The Construction of the Arch

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The old St. Louis riverfront was selected in 1935 as the site of a national monument to commemorate the westward expansion of the United States in the 19th century. An area of some 40 city blocks was purchased and all buildings were cleared, but because of World War II, further progress on the Memorial was halted.

In 1947 the Jefferson National Expansion Memorial Association, a group of public-spirited citizens, held a nationwide competition to obtain an appropriate design for the Memorial. The winner in the competition was the late Eero Saarinen, whose design was dominated by the now famous Gateway Arch.

The Memorial includes, in addition to the Arch, an underground visitor center located directly beneath the Arch. The center contains the Museum of Westward Expansion, which tells the century-long story of the opening of the West in the 1800s, as well as theaters with movies on westward expansion and the Arch's construction.

Magnificent in its concept, majestic in its setting, unique in its execution, the Gateway Arch towers 630 feet above the banks of the Mississippi River, a part of the $30 million Jefferson National Expansion Memorial. The smooth, graceful lines of the Arch, designed by Eero Saarinen, also serve as one of three firsts in the history of engineering in this country, all in the City of St. Louis.

Historic Eads Bridge, the first tubular steel arch structure of its kind, completed in 1874, forms the northern boundary of the Memorial. At the southern boundary stands the steel plate girder bridge designed by Sverdrup and Parcel -- the first U.S. bridge of this size to employ orthotropic design. The Gateway Arch, in neighborly spirit, borrows the arch concept from Captain Eads and makes use of the new concept of stress analysis and structural design from Sverdrup and Parcel.

Eero Saarinen, in designing the Arch, conceived of it in stainless steel, and asked Fred Severud to study its feasibility from the structural engineering point of view, again demonstrating the need for joining the skills of more than one discipline in order to create a project of this magnitude.

The stainless-steel-faced Arch spans 630 ft. between the outer faces of its triangular legs at ground level, and its top soars 630 ft. into the sky. It takes the shape of an inverted catenary curve, a shape such as would be formed by a heavy chain hanging freely between two supports.

Each leg is an equilateral triangle with sides 54 ft. long at ground level, tapering to 17 ft. at the top. The legs have double walls of steel 3 ft. apart at ground level and 7-3/4 in. apart above the 400-foot level. Up to the 300-foot mark the space between the walls is filled with reinforced concrete. Beyond that point steel stiffeners are used.

The double-walled, triangular sections were placed one on top of another and then welded inside and out to build the legs of the Arch. Sections ranged in height from 12 ft. at the base to 8 ft. for the two keystone sections. The complex engineering design and construction is completely hidden from view. All that can be seen is its sparkling stainless steel outside skin and inner skin of carbon steel, which combine to carry the gravity and wind loads to the ground. The Arch has no real structural skeleton. Its inner and outer steel skins, joined to form a composite structure, give it its strength and permanence.

Entrance to the Arch is from the underground George B. Hartzog, Jr. Visitor Center, located directly beneath it. Visitors are carried from the lobby level below to the observation platform at the top of the Arch by a unique conveyance system - a 40-passenger train made up of eight five-passenger capsules in each leg. Operating at the rate of 340 ft. per min., the ride takes 10 minutes for the round trip. The observation platform is 65 ft. by 7 ft., with plate-glass windows providing views in the east and west directions. There is also a conventional maintenance elevator in each leg as far as the 372-ft. level, and stairways with 1,076 steps in each leg rise from the base to the top of the Arch. The elevators and stairways are for maintenance and emergency use only.

Foundation 60 ft. Deep

Reinforced concrete foundations sunk 60 ft. into the ground extend 30 ft. into bedrock and contribute substantially to the structural strength of the Arch. Structural engineers Severud, Elstad, Krueger and Associates report that under a wind load of 55 psf (equivalent to a 150-mph wind), the Arch will deflect at the top only 18 in. in the east-west direction. Its legs are oriented on a north-south line.

To prepare the site for the Arch foundations, the visitor center and museum, MacDonald Construction Company, general contractor for the project, excavated 300,000 cu. ft. of earth and rock.

Alloy-steel tensioning bars or tendons, 252 of them for each leg, extend 34 ft. below the top of the foundations to anchor the structure securely to its base. At ground level, only the two outside corners of each triangular base are prestressed by two groups of 63 steel bars in each corner. To facilitate the fabrication, shipping, positioning, and erection of the 35 ft.-long steel bars, the fabricators, Stress Steel Corp., chose to pre-assemble them into groups of 21 each, which could be shipped and erected as a unit. Each unit has three rows of seven bars each, the bars in the middle row starting 10 ft. above the bottom. Specially designed jigs were used in the shop to fabricate and assemble the steel bars, grout tubes, anchors and bracing.

The bars, 1-3/4 in. in diameter, are made of alloy steel with an ultimate strength of 145,000 psi. The ends of the bars were threaded into steel end plates, 1-3/4 in. thick.

Rigid welded steel tubing of 1-1/2 in. inside diameter, tack welded to the end plates, served as grout tubes around the steel bars and acted as stiffeners for the 21-bar assemblies during shipping and concreting. Steel angle braces were attached to each group of bars for added rigidity during handling and erection, as well as steel cross-plates for extra support.

A completed bar assembly weighed less than 3 tons and could be handled quickly and easily. Six such assemblies (126 bars) made a truck load for shipment to the job site. Three bar assemblies (63 bars each) were placed on each side of the two exterior corners of each triangular Arch leg.

Prestressing the Foundation

Each group of tensioning bars required careful positioning because the bars had to be inclined in two directions-- to fit the curvature of the Arch as well as the tapering cross-section of the legs. With the steel-work in place, concreting proceeded in lifts of about 5 ft. each. The bars were post-tensioned after the 5,000-psi concrete reached a strength of 4,000 psi--usually after 7 to 10 days.

The stressing was done by a hydraulic jack, which applied a load of 71 tons on each bar, or a total of 18,000 tons for each leg. Bars were tensioned in a strict sequence specified by the engineers. The full load was applied to each bar in one operation with a center-hole hydraulic jack of 100- ton capacity, which reacted against a steel jacking plate 1-3/4 inches thick, embedded in the top of the concrete.

Welded steel tubing around each 1-1/4 inch diameter bar had an inside diameter of 1-1/2 in. This left little space between the bar and the inside wall of the tubing, so that relatively high pressures were needed during grouting. To simplify this operation, pairs of grout tubes on adjacent tensioning bars were connected at their lower ends by specially fabricated steel grout pipes 1 inch in diameter.

Grouting was done by a worm-type, high-pressure pump which forced the grout down one tube and up the adjacent tube. This procedure enabled the contractor to take advantage of the hydraulic head in the first tube to grout the second tube and eliminated the need for special grout pipes and bleed openings. The top of the second tube served as a bleed opening to insure complete expulsion of air.

When steel erection on the south leg had reached an elevation of about 120 ft., it was noticed that the bars would not elongate properly under post-tensioning because of jamming in the grout tubes. The post-tensioning tendons were coupled on each station line about 12 ft. apart. A "coupler shield," essentially a piece of tubing with increased diameter, surrounded each coupler. When concrete seeped into the tubing, the space above the coupler (inside the shields) was filled up; it was decided to add 12 tendons to each leg from that elevation to the 300 ft. mark, where concreting ended. Also, additional steel was used in the upper sections of the Arch.

When the keystone sections were placed, a crown thrust was applied by hydraulic jacks to increase the compressive bending stress in the extrados of the Arch legs to offset tensile stress under wind load. Following the trouble with the tendons, it was decided to apply an additional 10 percent of crown thrust so that the increased compressive bending stress in the extrados of each Arch leg could offset the prestress loss caused by the jammed tendons. The extra steel in the upper region of the Arch resists additional axial and bending stresses due to the increased crown thrust.

In addition to the vertical, or near vertical, prestressing of the concrete foundation, horizontal post-tensioning was utilized to prestress that part of the foundation slab designed as a cover or bridge above the access tunnel to the Arch. Forty-two bars of 1-1/4 inches diameter, in flexible steel grout tubes, were used for this operation. They were prestressed the same way as the vertical bars.

Above the foundation, concrete in the walls of the Arch was prestressed up to a height of 300 ft. Above this level the space between the inner and outer walls is hollow and steel bracing joins the inner and outer skins. This design reduces sway because the bulk of the weight is in the concrete-filled lower sections of the Arch.

Massive foundations and filled walls are typical of a weighted catenary arch, structurally the soundest of all arches, for the thrust passes through the legs and is absorbed in the foundations. In other arch shapes, pressure tends to force the legs apart.

In cross section, each Arch leg is a double-walled equilateral triangle with a hollow core 40 ft. wide at the base, tapering to 15-1/2 ft. at the top. The inner skin is of A-7 carbon steel, 3/8 in. thick, except at the corners where it is 1-3/4 in. thick to provide greater stiffness. The outside surface was fabricated from 900 tons of polished stainless steel in panels 14 in. thick, varying in size from 6 x18 ft. to 6 x 5 1/2 ft. The outer and inner walls were fabricated in sections and bolted together at the Pittsburgh and Warren, PA., plants of the Pittsburgh-Des Moines Steel Company, steel fabricators and erectors for the Arch.

In the shop, the fabricator designed and built two house-size welding fixtures, one for butt welding the inner shell plates of carbon steel and filleting angles to them, and the other--the larger one--for butt welding the stainless steel.

MIG (metal inert gas) welding with an automatic electrode head, utilizing a shielding mixture of 75 percent argon and 25 percent carbon dioxide, was selected for joining the stainless-steel plates on the polished side only. Nondestructive testing with spot X-ray was used to check the welding both in the shop and in the field. Electrolytic cleaning removed the halos on the stainless steel caused by heat from welding.

After the stainless-steel plates for the sections up to the 300-ft. level were welded together, they were turned over and moved to a work table where they were cut to size. Operators using templates welded rows of 5/16-in. stainless-steel studs to these plates. Then Z-bars were fastened to the studs with carbon-steel nuts tightened to 22-1/2 ft. -lbs. with a torque wrench.

For the Arch sections up to the 300-ft. level, high-strength steel bolts were attached to the Z-bars. These bolts passed through holes in the inner skin of carbon steel and were held in place by nuts that applied a squeezing force to the concrete core of the wall "sandwich," creating a friction bond. To resist local bending, the outer and inner skins act as the top and bottom flanges of a beam, providing a stressed-skin action comparable to that employed in modern aircraft design.

From the top of the composite wall section to the crown of the Arch, all direct compressive loads are carried by the outer stainless steel skin and the inner carbon-steel skin. Vertical steel diaphragms, spaced 2 ft. on centers, connect the two skins and serve as stiffeners to prevent buckling of the inner skin. Steel angles spaced halfway between each diaphragm stiffen the outer skin. The stiffeners and diaphragms are interrupted at each field splice and do not contribute to Arch actions.

Spot welding was chosen for attaching the carbon-steel stiffeners to the stainless-steel skin to eliminate the warping that would be caused by heat if arc welding were used. Except for a few seconds of localized heat, spot welding is practically heatless.

The completed Arch sections were shipped to St. Louis on gondola cars. Two "sandwich" wall sections rode side by side, their stainless sides facing each other but held apart by steel uprights covered with wood and neoprene. Steel rods welded to the carbon-steel plates and to the steel sides of the cars secured each section.

Assembly and Erection at the Site

At the job site, cranes equipped with a tubular steel spreader-bar placed the sandwich panels upright in a specially constructed storage area. Initially, the sides of the triangular sections were prefabricated at the plant and sent to the site as three legs of a triangle. Assembling these sections at the site required extremely rigid controls for positioning and welding the corners, but any additional pre-assembly in the shop was impossible because the resulting sections would have been too large for shipment. Triangular sections for higher positions in the Arch had smaller dimensions and could be fabricated and shipped as three dog-leg-shaped pieces, each with a short side and a long side. Thus the corner connections could be made in the shop, leaving the simpler and faster task of welding along the sides for the field crews.

At the site the triangular wall sections were assembled on a 56 x 125 ft. concrete welding pad. To shield the welding operations, the pad was equipped with a steel-framed shelter 56 x 60 ft., 20 ft. high and roofed with corrugated galvanized steel. Canvas tarpaulins that could be raised and lowered protected the ends. The entire structure rode on wheels and moved back and forth over the pad as successive sections of the Arch were assembled.

A crane lifted a completed section from the welding pad onto a specially designed railroad car with a 42 x 52 ft. deck composed of 24 WF beams. The car was equipped with an outrigger that rode on rubber-tired wheels and supported one corner of the triangular Arch section. A tractor pushed the railroad car along special tracks to a position near the Arch leg.

Specially designed creeper cranes climbing the Arch legs lifted a completed section into position 4 inches above the previously placed section and set it on three 35-ton screw jacks. The jacks positioned the section accurately, leaving a gap between the sections just wide enough for the welds. The first section on each leg was attached to the foundation by anchor bolts 5/8 inches and 1inch in diameter. These were tightened with a manual wrench. To stiffen the triangular section during moving and concreting, the corners were braced with adjustable steel pipe struts of 5-in. diameter and 12 WF steel-beam wales.

The inner plates of carbon steel were welded with low hydrogen electrodes using a normal welding procedure. Semiautomatic gas-shielded welding was used to join the outside stainless-steel surfaces. After welding, concrete was placed in the walls and post-tensioned. Concreting was stopped at the 300-ft. level; above this point the triangular sections were fabricated with diaphragms between their outer and inner skins.

Welding sections for the assembly of a triangle caused some deformation due to heat shrinkage of the welds. Later, these sections were forced into the proper position for welding on the legs, causing a slight buckling of the stainless-steel surface. After a study of the situation and of the welding operations, the steel erector decided to camber the walls of each triangular section about 1-1/2 inches in 35 feet, so that the walls would be in the desired straight line after the welding shrinkage occurred.

It should be pointed out that all the welding on the Arch was done by expert welders who not only successfully completed welding tests but also showed exceptional welding skills.

Interior installations, including prefabricated steel stairs, tracks for the passenger-train conveyor system, utility pipes and electrical wiring were put in each Arch leg both from the bottom entrance and from the top, depending on the level of the construction stage.

Creeper Derricks

Both legs of the Arch acted as free-standing cantilevers before completion and were erected simultaneously without scaffolding. The first few triangular sections, up to a height of 72 ft., were handled by crawler cranes operating from the ground. Above that height two creeper derricks, each weighing 100 tons, were used to raise the 12-ft. high, 50-ton sections.

The derricks pulled themselves up the curved legs of the Arch; their adjustable supports kept them level regardless of the height and curvature of the legs. Because the height made it impracticable for workmen to climb to and from the work area, the derrick platforms (43 X 32 ft.) were reached by a passenger elevator and were equipped with a tool shed for workmen, sanitary facilities, and communications equipment.

Two vertical tracks held the sled that supported the derrick and platform. These tracks, made from 12 WF steel beams with cover plates on both sides, were spaced 24 ft. apart. Each track was about 2 ft. from the extrados of the Arch leg and was attached to brackets held by four high- strength steel bolts of 1-1/4in. diameter.

Four high-strength steel pins of 5-3/4 in. diameter connected the sled to the tracks. The telescoping steel legs that extended between the outer corners of the platform framing and the lower part of the sled had pin connections at both ends. As construction progressed, and the curvature of the Arch increased, the telescoping legs were shortened to keep the derrick platform level. Sections of track were added in about 48-ft. lengths, and the entire derrick crept up after it had placed four sections of the Arch. Lifting an Arch section into place took only about an half hour.

The Stabilizing Truss

The preliminary design for the Arch called for guy cables at about the 530-ft. mark to stabilize the structure. Computations indicated that such stabilization would require one 6-in. or two 3-in. cables on each leg--resulting inconsiderable cost as reuse of the cables would not be practicable. This, and some additional problems with the cables, led designers to the idea of using a stabilizing strut or truss at the 530-ft. level.

When this level was reached, the two creeper derricks working together raised and positioned a steel stabilizing truss 255 ft. long, which connected the ends of the two legs and braced them against each other while the remaining sections were put in place to complete the Arch. The bridge-like truss was shop fabricated of small wide-flange beams and tubular members made from high-strength constructional alloy steel. It was assembled at the site with A-325 high-strength bolts and lifted into place as a unit.

The truss was 40 ft. wide, 15 ft. deep and weighed about 60 tons. It was connected to the Arch by means of a steel harness fitted around each leg so that the loads due to the increased weight and wind force on each leg would be transferred directly to the foundations. Two 45-ton horizontal jacks were used at each end, at the points of contact of the strut and the harness, to fit the brace against the legs.

After the stabilizing truss was erected, 21 sections were added to each leg. The next step was to put the final "keystone" section into place to complete the Arch. A jacking frame was used to exert pressure against the two legs so that this section could be set in. With the Arch completed, the stabilizing strut was lowered by the creeper derricks before they started their trip down the legs, dismantling and lowering their tracks as they progressed. At the same time the bolt holes in the stainless-steel surface were plugged and ground smooth.

An important phase of the project was the method of survey control. Triangulation was used with the aid of four monuments, which formed a rectangle 300 x 720 ft. around both center lines of the Arch. By using the two north monuments for triangulation on the south leg, and the two south monuments for triangulation on the north leg, all three corners of each leg could be seen. All survey work was done at night to eliminate distortion caused by the sun's rays striking one side of the Arch while the other two sides were in shadow.

The Workmen's Elevator

A unique temporary elevator system was devised to transport workmen up and down during the project. This system, designed by Marshall Elevator Co., had several unusual features--a travel path that could be extended as construction of the Arch progressed, an interference-free radio control inside the car that eliminated the need for collector rails or hanging electrical cables, and a device to keep the cab level.

One creeper derrick track on each leg served as the guide for the elevator car. Two hoist cables, attached to the top of the car, led directly up one track beam to the base of the creeper derrick, across the 24-ft. span to the other track beam, then down to the base, and horizontally to separate drums on a hoist at ground level.

The elevator consisted of a main structural-steel frame or sling to which was welded the structural steel sub-frame that supported the tiltable cab. The main frame was held to, and guided by, the flange of the track beam by means of two sets of six steel rollers mounted at the top and bottom of the frame. A specially designed tilt-sensing mechanism and a motor-operated leveling device kept the cab level at all times.

The Memorial development was financed jointly by the Federal Government and the City of St. Louis on a ratio of $3 to $1. The Bi-State Development Agency of the

Missouri-Illinois Metropolitan District, in a contract with the National Park Service, the owner, financed the transportation system within the Arch.

The architects were Eero Saarinen and Associates, in cooperation with Severud, Elstad, Krueger and Associates for the structural engineering. The prime contractor was the MacDonald Construction Company of St. Louis. Fabrication and erection of the Arch was done by the Pittsburgh-Des Moines Steel Company, subcontractor to MacDonald.

Acknowledgment is due to the many people who carried out the construction and erection of this monument with care and precision - the structural men, electricians, steamfitters, sheet metal journeymen, and others who risked life and limb in using their skills to meld all the component parts together into a lasting monument for the inspiration of future generations. Although it was estimated that 13 workers might lose their lives on the project, there were no fatalities. The dedication and determination on the designers, engineers and workers on the Arch echoed the pioneer spirit of those in commemorates, the people who explored and settled the American West.