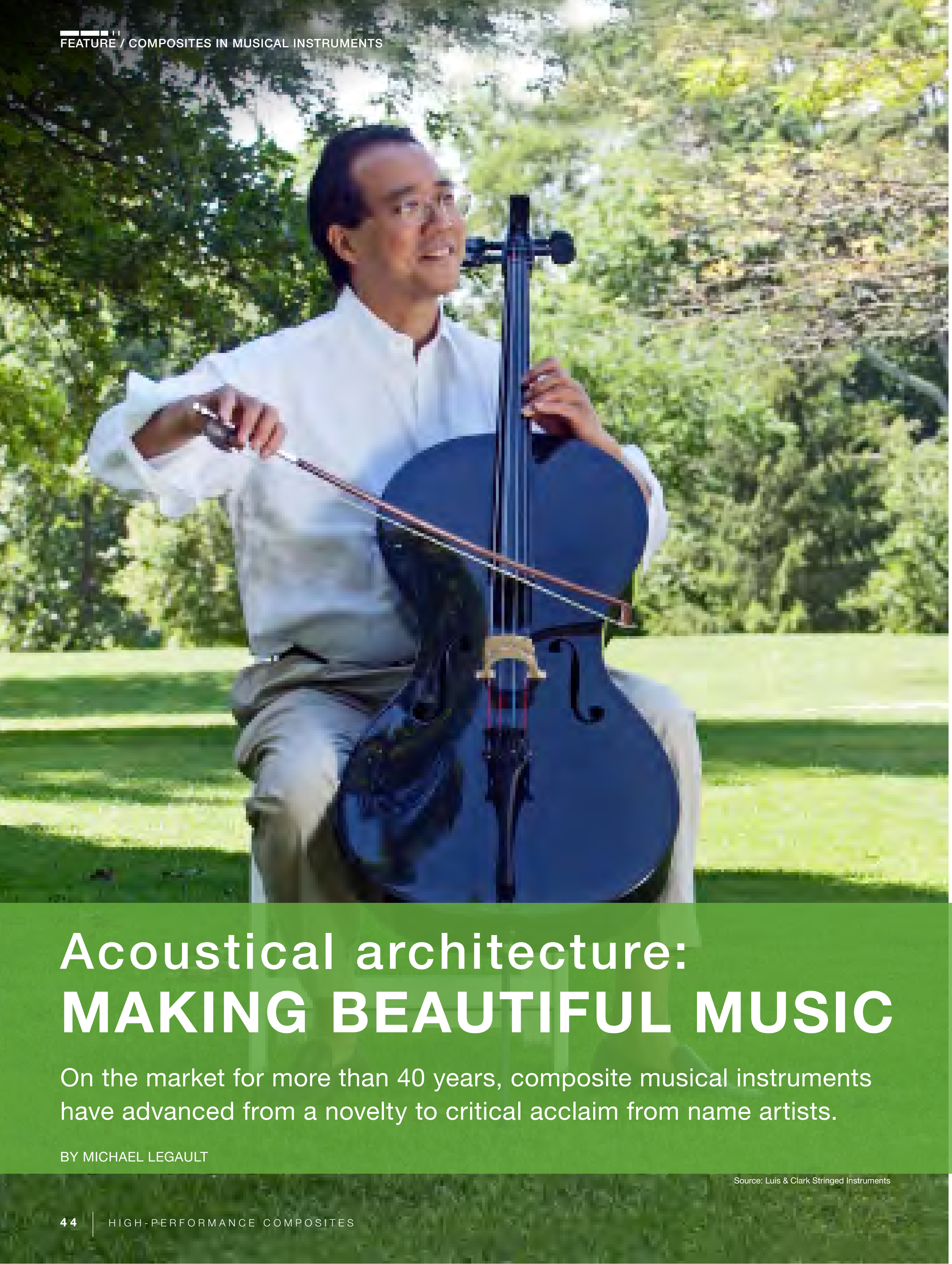
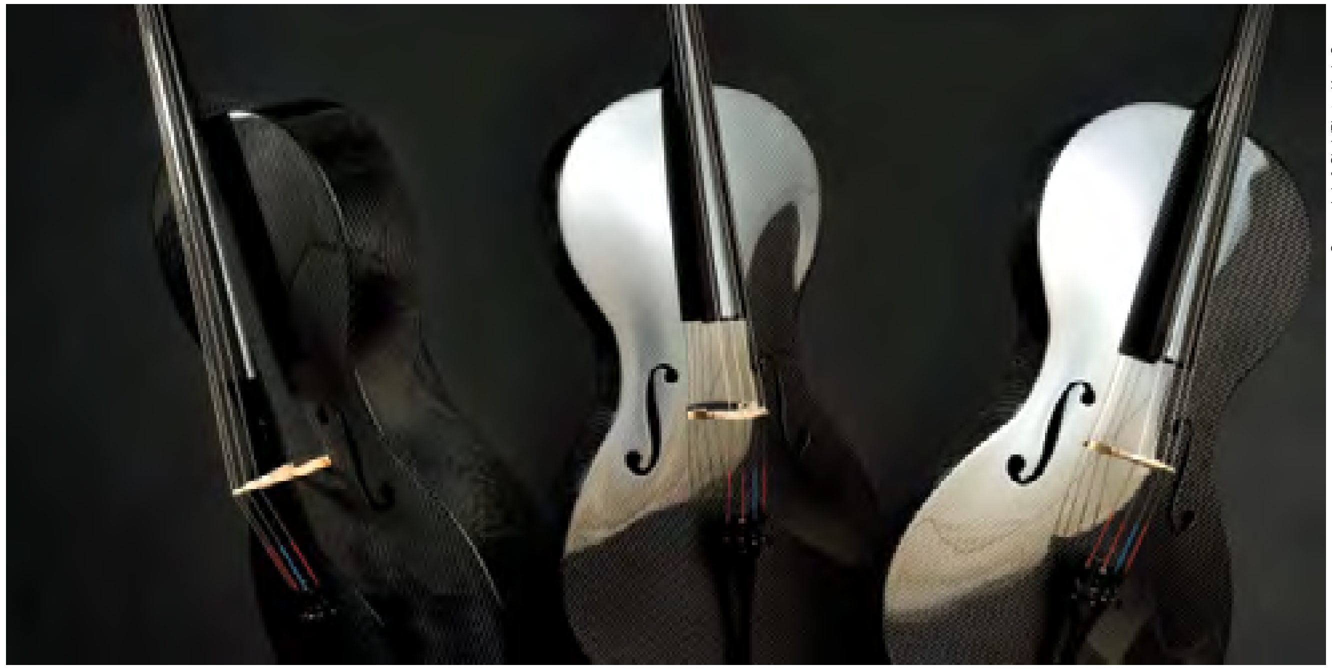


Acoustical architecture: MAKING BEAUTIFUL MUSIC

On the market for more than 40 years, composite musical instruments have advanced from a novelty to critical acclaim from name artists.

BY MICHAEL LEGAULT

Source: Luis & Clark Stringed Instruments



Source: Luis & Clark/Photo: Kevin Sprague

When one thinks of music, composites usually are not the first things that come to mind. But a growing number of instrument makers with engineering and advanced composites backgrounds are successfully adapting composites to a field with a long tradition in wood and metal. Over time, these modern challengers to traditional woodworkers and metal crafters have discovered ways to combine high-performance materials and advanced manufacturing processes to produce instruments that, like this sampling of commercially available composite acoustical architecture, are earning high marks for durability, dimensional stability and aesthetics, both aural and visual.

Departing from (but not violating) tradition

In a branch of the musical family long steeped in the classical tradition, Luis & Clark founder and cellist Luis Leguia has sold 700 of his all-carbon cellos as well as 285 violins, 180 violas and 18 basses.

A top performer for a top performer

Builders of carbon composite orchestral strings for more than two decades, Luis & Clark's Stringed Instruments (Milton, Mass.) now benefits from endorsements from professional musicians, including world-renowned cellist YoYo Ma, shown here with the company's signature cello.

That roundback guitar

One of the earliest people to see the potential of composites in musical instruments was Charles Kaman. In the mid-1960s, this aeronautical engineer founded Ovation Instruments (now Ovation Guitar Co., New Hartford, Conn.), which became one of the first companies to design, build and sell a guitar with a glass-fiber reinforced composite body. Kaman's other company, Kaman Corp. (Bloomfield, Conn.), was already responsible for a number of innovations in helicopter design, including the first gas turbine-powered helicopter engine and the fabrication of some of the first helicopter rotor blades made from composite materials. When he was working with composites to build rotor blades, Kaman, also an avid guitar player, realized that the unique acoustic and structural properties of composites might make the materials suitable for guitars.

Kaman first built a series of prototype composite acoustic guitars, then he measured and compared their sonic characteristics with dozens of conventional wooden guitars. He initially set out to mimic the design of flat-backed bodies of conventional wooden guitars but quickly discovered that laying up and infusing glass fabric at the 90° junctions of the guitar's back and curved sides was problematic and, as is true with a wooden counterpart, the back would require additional bracing, says Darren Wallace, director of engineering at Bloomfield-based KMC Music, a subsidiary of Fender Musical Instruments Corp. (Formerly a division of Kaman Corp., KMC was purchased by Fender in 2007). Further, wood bodies are reinforced with blocks at the head and neck, and they have other internal bracing that provides structural support for joints and walls, in addition to absorbing or deadening some of the sound. Partly out of necessity, then, Kaman and his team tested much simpler, semiparabolic bowl designs and discovered that the shape, molded in one piece *without* bracing, produced a sound with unique, responsive acoustics and powerful projection. The result was the Ovation Roundback, which made its debut in 1966.

Kaman tested different glass-reinforced materials and settled on a construction for the first roundback guitars consisting of two layers of 16-oz 1583 E-glass supplied by Hexcel (Stamford, Conn.). Engineers "tuned" the material to enhance its musical resonance, and Ovation markets the patented ma-

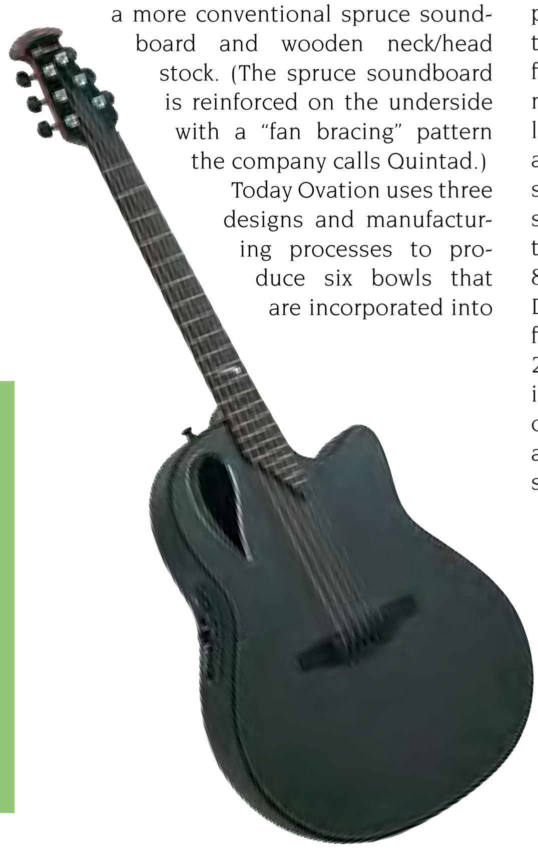
Source: KMC Music

Popular SMC/spruce combo

Al DiMeola plays a guitar custom-built by Ovation Guitar Co. (New Hartford, Conn.) with a body made of compression-molded SMC body and a more traditional soundboard of Sitka spruce. Ovation also builds custom guitars for Mellissa Etheridge, Glen Campbell and other musicians, styles which are also available for purchase by the public.

terial under the registered trademark Lyrachord. The glass fabric layup was bagged in a mold and infused with epoxy under vacuum, then it was attached to a more conventional spruce soundboard and wooden neck/head stock. (The spruce soundboard is reinforced on the underside with a "fan bracing" pattern the company calls Quintad.) Today Ovation uses three designs and manufacturing processes to produce six bowls that are incorporated into its series of 19 commercially available roundback acoustic/electric guitars. (All Ovation guitars come standard with an electronic pickup and onboard preamp; they are available as acoustic only on a custom-order basis.) The first is a modified version of the original bowl that employs wet layup of two layers of 16-oz 1583 glass sprayed with a polyester resin. The second bowl design is compression-molded polyester sheet molding compound (SMC). The third bowl comprises four layers of an 8-oz Hexcel 7781 E-glass prepreg and DA-409 epoxy resin from APCM (Plainfield, Conn.) cured in an autoclave at 250°C/482°F. The company began using the autoclave process around 2003 on newer, high-end models to achieve a more aesthetically pleasing exterior surface finish. For all bowl designs, the target nominal wall thickness is 0.43 inch/10.92 mm.

In 1976, Ovation was the first company to build a guitar with a carbon fiber soundboard. The laws of physics say that the thinner the soundboard, the better the sound quality. Physics also dictates a lower limit on thickness. Because the soundboard must be strong enough to anchor the bridge, which is the terminus for the highly tensioned strings, and survive impacts from strumming, the minimum thickness achievable with a spruce soundboard is in the range of 0.125 inch to 0.110 inch (3.18 mm to 2.79 mm). Kaman and his engineers designed and built a soundboard of less than half that thickness. They used a 0.040-inch/1-mm thick birch core sandwiched between two layers of NCT301-1 34-700 G150 unidirectional carbon fiber prepreg, each with a thickness of 0.005 inch/0.0127 mm, and joined them with an epoxy adhesive for a total thickness of 0.050 inch/1.37 mm. The prepreg and adhesive are supplied by Newport Composites and Adhesives Inc. (Irvine, Calif.). The soundboards are then cured in an autoclave at 250°C/482°F. In one design, the birch core is oriented at a 60° angle relative to the axis of the neck for longitudinal strength; and several other orientations also are used. The soundboard is incorporated on the company's Adamas line of guitars (see photo, this page). Ovation also makes a soundboard from a 2x2 twill carbon fiber prepreg supplied by Gurit (Bristol, R.I.). This soundboard has a birch core with grain oriented along the 0° axis (in the direction of the neck) and is included on the company's 2080 Adamas guitar line. Ovation still makes guitar necks from wood, primarily black walnut and mahogany, but each neck is reinforced internally with carbon fiber inserts that run lengthwise from the seventh fret to the neck/body joint.



Carbon composite sandwich soundboard

Source: KMC Music

Ovation's 2080 Adamas guitar comes with a soundboard constructed of a birch core sandwiched between two layers of 2x2 twill carbon fiber prepreg. The soundboard is more than half as thin as a typical soundboard made of spruce, providing a more responsive, powerful sound.

All-carbon, but conventional

Dr. John Decker was attending an outdoor wedding in Maui when it began to rain and the guitarist abruptly stopped playing. The guitarist told Decker the decision was a no-brainer: he could lose a paycheck or lose a guitar.

The incident spurred Decker, a physicist, to begin tinkering with all-carbon guitar designs. Eventually he founded Rainsong Graphite Guitars (Woodinville, Wash.). Since 1995, the company has manufactured a line of all-graphite guitars, which can feature any of four body shapes and three neck styles in two six-string versions and one 12-string version. Rainsong's guitars are made entirely without bracing, which provides greater acoustic volume. The guitar bodies are made from 4x4 twill weave carbon/epoxy prepreg. A typical construction of a soundboard comprises a 2x2 twill weave on the front and a 4x4 twill weave on the back. Prepregs for guitar bodies and soundboards are hand laid in aluminum molds, vacuum bagged and cured at 66C°/150°F. The postmold thickness of a soundboard and body is typically about 0.125 inch/3.17 mm. The neck is constructed with a core of unidirectional fabric on the front and back sides. The core of the neck is wrapped with a 2x2 plain weave and injected with a marine-grade epoxy by a resin transfer molding process.

Rainsong president Ashvin Coomar says the rationale for building an all-carbon guitar is founded on his experience, which has shown that the inclusion of any wood creates a weak link in a guitar's durability and performance. "Even top-of-the-line wood guitars are notorious for not being able to handle changes in temperature and humidity," Coomar says. (To read about another all-composite guitar design online, see "Learn More.")

Because a segment of the guitar-playing community will always view an all-carbon guitar as radical, Coomar tries to mitigate that perception by using traditional guitar body designs and shapes. For example, Rainsong's JM model, which the company markets as capable of greater sound volume than any acoustic guitar ever built, has a standard hourglass-shaped, classical guitar body. "We view our strength as our materials, which are relatively new to music in the first place, so we want to stay within the comfort level of guitarists with the design and shape of our instruments," Coomar says.

Carbon classics

Although composite guitars represent a radical departure from a long history in wood, those who play them are no strangers to innovation in musical styles and instruments. Those who play other instruments in the string family, however, are likely steeped in musical tradition dominated by the names Bach, Brahms and Beethoven, and they play an instrument for which there is a single (if disputed) standard, the Stradivarius. But violins, violas, cellos and double basses made by the Stradivari family in the 17th and 18th Centuries are rare, delicate and extraordinarily expensive — not so, those from Luis & Clark Stringed Instruments (Milton, Mass.). Company founder Luis Leguia, a cellist for 44 years with the Boston Symphony before retiring five years ago, reports selling more than 1,100 of his carbon fiber composite instruments since he began commercial production in the mid-1990s. Given his background, the biggest sellers have been cellos — at 700 instruments — but he also has sold 285 violins, 180 violas and 18 basses (see photo on p. 45).

Leguia's business grew out of an epiphany he had while sailing as he became aware of the sound transmission qualities of glass fiber hulls. After making a cello for himself out of fiberglass, he teamed with boatbuilder and carbon fiber expert Steve Clark (Vanguard Sailboats, Portsmouth, R.I.) to design and build four prototype all-carbon cellos. The third cello, with minor changes, became the model for his successful line of commercial cellos.

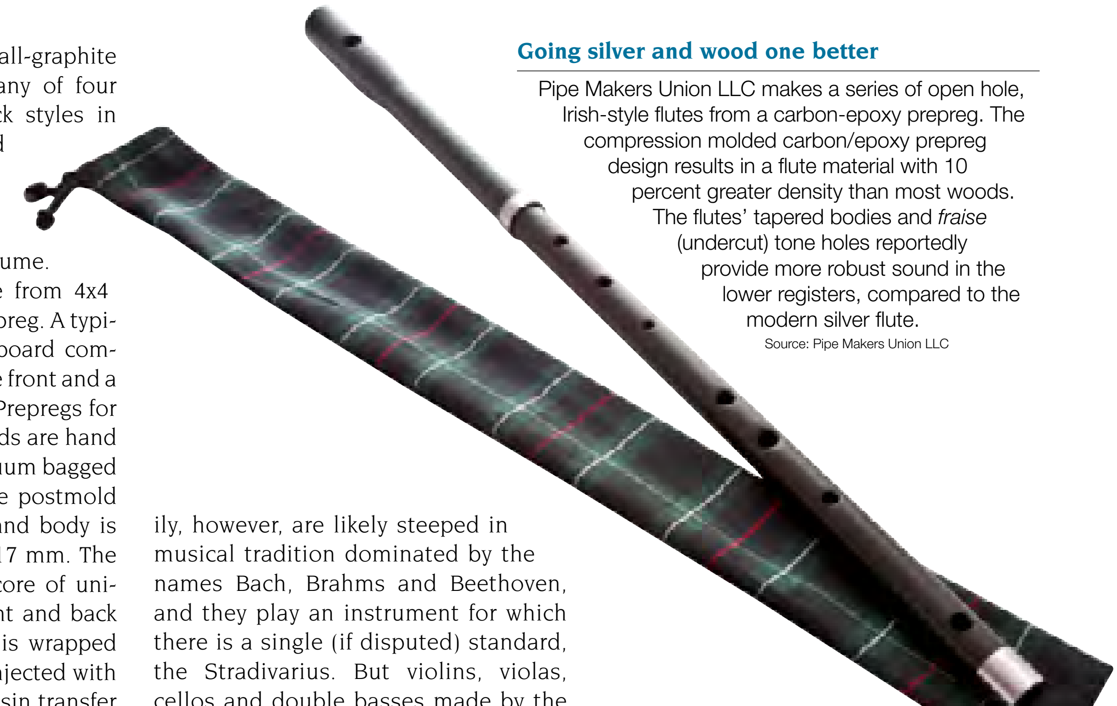
"Our cello, as well as the violas and violins, have a baritone quality that is deeper in upper registers and a marvelous reverberation that many musicians appreciate and love," Leguia says. He also allows, however, that his carbon cello does not exactly match the penetration on the high A string of, say, a Stradivarius. He declines to reveal the type of carbon fiber, resin or molding process he uses to make the instruments, but he reports that the choice of carbon over wood gave him the freedom to make several design changes that, he contends, enhance the sound and playability of the cello.

One of the strengths of his carbon design is dimensional stability. All stringed instruments are built with an arch across the soundboard that peaks on the line formed by the bridge and strings. On a cello, that arch is approximately 21 to 27 mm (0.82 to 1.2 inches). Leguia says he has seen a top-of-the-line wood cello worth more than $200,000 on which the soundboard and bridge had sunk by more than 10 mm/0.39 inch. The sinking is caused by the tension of tuning and playing the instrument over many years. By contrast, much stiffer carbon offers better resistance to this tension, keeping the original design and rich, full sound of the new instrument intact.

The use of carbon also enabled Leguia to build a cello without *cornices*, the indentations in the cello sides, which house blocks for structural support. Like braces in guitars, the blocks damp sound inside the resonating chamber, he notes. Eliminating the blocks contributes to the baritone resonance.

Celtic carbon

Composites also are making inroads into wind instruments, includ-



Going silver and wood one better

Pipe Makers Union LLC makes a series of open hole, Irish-style flutes from a carbon-epoxy prepreg. The compression molded carbon/epoxy prepreg design results in a flute material with 10 percent greater density than most woods. The flutes' tapered bodies and *fraise* (undercut) tone holes reportedly provide more robust sound in the lower registers, compared to the modern silver flute.

Source: Pipe Makers Union LLC

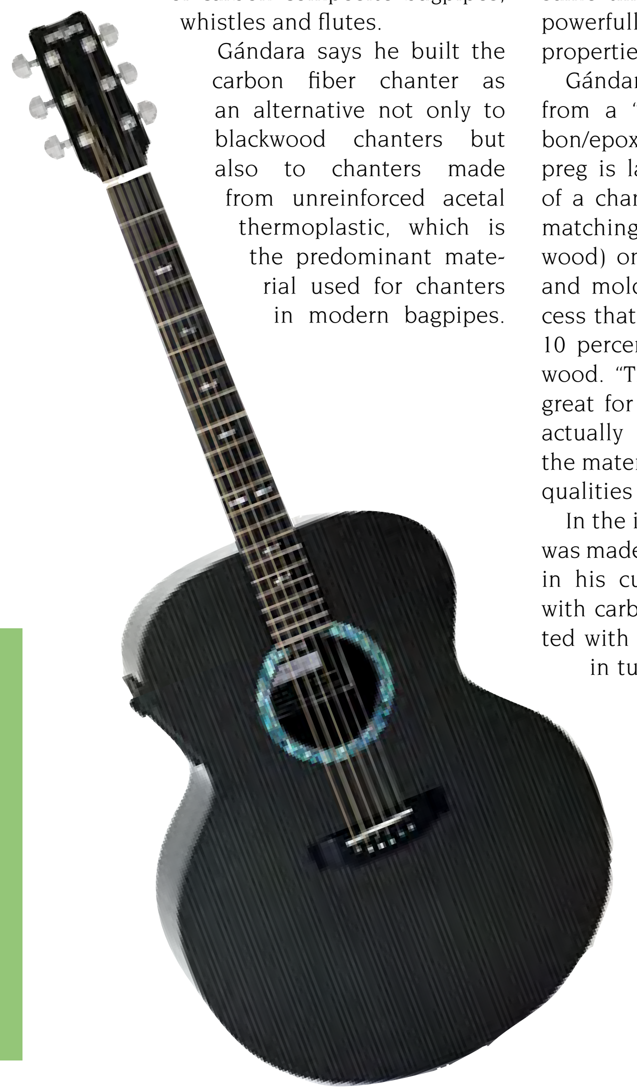
ing flutes, clarinets, saxophones and oboes. One of the most unusual is another incursion into a particularly history-rich musical tradition, bagpipes. Rob Gándara's foray into the manufacture of carbon fiber wind instruments began with a broken bagpipe *chanter*, the long, hollow main tube of the bagpipe upon which the player creates the melody. Traditionally made of African blackwood, the chanters are susceptible to swelling, drying and cracking. When the blackwood chanter of his bagpipe cracked three weeks before a scheduled St. Patrick's Day concert, Gándara, an engineer by training, implemented a plan to tap his knowledge of advanced materials and build one out of carbon fiber. By 2006, he resigned from his job at Hewlett-Packard, founded Pipe Makers Union LLC (Corvallis, Ore.) and inaugurated his Carbony Celtic Winds line of carbon composite bagpipes, whistles and flutes.

Gándara says he built the carbon fiber chanter as an alternative not only to blackwood chanters but also to chanters made from unreinforced acetal thermoplastic, which is the predominant material used for chanters in modern bagpipes. "Pipers have moved away from blackwood because it is not durable," says Gándara, "but at the same time, these [acetal] instruments have lost some of the finer qualities of resonance." He reports that his carbon fiber composite comes very close to recapturing the tonal quality of blackwood, while at the same time projecting the sound more powerfully as a result of the acoustic properties of carbon.

The audience for these composite musical instruments continues to grow. As the fan base ... expands, the makers of these instruments, and aftermarket components for them, are proliferating. So, too, is the view that beautiful music can be made from space-age materials.

Gándara makes all his instruments from a "standard industry-grade, carbon/epoxy-based prepreg." The prepreg is layed up by hand (in the case of a chanter with the fiber orientation matching the direction of grain in blackwood) on aluminum or steel mandrels and molded using a compression process that results in material with about 10 percent greater density than blackwood. "The strength of carbon fiber is great for durability," he says, "but it is actually the density and thickness of the material which account for the tonal qualities and feel of the instrument."

In the initial models, only the chanter was made from carbon, but the bagpipes in his current line are also equipped with carbon fiber *drones*, three pipes fitted with a reed that play a single note in tune with the key of the chanter.



An all-carbon composite "first"

Rainsong Graphite Guitars (Woodinville, Wash.) manufactures what the company claims were the first guitars built completely from carbon. The company also claims that its JM model (shown here) produces the greatest sound volume of any acoustic guitar ever built.

Source: Rainsong Graphite Guitars

Gándara's chanter tapers from an inner diameter of 25.4 mm/1 inch at the top to about 4 mm/0.16 inch at the bottom; the diameters of the drones, which do not taper, vary from about 6 mm to 12 mm (0.24 inch to 0.47 inch) depending on the key. The wall thicknesses of all the company's wind instruments depend on pitch, ranging from less than 1 mm/0.04 inch for high-pitched whistles to 5 mm/0.20 inch for the lower-pitched chanters and flutes.

Flouting flute convention

Gándara's company and a European competitor, Acrobaatti Oy/MATIT Flutes (Helsinki, Finland), both manufacture carbon fiber flutes marketed as improved acoustical alternatives to Western metal concert flutes made of nickel, solid silver or silver-plated brass and are often called, simply, silver flutes. The latter instrument is patterned on the flute invented in the early 19^{th} century by Theobald Boehm, a German goldsmith, composer and industrialist. Prior to Boehm, flautists played an instrument with a tapered body, usually made of wood, by placing their fingertips directly on the holes to produce notes. The body of Boehm's metal flute, and today's silver flute, has a uniform diameter. Boehm also enlarged the holes and invented a key mechanism that gave players a mechanical means to control holes beyond their reach. Although the innovations improved the flute's dynamic range and playability, the trade-off, in the view of many musicians and instrument makers, was a loss of harmonic power in the lower registers.

Gándara's answer to the Boehm flute is a series of Irish-style flutes with tapered bodies and open holes. The flutes usually taper about 10 mm/0.39 inch over a length of 500 mm/19.69 inches. Tapering the body helps "tune" a flute, he says, allowing it to present consistent harmonics as a musician goes to higher registers. The flutes also incorporate two other innovative features designed to restore lost harmonic range. The first is a sharp 7° angle on the lip of the *embouchure* — the oval opening over which the flautist blows to create sound. Gándara uses a special carbide-tipped router to fashion the embouchure in the tube's carbon composite wall. The second involves the flute's tone holes. These feature a *fraise*, or undercut geometry. That is, the hole diameter is larger on the inner wall of the flute than it is at the outside. The fraise is created by inserting specially shaped tool bits inside the flute to widen the inside perimeter of each hole. This geometry imparts more power to each note. Gándara says his goal with the design is to resuscitate the sound quality of the pre-Boehm flute using 21^{st} Century materials and accuracy. "My carbon flute recaptures the rock-solid low-D note that modern musicians shy away from when playing the silver flute," he claims.

In pursuit of his flute design, Acrobaatti Oy/MATIT Flutes founder Matti Kahonen conducted extensive acoustic tests on flutes made of various materials. He found that the measured maximum volume of a carbon composite flute body was noticeably more powerful than flutes made of silver and wood. Further, the measured tonal spectrum of the carbon flute was richer than its counterparts. Although he acknowledges that proper design of the embouchure and tone holes influences the quality of a flute's sound, Kahonen concluded the most *important* factor in achieving superior sound is the superior stiffness of carbon, which results in less energy absorption compared to other materials. He began building carbon flutes in 1994, and today his line of MATIT flutes comprises three models.

Acrobaatti Oy/MATIT flutes are available with open or closed keyholes, the latter via a patented key mechanism. The mechanism employs magnets instead of needle springs, and the magnets create returning power to the keys. The wall thickness is typically 1 mm/0.04 inch, and the inside diameter is 19 mm/0.75 inch. The flutes are manufactured from a high-modulus, 2x2 twill carbon-epoxy prepreg and cured in an autoclave. Kahonen says the proprietary process creates a very smooth surface finish on the inner diameter, which is critical for a clean, crisp sound.

Growing applause

The audience for these composite musical instruments continues to grow. After initially selling his instruments strictly to players of Celtic music, Gándara reports new sales of his flutes to musicians who play folk music and jazz. Rainsong's Coomar says the company is targeting hobbyists and collectors, as well as professional musicians, for its all-carbon guitars. As the fan base for composite instruments expands, the makers of these instruments, and aftermarket components for them, are proliferating. So, too, is the view that beautiful music can be made from space-age materials. ■

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Read about another all-composite guitar in "Carbon/epoxy guitar: Competitive in quality and price," *HPC* January 2007, P. 31 or visit http://short.compositesworld.com/W9BWGG3n.