Bridging the Gaps

"Cast iron will resist a greater crushing force than any other substance whose cost will admit of its being used as a building material," the U.S. engineer Squire Whipple wrote in his 1847 treatise, *A Work on Bridge Building*. "Steel has a greater power of resistance, but its cost precludes its use as a material for building. Wrought iron resists nearly equally with cast iron, but its cost is twice as great, which gives cast iron the advantage. On the other hand, wrought iron resists a tensile force nearly four times as well as cast iron, and twelve to fifteen times as well as wood, bulk for bulk."

This brief analysis summarizes the choices faced by bridge designers throughout the ages: the tradeoff between materials properties and cost, with availability surely implied in the cost factor. Since the three basic bridge structures—beam, arch, and suspension—were invented in ancient times, virtually every structural material provided by nature or invented has been used in bridge building. Wood, stone, and plant fibers, readily available and workable with simple tools, predominated early on; iron, steel, concrete, and composite structures, requiring costly fabrication, have been prominent in the last several centuries.

Each basic bridge form places different strength demands on its components. When a beam suspended between two supports is subjected to a vertical load, the underside of the beam is stretched in tension, while the top side is compressed. These forces present no problem to a stone or wooden beam spanning a short distance. However, as the distance between the supports increases, the load that the beam can withstand decreases; clearly, a single beam is not a solution for long span distances. The earliest bridge-building efforts were confined to lengths readily available in standard monoliths or timbers. In the Dartmoor district of England (River Dart), slabs ~15 ft long transported from a nearby quarry by Neolithic humans span boulders in a streambed to this day. It is known as the Post Bridge.

Suspension bridges transfer their vertical loads to curved cables in tension, and eventually to abutments in the surrounding rock structures. In *The Conquest of Peru*, William H. Prescott describes suspension bridges "made of the tough fibers of the maguey, or of the osier of the country, which has an extraordinary degree of tenacity and strength. These osiers were woven into cables of the thickness of a person's body. The huge ropes, then stretched across the water, were conducted through rings or holes cut in immense buttresses of stone raised on the opposite banks of the river, and there secured to heavy pieces of timber." These early suspension bridges were constructed by the ancient Incas, who apparently had insight into, or perhaps catastrophic practical experience of, the tensile failure of materials.

Arch bridges support vertical loads through compressive forces extending through the curve of the arch to place both vertical and horizontal forces on its foundation and abutments. Stone, with its high compressive strength, has been used extensively throughout history for arch construction. (Ironically, stone is still readily available, but precision stonecutting techniques make it prohibitively expensive.) Because each stone is under compressive forces, proper construction techniques using wedge-shaped stones permit the building of an arch with no mortar. The earliest examples of such "true" arches uncovered by archaeologists date from 4000 B.C. in Mesopotamia. The oldest known surviving stone arch is found in Smyrna, Turkey, over the Meles River. Undoubtedly, though, the use of the arch for bridge building reached its peak in ancient Rome. The Romans spanned the rivers and chasms of their vast empire with stone bridges to transport armies to distant locations; they also moved water from remote streams to major cities via aqueducts. The Pont du Gard near Nimes, an aqueduct consisting of three tiers of arches reaching 155 ft above the river, is perhaps the grandest of the Roman structures still standing.

But, for all their engineering prowess, the Romans never advanced beyond the concept of the semicircular arch. The Chinese engineer Li Chun in the late 6th century demonstrated the feasibility of the "segmental" arch, so called because it represented only a segment of the semicircle, and thus was longer and flatter than the upright semicircular structure. When the swiftly flowing waters of the Xiao River made stone piers in the streambed impractical, Li spanned the entire 131-ft gap using only one arch. The "zhaozhou" or Great Stone Bridge, better known as the Anji Bridge, stands to this day in Zhao Xian in the Hebei Province in northern China. Another 800 years would pass before segmental arches were used in the West.

Everywhere throughout the next thousand years, the strongest, most readily available materials were exploited for building bridges. The Buddhist scholar Hsuan-Tsang, visiting India in A.D. 630, reported the existence of iron bridges across the Indus River; historians familiar with the metallurgical prowess of the Persians and the Indians at the time believe these were suspension bridges that used iron chains for support. In the Middle Ages, the Persians were the first to use bricks in bridge structures, fashioning them into pointed arches. Stone continued to be the chosen medium in areas where it was readily available; where trees were plentiful, wooden bridges based on the triangular truss were common. The relatively low mechanical strength of timber (which is good in compression but poor in tension) was compensated by the triangular truss, which resists deformation. The truss had been in use for centuries as a roof support structure in houses and barns, so its adaptation to bridges was not a great leap. In the United States, "covered bridges" started as a means to protect the structural timbers from the wet and dry cycles of the weather, and later became appreciated for their romance and beauty.

In 1777, John Wilkinson and Abraham Darby erected the first iron bridge over the Severn River near Coalbrookdale in England. Darby had recently shown that smelting cast iron with coke greatly reduced its cost; the Iron Bridge was a public demonstration on a grand scale of the affordability of this material. Taking advantage of cast iron's high compressive strength, the bridge was built along masonry lines, with 800 preformed castings laid in place to form a semicircular arch spanning 140 ft.

In 1810, Thomas Telford decided that a suspension bridge was needed to span the 579-ft gap over the Menai Strait between mainland Wales and the Welsh island of Anglesey. Clearly, cast iron would not serve the purpose, but wrought iron, with its high tensile strength, would be perfect for suspension chains under tension. Telford performed tensile testing on hundreds of bars of wrought iron, and personally approved all 935 iron links that would make up the 16 cables of the suspension structure, which opened in 1826.

Combining the best of these two approaches, Whipple, working in the mid-19th century, solved his design dilemmas by constructing bridges using cast iron compression members and wrought iron tension members, thereby optimizing the strength-cost factor.

Ultimately, of course, the demands for high-strength materials coincided with the development of Bessemer's process in

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1856 and the open-hearth method in 1867 to make steel the material of choice for bridge builders. But steel was an untried structural material when James B. Eads proposed to use it in his triple-arch bridge across the 1500-ft-wide Mississippi River at St. Louis in 1867. Taking a hint from Telford, Eads specified that all materials had to be inspected, tested, and approved prior to acceptance. For the anchor bolts that would attach the bridge to its abutments and piers, crucible steel with a minimum tensile strength of 100,000 psi was specified. However, when the first batch of bolts failed at approximately 30,000 psi, Eads called instead for chromium steel. This material passed the tensile tests, and the anchor bolts and tubular arches of "Eads' Bridge" were ultimately constructed of a low-alloy steel containing 0.53% carbon and 0.4% chromium. Thus, the first steel bridge was also the first alloy-steel bridge. It was officially opened on the Fourth of July, 1874, with a gala celebration.

John Roebling specified galvanized steel wires with a tensile strength of 160,000 psi, spun in place into strong cables, in his 1867 proposal for a bridge linking Manhattan with Brooklyn. Steel wire was untried in suspension bridges at that time; Roebling's previous successful efforts at Niagara and Cincinnati used iron wires. When the disreputable J. Lloyd Haigh won the contract for the steel wire, Washington Roebling (who took over after his father's death) demanded that every wire be tested, instead of every tenth wire, as originally specified. This caution paid off when it was discovered that Haigh was fraudulently shipping rejected wire to the construction site. Roebling calculated that approximately 221 tons of rejected wire were already in place on the bridge, but that this bad wire merely reduced his safety margin from a factor of 6 to a factor of 5, which he could live with. The Brooklyn Bridge opened in 1883 and still stands as a testament to Roebling's engineering abilities.

Reinforced and prestressed concrete structures became popular in the last half of the 20th century. Adding the tensile strength of iron or steel to the compressive strength of concrete provides the perfect solution to the problem of underside tension and top-side compression encountered in the earliest beam structures. Such composite structures also suggest the use of other components, such as carbon fiber, polymer, or glass reinforcement components to maximize mechanical properties. In so-called "self-monitoring concrete," conductive carbon filaments have been used to measure a change in electrical resistance when a current is passed between electrodes at either end of a bridge; increased resistance indicates a break in the conductive path, perhaps caused by a crack. Smart sensors embedded in a bridge structure can instantaneously monitor the load and indicate when acceptable levels have been breached. Materials developments have brought us to the point that the bridge of the future will tell us if something is wrong.

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FOR FURTHER READING: Joseph Gies, *Bridges and Men* (Doubleday, Garden City, NY, 1963); Scott Corbett, *Bridges* (Four Winds Press, New York, 1978); Judith Dupré, *Bridges* (Black Dog and Leventhal Publishers, New York, 1997); Rudy Dirscherl, "Eads' Bridge Pioneered New Era in Steel Usage," *Metal Progress*, December 1981; Eric DeLony, ed., *Landmark American Bridges*, (Little, Brown, New York, 1993); Neil Cossons and Barrie Trinder, *The Iron Bridge: Symbol of the Industrial Revolution*, (Moonraker Press, Bradford-on-Avon, 1979).

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