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Ford's safety experts talk exclusively about crash testing under the One Ford philosophy

Pedestrian impact

How Euro NCAP's tougher scoring system is driving up standards

Carbon fiber

The long road to predicting the crash behavior of composite materials

Rollover innovation

The National Crash Analysis Center's new proposal for repeatable rollover testing

CRASH TEST ZONE

A look ahead to the innovative crash test technology at Automotive Testing Expo North America

CASE STUDIES

The safety development programs for the Volvo V40 and Mercedes-Benz GL

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Carbon footprint

Road cars are moving ahead of their racing counterparts in many areas of composite technology, but carbon crash structures have yet to make the jump from track to street

WORDS BY GRAHAM HEEPS

In 1981, the McLaren MP4-1 became the first complete carbon-fiber composite racer to compete in the Formula 1 World Championship. Skeptics were quickly won over, first by the car's speed, and then by its safety. Following John Watson's high-speed crash through the Lesmo curves at the 1981 Monza GP, the rest of the grid was quick to play catch-up.

The following three decades have seen composites and motorsport develop a symbiotic relationship that has advanced both industries, with speed and safety remaining the key drivers. Now, in an era of carbon-fiber airliners and the 2013 launch of BMW i3 and i8 touted as the moment when composite structures will truly cross into the automotive mainstream, it seems that motorsport is no longer at the cutting edge of composite material development.

"What's happening in automotive is similar to what we've seen in aerospace," says Paolo Feraboli, a research associate professor in the Department of Aeronautics and Astronautics at the University of Washington, and the

Lamborghini built the Sesto Elemento ('Sixth Element') as a showcase for what's possible with carbon-fiber structures

director of the Automobili Lamborghini Advanced Composite Structures Laboratory (ACSL). "Originally, the innovations were for military aircraft – the F-22, B-2, and the like. Times have changed, economies have changed, and the technology has matured. Now the innovations come from the commercial side of aviation. Similarly for automotive, where originally motorsport was the driver for innovation because of cost, production methods, and so on, now the real innovation is coming from mainstream passenger vehicles and/or high-end cars such as Lamborghini."

Road cars are leading the way when it comes to composite process and production breakthroughs, as already witnessed by developments such as Mubea Carbo Tech's industrialized tooling for the McLaren MP4-12C's carbon tub, or, more dramatically, the opening of the factory in Moses Lake, Washington, USA, that's a joint venture between SGL and BMW Group. This US$100 million facility is churning out raw material solely for use in carbon-fiber reinforced plastics (CFRP) in the forthcoming BMW i3 and i8 road cars.

Case study: Lamborghini Aventador

The first road car to emerge from Lamborghini's collaboration with Boeing and the University of Washington is the Aventador supercar, which hit the market in 2011, and features a carbon-fiber monocoque.

"The ACSL laboratory and other facilities around the world mean that we are now able to simulate the crash behavior of the carbon fiber material based on technology that is really unique and used only in the aeronautical field," explains Maurizio Reggiani, Lamborghini's director of R&D.

"We use a building-block approach. To simulate the monocoque of the Aventador we probably built around 10,000 coupons of different materials, different technologies, in order to simulate, part by part, every single item. This is the knowledge that we at Lamborghini have built, and now we have the capability to predict the dynamic behavior of every single element of the carbon fiber [structure]. With the laboratory and the partnership with Boeing, we can say that we are the leader in this kind of simulation of carbon fiber material."

Reggiani adds that PAM-Crash simulation software is used by the company, along with a package developed by Boeing itself. The stumbling block is not the availability of suitable software, however; it's the need for reliable and comprehensive material characteristic data."Being able to simulate something that is not linear like metal is, depends on different kinds of issues, not only the angle of the fiber, but also the kind of resin, the kind of geometry you use, the kind of technology that you use to produce the material," he says. "In one place you might have braiding technology; in another, pre-preg with braiding inside; in another, RTM-Lambo [the company's patented resin transfer molding process]. Only by building the characterization of the material, part by part, joining it together and re-simulating it, are you able to simulate all these different technologies. And every time you run a simulation you must also make a physical test to prove that what you have simulated is in line with what you have predicted.

"This starts from a small piece and you get bigger and bigger – 1,000 of this piece, 2,000 of this piece. Then you make this piece with another technology, you re-simulate it, and you test it. And only once you have this database of knowledge can you make a total simulation of a chassis – in terms of crash behavior, in terms of side pole impacts, in terms of rolling of the chassis – otherwise it is guesswork. And I can say that [for Aventador], when we did the crash homologation, we were able to achieve 100% alignment between the simulation and the real crash."

Reggiani estimates that his engineering team carried out six or seven physical crashes and around 100 full-car simulations during the Aventador's development.

ABOVE: The recent Lamborghini Aventador features a carbon occupant cell, but combines this with an aluminum crash section

But as pioneering as BMW's newcomers will be, not even these models will employ carbon-fiber crash structures front and rear; aluminum will be used instead as part of the 'Drive' module, with the CFRP 'Life' module forming the passenger cell. Of the four road cars that currently boast a carbon-fiber monocoque (MP4-12C, Lamborghini Aventador, Bugatti Veyron, and Lexus LF-A), only one of them (the Lexus) has some of its crash structure made of carbon.

Motorsport thus remains ahead of mainstream automotive in predicting the crash behavior of carbon fiber, with Engenuity's crush-test rig for characterizing composite material behavior and C-Zone crush-prediction software among the products at the forefront of this field.

"The noses on several 2012 F1 cars are, on the face of it, less amenable to good crash performance [than previous designs], so to be able to get those to crash successfully is a major achievement," observes Graham Barnes, Engenuity's managing director, who adds that C-Zone, licensed through Simulia, is used by several F1 teams. "That's what the software is there for – to be able to analyze complex structures, enabling the aerodynamicists to have their way without needing to [physically] prototype lots of designs."

There's no doubt that the simulation of composite material behavior, though still an emerging art, has advanced rapidly in the past decade. Phil Hall, boss of Caterham Composites, points to the pre-manufacturing area as being particularly robust, but still has reservations about predicting composite crash behavior.

"I personally think we are not at a stage were you could iterate to a result at a rate that the auto industry would

"Times have changed, and the technology has matured. Now innovation comes from the commercial side of the aviation and automotive industries"

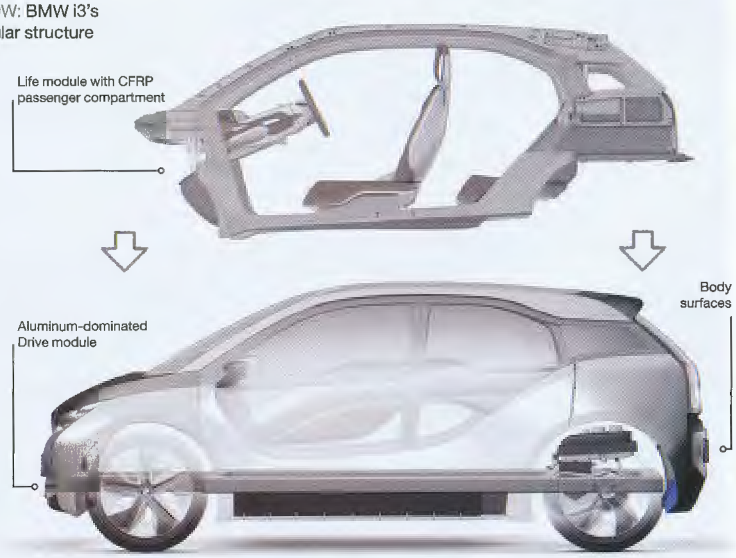
Paolo Feraboli, research associate professor, department of aeronautics and astronautics, University of Washington

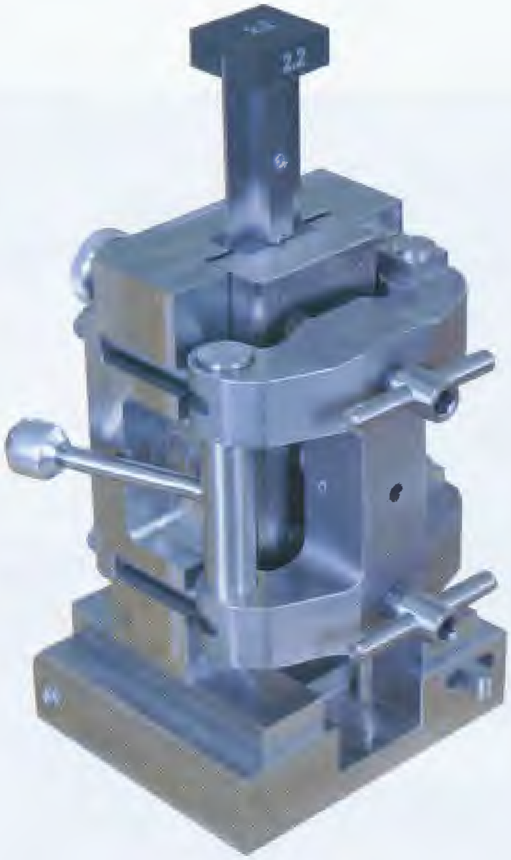
require," he says. "In motor racing there is a very quick turnaround on components, so we can iterate and retest again very quickly. In an automotive scenario, with a whole car to crash and the associated costs, you don't want to be doing three to four tests on a full car to prove out your pre-simulation. Different software companies have come up with some ingenious codes to try to solve that problem. But to my knowledge, at present, there isn't one that you could put your hand on heart and say, 'Yes, that will give us the result we need out of the box'."

The uncertainty, Hall feels, lies particularly in the complexity of a dynamic crash scenario.

"Linear, static-wise, the simulation is very reliable and repeatable. Dynamic crash-wise, it's still very much open and that's largely down to two things: one, the materials database and material properties aren't readily available and therefore you'd have to undergo a series of material characterization tests to get the information you need; and two, the mechanisms of failure in a dynamic crash are still very complex, with many variables. So depending on resin, impact speeds, strain rate dependencies, and so forth, the combination of all those mechanisms presents the ultimate performance of a dynamic impact. We have

BELOW: BMW i3's modular structure





ABOVE AND RIGHT: Engenuity crush-test coupons and the crush-test fixture

BELOW LEFT: fe-safe/Composites combines multicontinuum theory (MCT) with kinetic theory to predict fatigue life in composite structures

developed tools based on more than 15 years of dynamic testing; we have a very broad knowledge of what does and doesn't work in a dynamic impact case. We can also substitute different fibers and resins, and predict the behavior of them. But I think we are still some way off getting to the same level of prediction and simulation that can be achieved linear statically with composites, and with metals."

Hall's reticence is echoed in comments from Professor Feraboli, who notes that, even at the top end of the street car market, misconceptions about the crash performance of carbon fiber persist.

"The behavior of composites in the eyes of customers and press is often erroneous, even though Formula 1 cars and the Boeing 787 use crash structures out of carbon. It doesn't matter – the perceived behavior of carbon is that of a brittle material. Therefore we [Lamborghini] decided to stick with the central cell for the Aventador, and with the Sesto Elemento technology demonstrator, go forward and show that we can actually design a carbon-fiber crash structure, as well as other innovations such as the carbon-fiber suspension, to help prepare the public for the future."

However, there's no reason to suggest that such a state won't be achieved within a few years, with the might of mainstream automotive likely to help push the technology forward. For as Feraboli observes, "With rigorous approaches it is possible to certify an airplane for crash, so it must be possible to certify everything else."

It could yet be the case that knowledge gained in motorsport helps bridge the gap to the automotive mainstream, particularly given the unique nature of composite materials.

"If you look at F1 in particular, the wealth of experience in designing, engineering, and testing very, very advanced composite structures is commonplace," notes Caterham's Hall. "Industries such as automotive come from a metal stamping background. People tend to start off with a metal structure and just replace the material, without a great deal of thought to the underlying, first-principles geometry. And therefore the composites don't function to the maximum potential of their strengths. So it needs that transfer of technology and knowledge."

In the short term, there will be no substitute for materials characterization tests. Automotive OEMs looking to take composites into the mainstream should note that Lamborghini crushed some 10,000 material coupons in building the database that underpinned the development of the Aventador's composite monocoque.

"You still need to build the materials database – do the work in the background to understand how the materials are working, then select the best materials to go forward," urges Engenuity's Graham Barnes. "Now is the time to build the understanding, so that when you do need to deploy it, you're ready." ❮

• *Additional reporting by John O'Brien*

Fatigue prediction

"Composites are intrinsically different from metals," says John Draper, CEO of fatigue specialist Safe Technology Ltd, who has worked with Firehole Composites on fe-safe/Composites, which help predict fatigue life in composite structures. "The multiple constituents have unique material properties, which contribute separately to the load response. As such, even simple load states can lead to complex behavior in the individual constituents and the composite structure.

"Composites therefore require a different approach to structural analysis and simulation. Advanced, composite-specific analysis technologies enable optimized designs and minimize the need for over-design; the insight afforded enables engineers to fortify only where necessary. This is essential when weight and material costs are of prime importance."