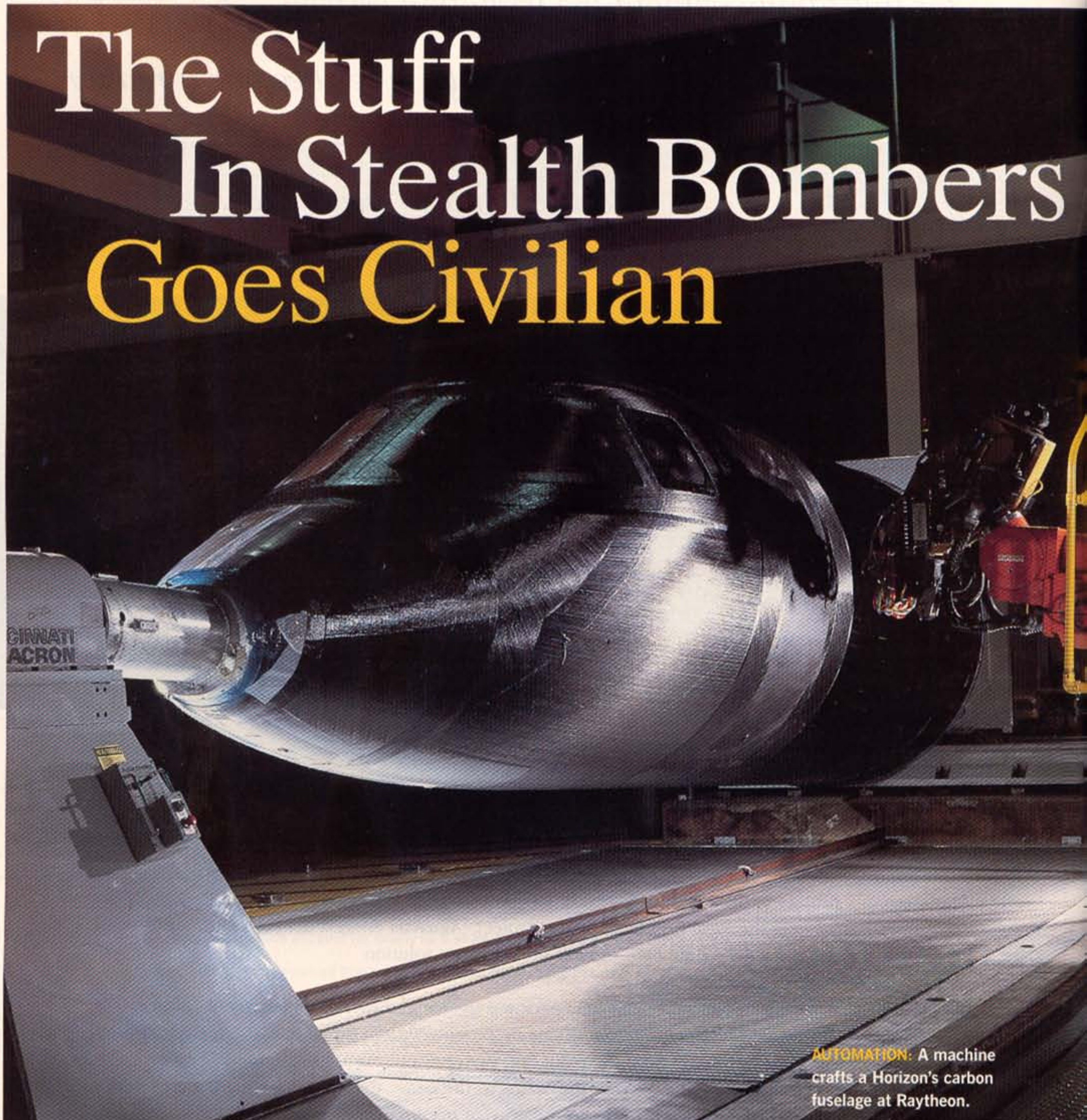
The Stuff In Stealth Bombers Goes Civilian



AUTOMATION: A machine crafts a Horizon's carbon fuselage at Raytheon.

As clever machines shrink the cost of making big parts from carbon composites, they're going into business jets and commercial rockets. BY STUART F. BROWN

The same carbon-fiber composites that help the Air Force's $2 billion, bat-shaped B-2 bomber sneak past enemy radar are finding a new market in business jets and commercial rockets. Automated production, using dexterous machines painstakingly developed under Cold War military programs, has slashed the once forbidding costs of making airplane parts from these materials. It's a far cry from 15 years ago, when parts were built up by hand and an aircraft engineer at a composites shop confessed to a visitor, "We're still learning how to make airplanes out of string and glue."

Composites are becoming the way to design in high performance, often at lower cost. Dramatic evidence can be seen at Raytheon Aircraft's plant in Wichita, where they are literally reinventing the way airplanes are built. Sophisticated "fiber-placement" machines from Cincinnati Ma-

PHOTOGRAPHS BY PAXTON

chine make entire fuselages for the new Beech Premier 1 business jet, using just two large structures of carbon-composite material. The same equipment makes fuselages for the larger Hawker Horizon business jet in only three pieces. Raytheon engineers estimate that to build comparable fuselages in the traditional way, from aluminum, they would need thousands of components and fasteners assembled with a lot more labor and tooling. The planes would weigh about 20% more and gulp more fuel.

The four-passenger Premier 1 is on its way to receiving FAA certification, and four of the $4.5 million, 530-mph entry-level jets are being test-flown. Without a single customer's having taken delivery, Raytheon has booked more than 200 orders for the plane, which is going into production at the rate of 60 per year. If you order now, you'll have to wait for delivery until January 2004. About a year behind is the eight- to 12-passenger Hawker Horizon. Raytheon says it has 150 orders and options for the $16.5 million craft, 100 from Executive Jet, the aircraft time-sharing company owned by Warren Buffett's Berkshire Hathaway.

Composites are going civilian on another front, with the help of a fiber-placement machine from Ingersoll Milling Machine of Rockford, Ill. At Boeing's development center in Seattle, the 150-foot-long machine is making lighter, lower-drag carbon-fiber payload fairings for the Sea Launch commercial rocket program Boeing runs with a Norwegian shipbuilder partner and with Russian and Ukrainian rocketmakers. A payload fairing is the aerodynamic shell that protects satellites during their three-minute ride into space. On Oct. 9, a Hughes/DirecTV satellite stowed in one of these fairings made it safely into a geostationary orbit. To put it there, the rocket venture made its first revenue-earning launch from an ocean platform towed to the equator, where the earth's spin gives rockets a maximum assist in their struggle against gravity.

As the cost of making carbon-fiber parts has come down, the world's appetite for the black stuff has risen. According to fiber producer Toray Composites America in Kirkland, Wash., worldwide consumption has grown steadily from about 3,000 tons in 1985 to about 13,000 tons this year, worth about $500 million. Toray predicts that industrial uses such as automotive components, bridge decks, and offshore-platform structures, which account for slightly more than half of current carbon-fiber use, will be the fastest-growing segment in the years ahead. Aerospace demand is expected to stay fairly constant, but only because declining military production will offset rising use in commercial planes and rockets. Little further growth is expected in sporting-goods applications such as golf-club shafts and skis.

As their name indicates, composites are not homogeneous materials like metals or plastics. They consist of fibers embedded in a solid matrix of resin—somewhat like wood, which has been called "God's composite." The first widely used man-made composite was glass fiber and resin, a.k.a. Fiberglas, an Owens Corning trademark. In the 1970s prototype parts made of high-performance carbon and Kevlar fibers were tested and then designed into military and commercial airplanes. Kevlar is still used in many composite structures, though not in the aerospace parts described in this article.

Carbon-fiber composites caught on with military aircraft designers because the material is less radar-reflective than aluminum. It can also be formed into structures with very few joints and surface imperfections that generate "spikes" on an unfriendly radar screen. For years observers of the lonely night skies near places like Area 51, the Air Force's secret test site in the Nevada desert, have sighted mysterious aircraft—let's call them batmobiles—displaying compound contours suggestive of composite construction. Such contours keep radar waves from returning to enemy trackers.

For civilian as well as military airplanes, composites appeal to designers because they are three times as strong per pound as aircraft-grade aluminum. They are also about 70% stiffer, which means that many parts require little or no structural underpinning. Another attribute designers love about composites is directionality. While metals are isotropic—they react the same

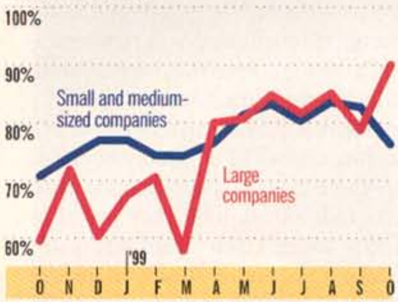
A BIG STEP: A Beech Premier 1's two-piece carbon fuselage gets mated with its aluminum wings.

THE NAM / FORTUNE MANUFACTURING INDEX

Divergent Views

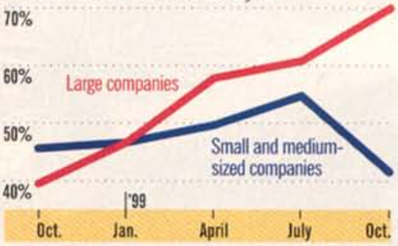
Large manufacturers' optimism swelled in October. A survey of more than 200 companies by the National Association of Manufacturers and FORTUNE showed that 90% of large companies—those employing 1,000 or more—felt positive or somewhat so. Among small and medium-sized companies, the percentage of optimists slipped to 76%.

Percent of manufacturers with a positive business outlook

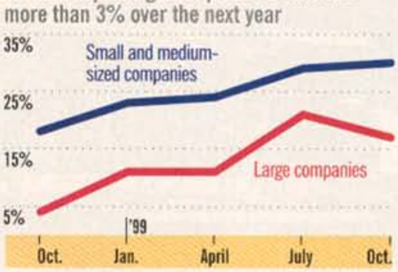


Differing sales expectations help explain the differing trends. Fully 70% of large companies—the most since the surveys began in October 1997—expect their sales to rise more than 5% in the next 12 months, but only 42% of smaller firms gave the same answer.

Percent expecting their sales to increase more than 5% over the next year



Percent expecting their prices to increase more than 3% over the next year



FORTUNE CHARTS

way to stresses from any direction—a composite's strength runs along the axis of its fibers. Thus, a designer who correctly understands the stresses that a part will experience can make a structure with a high strength-to-weight ratio by laying up plies of composite in contrasting directions, somewhat like the alternating 90-degree grain orientations that stiffen plywood.

For all their superb qualities, carbon-fiber composites long remained on the sidelines except for a few cost-be-damned military applications. Expensive hand-fabrication of composite parts played a role in dooming an earlier Raytheon business plane, the Beech Starship. Composites made up the wings as well as the fuselage and many other parts of that unorthodox twin-turboprop, pusher-propeller aircraft. The plane was conceived by maverick designer Burt Rutan, who went on to build the history-making *Voyager*, a spindly composite plane that carried its crew of two around the world nonstop without refueling. The first Starship was delivered in 1989, and a total of 53 were built. But the craft missed its payload, speed, and range goals and was priced higher than competing airplanes that performed better. Raytheon is believed to have lost hundreds of millions of dollars on the ill-starred Starship.

In the people-intensive business that aerospace composites manufacturing was in its early days, plies of woven materials were cut out and carefully stacked by hand to form laminates on "tools"—dressmaker's dummy–like forms that defined the contours of parts. Drenched with resin and bagged in plastic drawn tight under a vacuum, the string-and-glue parts then went off for curing in an autoclave, a big pressure cooker filled with inert nitrogen gas. Heat permanently hardened the resins, transforming the limp, gooey stack of plies into a light, solid structure. Many low-volume composite parts are still produced this way.

Without the machines that Raytheon and others are now using, the making of composites would still resemble the busy-fingers garment industry. "Developing the machines took Air Force money. Without it, the composites industry would be back where it was in about 1978," says Bill Benjamin of Benjamin Diversified Consulting in Gilbert, Ariz.

The first generation of composites automation began in the early 1960s, with the development of filament-winding processes that wrap a continuous strand of threadlike resin-soaked fiber around a rotating, cylindrical tool, or mandrel. Filament winding is still widely used to make geometrically simple parts such as solid-rocket motor casings, which have a constant diameter like a big piece of pipe. Filament-winding machines have major limitations, however. They can't create concave features because the taut fiber winding onto the part bridges over a depression instead of following its contour. Filament-winding machines also have a hard time applying fiber along the long axis of a part, as designers sometimes want to do.

Composites machinery made a giant leap forward in 1983 with the introduction of the first "tape layers." These machines, following computer-aided design (CAD) blueprints, lay down bands of resin-impregnated composite material in much the same way that a shipping clerk seals cartons with a handheld tape dispenser. Tape layers can pay out tape up to 12 inches wide to make flat parts. These machines, too, are unable to produce concave surfaces, though the more elaborate contour tape layers can build up the gentle convex shapes found on the surfaces of wings and other aircraft structures. Carbon-fiber skins for the tail of the big 777 jetliner are made this way at Boeing's plant in Puyallup, Wash. Airbus in Europe uses the same method to make tail skins for its A330 and A340 jets.

Fiber-placement systems are the third and most versatile type of composites machinery to be developed. Cincinnati delivered its first fiber-placement machine in 1990, but years went by before airplanes were designed to take advantage of it. These remarkable devices combine a contour tape layer's agility with a means for continuously varying the width of the band of composite to produce a greater variety of shapes. When the tape layer moves diagonally toward a fuselage window, it can snip off strands, in the proper pattern, to create the opening.

In taking a second crack at composites with the Premier I and Horizon, Raytheon enjoyed a special advantage. These are the gray heads in Wichita who spent time on the edge of the technology with the Starship. Because of lessons learned the hard way, the new planes are not all-composite. Aluminum wings will bear the carbon fuselages aloft because Raytheon's experts now believe that is the most cost-effective division of labor between the two materials. Says Richard Danforth, vice president of operations: "Carbon fiber wins for a fuselage because you can use a fiber placement machine to wrap it over a mandrel. But we think that aluminum parts made on high-speed milling machines work best for the wings, so that's how we're making them."

The carbon fiber used in the planes sells for about $100 a pound, vs. about $3 a pound for aerospace-grade aluminum. But fiber won the day as a fuselage material after engineers weighed all the pluses and minuses of competing materials and how they ripple through the entire aircraft. For one thing, says Duncan Koerbel, director of the Premier 1 business unit, "we've ended up with an airplane that has about 5,000 parts, compared with about 15,000 parts in our Beech Jet." Koerbel says that in that plane, an older, seven- to nine-passenger model in Raytheon's lineup, "each part gets a number, and it has to be produced, inspected, tracked, assembled, stocked as a spare, and illustrated in the manual. We'll be building this new airplane for a lot less than it costs to make the Beech Jet. Fastener-wise, there are almost none in the carbon fuselage, vs. a bazillion in the Beech Jet."

Market research also influenced the choice of carbon fiber. Because a spacious cabin tops most customers' lists of desired features, maximizing the interior volume and headroom guided the Premier 1's design from the outset. Aside from insulation, all that's between a passenger and the very chilly air at 41,000 feet is a 0.81-inch thick structure made from carbon-fiber inner and outer skins sandwiched over a core of plastic honeycomb material called Nomex. Like a cardboard tube used to mail rolled-up documents, the Premier 1's rigid carbon-fiber fuselage needs no skeleton—the ring-shaped internal frames and longitudinal stringers that serve the same function as studs and joists in a wooden house. Making an aluminum fuselage with the Premier 1's interior volume would have required a fuselage four inches fatter in diameter, as well as heavier.

The fuselages take shape in Raytheon's Plant 3. That's where the company keeps its Vipers, the $5 million Cincinnati Machine fiber-placement systems that got their name when a marketing guy observed that the strand of carbon fiber coming out of the machine's placement head looked like a serpent's flicking tongue. Raytheon is completing the installation of its second Viper, and a third is coming soon to keep up with demand for its hot-selling new jets.

The 62-foot-long Viper is quite a piece of work, the culmination of about 15 years of development by Cincinnati engineers working with aerospace customers. Its placement head moves by computer direction, applying sticky yarnlike strands, or "tows," of resin-coated carbon fiber to a contoured mandrel that rotates slowly, also under computer control. The mandrel for a forward fuselage looks just like a forward fuselage, and it imparts this shape to the composite material applied to it. The Premier 1 fuselage is made on two mandrels, fore and aft, while the longer Horizon is a three-part design with an additional center-section mandrel. Cincinnati Vipers come with placement heads dispensing as many as 32 tows of fiber. The one now making fuselages at Raytheon is a 24-tow model.

Formidable software programs drive these machines, which can move in seven axes. Fiber placement is like having a dispenser that can pay out tape of varying width to suit the details of the part being made. The difference is that, instead of tape, the machine dispenses parallel tows of an eighth-inch-wide fiber. The number of tows can be varied from one to 24 as the placement head moves along, effectively changing the width of the band anywhere from an eighth of an inch to three inches to work around various features.

This makes for a complicated machine, because it must have 24 of everything: spools of carbon, feed rollers, tension controls, and cutoff knives. There are additional complexities, like refrigerating the spools of carbon to protect their chemistry in the glass-windowed "creel" where they reside. Then the stands must be quickly heated to increase their tackiness before they run under the placement head's compaction roller and onto the mandrel. The whole apparatus trundles back and forth on rails as it works from one end of the mandrel to the other. Breathtaking to see in action, the machine makes a visitor think of the years of hair-pulling it caused unsung engineers.

One of the key benefits of fiber placement is being able to make parts with apertures such as doors and windows by dropping and adding tows, or stopping all the tows at once, as the head passes over areas where openings are called for. Thus, little of the expensive material gets thrown away as scrap. The Viper's multiaxis head can also steer tows around moderate-radius curves to achieve the fiber orientation a designer wants for dealing with local stresses. The weirdest thing the machine can do is lay down tows in an area of pronounced concavity, where the compaction roller on the tape head forces the material to stick. This capability enabled the Premier 1's designers to sculpt a pinched area on the aft fuselage, just inboard of the engines. An elegant aerodynamic tweak, it let them shorten the engine pylons for weight savings while maintaining low-drag air flow between the engines and the main body.

After the Viper has finished applying the inner layer of carbon for a fuselage, workers manually attach precut sections of Nomex honeycomb with adhesive. They're guided by a low-power laser that projects flickering red outlines of the correct locations for the honeycomb onto the mandrel. The laser system replaces physical templates once used to guide such tasks and fetches up the outlines from a database running CATIA

PAUL BOWEN

ROOMIER INSIDE: **The use of composites gives the Premier 1 a bigger cabin.**

BUSINESS END: The head of a Cincinnati machine builds up a Horizon's nose.

design software supplied by Dassault Systèmes of France. With the Nomex in place, the Viper goes back to work applying an outer layer of carbon atop the honeycomb. Over this goes a final ply of carbon-fiber woven fabric with fine aluminum wires running through it to provide protection from lightning.

The mandrel is then removed and the limp part, its shape maintained by an inflated bladder inside and an outer mold, goes to the autoclave for an eight-hour curing cycle at 350° F. After it cools, the now tough part gets its edges trimmed with water jets. Next, ultrasonic and laser devices inspect it for hidden voids or inclusions—foreign matter that doesn't belong in there. After workers repair defects with resin or bonded-in titanium metal patches, the big, black chunk of airplane is ready for the final assembly line. The first carbon Premier 1 fuselage took about 20 days to make, Koerbel says. As the composite-shop crew has gained experience with the process, the build time has come down to about five days. Koerbel adds, "Our scrap is 2% now, vs. 40% to 60% in the Starship days."

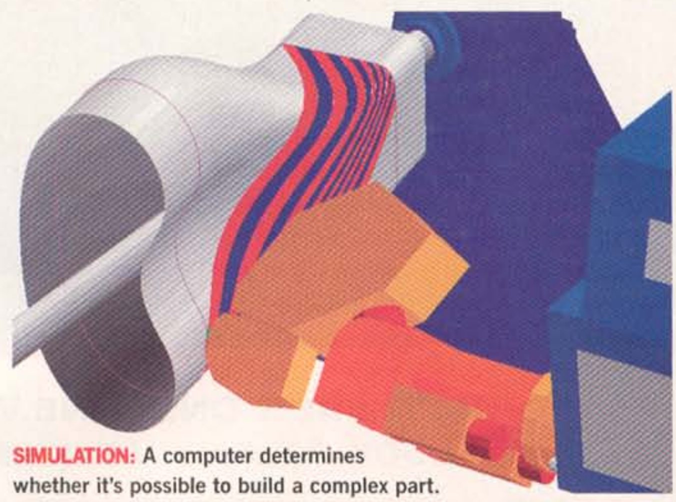
The programmability of fiber-placement systems makes design changes cheap. When Raytheon engineers were conducting a torture test, applying maximum bending loads to an early experimental version of the Horizon's 1.06-inch-thick center-fuselage section, it failed at 143% of maximum load, instead of the 150% target. By fiddling with the fiber orientations in the Viper's software, the engineers strengthened the part so that the next sample passed the test without gaining any weight. In an aluminum airplane, such a fix would have required metal reinforcements and extra pounds.

Carbon-fiber composites are old stuff at Boeing's development center on Seattle's outskirts. You needed a lot of special badges to get into the place during the late 1980s and early 1990s, when the center, using contour tape layers, was quietly producing about 60% of the composite structures for the B-2 Stealth bomber. In the composites shop, a pair of autoclaves 90 feet long and 25 feet in diameter, a 90-foot-long ultrasonic inspection machine, and two 90-foot-long gantry-type routers for trimming the edges of parts attest to the scale of the big bird that took shape here. With a wingspan of 172 feet, the B-2 is the biggest piece of carbon that ever left the ground, says consultant Bill Benjamin, who was Boeing's manager of composites automation and later technology manager of the B-2 program at Northrop, the plane's prime contractor. Congressional cutbacks in the B-2 program helped drive up the plane's unit cost.

Among its many composite parts, the B-2 has elegant, highly sculpted S ducts. They supply air to the bomber's engines, which are hidden deep within the fuselage. The S ducts' curvature denies enemy radar waves a direct "line of sight" to the highly reflective metal parts at a jet engine's front end; radar waves check in, but they don't check out. The ducts were built up by hand from layers of carbon and other structural fibers as well as radar-absorbing materials. Today, fiber-placement equipment could handle the job. Tape-laying machines formed the B-2's wings, whose roots—where they join the fuselage—have 118 plies of carbon material. Says Benjamin: "With that number of plies, the labor hours would be enormous, and you could really get into trouble cutting patterns and positioning each one exactly right."

Boeing's development center is now doing impressive things with newer fiber-placement technology. By making the 13.5-foot-diameter, 3,800-pound Sea Launch rocket payload fairings on its big Ingersoll machine, it has reduced by two-thirds the number of labor hours needed to produce the part, compared with hand lay-up. The Ingersoll machine's ability to avoid unnecessary ply overlaps, another problem with hand lay-up, enabled engineers to build the fairing closer to the ideal shape as calculated by computational fluid dynamics software. The payoff is a 10% reduction in aerodynamic drag, says Eric Wetzel, the Sea Launch director of product development. Fiber placement also makes it easy to build in access panels of varying size and location that customers need so they can tinker with their satellites until blastoff time.

The Ingersoll machine, which was delivered to Boeing last year, can move in seven axes. Bigger than the Cincinnati Vipers at Raytheon, it can work on one part up to 70 feet long while a second mandrel is being loaded at its other end. The work carriage shuttles on 150-foot-long rails from one workpiece to the other, dispensing as many as 32 tows of carbon fiber in a band up to four inches wide. The machine justifies its \$10 million cost when it's laying down carbon at the rate of about ten pounds an hour; it has achieved placement rates as high as 70 pounds an hour when producing simple shapes at its maximum speed of 150 inches a minute.



SIMULATION: A computer determines whether it's possible to build a complex part.

Like Raytheon's jet fuselages, Boeing's payload fairing has a sandwich structure. To build it, the machine first lays down an inner shell of carbon fiber. Next, workers attach a layer of aluminum honeycomb by hand. Finally, the machine applies an outer carbon shell, forming walls an inch thick. The fairing's tapered shape permits it to be constructed by fiber placement around a one-piece mandrel made of a carbon-composite tooling material. Because this material has the same thermal expansion coefficient as carbon-fiber composite, the mandrel doesn't distort the part while it's cooking in the autoclave.

After autoclave curing, Boeing saws the fairing in half on its long axis to remove it from the mandrel. Then it installs latch mechanisms that will hold the halves together until the rocket leaves earth's atmosphere. That's when the now superfluous fairing opens like an alligator's jaws and falls away, reducing the weight of the rocket's third stage. The fiber-placement machine is also used to make a carbon-composite part known as the payload structure, a platform that connects the satellite to the rocket's upper stage.

Fiber placement may have a big future at Boeing. A second workpiece recently seen on its Ingersoll machine was an experimental carbon-fiber "box spar" for the tail of the 777 jetliner. The tail's carbon spars and other inner structural members are currently laid up by hand, and researchers want to learn whether the parts are good candidates for automation. As the machine is configured now, it can produce parts up to 20 feet in diameter. But it could be modified to make larger structures. "We think fiber placement is a viable production process now, and we are looking into using it for airliner fuselage sections and large fuel tanks for commercial rockets," says Tom Tobey, Boeing's director of manufacturing research in Seattle.

CONTAINER: Boeing builds a rocket's payload fairing of carbon on a huge Ingersoll machine.

The machines opening up these possibilities took not only years of development work by the toolmakers but also some of their own money when top-secret military programs weren't paying the bills. "Tape layers and ultimately fiber-placement machines were developed for discretely funded programs for particular aircraft," recalls Cincinnati Machine President Kyle Seymour. "Our customers, the prime contractors, talked to us cryptically. They would give us wooden mockups of portions of a contoured surface, and we would lay some tape on it for them to prove out a machine design."

Convinced that composites automation would eventually have commercial applications, Cincinnati invested about $15 million to keep the R&D going during the lean years. Orders for composites machinery rose to nearly $20 million in 1999, compared with $3 million to $5 million annually in previous years. Says Seymour: "We're reaching the point where there's a critical mass of business in the aerospace industry." For proof, a skeptic need only look at all those new business jets in Raytheon's fat order book. F

BLASTOFF: A Hughes/DirecTV communications satellite rode aloft in the fairing when the rocket was launched at sea on Oct. 9.