CARBON

Whitepaper

E2 Carbon Fiber Wheels **PUT TO THE TEST**

Background

For nearly four years, ESE Carbon has been working to develop the E2 carbon fiber wheel. The E2 is the first one-piece carbon fiber automotive wheel made in the U.S.

With an eye on the North American market for initial deliveries, the team has relied on the engineering practices set forth in the Society of Automotive Engineers (SAE)'s Recommended Practices for wheels (see inset). These documents provide fatigue and impact test methods which manufacturers can use to test the strength and durability of their wheels.

SAE Recommended Practices: Traditional Metal Wheels

The fatigue tests specified in SAE J328 and J2530 include a **Dynamic Cornering Fatigue** method, which assesses the durability of a loaded wheel during turning/cornering using a laboratory machine that spins the wheel and applies a bending moment to the face of the wheel. The other fatigue test, **Dynamic Radial Fatigue**, addresses durability during straight line driving. In this test, the wheel has a tire mounted to it and is then spun up to speed by loading against a spinning mandrel.

Success in these tests requires completing a minimum number of load cycles without significant cracking or gross failure and, in the case of radial fatigue, without air loss.

SAE J2562 (biaxial fatigue) essentially combines these two loading modes, using real world (or proving ground/ test track) load history as the inputs.

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- **SAE J328 Wheels** — Passenger Car and Light Truck Performance Requirements and Test Procedures
- **SAE J2530 Aftermarket Wheels** — Passenger Cars and Light Truck — Performance Requirements and Test Procedures
- **SAE J2562 Biaxial Wheel** Fatigue Test
- **SAE J175 Wheels** — Impact Test Procedure — Road Vehicles

SAE J175 provides a standardized method for assessing **lateral (curb) impact** resistance. In this test, the wheel and tire are mounted to a semi-rigid support fixture, which provides some compliance to simulate the suspension of a vehicle. It also orients the wheel at an angle of 13° relative to the horizontal to simulate the common slant angle of cast concrete curbs. A striker of specific geometry and mass is then dropped from specified height using a drop tower to impart an energy determined using the target vehicle's wheel rating and a formula provided by SAE J175. Passing the curb impact test requires sustaining the impact without gross failure and or air loss.

Putting E2 Wheels to the SAE Test

Despite a rather aggressive wheel load rating of a heavy SUV such as the Tesla Model X, ESE Carbon's E2 wheel successfully passed all four tests.

To do so with only 5 spokes resisting the impact load speaks to the rigorous engineering analysis and testing employed throughout E2 wheel's development and to the innovation contained within the patent-pending design.[1]

The real-world durability of the design has also been demonstrated on the road and track, including proving grounds trials in 2020 **Click here to read the article or view the report**

Establishing Unique Requirements for Composite Wheels

Up until 2020, the SAE Recommended Practices only addressed metallic wheels. ESE was forced to adapt the test requirements for aluminum alloy wheels to the E2 composite wheel.

In some ways, this approach was very conservative. But carbon fiber reinforced polymer (CFRP) composite materials are unique in their mechanical behavior and their sensitivity to environmental factors.

For example, composite materials do not typically fail due the formation and growth of a single crack, as metals do. Rather, the fibers act to blunt microcracks such that many such cracks may accumulate before large scale failure occurs. This superior damage tolerance provides increased strength and fatigue life.

Composites also do not rust or corrode like metals. However, they are sensitive to temperature, moisture, and UV light. To account for these differences, ESE Carbon internally imposed requirements more rigorous than SAE to ensure a robust and conservative design.

At the same time, an SAE task force was developing a new Recommended Practice specific to composite wheels. Dr. Michael Hayes, ESE Carbon's Head of Engineering, served on the committee, lending his expertise in the mechanics and durability of composite materials. In September 2020, SAE finalized the document.

SAE J3204 adapts the Recommended Practices for metallic wheels to composite wheels, imposing new requirements, including:

[1] U.S. Application No. 17/ 215,806

- Strength reduction factors (SRFs) to account for environmental effects
- Maximum operating temperature test
- Electrical conductivity test

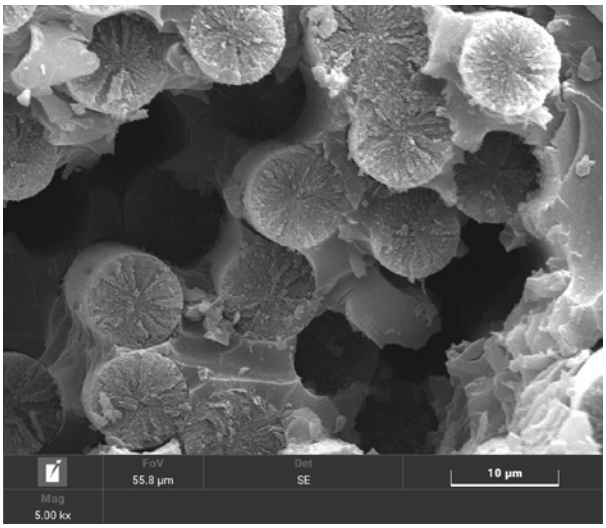
The SRFs are to be determined by the wheel manufacturer and used like load enhancement factors—that is, increasing the test loads. ESE Carbon's approach to establishing SRFs is to perform mechanical testing of coupons cut from panels made using our process and materials.

Testing conditions include:

- room temperature + as-received moisture content
- hot + as-received moisture content
- cold + as-received moisture content
- hot + wet (saturated at high relative humidity)

To complete the testing, ESE Carbon has partnered with several laboratories, including Oak Ridge National Laboratory (ORNL) through the DOE-sponsored LightMAT program **Read the article for more details.**. As this testing concludes and suitable SRFs are determined, ESE will be submitting wheels for SAE J3204 testing.

SAE J3204 Aftermarket Composite Wheels Made of Matrix Material and Fiber Reinforcement Intended for Normal Highway Use - Test Procedures and Performance Requirements



ESE Carbon conducts extensive coupon testing and laboratory analysis of its composite materials.

European Requirements

While the SAE Recommended Practices have been adopted widely throughout the world and have formed the bases for many Original Equipment Manufacturer (OEM) specifications, Europe has taken a somewhat different approach.

For example, Germany's TÜV (Technischer Überwachungsverei) regulation governing custom wheels for road vehicles includes most of the SAE recommendations, plus additional requirements. For composite wheels, they require a radial impact test based on the AK-LH 08,[2] which simulates pothole impacts. TÜV requires the wheel to sustain a "Stage 3" impact at high energy without separation of a spoke from the rim or mounting area and with limited cracking.

In addition, TÜV requires a wheel to pass the biaxial fatigue test following a series of potentially damaging events, including a "Stage 1" radial impact, which is less than 10% of the Stage 3 energy.

[2] AK-Requirements Document LH 08, Section 4.42 Radial-impact test

Radial Impact Testing Methods

Although SAE offers a Recommended Practice for radial/pothole impact (SAE J1981 pendulum test)[3], the AKR method is considered the gold standard for such testing. Alternately, wheel manufacturers may use one of the OEM-specific tests, which employ different striker geometries, striker mass and drop height settings, and wheel mounting strategies. SAE currently has a committee (SAE J3203)[4] working to develop a test method like AKR's. In the meantime, ESE Carbon has been testing E2 wheels to the AKR method and participating in the SAE J3203 test development through its representative, Dr. Hayes.

In addition, ESE Carbon's proving ground testing of the E2 wheel included various chuckhole impacts on a profile road. For example, E2 wheels were mounted on a Tesla Model S test mule and repeatedly driven across 1.5" deep and 4" deep chuckholes at speeds up to 50 mph **View the test details here.**. These wheels not only survived the impacts, but they also exhibited no visible damage and proceeded to road testing without incident.

Going Wheel-to-Wheel with Alloy

With that background on the SAE and TÜV testing methods, it is worth discussing the impact performance of composite wheels in greater detail, as impact resistance is often cited as a concern or a weakness of composite wheels.

For one, traditional composite materials comprised of carbon or glass fibers tend to be relatively brittle with less ductility than metals. Secondly, the polymer resins that comprise the matrix of the composite (e.g., epoxy) are sensitive to temperature and loading rates, sometimes demonstrating reduced strength and fracture toughness at cold temperatures and high strain rates due to their visco-elastic nature.

Consequently, skeptics of carbon fiber wheels may argue that they are more likely to shatter as compared with aluminum alloy or steel wheels. However, this perception is likely based on outdated, historical experience prior to the advent of the SAE and TÜV test methods, as well as recent technological progress in the field of composites.

In fact, if designed properly, composite parts and structures can provide **superior impact resistance**. Due to the multiple damage mechanisms available within composites to dissipate energy (matrix cracking, fiber-matrix debonding, delamination, and fiber fracture), a composite part such as a wheel can withstand higher impact energies before experiencing ultimate failure. And at lower impact energies associated with more typical potholes, composite wheels may hold up better than their alloy counterparts.

ESE Carbon has benchmarked the E2 wheel against several aftermarket alloy wheels of similar size and found that at radial impact energies large enough to cause dents in the alloy wheel – damage that is likely beyond

[3] SAE 1981 Road Hazard Impact Test for Wheel and Tire Assemblies (Passenger Car, Light Truck, and Multipurpose Vehicles)
[4] SAE J3203 Wheels - Radial Impact Test Procedure - Road Vehicles (work in progress)

the limit of safe repair – the E2 composite wheel demonstrates no visible damage.

How is this possible? The strength of CFRP in the fiber direction is much higher than aluminum. Taking advantage of this fact, the E2 wheel incorporates cores of purely circumferential fiber at high fiber volume fraction in both flanges. And because the density of CFRP is 30 to 40% less than aluminum alloys, the E2 flanges offer superior strength to aluminum with no weight penalty – even with stout flanges. The flange cores are also wrapped in multiple layers of braided carbon fiber, which is very good at dissipating impact energy.

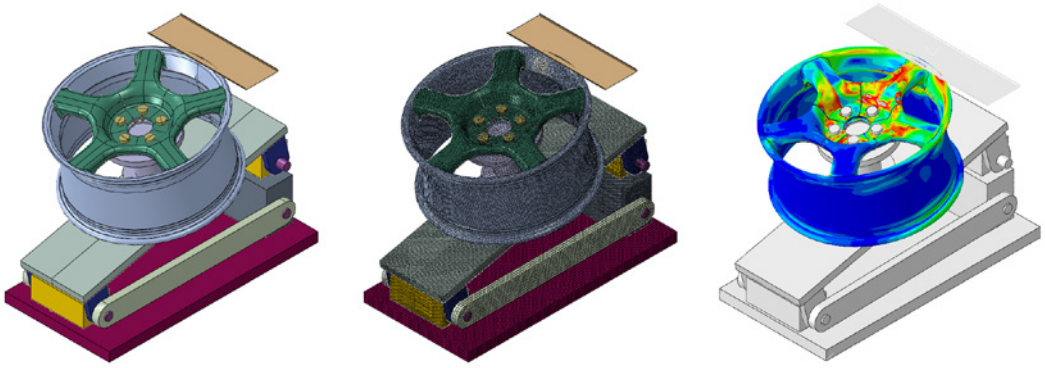
Curb Impact Damage: Alloy Wheel

Are Composites More Prone to Failure?

The common concern that composites are too brittle is not entirely unfounded Traditional composite parts and structures do exhibit linear-elastic behavior and failure at low strains when the critical failure mode is fiber fracture. But seldom is the failure mode so simple. The various damage mechanisms listed above may provide pseudo-ductility and significant energy absorption prior to ultimate failure. The addition of just a little off-axis fiber (for example, fibers running perpendicular to the primary laminate direction) can increase the strain to failure significantly. And the formation of delaminations provides additional means of energy dissipation to provide a more nonlinear failure like metals.

The ultimate failure mode may vary depending upon the type of impact and the wheel design.

In the development of the E2 wheel, the team found that insufficient connection between the spokes and rim could lead to fiber fracture in the plies connecting the two during the SAE J175 curb impact test. But as those connections were strengthened through the addition of more plies (or better ply design), the primary damage mechanism became delamination within the spokes or center hub area. This delamination is perfectly acceptable in the curb impact test, as that test does not anticipate that a wheel subjected to an equivalent impact on the road would be repairable afterwards. **The primary concern is safety**, and the internal delaminations are beneficial in that they dissipate energy to ensure no failure of the wheel.

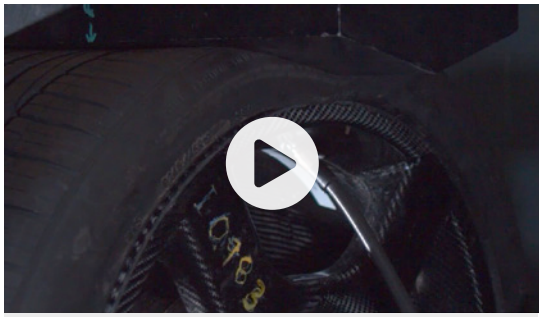


Finite Element Analysis (FEA) of SAE J175 Curb Impact Test

Impact Damage

In the case of pothole impact, we observe a combination of compressive fiber failure and delamination within the E2 flanges. At low impact energies that cause dents in alloy wheels, the E2 experiences only internal delamination. At higher (but moderate) impact energies, some fiber fracture occurs. Still, even these failures are benign with little permanent deformation, no through-section failure, and no loss of air.

It is only at very high energies that a composite wheel may (although not always) perform worse than alloy. However, alloy wheels experience significant and irreparable damage in these impact events, too. Indeed, impact damage is not a challenge unique to composites. There are plenty examples today of alloy wheels failing during service due to potholes even after decades of development experience.



Pothole Impact Test - Standard Temp

Curb Impact Test -40 Degrees

Cold Temperature Impact Testing

Another common concern with composites is the effect of cold temperatures on impact resistance. A decrease in strain to failure and fracture toughness below freezing may reduce impact resistance. Unfortunately, neither the SAE nor TÜV test methods consider the effect of cold temperatures directly. Both are conducted at room temperature. To its credit though, the new SAE J3204 practice includes a Strength Reduction Factor for impact (SRF-I). But ESE Carbon's coupon testing has demonstrated no loss in fiber direction strength at -40˚C (-40˚F), for example. And other literature data supports this, even showing increases in strength at cold temperatures.[5]

Still, not content to rely on coupon data to predict wheel performance, ESE Carbon sent E2 wheels to an independent test lab to repeat the SAE J175 curb impact and AKR pothole impact tests at -40˚C. The lab used dry ice to chill the wheels prior to testing and then monitored the wheel temperature during test setup using an infrared camera. They were able to ensure that the wheel temperature remained at -40˚C or lower.

The E2 wheel passed both tests at the same impact energies as the room temperature tests, demonstrating no adverse effect of the cold temperature. This exercise speaks to the thoroughness of ESE Carbon's development process. We are not aware of any other composite wheel manufacturer running such tests.

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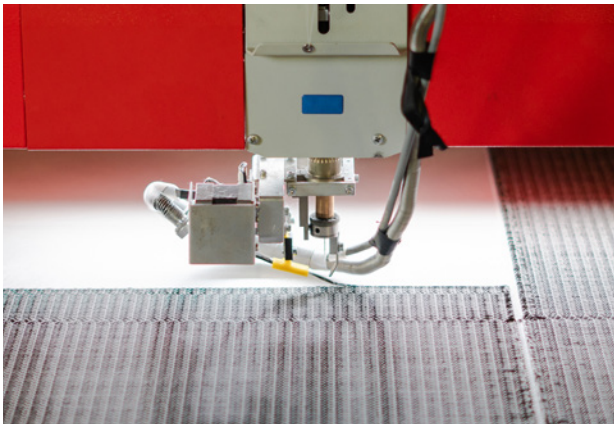
[5] Advanced General Aviation Transport Experiments, B – Basis Design Allowables for Epoxy – Based Prepreg FiberCote Graphite Unitape T700 24K / E765, AGATE-WP3.3-033051-104 [Revision 1], March 2004, J. Tomblin, J. McKenna, Y. Ng, K. S. Raju, National Institute for Aviation Research

ESE Sets the Bar High & Then Surpasses It



ESE Carbon's due diligence continues today as we seek continuous improvement of the current E2 wheel and future wheel designs. Our goal is to not only match the impact resistance of metal wheels but to surpass it. We have implemented several innovative technologies to help accomplish this. Our R&D group has identified material and processes changes that have boosted the strength of the E2 wheels.

For example, the plies in certain portions of the E2 wheel are manufacturing using **Tailored Fiber Placement (TFP)**. This process allows for custom-tailored plies with arbitrary fiber direction, minimal waste, and vertically integrated production. Several TFP parameters are available for process optimization, including stitch settings such as tow spacing and stitch density. Alternate materials such as backing veils, higher strength fibers, and higher toughness fibers are also available.

ESE Carbon's product development team also pushes the performance envelope by optimizing design variables at its disposal. Stress analysts are busy running hundreds of finite element simulations to optimize the designs for strength, fatigue life, impact resistance, stiffness, and weight.

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ESE Carbon's mission is 'Making Composites Accessible.' For our customers, this means providing a safe and high-quality wheel. They can rest assured that each American-made wheel coming out of our factory is backed by years of testing, engineering and craftmanship.

CEO Carlos Hermida

About ESE

ESE Carbon Company was founded in 2011 by a small, talented team in Jasper, Georgia with the goal of making carbon fiber composites more accessible. Eleven years later, we continue to drive innovation in areas such as tailored fiber placement (TFP), high-pressure resin infusion, engineering design and analysis. We also serve on the SAE Wheel committee, which is developing standards for carbon fiber wheels.

ESE Carbon Company is a division of ESE Industries, which is leading the way in industrial carbon fiber applications such as automotive, aerospace and marine industries. We are leveraging the ESE Industries expertise, vertically integrated product development, mold fabrication and composite part manufacturing to bring the E2 carbon fiber wheel to production.

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