking sequence.

Define the reference angle. Sheets of prepreg are placed on a structure either lengthwise, edgewise, or at some angle. The angle affects analysis results. Of course, a structure's fiber orientation can be complex, especially in doubly curved surfaces where fibers want to follow "great circle" routes — the shortest distance between two points. FEA programs such as NEiLaminate Tools perform draping analyses to cal-

Hill

$$\frac{\sigma_1^2}{x^2} - \frac{\sigma_1\sigma_2}{x^2} + \frac{\sigma_2^2}{y^2} + \frac{\tau_{12}^2}{s^2} = I_{failure}$$

A few theories on failure

In a composite, each ply can have stresses in tension or compression, either along fibers or transverse to them, and in plane and transverse shears. A failure criterion is needed to determine whether each ply is near failure. Early methods used simple rules such as maximum stress or strain. Maximum strain is still useful for an overall design check, but stress theories have become more sophisticated. They now take into account differential effects of direction and sign.

Hoffman

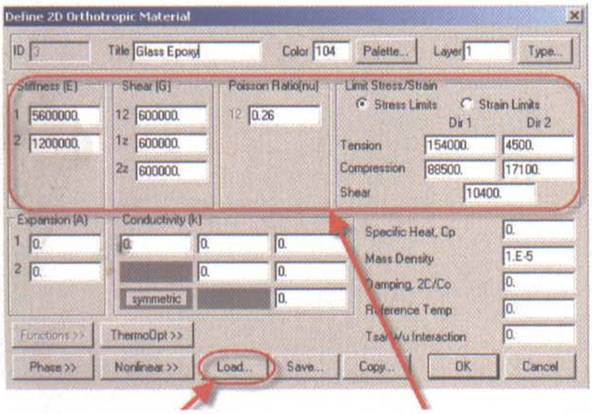
$$\left(\frac{1}{x_t} - \frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t} - \frac{1}{y_c}\right)\sigma_2 + \frac{\sigma_1^2}{x_t x_c} + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{s^2} - \frac{\sigma_1\sigma_2}{x_t x_c} = I_{failure}$$

Tsai-Wu

$$\left(\frac{1}{x_t} - \frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t} - \frac{1}{y_c}\right)\sigma_2 + \frac{\sigma_1^2}{x_t x_c} + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{s^2} + 2F_{12^{\sigma}1^{\sigma}2} = I_{failure}$$

One widely used failure method, Tsai-Wu, requires an experimentally derived term, making it unreliable if good material data is not available. More recent forms, such as Puck or NASA Langley Larc02, provide alternatives. Both of these are supported in NEiNastran. They take into account fiber direction and sign, but avoid extra terms.

Another useful extension is a failure-index form in which anything greater than 1.0 denotes failure. The index is nonlinear and it is difficult to make quantitative judgments based on it. A strength-ratio form treats anything below 1.0 as a failure. The strength ratio has the distinct advantage of being linear, so if it is 0.5, you might first consider doubling material thickness.



Define 2D Orthotropic Material

ID: 3
Title: Glass Epoxy
Color: 104
Layer: 1

Stiffness (E)		Shear (G)		Poisson Ratio(nu)	
1	5600000.	12	600000.	12	0.26
2	1200000.	1z	600000.		
		2z	600000.		

Limit Stress/Strain: ● Stress Limits ○ Strain Limits

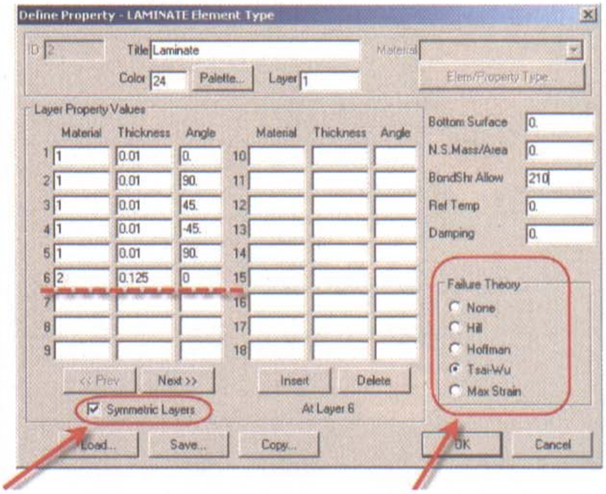
	Dir 1	Dir 2
Tension	154000.	4500.
Compression	88500.	17100.
Shear	10400.	

Expansion (A): 1: 0. 2: 0.
Conductivity (k): 0. 0. 0. / 0. 0. / 0.
Specific Heat, Cp: 0.
Mass Density: 1.E-5
Damping, 2C/Co: 0.
Reference Temp: 0.
Tsai-Wu Interaction: 0.

Library of previously used composite lay-ups

Stress and stiffness terms

A 2D orthotropic material is defined in NeiNastran through this window. Values come from the material manufacturer or testing.



Define Property - LAMINATE Element Type

ID: 2
Title: Laminate
Color: 24
Layer: 1

Layer Property Values

	Material	Thickness	Angle		Material	Thickness	Angle
1	1	0.01	0.	10			
2	1	0.01	90.	11			
3	1	0.01	45.	12			
4	1	0.01	-45.	13			
5	1	0.01	90.	14			
6	2	0.125	0	15			
7				16			
8				17			
9				18			

☑ Symmetric Layers
At Layer 6

Bottom Surface: 0.
N.S.Mass/Area: 0.
BondShr Allow: 210
Ref Temp: 0.
Damping: 0.

Failure Theory: ○ None ○ Hill ○ Hoffman ● Tsai-Wu ○ Max Strain

Symmetry is switched on to easily define layups.

Choose one of four failure criteria.

The input window for NEiNastran Modeler shows a six-ply composite. After defining the stackup, the recipe can be copied, modified, and stored to a library for reuse.

culate the continuous variation in orientation angle.

In other cases, software can project cylindrical or spherical coordinate systems onto structure surfaces to produce a reasonable representation of ply orientation.

Represent the outer mold line. It is important to visualize the relative thickness and positions of shell structures so they can be modified as simulations reveal shortcomings.

Postprocessing. Once analysis completes, results must go to postprocessing. There is a lot of data involved in complex layup and multi-ply structures, so clear presentations needs logical approaches.

To get a feel for actual stress distributions, look at them for longitudinal, transverse, and shear directions. The combination of stresses in the X_1, Y_1, and XY directions contribute to the failure index. The bicycle frames in the accompanying images uses the NASA Langley Larc02 method, which takes into account tension, compression with and transverse fiber, and shear terms. **MD**

A few applications for composites

Athletes often demand high performance from sporting equipment such as fishing rods, ski poles, bicycle frames, and gym equipment. Materials used in the sporting industry vary widely both in fiber and resin types. Glass fibers are often used as an alternative to expensive, high-strength carbons. And Kevlar may be used because of its toughness.

The analysis also varies in a similar way. Many applications are built on experience and testing. Other designs need FE analysis. There's often natural synergy between a company's practical experience with this product and manufacturing methods and the FEA's predictive capabilities.

Forensic analysis is one way to improve product design and reduce physical testing. In this phase, past design failures are compared to analysis, and then analysis is put into the design cycle.

The marine industry has been using composite fiberglass and plywood hulls for years, well before the aerospace industry. Hull designs initially used proven experience rather than formal analysis. A wide range of vessels — from dinghies to aircraft carriers — now use formal analysis to get the best out of designs.

Racing cars have been the significant force in the automotive industry. Formula One, which dominates European racing, has been aggressively using advanced composites for years. Sophisticated analysis tunes the racing-car tub for stiffness and energy absorption. The remarkable strength-to-weight ratios and durability of these structures are testament to the long involvement with high-end analysis and testing of composites.

Mainstream automotive industry has seen little uptake for major structural parts, because of production and cost issues. It is only when performance is the goal that carbon composites are used. A curious anomaly was in the production of cheap, high-volume fiberglass cars in Europe in the 60s and 70s. Safety considerations and a higher demand for comfort saw to their decline.

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