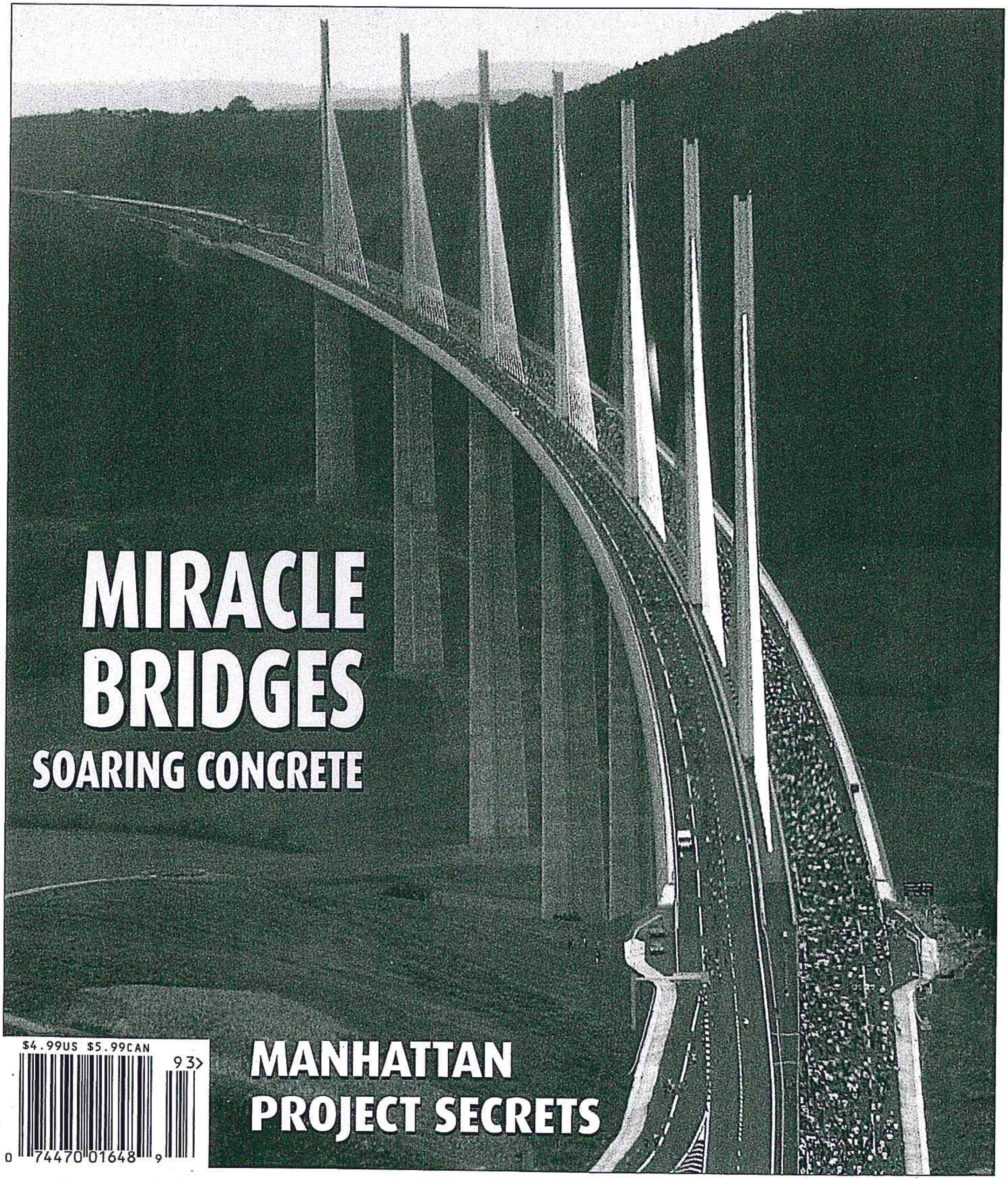
FIRST VIDEO GAME | RESTORING STEAM ENGINES | PROSTHETICS HELP VETS

American Heritage's

Invention & Technology

FALL 2009 | VOLUME 24 | NUMBER 3



MIRACLE BRIDGES

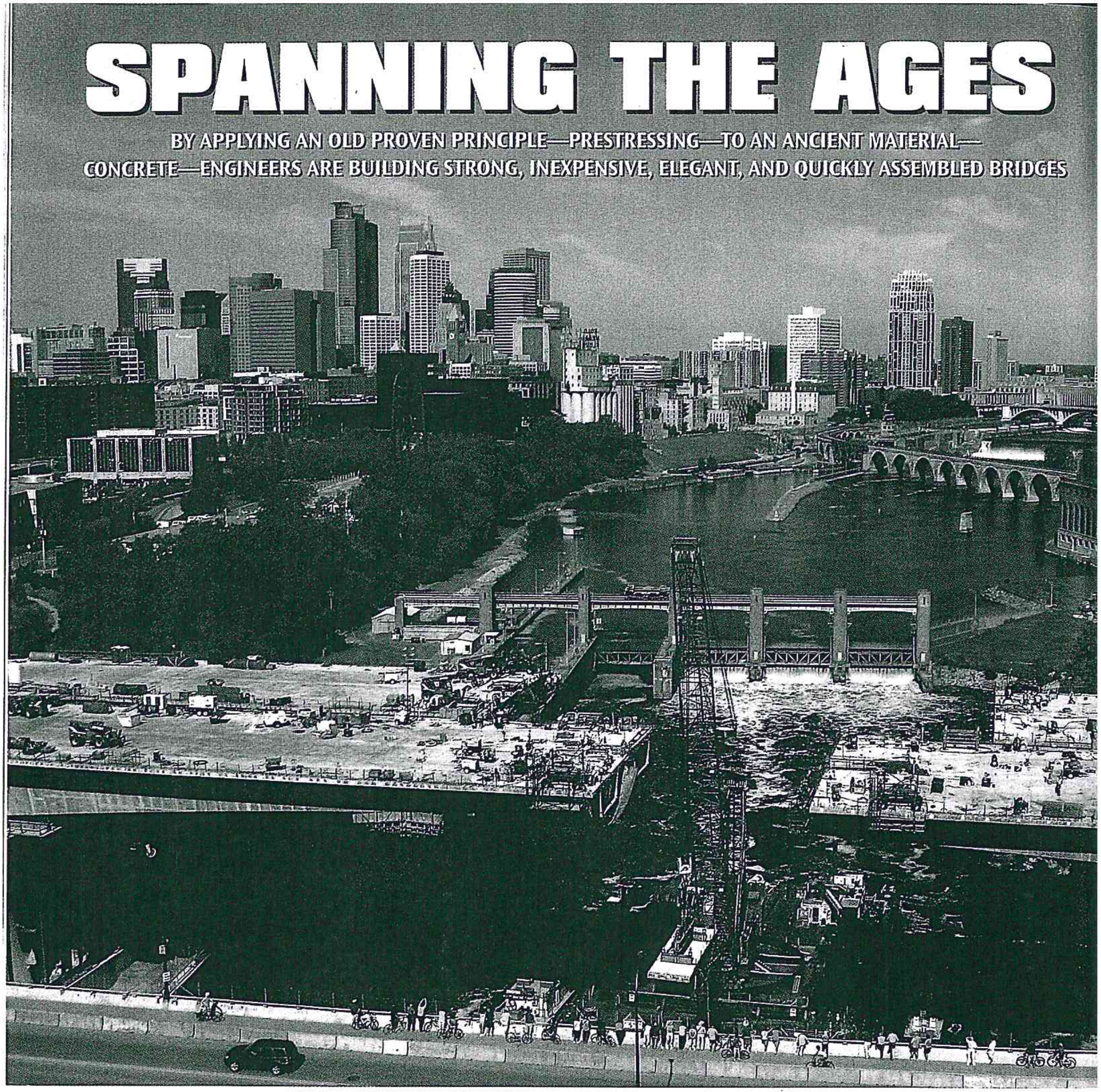
SOARING CONCRETE

MANHATTAN PROJECT SECRETS

$4.99US $5.99CAN
93>
0 74470 01648 9

SPANNING THE AGES

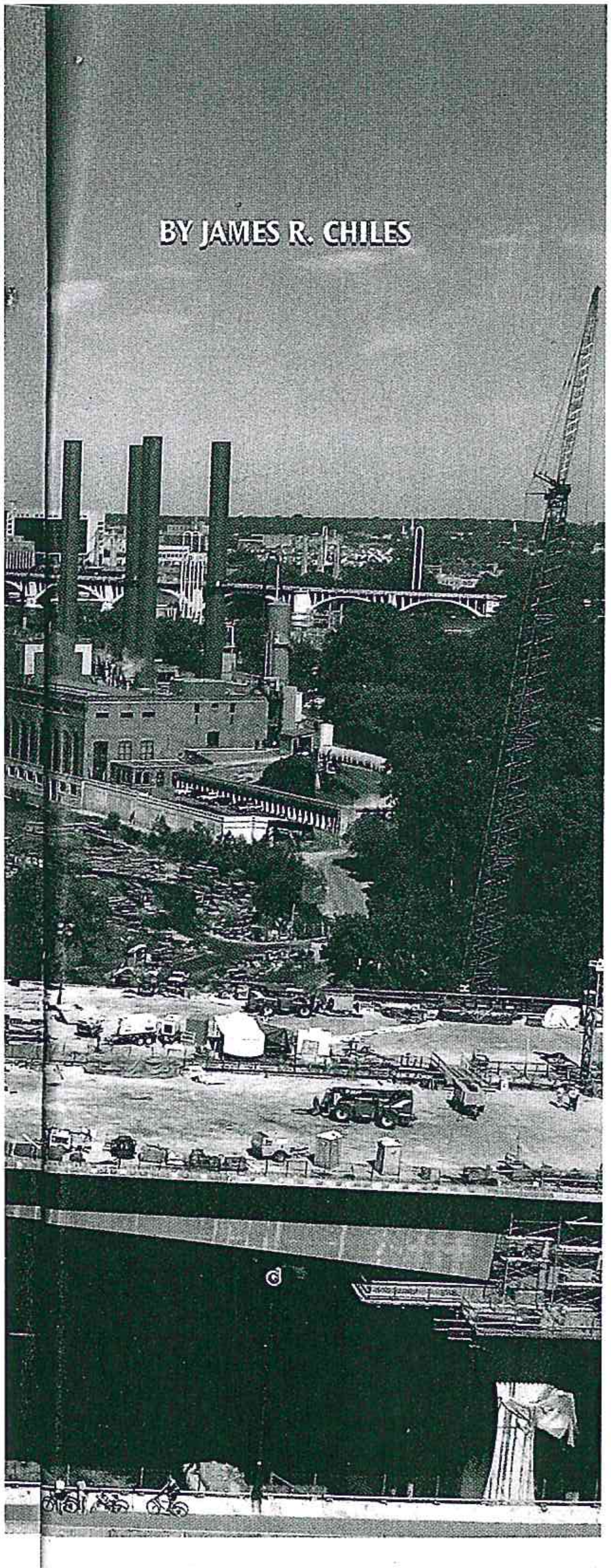
BY APPLYING AN OLD PROVEN PRINCIPLE—PRESTRESSING—TO AN ANCIENT MATERIAL—CONCRETE—ENGINEERS ARE BUILDING STRONG, INEXPENSIVE, ELEGANT, AND QUICKLY ASSEMBLED BRIDGES



COURTESY MNDOT

AFTER MINNEAPOLIS'S I-35W steel truss bridge collapsed into the Mississippi River at 6:05 p.m. on August 1, 2007, the first job was survivor rescue, followed by recovering bodies and clearing of vehicles and wreckage. Well before that was finished, planning for a 1,223-foot-long replacement structure was under way. The state tallied a daily tab of $400,000 in delay and lost business, given that 140,000 vehicles had been using its eight lanes each weekday. Normally, says structural engineer Alan Phipps of FIGG Engineering Group, a typical bridge of this size takes 30 months to build.

This job would be different. Phipps served as design manager for a team that won a lightning-fast four-way bidding competition. The Flatiron Constructors–Manson Construction joint venture promised to install two concrete bridges—one handling northbound traffic, one southbound—for $234 million. Crews swarmed the site on November 1 to prepare for boring holes and pouring pier foundations at the river's edge, even as engineers continued to detail the superstructure plans. Taking advantage of the rare fact that this

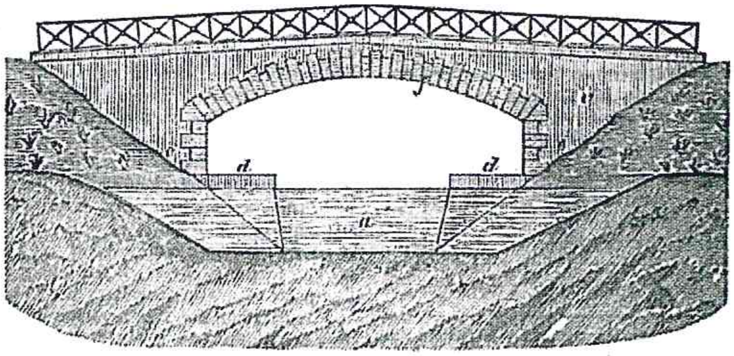


BY JAMES R. CHILES

bridge could be built without having to cope with daily highway traffic, crews commandeered the road on the south side of the river to lay out eight precast-concrete assembly lines, featuring four-story-high heated buildings on wheels. These enabled the bridge segments to be cast day and night in defiance of subarctic weather. The crews' job was to build forms, set reinforcing steel, and pour 120 pieces for assembling the river crossing. The segments measured up to 16 feet in length and weighed up to 200 tons, depending on their location along the gently curving spans. "We couldn't wait for the four- to six-month lead time to order steel forms, so Flatiron built them out of timber," says Phipps.

By late April 2008 the first span segment, numbered 2 SB1 EXT, was ready to be taken half a mile down to the river's edge aboard a 64-wheeled transporter. There a crane loaded it onto a barge and tugboats pulled it upriver to the bridge site. On May 25 a crowd of 800 watched from a neighboring span as a barge-mounted crane eased it into place next to the top of a pier, then held it steady as it was locked tight with eight thick steel bars. Plans to set another segment that afternoon had to be postponed after a small tornado passed nearby, but the pace only accelerated in the following days as the crew rose to 400 men and women working by day and 200 by night, seven days a week. More segments followed, each joint daubed with epoxy before hydraulic jacks clamped it into place with steel "post-tensioning" cables. (These jacks, which can apply up to 500 tons of force, effectively shortened the bridge about two inches by squeezing the concrete.) The 120th segment went up in July, completing the 504-foot span. The bridge opened for traffic in September 2008, just 11 months after construction began. Spurred by $20 million in bonus payments from the Minnesota Department of Transportation (MnDOT) for rapid progress, the contractors finished more than three months early.

MnDOT is expecting the bridge to hold up at least through 2108, its assumptions resting on a concrete mix blended for extra strength and weather resistance; a box-girder design whose redundancies protect against collapse; a network of "smart bridge" sensors to sound alarms long before cracks or corrosion threaten destruction; 7,500 tons of steel reinforcement bars coated with rust-fighting epoxy coating; and hundreds of miles of tightly strung steel tendons. By clamping the concrete end to end and side to side, these "prestressing" tendons take concrete to a whole new level of performance. Phipps ascribes to the bridge a safety factor of two, meaning it could tolerate double the expected load. Engineers built in the option of adding more tendons in future years that can raise the load-bearing capacity another 10 per-



Only 11 months after Minneapolis's I-35W steel truss bridge collapsed into the Mississippi on August 1, 2007, the barge crane "Big Ben" hoisted one of the final precast segments of its 1,223-foot-long concrete replacement, opposite, reinforced by more than 750 miles of pre- and post-tensioned steel cables, a technology that has enabled engineers to erect long, durable bridges quickly and cheaply. The first modern bridge using concrete spanned the 39-foot-wide Garonne Canal in Grisolles, France, above, in 1840.

cent, in case future trucks get heavier.

Prestressed concrete provides the backbone for the 1,815-foot-tall CN Tower in Toronto, the 1,000-foot-tall Troll A deepwater natural gas platform in the North Sea, containment vessels for nuclear power plants, giant floating tanks to hold ultracold liquefied natural gas, the soaring pylons of the Millau Viaduct in southern France, and a 722-foot-tall condominium in Chicago.

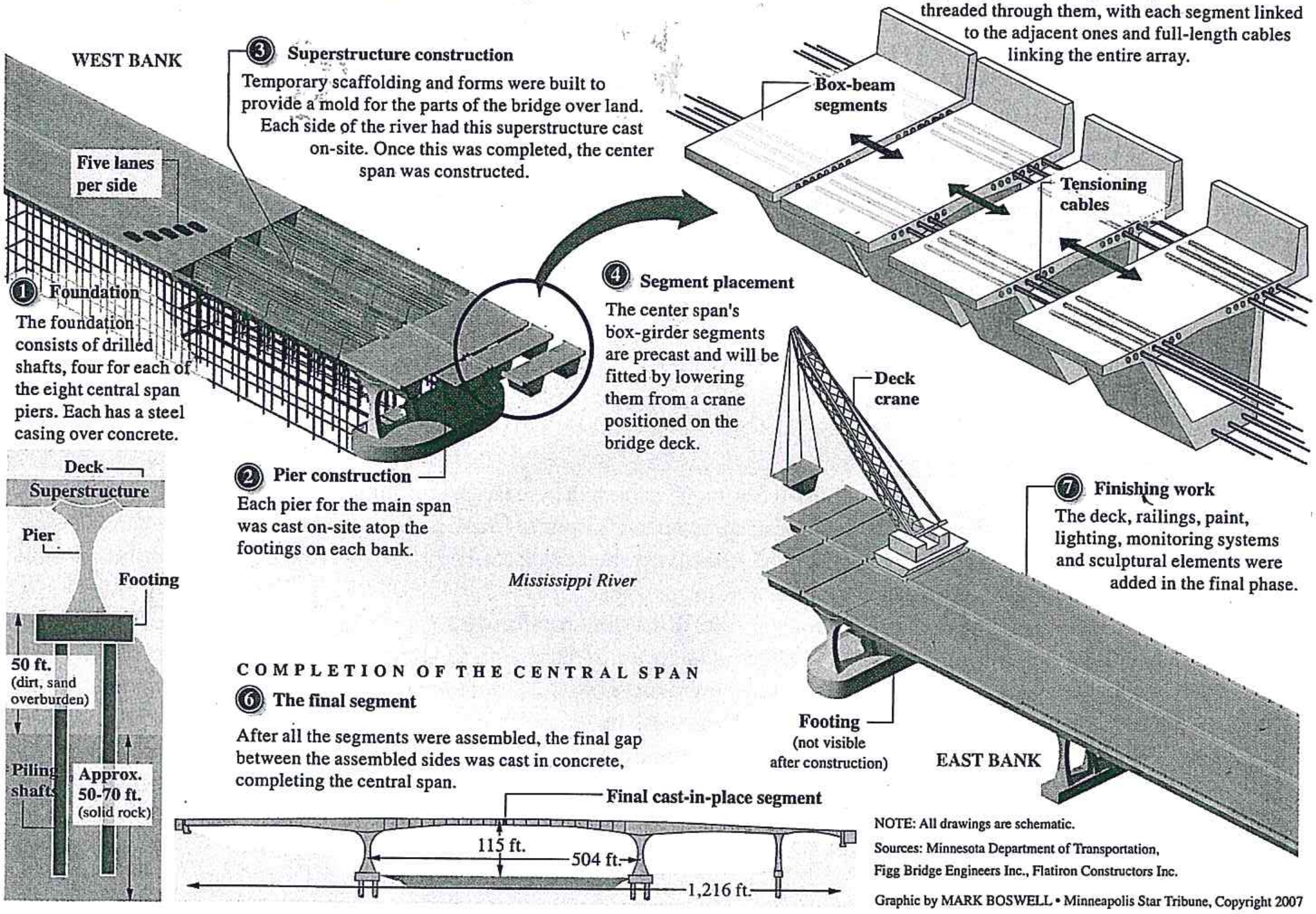
Although this story stars chunks of high-strung concrete, it illustrates a broader issue: many favorable factors must be in place before a radically new technology can take hold in a slowly changing field such as structural engineering. Those factors include champions who will not quit, a complete system of techniques and hardware, and a wide-open market niche. Despite scattered patents and experiments concerning prestressed concrete dating to 1886, nothing significant happened until Eugène Freyssinet took a patent in 1928 and then established critical follow-up patents covering materials and methods. The European bridge market saw all the necessary elements for a bridge boom come together immediately after World War II. "They used [prestressed concrete] to rebuild a vast number of bridges destroyed in the war," says Phipps. "They lacked sufficient structural steel, so this offered a more efficient use of materials." (Two other bridge-building breakthroughs that helped fill the gap were the cable-stayed span and a strong, lightweight steel bridge deck.)

While innovators in the United States had been using prestressed concrete for fence posts, pilings, and large tanks through the 1930s, Americans were slow to adopt prestressing for bridges until the federally funded highway boom was well under way in the 1950s. Even then its use was initially confined mostly to short-span bridges. As evident from the features bundled into Minneapolis's new I-35W bridge and other prestressed designs, U.S. concrete enthusiasts want to catch up.

PRESTRESSING MEANS that a powerful compressive force is locked into concrete before it enters service, to counteract sagging and cracking from the dead weight of the structure plus the weight of live loads like trucks and trains. Prestressed devices have been common in history, particularly for weapons and transportation. Examples include ancient Egyptian barges, archers' bows, wire-wound cannon barrels, bicycle wheels, and wood-truss

A new design, techniques and materials for I-35W bridge

The bridge is actually two parallel bridges, each supported by two box girders. There are five lanes of traffic in each direction, with room for additional lanes, light rail or bus transit.



① **Foundation**
The foundation consists of drilled shafts, four for each of the eight central span piers. Each has a steel casing over concrete.

② **Pier construction**
Each pier for the main span was cast on-site atop the footings on each bank.

③ **Superstructure construction**
Temporary scaffolding and forms were built to provide a mold for the parts of the bridge over land. Each side of the river had this superstructure cast on-site. Once this was completed, the center span was constructed.

④ **Segment placement**
The center span's box-girder segments are precast and will be fitted by lowering them from a crane positioned on the bridge deck.

⑤ **Assembly**
Segments are linked together by steel cables threaded through them, with each segment linked to the adjacent ones and full-length cables linking the entire array.

COMPLETION OF THE CENTRAL SPAN

⑥ **The final segment**
After all the segments were assembled, the final gap between the assembled sides was cast in concrete, completing the central span.

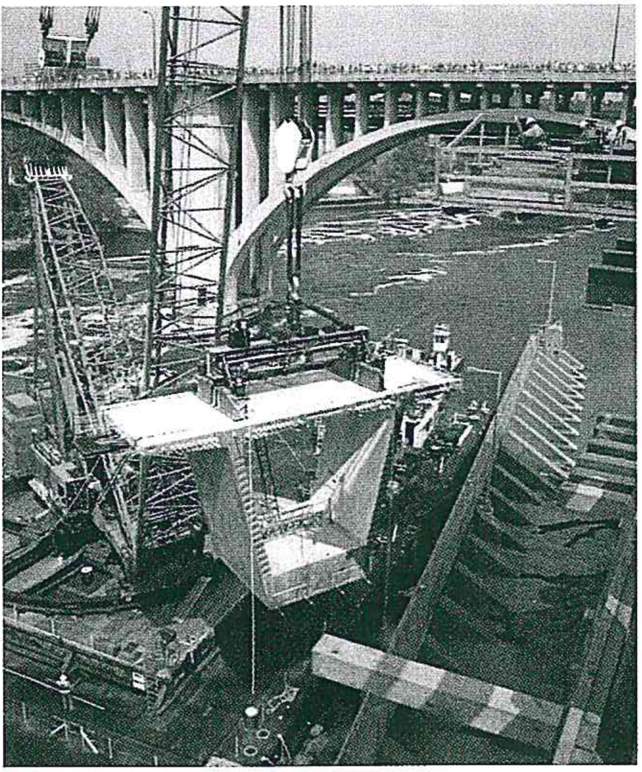
⑦ **Finishing work**
The deck, railings, paint, lighting, monitoring systems and sculptural elements were added in the final phase.

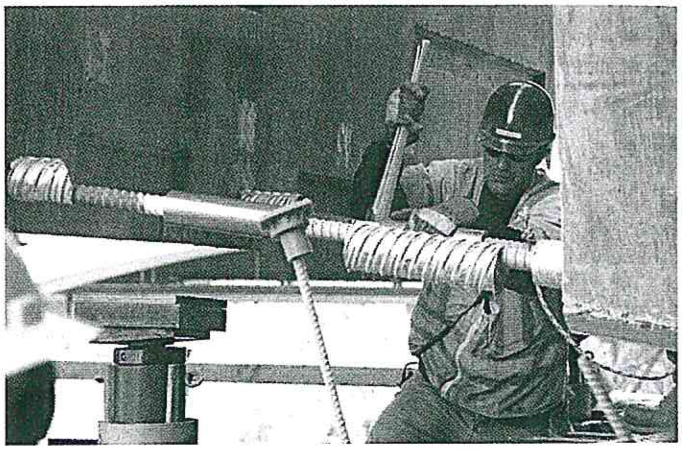
NOTE: All drawings are schematic.

Sources: Minnesota Department of Transportation, Figg Bridge Engineers Inc., Flatiron Constructors Inc.

Graphic by MARK BOSWELL • Minneapolis Star Tribune, Copyright 2007

MARK BOSWELL/*STAR TRIBUNE*





During construction of the I-35W replacement bridge, each of the more than 120 precast concrete box segments, left, which weigh between 150 and 200 tons, were lifted into position by crane. Workers then threaded heavy steel reinforcing bars through the segment, above, linking it to the previous segment. A hydraulic jack, below (resting on girder), exerts approximately a million pounds of force on the strands in each tendon, which are then tied off with an anchor to retain the tension.

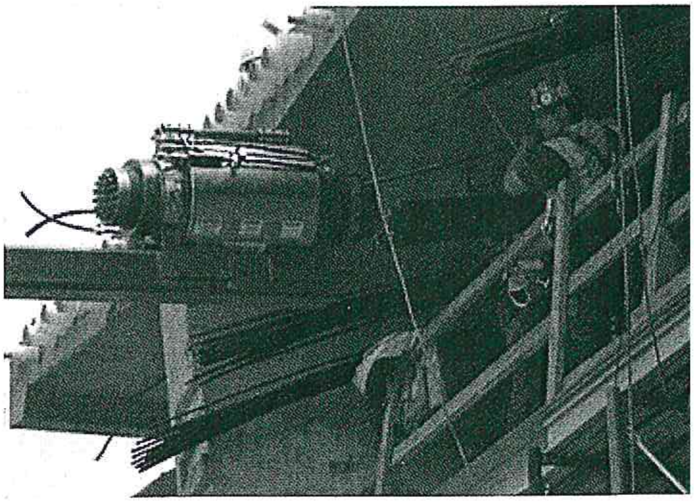
bridges. By enabling the builder to focus tensile and compressive stresses on the materials best able to cope with them, prestressing saves weight and boosts performance.

How does it work in concrete? Imagine picking up a stack of five bricks, the kind with holes through the middle. One can turn that stack horizontally, but only if one's arm-strength is sufficient to press them together very tightly. But there's an easier way: run a steel cable through the holes, tighten it with a lever and anchor the ends to the outermost bricks. Now it's a composite of brick and steel that can be turned any which way. String together enough of them like beads on a string, and voilà: a narrow footbridge, flexible yet strong. The safe working load will, of course, depend on a number of factors, such as the exact placement of the wire, the bricks' resistance to crushing, and the steel's resistance to stretching.

The reinforcement wires running through the underside of the new I-35W bridge decks are so strong that the hydraulic jacks used to tighten them could raise a locomotive with power to spare. Prestressed concrete counts as a new material, though by weight it's mostly the old familiar compound of sand, gravel, and cement powder activated by water.

Prestressing grew out of experience with conventional reinforced concrete, which used iron as a strengthening agent but did not attempt to compress the concrete by tensioning the metal. Setting aside Roman and medieval experiments with metal chains and straps to strengthen masonry structures, the first attempt to use metal to strengthen cement came in 1849, when Joseph-Louis Lambot constructed a functional boat by slathering mortar around a boat-shaped array of iron mesh. In 1867 Parisian gardener Joseph Monier followed up with patents on using iron mesh to reinforce flower pots; the German firm Wayss and Freytag later adapted his ideas for full-sized structures. In 1875 William Ward built a large house in Port Chester, New York, entirely out of reinforced concrete. Out of such experiments came the realization that metal bars could help overcome the tendency of concrete to crack when placed under tension, which usually happens at the bottom of a beam or slab or at the base of a cantilever. While the virtue of embedded reinforcing bars was fairly obvious, the possibility of applying extreme tension to that steel and compressing the concrete was neither intuitive nor practical in the early years of concrete construction.

The use of reinforced concrete proceeded more rapidly in buildings than



COURTESY MNDOT

In 120 C.E. the Emperor Hadrian used the resilient Roman Pozzolana concrete, mixed from volcanic ash, lime, and a small amount of water, to erect the 142-foot diameter dome of the Pantheon in Rome, which still stands to this day.

CUBOIMAGES SRL/ALAMY

bridges because it had one particularly powerful advantage: concrete frames stood up longer in a fire than bare frames of iron or steel, a point of obviously urgent importance in the baleful light of citywide fires in Chicago (1871), Seattle (1889), and Baltimore (1904). The field grew thick with inventors equipped with little theory or rigorous experience to guide them, each hoping to license a proprietary approach to reinforced concrete. The American engineer Albert Colby counted 144 separate "systems" during his 1908 tour of Europe.

In energy, conviction, and ambition, one stood out: the Hennebique system, an internationally franchised package of ideas from the self-taught French builder François Hennebique, whose network of firms offered a magazine, brochures, lectures, trade shows, and celebratory dinners to reward employees and consultants. His system favored a stout grid of interlinked reinforcing bars that treated buildings as unitary structures, rather than a collection of weakly linked walls, floors, and columns. More than 7,000 structures were completed under Hennebique's license by 1902. While the grander aspects of the plan faded after 1910, as key patents expired and government regulations specified additional construction methods for safety, "Maison Hennebique" continued in the role of consulting engineers.

"Hennebique saw how to build with reinforced concrete and how to set up an organization," says engineering historian David Billington of Princeton University, author of *The Tower and the Bridge*. "One of Hennebique's major contributions was to bring many people into the field. He was a genuine pioneer." While principally aimed at the market for new factories, offices, and apartments, the Hennebique system did extend to bridge design, such as his Châtellerault Bridge in 1899.

The earliest American customers for concrete bridges were city parks in California and New York. One of those pacesetters, the Alvord Lake Bridge of 1889, still stands in San Francisco's Golden Gate Park, decorated to look like stone and mortar but concrete for all that. These beginnings multiplied, and by the turn of the century the day of the large-span stone arch was over.

America's first major reinforced-concrete bridge, completed in 1898, spanned the Kansas River at Topeka. Its builders relied on the competing Melan system, which was so conservative that it began by building a stout skeleton arch of steel ribs, only then to be wrapped in concrete. (A similar approach was recently used for the record-breaking quarter-mile-long Wanxian Bridge over the Yangtze in Chongqing, China.)

Even as steel arches, trusses, and cable-suspended spans held sway over the construction of new major railroad and road bridges, reinforced concrete gained ground for shorter spans. While occasional landmark bridges employed reinforced-concrete arches to leap amazing distances—up to 600 feet—these were the exception. The sheer mass of the concrete and reinforcing steel required for long spans brought problems of its own, which only prestressing would resolve.

A problem inherent in concrete is "creep," its tendency to flow slowly from areas of high compression to lower, a phenomenon that can persist for a decade after a bridge is erected. One of the first to measure creep and act on it was the French civil engineer Eugène Freyssinet. From the outset of his career, he was keen on slimming bridges down to the absolute essentials. Months after completing a slender, three-span concrete bridge near Vichy in 1912, he was dismayed on returning to learn that the centers of his Pont le Veurdre spans had settled and were still dropping. In working out a fix, Freyssinet took advantage of an unusual feature of the design, which had left a joint in the center of each span to aid in the removal of falsework during construction. Working with a small crew at night and on his own authority, he inserted hydraulic jacks at these spots, pushed the halves of each arch apart, raised the centers again, and filled the gaps with concrete. Most important, he followed up with experiments using hydraulic jacks to strengthen other concrete bridges. In 1928 he patented a method relying on steel wires to prestress concrete.

"Prestressed concrete was not a new idea," explains Billington. "It had been tried ever since concrete was reinforced, but there was a fundamental flaw. They did not understand well enough the response of concrete under compression.

Think of a big column with a weight on it. It shortens elastically. Steel will deflect and stay that way. But if the column is concrete it deflects, and then continues to deflect. . . . This problem happened with all experiments in early prestressed concrete. They used ordinary steel wire in the late 1800s and the prestress dropped precipitously. But with high-strength steel you could start at 100,000 psi, say, and if you lost 20,000 psi and if you accounted for that, you'd have stress remaining."

Three years later Freyssinet resigned from his prestigious and high-paying engineering job with Société Limousin et Compagnie to set up a business making power line poles out of prestressed concrete. While his prestressed poles worked as promised, the worldwide Great Depression cut the market out from under him and left him bankrupt. Salvation came in 1935, when harbor authorities at Le Havre discovered that a new railway terminal was in the midst of a slow-motion collapse. Built half on rock and half on pilings driven into soft ground, the weaker half of the Gare Maritime was falling away. Nothing worked until Freyssinet took on the job, installing a set of prestressed underground beams and tying them to pilings.

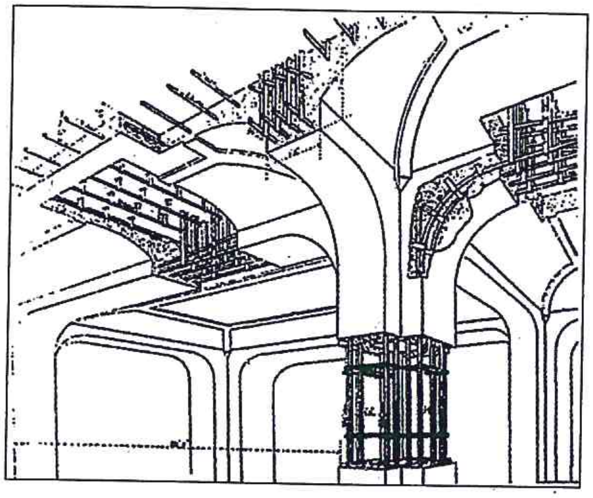
He employed what is now called post-tensioned concrete, in which the reinforcement wires are tightened only after the concrete has cured. These wires can be run through hollow ducts cast into or alongside the concrete. Post-tensioning is still the key to high-performance, large-span concrete structures, including the I-35W bridge. Pre-tensioned concrete differs in the timing: reinforcing wire is pulled tight across a form before the concrete is poured. The taut steel is thus embedded in the mix as it cures, giving the cement a tight grip on the metal. Later, workers snip the wires and pull the completed piece out of the mold, a procedure well suited for mass producing components for later assembly at a job site. During the Second World War, the Swedish firm Betongindustri in Stockholm produced pre-tensioned concrete beams, poles, and pilings in extra-long forms, storing the products and then sawing them to length as orders came in. Betongindustri also sold prestressed concrete lampposts and even bathtubs.

Taking advantage of the expertise brought over by German refugee Karl Mautner, Wayss and Freytag's former technical director, British engineers used prestressing when constructing an attack-proof shelter for its Royal Air Force arsenals, for casting concrete beams used in bridge repairs, and for mass-producing concrete railroad ties. On the German side was Ewald Hoyer, who used concrete prestressed with piano wire–like strands to great effect in armoring bunkers and factories across Fortress Europe, until he perished in the 1945 firebombing of Dresden. The thickest portions of Hoyer's prestressed concrete roof over the Bremen-Farge U-boat factory never collapsed, even under the Allies' 11-ton earthquake bombs.

In short, even before the war's end, prestressing was well on its way to transforming a major portion of the concrete industry from slow craftwork at construction sites to the mass production of interchangeable parts at centralized plants, where quality could be controlled. Belgium and France began using prestressed concrete in bridge repairs even before the Germans retreated, and its use among bridge builders accelerated greatly after VE Day.

The war destroyed more than 10,000 bridges in France and Germany. Recalling his tour of the reconstruction work with the head of Belgium's highway bureau, David Billington recalls seeing bridges that had been destroyed, repaired, and blasted again up to four times during the war "You could say that bridges went through more than some of the people did."

"The war had a lot to do with the advancement of prestressing, due to the steel shortage," says Robert Bruce, engineering professor emeritus at Tulane University. "Prestressed bridges used one-fifth as much steel. All the bridges on the Rhine had been destroyed, and hundreds were replaced with prestressed concrete." After the war, Bruce assisted in the high-speed construction of the world's longest bridge, a pair of concrete causeways across Louisiana's Lake Pontchartrain built



In 1870, Frenchman François Hennebique, above, pioneered the concept of reinforced concrete construction by incorporating a grid of interlinked steel bars, right, into his concrete structures, treating them as strong, unitary structures rather than a weakly connected series of walls, floors, and columns.

COURTESY MOUCHEL

World War II bombing destroyed more than 10,000 European bridges, including those spanning Frankfurt's Main River, above. The urgent need for bridge replacements and the shortage of steel led to widespread implementation of prestressing systems, a technology invented by French engineer Eugène Freyssinet, below left, which relied on an anchorage, below right, to tighten high-tensile wires running through the concrete and to minimize cracking and sagging.

atop 9,500 prestressed concrete pilings.

Back in France, having completed his prestressed Luzancy Bridge over the Marne in 1946, Freyssinet cloned that design by setting up a factory at nearby Esbly that prefabricated standard parts for five similar bridges, delivered by barge.

The United States remained distinctly slower to accept prestressed concrete as an alternative to conventional bridge building. It had abundant steel-making capacity left from the war, and the civil engineering profession needed more persuasion before taking on radically new methods for so highly prominent and safety critical a field. The same holds true today, observes Andrea Schokker, head of the civil engineering department at the University of Minnesota, Duluth: "In our industry we're slow to change because we need [both] proven materials and equipment that is readily available. It's not like the electronics industry."

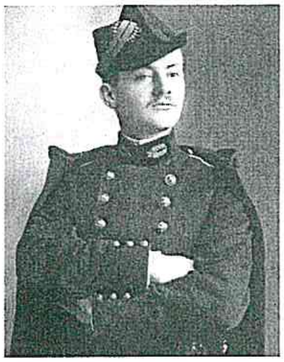
The change agent landed here in 1947: Belgian engineer Gustave Magnel. His book about European prestressing methods and his lucid lectures across the United States changed doubters into believers. Magnel had even equipped his Sclayn Bridge in Belgium with a full set of instruments inside to verify that all elements were performing as designed.

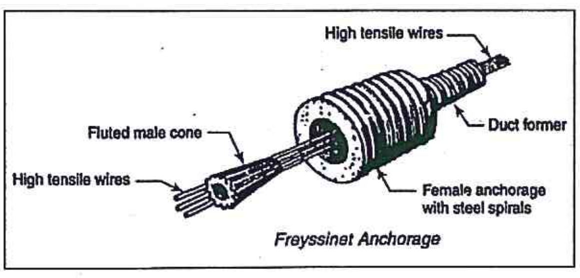
Billington, who also worked in Belgium during the reconstruction, noticed the differences in style and theory between Freyssinet and Magnel. "Definitely they were rivals," Billington recalls.

Reassured by Magnel's explanations and encouraged by advances in postwar steel making that made high-quality, high-strength cables available in volume, the city of Philadelphia approved construction of a replacement for the first Walnut Lane Bridge in Fairmount Park. This project required beams so long—160 feet—that the contract insisted on a preconstruction test. At the final stage of testing, in October 1949, hundreds of dignitaries and engineers gathered on a parade stand to watch the beam bend, creak, and finally crack. Reassuringly, it tolerated ten times the required load before failing. While less spectacular, a set of tests on the full range of highway materials later that decade along a stretch of simulated interstate near Ottawa, Illinois, verified that prestressed beams would also hold up under constant use by heavy trucks, even overloaded ones. Sponsored by the federal government and the American Association of State Highway Officials, the AASHO Road Test remains unique in engineering history for its thorough fatigue testing, according to John Fisher of Lehigh University, who served as an engineer on the effort.

The haze of publicity over the Walnut Lane Memorial Bridge obscured this tidbit: the first prestressed concrete bridge to enter service in the United States was a two-lane bridge along a rural road in Madison County, Tennessee, assembled without fanfare by the county road department and engineered by a two-man firm in Nashville. While work started later there than at Walnut Lane, it finished sooner.

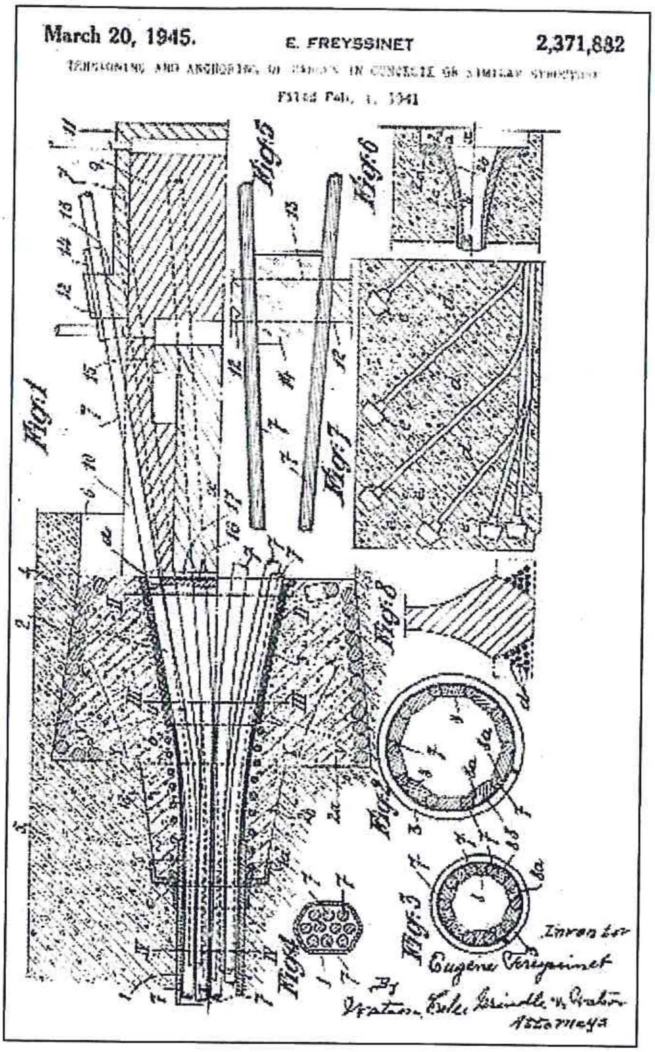
Having heard about the work of Freyssinet and Magnel, Ross Bryan and





Freyssinet Anchorage

COURTESY KEVIN TROTMAN



Culver Dozier had begun experimenting with scale models in the basement of their office building. Their first prestressed project was stadium seating for Tennessee's Fayetteville High School. Employing precast concrete segments of seating clinched by tight steel strands, held up at intervals by conventional concrete supports, the stands went up so quickly and inexpensively that Madison County hired the pair to draw up designs for prestressed concrete bridges. Bryan went on to design a prestressed concrete commercial structure, the two-story Doric Building in Nashville, Tennessee.

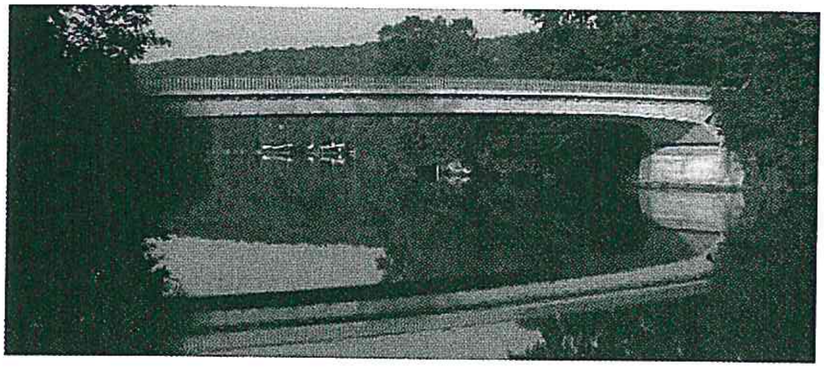
While the Bryan and Dozier story has appealing elements of country boys making good, it wouldn't have been possible without the advice and cold-drawn wire from John A. Roebling's Sons Company (JARSCO), a New Jersey–based firm descended from the creator of the Brooklyn Bridge. JARSCO also provided wire for the prestressed Walnut Lane Bridge. JARSCO had started experimenting with prestressed concrete slabs in 1946, when it used the method in constructing a special section of its warehouse floor in Cicero, Illinois, to see whether it would stand up better to the fully loaded spools of wire rope than conventional reinforced concrete. Dario Gasparini, a professor of civil engineering at Case Western Reserve University, who has studied the spread of prestressing technology, explains that JARSCO had ambitious postwar plans of offering a turnkey service that would design and erect state-of-the-art prestressed bridges, but it encountered so much resistance that it fell back to offering advice and making wire.

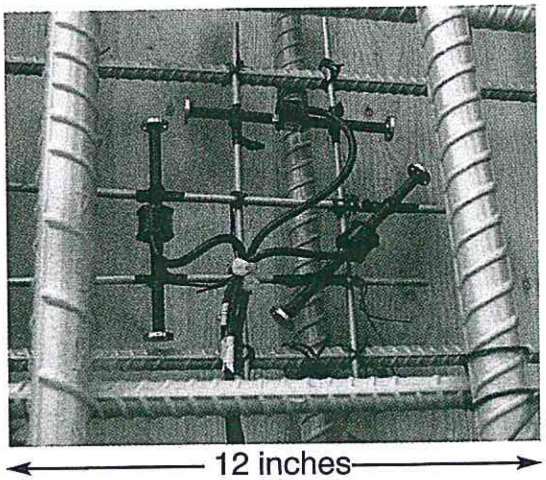
American bridge building lagged for such reasons. "It is irrefutable that most of the design innovations in the last, say, 50 years have come from Europe and Asia," says Gasparini. "Regarding prestressed bridges, the U.S. chose to go the route of precast, prestressed girders for small spans and abandoned unique, labor- and technology-intensive, post-tensioned designs for larger spans to the Europeans, even though the Roebling company had developed all the necessary post-tensioning technologies."

APPROACHING ITS 60TH anniversary in the United States, prestressed construction technology now accounts for half of new bridges built each year. One growth field is rapid bridge replacement, which offers a way for state highway departments to remove decaying infrastructure without blocking traffic for months. An example is a new concrete bridge installed in 2006 over I-4 near Orange City, Florida. After careful measurements on the old bridge, contractors built a new span in two sections nearby, each with a cast concrete deck atop prestressed concrete girders. Upon completion, each 143-foot-long section weighed 1,300 tons—not too much for the Dutch subcontractor Mammoet USA, which deployed super-high-capacity transporter platforms originally designed for work at refineries and chemical plants. In just two weekends Mammoet whisked out the old sections and trundled in the new.

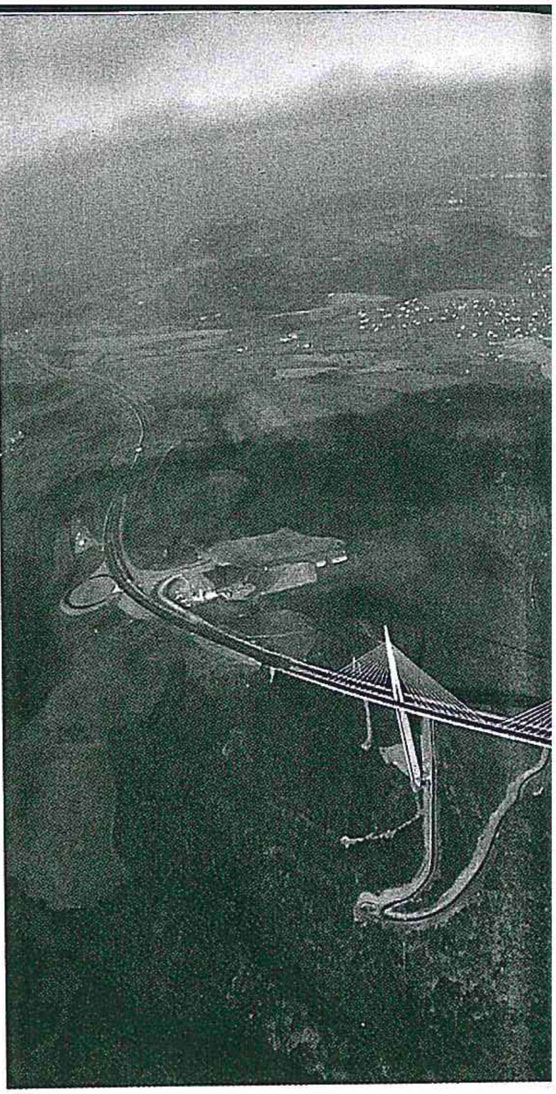
In another innovation, prestressed concrete segmented bridges are offering relief in the form of new elevated lanes to congested cities such as Tampa and San Antonio. Because the spans

In 1945 Freyssinet patented his concrete post-tensioning system in the United States, above, and used it the next year to build the 180-foot, single-span Luzancy bridge over the Marne, right.



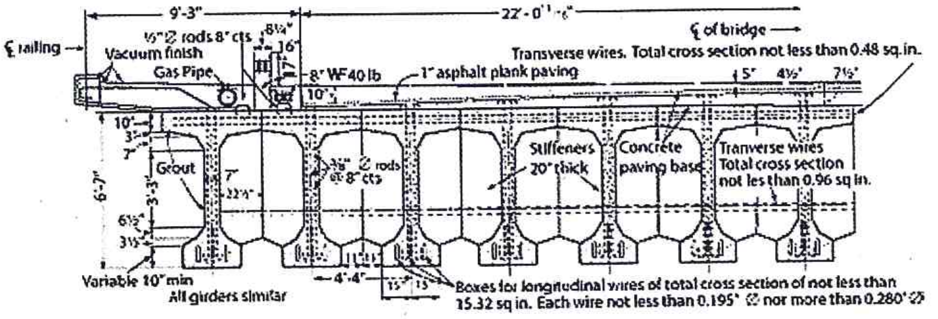


Engineers in the United States were slow to embrace Freyssinet's revolutionary technology, building the first major American prestressed concrete structure, the Walnut Lane bridge, its main span shown in schematic cross section below, in 1950. New innovations followed, including the use of "smart" sensors in the I-35W bridge replacement, left, which will alert engineers about the effects of weather and time on the concrete.



are strong enough to stand atop a single line of concrete columns, the only real estate required is a strip six feet wide in the median of an existing divided highway. Drawing segments from a prefabrication yard elsewhere, one crew can build about three miles of elevated highway per year even as traffic moves along at ground level.

How long will it be before the new concrete bridges themselves need replacement? Looking back on the first 150 years of modern concrete construction—what might be called the second advance of concrete following Roman works—the records of durability are sometimes encouraging, sometimes sobering. High hopes expressed at the beginning of the 20th century that concrete could stand for thousands of years without maintenance have been proved wrong, at least when it comes to concrete spans pounded by trucks and nibbled by salt-laden water.



Cross Section Main Span

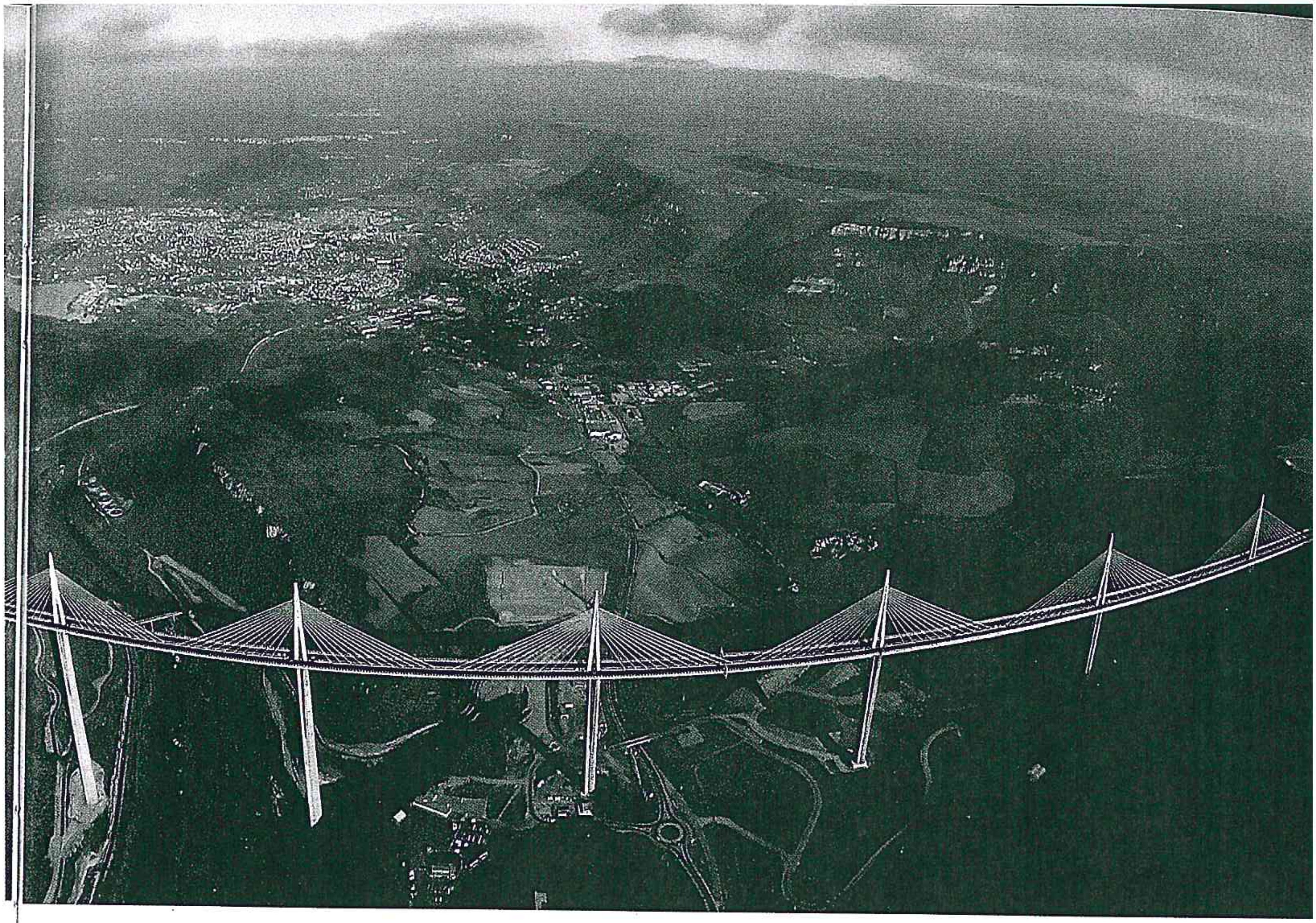
"Corrosion was one issue not tested in the AASHO Road Test, since it lasted only a finite period. It affects both steel and concrete bridges," cautions John Fisher. "It's the main challenge now and will remain so for structures in an exposed environment, especially in northern climates."

Magnel's Walnut Lane prestressed bridge, completed in 1951, developed a serious case of cracked concrete and salt-corroded tendons by 1969. After multiple repair attempts failed, the Pennsylvania traffic authority pulled off the entire set of beams and replaced them in 1990.

Whether from seawater spray, road salt, or salt-contaminated cement mixes, saltwater transforms steel to rust. Road crews' reliance on salt began to rise greatly in the late 1940s, prompted by demands by commuters and truckers for safer high-speed winter travel. By 1980 use had climbed to 10 million tons each winter.

"After two [bridge] failures, the Europeans realized you've got to be careful with this," says Andrea Schokker. "But the United States didn't respond quickly. We thought that those problems were due to unique conditions not found here." A new attitude took hold in 1999 and 2000, after tendons snapped on Florida's Niles Channel and Mid-Bay bridges because of sea salt corrosion. While no collapse ensued, urgent repairs and inspections began. State inspectors found that, in hundreds of concrete bridges, poor construction practices had left long stretches of post-tensioned steel tendons devoid of the cement sheath (called grout) that was supposed to protect the steel from water and salt.

While high-tech "smart bridge" sensors, better cement additives, and corrosion-resisting steels can help prevent prestressed-concrete collapses, there's no substitute for a thorough injection of grout to protect tendons deep inside the structure. Another key to longevity is maintaining a crack-free concrete pavement above. Crack-free



concrete bridge decks are critical in blocking the infiltration of salt-laden water down to the tendons. Such integrity depends greatly on how the concrete is treated immediately after the riding surface (the uppermost layer of a bridge deck) is poured. "Proper curing has been neglected in recent years," reports Basile Rabbat, head of structural codes at the Portland Cement Association. "If not cured properly, the concrete on the surface shrinks and cracks." Proper curing usually requires that a newly poured deck be kept moist and covered with plastic sheeting for at least seven days. The solutions at the new I-35W bridge in Minneapolis were to incorporate the riding surface into the segments themselves as part of the precasting process, to use a high-strength mix incorporating fly ash and silica fume, and to allow plenty of time for proper curing. In future decades, the top layer can be milled off and replaced.

Rabbat predicts that, if enough care is taken, modern bridges could stay in service for 200 years. It is encouraging that Europe's first generation of prestressed spans, Freyssinet's Luzancy Bridge and Magnel's Sclayn Bridge, are still taking traffic, sixty years on.

Bridging chasms has always required a leap of faith from builders and users, and now the leap is longer than ever. Compared to other massive structures, today's bridges must be all-around champs. They must go up quickly and stay on budget; defy frost, water, wind, and corrosive road salt; and hold up under whatever volumes and weights of traffic that future commerce puts on the road. Given a field that is so highly demanding, yet slow changing, it's remarkable that Freyssinet and his followers managed to spread the gospel of prestressed concrete so quickly in Europe, then elsewhere.

In 2004 French engineers showcased prestressed concrete's potential by unveiling the 8,071-foot-long Millau Viaduct, above, which is anchored by seven immense concrete towers. The tallest tower (788 feet), along with its mast (288 feet), rises higher than the Eiffel Tower in Paris.

Here's a tip for future inventors in any field: take an old, proven principle (prestressing) and apply it to a completely different, even counterintuitive, setting (rigid concrete), which suffers from a major shortcoming (weakness in tension). The success of the prestressing experiment, revolutionizing an ancient field, suggests that there are more such transformations to come.

James R. Chiles, a member of our Editorial Advisory Board, last wrote "Heavy Rescue" in the Summer 2009 issue of *Invention & Technology.*