SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION

SOUTH CAROLINA HISTORIC BRIDGE SURVEY
STATEWIDE, SOUTH CAROLINA

HISTORIC CONTEXT FOR BRIDGE BUILDING TECHNOLOGY IN SOUTH CAROLINA

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HISTORIC CONTEXT FOR BRIDGE BUILDING TECHNOLOGY IN SOUTH CAROLINA

Introduction

The intent of the historic context for bridge building technology is to facilitate an understanding of the technological and engineering factors that influenced the types and designs of bridges built in the state prior to 1961 and which of those bridge types are historically significant based on their technological context. This historic context presents specific information about the history of technological development of the bridge types and design variations within specific bridge types found in the pre-1961 statewide population and why particular bridge types and designs were preferred over others. The emphasis of this historic context is on understanding the development of the most commonly used bridge types, which includes illustrating engineering advances in those types/designs and identifying benchmarks within long-lived technologies such as steel stringer and T beam bridges. The context recognizes that all bridge types reflect national trends and technological developments as well as the dominant role of the South Carolina State Highway Department in using certain bridge types. They were responsible for designing and building hundreds of nearly identical bridges (standard designs) to facilitate the efficient improvement of the state's primary and secondary highway systems in the 20th century.[1]

The development and refinement of standard plans and specifications was one of the most significant accomplishments of state highway bridge engineers, both in South Carolina and in state highway departments across the nation. The process of standardization within highway departments began in the late 1910s, and it is on-going to this day. The standardized bridge types offered economy, ease of maintenance, and nearly universal application to crossings in South Carolina. Standardized plans streamlined the design process, expedited approval of projects built with federal aid, and allowed engineers to efficiently design hundreds of economical bridges giving the state "good value" for its money. Standardization also facilitated cost comparisons and accurate estimates from project to project, thus serving as a check on material and labor costs. Cost accounting, uniformity of design, and use of quality materials were considered paramount to establishing the Department's credibility and technical expertise, especially during the early years when many South Carolinians yet viewed centralized state authority over roads and bridges with skepticism. Although hardly innovative, standardization was the goal and the dominant approach to improving the state's highway bridges. Joseph Barnwell, the highly respected state bridge engineer from 1919 to 1935, developed many of the first standard bridge plans and specifications that quickly became key components in the development of the state

[1] Refer to Lichtenstein Consulting Engineer's 2006 Historic Context for Transportation Networks in South Carolina for the other factors that influenced the pre-1961 selection of bridge types and bridge construction in the state.

highway system. That practice was ably continued by W. J. Gooding, Jr., who joined the Bridge Division as an assistant engineer in 1922, succeeded Barnwell in 1935 and served in that position until 1966.[2]

Figure 1. Old SC 7 over Shanklin Creek Bridge in Abbeville County stands as one of the complete early examples of the state standard design T beam bridge. It was constructed in 1924. Transystems.

When South Carolina State Highway Department embarked on the development of the primary highway system in the mid 1920s, state engineers already had a mature understanding of the most commonly used bridge types and materials of their day, like reinforced concrete T beams and steel trusses, and they had developed standard plans for bridges using creosoted timber beams, steel beams, steel trusses, reinforced concrete T beams, and reinforced concrete slabs (Figure 1). Consequently, and not surprisingly, South Carolina's bridges are strongly reflective of national trends and standardization. This often means that historically and technologically significant examples from large populations of standardized design bridges are the earlier, unaltered ones, or those that exhibit a detail representing some design or material advance within a long-lived technology, like the application of continuous design principles to rolled steel beam or reinforced concrete T beam bridges. A seemingly unremarkable appearing bridge may be significant in the state context because it is an early example of a prototype or standardized design that would go on to become a workhorse type and design in the development of South Carolina's highway system of state routes and local streets and byways.

Since the same engineering principles are applied to specific bridge types regardless of their construction material, bridge building technology is best understood beginning from the perspective of material because the qualities of the material from which a bridge is built directly influence its design. Three materials – wood, steel, and reinforced concrete – dominate pre-1961 bridge building technology in South Carolina. Prestressed concrete was first used in the state about 1955 and on state routes starting in 1957, but its profound impact on bridge construction did not occur until after 1960. Very few stone arch bridges representing the first permanent bridge type used in the state have also been identified. The one that does is the seminally important 1820 Poinsett Bridge in Greenville County built by the state's Board of Public Works as part of the Great Road connecting to western North Carolina. The handsome lancet arch bridge ranks as the oldest bridge in the Southeast and was listed in the National Register of Historic Places in 1970.

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[2] Rudolph E. Elling and Gayland B. Witherspoon, "A Study of Pre-1951 Non-metal Truss Highway Bridges of South Carolina," South Carolina Department of Highways and Public Transportation (June 1993), p. 7; John Hammond Moore, The South Carolina State Highway Department, 1917-1987 (Columbia: University of South Carolina Press, 1987), pp. 133-158; "Specialized Engineers Design Bridges," Carolina Highways (January 1955), p. 25.

WOOD BRIDGES

Timber Stringer Bridges

The stringer bridge type, also known as multi-beam, represents the oldest bridge technology, dating to time immemorial when felled trees were laid across streams. South Carolina's early settlers who laid out the first road networks relied almost exclusively on timber stringer bridges. They cut trees and shaped the logs by hand to form the beams and planks for the bridge's deck or traveling surface. Since the mid 19th century an increasing number of power machines have been used to perform the same cutting and shaping tasks, resulting in greater uniformity of dimensional lumber and opportunities to standardize timber stringer design. Timber stringer bridges are thus South Carolina's longest lived bridge technology, having been in use from the colonial period to the present day.

All stringer bridges rely on the bending strength of the beam material to resist loads; the principle is the same no matter the material or the shape of the beam. Individual span length is usually controlled by live-load deflection (vertical movement of member under load), making the modulus of elasticity of the wood species an important factor in the design of timber stringer bridges. Nineteenth-century bridge builders often expressed a preference for oak because of its durability and strength, but they were not adverse to using other locally available species. In many cases, they resorted to whatever trees were near at hand. Since the 1910s, various species of southern pine have dominated because of availability, low cost, and depletion of hardwood forests. Timber stringer spans generally range up to 20' in length, and any number of spans can be used to achieve the desired overall bridge length.[3]

Timber stringers are usually carried on a wood substructure composed of timber pile and cap beam bents upon which the stringers rest. The bents are typically made up of a series of piles supporting a cap beam. This technology takes advantage of the fact that timber is an excellent material in compression and piles can last unusually long periods of time when totally immersed in water. Since the piles last longer than the timber stringers and deck, they are often reused with replacement superstructures. The bents can have diagonal bracing to add rigidity and prevent movement and thus failure of the individual piles. The timber stringer bridge type was well suited to South Carolina's coastal area where lengthy, multiple-span bridges supported on timber piles spanned rivers and lowlands. Timber stringer superstructures are generally restricted to use on secondary roads, not primary roads where the load-carrying capacity requirement is greater. It was a bridge type favored by railroads for overpass bridges.

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[3] Richard Sanders Allen, Covered Bridges of the South (New York: Bonanza Books, 1970), p. 10. The first Ashley River bridge at Charleston, built in 1808-1810, was a multiple span, timber stringer and pile bridge that measured over one mile long. The reported length apparently included both the timber stringer on timber pile spans over the channel and the earth causeways carrying the approaches.

Figure 2. Typical timber stringer bridge construction with timber railings and timber pile bents. This bridge dates to ca. 1918 and crosses the Southern Railway in Spartanburg County.

The main span, generally the one over the railroad track or tracks, could be timber stringer, or, like the ca. 1918 Old Pacolet Road over Southern Railway bridge in Spartanburg County (4270004500100), the longer main span consists of rolled steel beams, and the approach spans are shorter timber stringers (Figure 2).

Wood is an abundant natural resource, but the material is not permanent and is susceptible to decay, mainly from moisture, fungi, and insects. By most estimates, untreated timber stringer bridges left exposed to the elements in South Carolina rarely lasted more than ten years. No timber stringer highway bridges from the 18th or 19th centuries are known to exist in the state, and finding a complete example of that age would be highly unlikely even though they once numbered in the thousands. They have long since decayed or been replaced during the campaigns to improve the state's roads and bridges for motor vehicles in the 20th century.[4]

Creosoting, a common treatment for extending the life of wood, has been in use for highway bridges in South Carolina since about 1900. It was the dominant method of to treat wood until environmental concerns began limiting its use in the 1980s. The creosoting process removes moisture and then impregnates the precut wood member by a pneumatic process with creosote, the second distillation of coal tar. Creosoted wood is not water soluble, is resistant to decay, and has a life expectancy of 25 to 35 years for bridge superstructures and longer if submerged as pilings. The creosoting process was developed in England in 1838, and it was first adopted in America for railroad ties in the 1870s. Creosoted wood spread to other applications, including bridge beams, piles, and utility poles by 1900. Many railroads operated their own creosoting plants and were among the first users of the material for bridges. South Carolina's county bridge builders were making use of creosoted wood by the early 1900s.[5]

The State Highway Commission developed its first standard plans for creosoted timber stringer bridges in 1918, and the bridge type was one of the most common built by the State Highway Department almost from its inception. Standard Plan No. S-401 called for 14'-long spans on timber pile bents. The bridges had wood plank decks and were finished with two-rail high wood plank railings. The spans could be repeated any number of times to achieve the desired length of crossing, and the standard unit

[4] M. Goode Homes, Good Roads: How to Build and Maintain Them, Bulletin of the University of South Carolina No. 28, Part IV (Columbia: University of South Carolina, 1912), pp. 76-80. Homes, a civil engineering professor at the university, reported that the average life of a wood bridge was seven years.

[5] Ibid.

bridges offered the State Highway Commission an economical type for bridging the rivers, lowlands, and swamps of eastern South Carolina where, as in the past, lengthy bridges were often required. One of the Commission's most historically important was the nearly 1.5-mile-long bridge over the branches of the Santee River near McClellanville, built in 1928, which became a vital link in the first direct route automobile highway between Georgetown and Charleston (US 17, Coastal Highway). The bridge was replaced in 1950.[6]

The Bridge Division continued to use standardized creosoted timber stringer bridges from the 1920s through the 1950s with plans prepared for various lengths (14' to 18' long) and roadway widths (16' to 22' wide). The standard plans ensured uniformity of design and economical use of material by contractors and state maintenance crews working in all parts of the state. From 1926 to 1928 alone, the Bridge Division reported building approximately 44,380 linear feet (8.4 linear miles) of creosoted timber stringer bridges. The bridges were used on the primary highway system until the early 1940s, after which they were relegated to use mostly on the secondary road system.[7]

In the late 1940s and 1950s, increasing labor costs, rising prices for larger dimension creosoted timber, and the need to replace hundreds of bridges on the secondary road system caused the Department to seek out economical alternatives to the timber stringer bridges; the most successful alternative was a precast reinforced concrete slab bridge that could be fabricated and erected by state maintenance forces (see more below). Most of the pre-1961 timber stringer bridges in the study population are on the secondary road system. They date to after 1945 and are generally characterized as having a high percentage of in-kind replacement material, placed as part of routine maintenance. As a category, these post-World War II examples are neither historically nor technologically significant.

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[6] Second Annual Report of the State Highway Commission for the Year Ending December 31, 1918 (Columbia, 1919), p. 36. [Hereafter referred to as Annual Report.] The commission reported as one of its accomplishments the preparation of standards for "timber pile and trestle" bridges. The standards had been approved by the U.S. Bureau of Public Roads for federal aid work.

A detailed description of the Santee River bridge is found in "Modern Structure Replaces One-Time Longest Bridge," Carolina Highways Vol 2., No. 5 (May 1950), pp. 8-9, 25. The bridge had pony-truss swing spans over the navigation channels and a reinforced concrete T beam span every 1,200' to create firebreaks in the creosoted timber stringer sections. Sections did burn in 1945 and 1947.

A short history of the Coastal Highway is in Jason Annan and Pamela Gabriel, The Great Cooper River Bridge (Columbia: University of South Carolina Press, 2002), pp. 4-5.

[7] Annual Report (1924). See pp. 62-63 for a list of the creosoted timber stringer "trestle" standards adopted to that date. Annual Reports throughout the 1920s and 1930s usually reported the different major categories of standardized bridge types built by the Commission in linear feet. The total of creosoted timber stringers for 1926 was 13,167 linear feet, for 1927 was 16,946 linear feet, and for 1928 was 14,267 linear feet. These were the three highest years for the 1920s and 1930s.

Wood Truss Bridges

In the early 19th century, the wood truss ushered in a new era of bridge technology in the United States and South Carolina. Until that time, stone arches or wood stringers generally limited builders to modest span lengths, as represented by the 1820 Poinsett Bridge in Greenville County. The truss – a series of triangular shapes in which the diagonal members transfer vertical forces in a horizontal direction – was known since at least the 16th century in Europe. What was innovative at the beginning of the 19th century was that basic truss patterns were multiplied many times over to span much greater distances. Builders and engineers soon discovered that there were dozens of ways to arrange the members of a truss. Over time, the patterns and arrangements of the chords, verticals, and diagonals came to be known by commonly agreed upon names, like the king post or queen post, or by the last names of inventors or patentees, like Town, Howe, Pratt, or Warren.[8]

County records and historic pictorial collections offer evidence of wood truss bridges in South Carolina from the 1820s to 1950s, but there is no accurate count of how many wood truss bridges once existed in the state. According to covered bridge historian Richard Sanders Allen, South Carolina had at least twenty covered bridges with siding and roof to protect the load-carrying trusses from the climate. The earliest covered bridges in the state were of the Town lattice design, and were built over the Wateree River at Camden, over the Pee Dee River at Cheraw, and at a third listed by Town only as "at Charleston" between 1823 and 1829. None of the Town lattice design bridges are extant. Another of the state's early long-span wood truss bridges was the 10-span Burr arch-truss built in 1828 over the Congaree River at Columbia. The Burr arch-truss superimposed the strength of a laminated timber arch with the stiffness of a wood truss. Burned in 1865 by the retreating Confederates in advance of Sherman, the Congaree River bridge was replaced by a metal truss bridge in 1870, which itself was replaced by the Gervais Street open spandrel arch bridge in 1926-27.

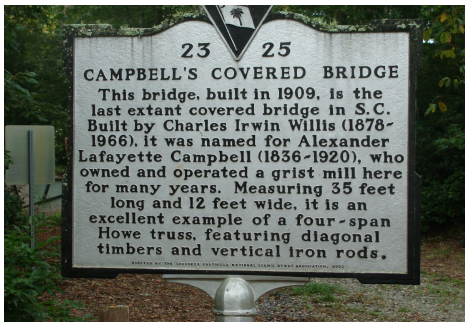


Figure 3. South Carolina's only surviving wood truss bridge located in Greenville County. The bridge is a Howe truss built by Charles Irwin Willis of Mountain View.

[8] T. Allan Comp and Donald Jackson, Bridge Truss Types: A Guide to Dating and Identifying (Nashville, TN: American Association for State and Local History, 1977). J. G. James, "The Evolution of the Wood Bridge Trusses to 1850," Journal of the Institute of Wood Science, Vol. 9, Nos. 3-4 (June/Dec. 1982), pp. 116-135, 168-193.

South Carolina wood truss bridge builders also used short truss designs such as the king post and the queen post. Several king post bridges are shown in a collection of black-and-white bridge inspection photos (ca. 1930-60) in the bridge design office of the South Carolina Department of Transportation. Unfortunately, many of these photos are not labeled with the date or location, and no king post or queen post trusses are known to survive on the state's highways.[9]

Wood trusses were not without inherent weaknesses that eventually made them less attractive as stronger, stiffer bridge types were developed. Wood truss bridges were susceptible to fire, insect damage, and moisture-related deterioration. The maintenance burden of repairing a covered bridge's roof, siding, and deck was high. The leading factor, however, in the decline of the wood truss was the development and promulgation of stiffer metal truss bridges during the late 19th century. The State Highway Department did not favor wood truss bridges, and they were never a standardized bridge type. The state's engineers moved quickly to replace wood truss bridges on the state's highway systems from the 1920s on. By the 1950s, nearly all wood truss bridges on the state's highways and byways had been replaced and disappeared. Only one historic wood truss highway bridge is believed to survive – the ca. 1909 Campbell's Covered Bridge carrying Old Pleasant Hill Road over Beaverdam Creek in Highland Township, Greenville County (Figure 3).[10]

STONE ARCH BRIDGES

Figure 4. 1820 Poinsett Bridge, the oldest bridge in the Southeast. Greenville County. Transystems.

The stone arch bridge technology was used since ancient times, and it was brought to this country by European settlers. The technology was well suited for the compressive strength inherent in natural rock, and it was the only technology available for permanent, substantial structures prior to the introduction of truss bridge technology during the early 19th century, like the 1820 bridges on the Saluda Mountain Road section of the the Board of Public Works' 1817-1821 State Road in Greenville County and the handsome 1820 Poinsett arch bridge over Little Gap Creek (Figure 4). The drylaid Gothic arch span ranks as one of the oldest extant bridges in the southeast

[9] Allen, pp. 9-14. Two long file boxes of bridge photos have been located in Bridge Engineer Douglass McLure's office. These are an invaluable collection documenting a variety of bridges and construction techniques in the state from about the 1920s to 1960s. Boxes of photographs are located in the NEPA Coordinator Office (2013).

[10] Jean Martin Flynn, Campbell's Covered Bridge, Greenville County, South Carolina (Greer, SC: Greer Citizen Press, 1992); Sue Wright, "Carolina's Covered Bridges," Carolina Highways (July 1950), pp. 10-12.

region, and it attests to the importance the state placed on internal improvements during the first half of the nineteenth century.

Stone arch bridges continued to be built for railroad and highway use through the first decades of the 20th century, but their construction was dependent on the availability of suitable stone from nearby quarries. In South Carolina, and throughout much of the South, stone arch construction was not as common as in the northern states, and relegated mostly to the piedmont or mountain regions where sources of natural building stone lay nearer to the surface than in the coastal plains. The 1993 SCDOT non-metal truss bridge survey identified seven pre-1951 stone arch highway bridges. All of the examples are believed to have been built by local units of government.[11]

The principle behind stone arch construction is that shaped stone blocks of the arch ring compress together under vertical loads. Historically, the stone arch was constructed by building the abutments and wingwalls, then erecting a wood, arch-shaped form, known as falsework or centering. The arch ring, spandrel walls, and parapets were placed, then the structure was backfilled, usually with stones, large rocks, and earth. Finally, builders removed the falsework, allowing the arch to compress into a locked and stable unit that supported itself through compression.

STEEL BRIDGES

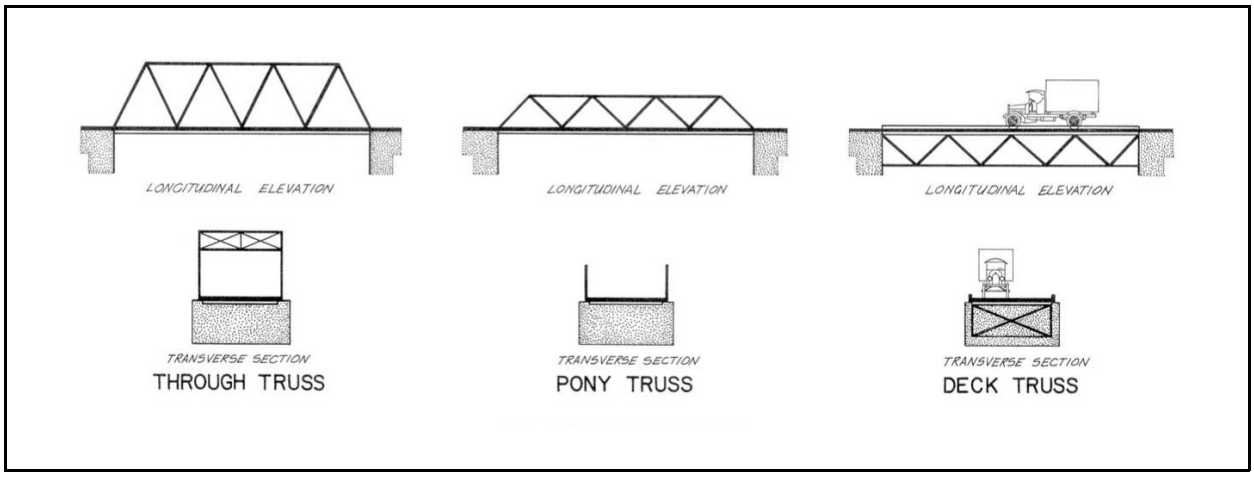
Metal Truss Bridges

The second half of the nineteenth century is commonly known as the "Age of Iron" because of the growth and profound impact of railroads on this country. Railroads and their ever-expanding need for long spans capable of carrying heavier live loads (the rolling stock itself and what was being hauled) stimulated the great era of iron truss bridge innovation and standardization that then spilled over to play a significant role in the development of America's network of trunk and farm-to-market roads. The era ushered in new scientific methods for analyzing and predicting the structural action of bridges, and advances in engineering education accompanied new standards and understanding of materials, design, and fabrication. A generation of college-educated civil engineers applied scientific theory and experimentation to truss bridge design and energetically sought out the cooperation of iron and steel manufacturers and fabricators. In reality, developing and refining metal truss bridges following the Civil War established the modern approaches to stress analysis, plans, standards, specifications, tests, and inspections that remain a foundation of professional bridge engineering today, and thus metal truss bridges are of particular significance to the history of bridge building and engineering in the United States. SCDOT's first historic

[11] Elling and Witherspoon (1993), p. 36.

bridge inventory in 1981 focused exclusively on metal truss bridges and identified more than 150 examples remaining at that date.[12]

Truss types and designs vary according to the configuration of the members. The three principal types are the thru, or high, truss; the pony, or low truss; and the deck truss. In a thru truss bridge, the road passes between the truss lines and is carried on the deck and flooring system connected to the bottom chords. There is lateral bracing connecting the top chords of the trusses. This type is generally used for spans of more than 100' long. A pony truss bridge is the same as a thru truss, but it does not have lateral bracing between the top chords. This type is generally used for shorter spans of 45' to 100' long. In a deck truss bridge the road is above the truss lines and the flooring system is on the top chords (Figure 5). No matter the location of the deck, the principles of the truss technology are the same; the members transfer live load through the members into the chords and to the bearings where it is transferred through the substructure to the ground.



5. HAER sketch of truss types. Originally published in 1976 by the Montgomery C. Meigs Original Chapter, Society for Industrial Archaeology as a poster.

In South Carolina, and in many other states, the application of metal truss bridges to highways was generally not as early, rapid, or crucial as compared to railroads. By the end of the 19th century, when metal truss bridges began appearing in numbers on

[12] Rudolf E. Elling and Gayland B. Witherspoon, "Metal Truss Highway Bridge Inventory for the South Carolina Department of Highways and Public Transportation" (Columbia: South Carolina Department of Highways and Public Transportation, 1981). For further information on the state's metal truss bridges see this previous survey.

Information about South Carolina's metal truss bridges can also be found in the National Park Service's Historic American Engineering Record (HAER) collection at the Library of Congress, Washington, D.C. Most of the bridges in the collection were recorded to mitigate replacement projects. Documentation includes large-format, black-and-white photography.

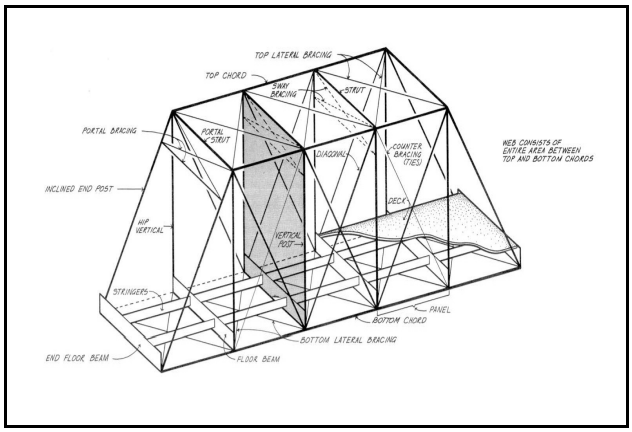


Figure 6. HAER sketch of thru truss. Originally published in 1976 by the Montgomery C. Meigs Original Chapter, Society for Industrial Archaeology as a poster.

South Carolina's streets and roads, the great era of technological innovation and variation in metal truss design spawned by the railroads were largely over. After about 1895, increasing uniformity in truss designs and construction details was driven by standardization and fact that a few truss designs, like the pin-connected Pratt, were more economical to fabricate and erect than the dozens of designs with which engineers had experimented in the 1870s and 1880s (Figure 6). The Pratt and Warren were by far the two most popular truss designs throughout South Carolina and the nation from the 1890s to 1920s. An important factor in the standardization of truss bridge design was the increasing availability and competitive cost of rolled steel shapes in from about 1890 onward. Steel performs well in both tension and compression, as does wrought iron, but steel generally has a higher tensile strength, is less brittle and is thus a superior material for truss bridges.[13]

Truss bridges were fabricated and marketed to South Carolina's county road commissioners and city officials by national, out-of-state bridge companies and their agents who were most active in the state from the mid 1890s to the early 1920s. South Carolina had no major in-state fabricators and relied on the regional and national fabricators to supply and erect its metal truss bridges.[14] Bridge companies varied in size, from those larger firms that operated nationally or regionally and were backed by major iron and steel makers, to those smaller independent contractors operating within a limited geographic area. The big companies, particularly the American Bridge Company that was established in 1901 as a subsidiary of U.S. Steel with control of about sixty percent of the nation's fabricating capacity, had advantages of scale and vertical integration that they used to dominate the prefabricated bridge market. Dozens of smaller companies filled market niches, especially selling trusses to local governments in rural areas, but they were dependent on prices set for rolled steel sections by the steel makers. Among the most active companies in the highway truss bridge market in South Carolina were the Virginia Bridge & Iron Company (Roanoke, VA) that was acquired by U.S. Steel Corporation in 1936 and a major contractor in

[13] Carl Condit, American Building Art The Nineteenth Century (New York, 1960), pp. 103-162; Allan T. Comp and Donald Jackson (1977).

[14] The only in-state bridge builder listed in Victor Darnell's 1984 Directory of American Bridge-Building Companies 1840-1900 is a Charleston firm listed as H.W. Crouch and Brother and B.F. Kramer. There is little information about their work. No South Carolina companies were part of the 1900 American Bridge Company.

South Carolina; the Roanoke Iron & Bridge Works (Roanoke, VA); the Converse Bridge Company of Nashville, Tennessee; Austin Brothers (Atlanta, GA); the King Bridge Company (Cleveland, OH); and the Champion Bridge Company (Wilmington, OH).

The Pratt truss design offered simplicity of design and fabrication and economical use of material, including standard rolled angle and channel sections, plates, bars, rods, and I beams. The original design, patented in 1844 by engineer/architects Thomas and Caleb Pratt of Boston, Massachusetts, was for a composite timber and iron truss, with the wrought-iron diagonals in tension and the timber verticals in compression. The Pratt design easily adapted into an all-metal truss with the use of eye bars and pins to facilitate field erection. Variations of the Pratt, such as the Camelback and Parker, were adapted to longer spans using the same basic web configuration of verticals and diagonals but with sloped upper chords to save on material and achieve the greatest depth at midspan where it is most needed to support loads. The Pratt and its variations dominated the last quarter of the 19th century and the first decade of the 20th century. The 141'-long, pin-connected Pratt thru truss bridge carrying Secondary Road 42 over Cuffeytown Creek in McCormick County fabricated in 1909 by Austin Brothers, was the oldest surviving on-system highway truss bridge in South Carolina identified by the 1981 SCDOT metal truss survey.[15]

Most metal truss highway bridges built before 1905, from the light Pratt pony trusses to the heavier thru or deck truss railroad spans, were assembled at the site with pinned connections. Pinned connections continued to be used through the 1920s, particularly by some smaller bridge companies, and in longer span truss designs because the pins minimized secondary stresses. Most pin-connected truss bridges surviving in South Carolina date from the 1910s and 1920s and are relatively late examples of the use of this method of connecting trusses. State highway engineers complained in the late 1910s and early 1920s that county road commissioners continued to purchase pin connected bridges that were too lightweight and too flexible, an indication that bridge companies were still selling light-capacity pin-connected truss bridges.[16]

The increased understanding of the strength of materials and metallurgy combined with 1890s improvements of field pneumatic riveting equipment, facilitated the transition from flexible pinned field connected to rigid riveted ones starting in the late 1890s. The straightforward Warren truss was particularly well suited to riveted connections. The Warren truss design is distinguished by its ease of construction with equal-sized members and by the ability of some of the diagonals to act in both tension and compression. It could be further stiffened by the addition of verticals. The Warren truss was patented by British engineers James Warren and Willoughby Monzani in 1848, but it did not enjoy widespread popularity in the United States until the first decade of the 20th century because it was better suited to rigid rather than pinned connections. It was

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[15] Condit, pp. 109-118; Elling and Witherspoon (1981), p. 170.

[16] Annual Report (1918), p. 15; (1920), pp. 13-14.

also a truss design that lent itself to standardization. The Warren is the most common surviving highway truss design in South Carolina with most examples dating from the 1920s and 1930s.[17]

State Bridge Engineer Joseph Barnwell prepared standard plans for rivet-connected Warren pony and thru truss bridges in the early 1920s (Standard Design Nos. E-1 to E-11). The plans offered bridges in standard lengths such as 60' long pony trusses and 150' long thru trusses with 18'-wide roadways. Barnwell recognized that truss bridges had advantages in some situations, for instance, when site conditions made the use of formwork for cast-in-place reinforced concrete impractical or when longer spans were required. The state's standardized design truss bridges are founded on well established engineering principles in use for decades and proven details rather than innovation, which was typical of state highway departments all across the country.

Figure 7. The cover of the April, 1952 issue of *Carolina Highways* illustrates the common postwar occurrence of replacing a narrow truss bridges with a wider one with greater elevation over the stream to lessen overtopping events.

But the important bridge type was not without its disadvantages, like cost of maintaining the steel (cleaning, painting, addressing corrosion, etc.) and having the superstructure at and above the roadway level thus exposing it to possible vehicle impact that could and did collapse spans. During the 1930s, other types of bridges, like continuous steel stringers and girder-floorbeams rather than trusses, often proved to be the most economical alternative in all but the longest span bridges, such as the Cooper River Bridge in Charleston or long swing (movable) spans. Few steel truss bridges were built in South Carolina after World War II.[18]

Truss bridges, especially the lightly built ones originally purchased by the county governments and the taken over by the State Highway Department starting in 1946, were the subject of concentrated bridge replacement programs begun in the 1920s and continued through the 1950s (Figure 7). The old truss bridges were often considered too narrow and under capacity for then-current usage. A well-known advantage of truss bridges recognized by the bridge division was that they could be disassembled and relocated. That practice of relocating truss bridges from the primary highway system to secondary roads accounts for many of the surviving examples, like the Sardis Road

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[17] Elling and Witherspoon (1981), pp. 20-29.

[18] South Carolina State Highway Department, Specifications, Contract and Bond (Columbia, 1919), p. 64.

Figure 8. 1922 thru truss span relocated to Union County in 1962 as part of new bridge over the Tyger River. Transystems.

(SSR 16) over Tyger River bridge (4470001600200) in Union County (Figure 8). The standard design thru truss span was relocated from to the Union County crossing by the Highway Department in 1962. New approach spans were constructed. As part of the relocation process, bolts were often used to replace rivets and repairs were often welded rather than using a mechanical connection. [19]

Steel Stringer Bridges

The steel stringer bridge consists of a series of parallel longitudinal steel beams supporting a deck, usually of wood planks or reinforced concrete. In the mid-19th century, an important advance in stringer bridge technology was the transition from wood to wrought-iron beams. The wrought-iron beams were made of either rolled sections (i.e., beams shaped by passing wrought iron through rolls with a succession of grooves) or of built-up beams composed of rivet-connected plates for the web and angles for the flanges. Riveting allowed fabricators to fabricate beams of sufficient depth using angles and plate to span greater distances than possible using then-available rolled beams.

Until the turn of the 20th century, iron or steel beam bridges were not common in highway bridge construction, nationally or in South Carolina. The reasons were primarily the high cost of the beams and the difficulties of fabricating and transporting them to the bridge site. Additionally most highway bridges did not carry the heavy loads that required use of metal beams and other types of bridges would suffice. America's bridge engineers certainly understood the superior bending strength of iron at the turn of the century, but the widespread application of the stringer bridge type to highways relied upon later improvements in the manufacture of steel and rolled structural shapes.

Improvements in the open-hearth steel making process resulted in larger quantities of structural steel being available at lower prices during the 1890s. As a result, bridge builders increasingly chose steel over wrought-iron. In 1908, a major technological breakthrough occurred when Pennsylvania's Bethlehem Steel Company produced the first wide-flange rolled steel beams using Grey mills, named after their inventor Henry Grey. The mills rolled beams at faster speeds, greater depths, and at an approximately ten percent savings in material with no reduction in beam strength. Although Bethlehem first met difficulties marketing the new 26", 28" and 30" deep I-shape beams, it had overcome the problems by the early 1910s. In his 1916 edition of Bridge

[19] Elling and Witherspoon (1981), pp. 38-43; "Bridge Salvage: South Carolina Re-uses Its Outmoded Steel Spans," Engineering News-Record (October 14, 1954), p. 35.

Engineering, J. A. L. Waddell, one of America's foremost bridge engineers, touted the superiority of the improved steel I-beams, calling them "a great boon to bridge designers and builders" because of their simplicity, compactness and lower price.[20] Waddell's high praise was justified, as rolled steel stringers dominated highway bridge building through the 1950s. They are truly one of the workhorse bridge types of the 20th century.

As a class, rolled steel stringer bridges proved ideally suited for the highway building campaigns beginning in the 1910s and 1920s. The bridge type was easily standardized with the length, depth, and spacing of beams picked off charts depending on the characteristics of the desired crossing. The advantages of the technology were particularly attractive to state and county bridge engineers for spans up to 60' in length. They could be easily erected and were cheaper than pony truss bridges. Rubber-tired trucks and improved heavy construction equipment eased the problems of transporting beams and on-site erection. With primarily accessible flat surfaces, stringer bridges were also easier to clean and paint than trusses. By placing formwork, like corrugated metal bent into a semicircular shape, between the beams, a brick or solid concrete deck, or jack arch deck, could be placed. The jack arch deck is based on the same theory as 19th century fireproof floor construction. Steel stringer bridges with concrete jack arch decks were being used in a few South Carolina cities, like Newberry and Greenville, by the late 1910s.

Carolina State Highway Department's earliest identified standard plans for steel stringer bridges were developed before 1924 and were for modest span lengths of 14' to 20' supported on concrete piles (Standard Plan Nos. S-301 to 303). By the late 1920s, steel stringers were becoming an ever more attractive alternative as continued improvement in the manufacturing process made beams available in longer lengths and greater depths at lower cost. The State Highway Department made increasing use of the technology, substituting it in places where it formerly might have used creosoted timber stringer or pony truss bridge types. Standard Plan No. 310, dated ca. 1930, featured a 25'-long steel stringer span with a concrete deck and timber pile substructure. Standard Plan No. 324, adopted in 1935, was for a 50'-long steel stringer span. During the 1930s, steel stringer bridges finished with reinforced concrete decks and standard concrete railings appeared in ever greater numbers on the primary highway system.[21]

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[20] J. A. L. Waddell, Bridge Engineering (New York: John Wiley & Sons, 1925), pp. 46-47; Thomas Misa, "Science, Technology, and Industrial Structure: Steelmaking in America, 1870-1925," Ph.D. Dissertation, University of Pennsylvania, 1987.

[21] Annual Report (1924); Box No. 43DN, "Very Old Bridge Design Notes," SCDOT Supply Depot Warehouse, Columbia.

Continuous Design Stringer Bridges

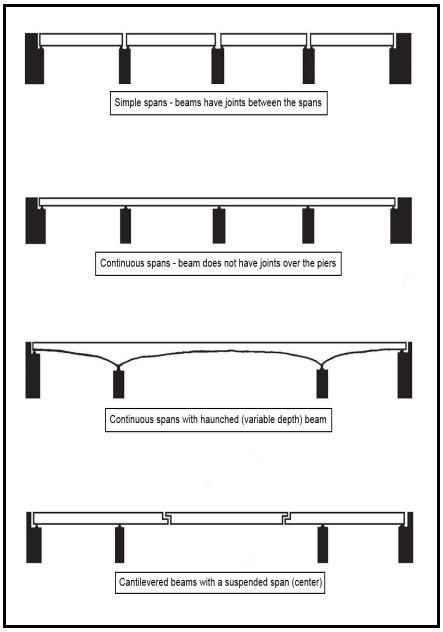

Figure 9. Sketch showing common beam bridge designs. Source: Lichtenstein Consulting Engineers.

In the middle 1920s and early 1930s, applying the principles of continuous design, where the beam continues uninterrupted over one or more piers, to rolled beam bridges gained currency with some state highway departments, including in South Carolina. Joseph Barnwell was one who did use continuous design steel stringer bridges in 1930. Prior to 1932 and American Society of Civil Engineers (ASCE) publishing standard methods and tables for calculating stresses, the design of continuous bridges was tedious, intricate, and time consuming, so consequently few state bridge engineers used them because of the problems involved in analyzing the indeterminate structures. Continuous designs have significant economic advantages because they use less material (smaller section beams) for a given span length than simply supported beams. A simple span must accommodate the entire load within the span, whereas the continuous span distributes loads from end to end over two or more spans. Continuous design decks also require fewer expansion joints, which greatly reduces the number of places joint failure can allow water to flow onto steel beams and cause corrosion (Figure 9).[22]

South Carolina's Bridge Division adopted its first standard-design continuous steel stringer bridge in 1930. Standard Plan No. S-314 was for a continuous two-span bridge with each span measuring 25' long and an overall length of 50'. The two-span continuous unit, or span, could be multiplied as many times as necessary to achieve the desired overall length. The highly economical bridge had a concrete deck and was supported on timber pile bents and finished with a concrete deck and open railings. The two-span continuous steel stringer bridge would remain a frequently used state standard through the middle 1950s with standard plans updated as needed for wider and

Figure 10. Detail of 1935 continuous beams that eliminate deck joints and spread live loads over more than one span.

[22] Engineers classify bridges as either "determinate" or "indeterminate." The stresses induced by loads in an indeterminate design cannot be solved or determined using the traditional principles of statics, i.e., the study of forces.

longer bridges. [23] By 1935, three-span continuous beam bridges were being used, like at SC 72 that has a 35'-48'-35' long continuous span over the Seaboard Air Line Railroad being a complete early example (Figure 10). The rolled beams were made continuous using riveted splice plates at the points of contraflexure. By 1938, there were four-span continuous beam bridges with 90'-110'-110'-90' span lengths. Aided by computers that could quickly run calculations, continuous design bridges of all types, not just steel stringers, became very popular nationally after World War II.[24]

Girder-Floorbeam Bridges

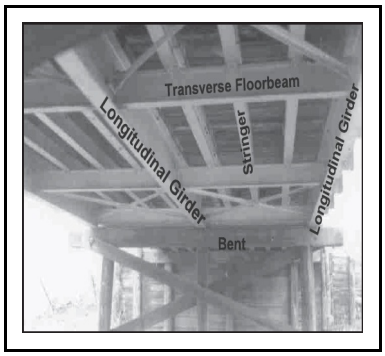

Figure 11. Girder-floorbeam bridge components identified.

Steel girder-floorbeam bridges consist of two or more longitudinal beams (i.e., girders that were generally built up) supporting transverse floorbeams and a deck (Figure 12). The strong, efficient and economical bridge type was developed by the railroads in the late 1840s, and proved to be the only serious competitors to metal trusses until about 1890. Since the built-up beams were almost completely assembled in fabricating shops, conveniently located on rail lines, the girders could be readily loaded onto flatbed cars and then quickly hoisted into position using cranes with minimum traffic interruption. [25] The ability to transport beams was often a factor limiting their length.

The girder-floorbeam technology was mature by the last decades of the 19th century, and consequently there have been few significant changes during the 20th century. In general, built-up girder-floorbeam highway bridges were not built in great numbers because of the difficulties of transporting the beams from railroad sidings to bridge sites and the fact that the bridge type was not as economical as other types of beam bridges for highway load requirements. The State Highway Commission made sparing use of the girder-floorbeam bridge type in the development of the state highway system from the 1920s to 1950s, and standard plans were never developed. Most extant girder-floorbeam bridges are associated with railroads.

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[23] Box No. 43DN.

[24] U.S. Department of Transportation, Federal Highway Administration, America's Highways, 1776-1976 (Washington, D.C.: U.S. Government Printing Office, 1976), p. 432.

[25] The oldest examples of metal girder-floorbeam bridges in South Carolina were railroad bridges. See, for example, Seaboard Coast Line Railroad Bridge, HAER No. SC-6, Historic American Engineering Record, Library of Congress (1980). The bridge, built in 1890, spanned the Savannah River between Abbeville County, South Carolina, and Elbert County, Georgia. It was the first permanent railroad crossing of the Savannah River upstream of the fall line at Augusta.

The two most common designs of girder-floorbeam bridges are the thru girder and the deck girder. In the thru girder, the floorbeams are placed in line with the bottom flanges of the girders with the travelway passing between the paired girders. The deck girder is where the floorbeams are placed near the top flanges of the girders and the travelway is located at the top of the girders with the deck bearing on the top flanges. Other than the placement of the floorbeams and travelway, there is no significant technological difference between the thru and deck designs. Deck girders are often associated with locations where vertical under clearance is not critical. When the girder-floorbeam bridge was placed over trackage, the flooring system was often encased in concrete to protect the steel from caustic locomotive blast.

The girder-floorbeam bridge type, like the steel stringer, lent itself to continuous designs beginning in the 1930s. It was an economical alternative to steel thru trusses for span lengths from about 100' to 150', and like its continuous steel stringer counterparts, it offered considerable savings in material and reduction in the number of expansion joints in comparison to a simply supported span. The built-up, riveted girders were usually haunched over the piers where the stresses are greatest in a continuous design. State Bridge Engineer W. J. Gooding wrote that he admired continuous girder-floorbeam bridges with haunched beams for their economy and pleasing lines. These continuous girder-floorbeam bridges were not standard designs, but rather were individual designs prepared for major river crossings. Among the earliest examples of the continuous girder-floorbeam bridges in South Carolina were the bridge over the Waccamaw River on US 501B (2620050103100) in Conway, Horry County, built in 1937 with a 91'-114'-91' three-span continuous main span. The US 501B bridge features architectonic details, like the reinforced concrete piers with scoring and lancet-arch shaped openings.[26]

REINFORCED CONCRETE BRIDGES

Reinforced concrete was introduced into the United States for bridge construction in the late 1880s, but it was not common for bridges until the first decade of the 20th century. After that, its advantages as a strong, versatile, and low-maintenance material were quickly and universally adopted for several bridge types, including the arch, slab, and T beam. Coming into common usage at the same time that the state highway department and county road commissions were improving highways and byways, reinforced concrete bridges were built by the hundreds prior to World War II. In fact, the earliest standard bridge plans adopted by the South Carolina State Highway Department, in 1917, were for reinforced concrete slabs and T beams. Both bridge types could easily be standardized for relatively short-span bridges. State Bridge Engineer Joseph Barnwell, like state bridge engineers throughout much of the United States, was an

[26] W. J. Gooding, "Bridge Building in South Carolina," Carolina Highways (November 1949), pp. 14, 25; US Route 1/601 Bridge (Howard F. Speaks Bridge), HAER No. SC-23, Historic American Engineering Record, Library of Congress (1997).

advocate of reinforced concrete. Slab and T beam bridges were among South Carolina's most commonly built bridge types through the 1950s (Figure 12).[27]

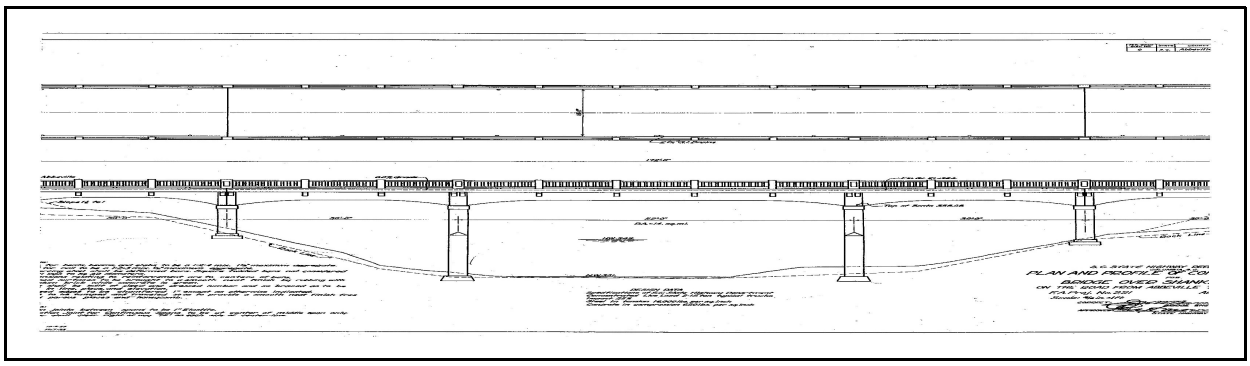

Figure 12. Plan sheet for 1923 continuous T beam bridge on Old SR 7 in Abbeville County, one of the earliest complete examples of the seminally important bridge type in the state. The custom design bridge reflects the department's emphasis on aesthetics.

Concrete, composed of sand, gravel, or other aggregate held together by a hardened paste of natural cement and water, has been known since Roman times, but it did not come to the fore as a modern building material until after the perfection of Portland cement in England in the 1810s and 1820s. Portland cement is an artificial hydraulic cement, noted for its strength and abrasion resistance. Initially it was very expensive and depended on the availability of English limestone deposits suitable for its production. As a result of the cost of importing Portland cement, its use in the United States was limited until David O. Saylor of Pennsylvania patented an American equivalent in 1871. This breakthrough gave rise to the American cement industry and provided great impetus to the experimentation and usage of concrete, which has good compressive strength but little tensile strength. Its earliest applications were for wall footings and bridge substructures.[28]

Figure 13. The 1910 slab bridge on Old Buncombe Road near Travelers Rest is one of the oldest reinforced concrete bridges in the state. Transystems.

The practice of reinforcing plain concrete with internal metal (either beams, rods or mesh) started in Europe in the middle of the 19th century. While most American engineers were familiar with a combination of concrete and metal reinforcing by about 1870, it took another thirty years of theoretical and empirical investigations before they had a good understanding of the composite material's capabilities and versatility. Engineers and builders were even uncertain what to call the new

[27] "First South Carolina Road Institute," Good Roads, vol. 19 (March 31, 1920), pp. 176-178.

[28] Condit, pp. 224-227.

hybrid material. Names included ferro-concrete, concrete-steel, and armed-concrete before "*reinforced concrete*" became the standard terminology about 1905. They tried many different reinforcing systems and shapes of reinforcing bars, but the most successful were those based on Ernest Ransome's mid-1880s design of twisted reinforcing bars distributed only in the tension zones of the structure. Ransome, a California contractor and concrete-block manufacturer, is credited with building America's first reinforced concrete arch bridge in San Francisco's Golden Gate Park in 1889. In 1884, he patented the square, twisted, reinforcing bar that he hit upon developing a factory-building material that offered superior resistance to earthquake, explosion, and fire. Ransome's twisted bar provided a good bond between the steel and concrete, but it took nearly two decades before it became widely recognized as being superior to wire mesh, steel beams, untwisted bars, or the myriad of other period designs. His reinforcing bars could be offered in a range of sizes, thus providing greater control over the available cross section and eliminating unnecessary metal.[29]

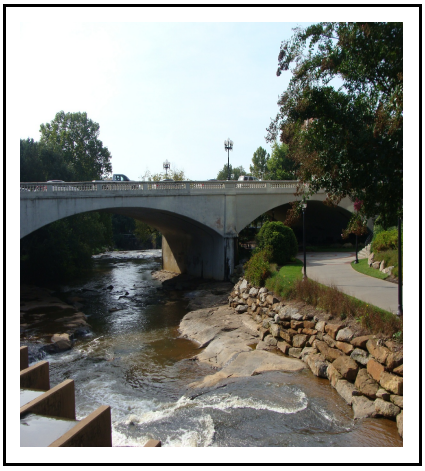

Figure 14. 1910 reinforced concrete arch bridge over the Reedy River at Greenville is the state's oldest documented arch bridge. Transystems.

Reinforced concrete bridge types were being constructed in South Carolina by 1910, and their numbers increased significantly through the 1910s. One of the earliest documented reinforced concrete bridges in the state is the center portion of the South Main Street bridge in downtown Anderson that dates to ca. 1902. There are two 1910 reinforced concrete bridges in Greenville County that show the versatility of the new material. One is a modest and plain slab bridge on Old Buncombe Road at Travelers Rest (2370028000100) (Figure 13) while the other is monumental urban arch bridge over the Reedy River in downtown Greenville (23990446100100) (Figure 14). One of the reasons for the rapid acceptance of reinforced concrete was that it was already being used for a variety of structure type s, like buildings, railroad ties, piers, and bulkheads. The knowledge transfer benefitted all. Consulting engineers, like L. A. Mullins of Atlanta and the Jordan Engineering Company of Savannah, whose bridges are represented in the state, also worked to advance the use of reinforced concrete as did the Southern Railway and other railroads. Additionally, individual promoters such as Daniel Luten and the Luten Bridge Company of Knoxville that built his deck arch bridges throughout South Carolina, and companies such as the Corrugated Bar Company that published "how-to" brochures on reinforced concrete bridges using their steel bars, aggressively marketed reinforced concrete as a building material. In the era before the State Highway Department, such promotional literature did much to spread

[29] Howard Newlon, "Concrete Bridge Patents: Useful and Otherwise," Proceedings of the Third Historic Bridges Conference, Columbus, Ohio (Oct. 5, 1990), pp. 41-50.

information about the advantages of reinforced concrete to county and municipal roads officials.

Professional engineering associations, university engineering departments, and government organizations, including the federal Bureau of Public Roads (BPR) aggressively conducted scientific examinations of the properties of reinforced concrete during the early 20th century. These studies determined the influence of temperature and climate, mixing and pouring processes, and other factors on the quality, strength, and durability of the final product. Organizations such as the American Society of Testing Materials (ASTM) and the American Concrete Institute (ACI) published the results and developed specifications. By the time South Carolina was launching its state highway system in the early 1920s, most of the problems with the quality of materials and construction methods had been solved. The State Highway Department published standard specifications that governed the quality and use of reinforced concrete and its placement. The specifications were based on, even copies of, the national guidelines developed by the federal government and industry associations, and they further promoted the standardization and uniformity of design that was the Department's goal in the development of the state highway system.

Reinforced Concrete Arch Bridges

In an arch, the outward thrust or vertical forces at the base of the arch ring must be countered by the abutments. The arch shape can be semicircular, elliptical, or segmental. Regardless of size, shape, or material, the principle behind the arch bridge type remains the same – the vertical forces have to be balanced by equal reactions at the abutments. The arch bridge type dates to ancient times with perhaps its most familiar application the stone arch aqueducts of the Romans.

Reinforced concrete arches are monolithic structures with the reinforcement distributed in the tension zones of the arch ring. In traditional stone arch or plain (no reinforcing steel) concrete arch bridges, the sheer mass of material is used to absorb the tensile stresses, but reinforced concrete arches use steel bars rather than mass to accommodate tension, and thus represent a more efficient use of both materials.

In the late 1880s and 1890s, the earliest reinforced concrete bridges built in the United States were closed spandrel deck arches where the arch ring supports the spandrel walls that retain the fill placed between the arch ring and the deck. When the technology was emerging, there were a variety of competing ideas about the shapes, type of reinforcement, and placement of reinforcing metal. A number of engineers patented and marketed different reinforcing systems, including ones that have a series of arch-shaped steel beams instead of reinforcing rods. The beams were then packed in concrete to create the arch ring itself. That design, which is more a an encased steel arch than a reinforced concrete one, was developed by Europeans Joseph Melan and Fritz von Emperger and introduced in this country in the middle 1890s.

The 1910 South Main Street Bridge over the Reedy River in downtown Greenville (2390446100100) (Figure 15) appears to be South Carolina's oldest extant reinforced concrete arch highway bridge. It was designed by the H.S. Jordan Engineering Company of Savannah and built by the Carolina Concrete Company of Greensboro. The bridge reflects the tenets of the City Beautiful Movement with classically inspired architectural details including balustrades with urn-shaped balusters and pilasters over the piers.[30]

The most famous and prolific of the engineers who promoted reinforced concrete arches was Daniel B. Luten, and one of his affiliated companies, the Luten Bridge Company of Knoxville, is known to have been active in South Carolina from the about 1915 through the middle of the 1920s. Luten was a tireless promoter of reinforced concrete, and a shrewd entrepreneur who established a nationwide business of associated contractors specializing in his patented reinforced concrete bridges. Between 1899 and 1913, Luten applied for fifteen reinforced concrete bridge patents, most for variations of arch design and reinforcing bar placement. In 1902, he organized the National Bridge Company of Indianapolis to construct his designs, and after 1905, he began making arrangements with other engineers and companies to act as his agents and contractors. Luten published lavishly illustrated catalogues with photographs and plans of his bridges, gave public talks on the virtues of reinforced concrete, and in plain simple terms explained to laymen why reinforced concrete arch bridges were superior from both economic and aesthetic standpoints. He probably did more than any other single individual to popularize the use of reinforced concrete highway bridges by municipal and county governments. By 1924, Luten claimed to have designed some 17,000 bridges with examples in 45 states.[31]

The affiliated company associated with all of the known Luten bridges in South Carolina was the Luten Bridge Company of Knoxville, Tennessee. The company established an office in Nashville by 1913 and shortly thereafter relocated it to Knoxville. The Tennessee office was an offshoot of the Luten Bridge Company of York, Pennsylvania, established about 1909, and neither the Pennsylvania nor Tennessee firms was owned by Luten. Rather, they had the license to use the Luten patents and name. The Luten Bridge Company of Knoxville helped to popularize the reinforced concrete arch technology in the southern states. The Knoxville office was active until 1946. Initially Luten's agents and other reinforced concrete bridge contractors active in South Carolina primarily marketed to county and municipal governments, like Spartanburg

[30] Elling and Witherspoon (1993), p. 18.

[31] Daniel B. Luten, Reinforced Concrete Bridges (Indianapolis, 1924); David A. Simmons, "Daniel Luten and the Luten Bridge Company," unpublished manuscript on file at Lichtenstein Consulting Engineers, ca. 1995. James Cooper, Artistry and Ingenuity in Artificial Stone Indiana's Concrete Bridges, 1900-1942, 1997.

County that in 1917 passed a road improvement bond issue.[32] Some of those bridges in the Campobello area were taken into the state highway system.

The South Carolina State Highway Department itself did not design or build many reinforced concrete, closed spandrel arch bridges. Because of site-specific conditions that impacted design, including natural foundations, desired grade of roadway (affecting the amount and weight of fill), rise (height from spring line to crown), length, and desired waterway opening, the bridge type was difficult to standardize. Their only standard arch plans were for arch culverts, really drainage structures that do not have headwalls and where the roadway is often carried above on fill or an embankment.

An arch bridge type noted for its aesthetics and built in small numbers by the State Highway Department was the open spandrel arch, which differs from the closed spandrel arch in that the use of material is significantly reduced and spandrel columns rather than solid walls are used to support a deck slab. With an open spandrel, there is no need for fill. Open spandrel arch bridges were built nationally starting about 1905 and were used in urban and scenic settings where aesthetic considerations were important. Although they offered economy of material (less dead load) in comparison to closed spandrel arches of similar size, they also required more complicated formwork and were thus best suited to long-span crossings where a graceful yet powerful bridge was desired and the economy of material could be used to best advantage. The open spandrel arch bridges were considered the aesthetic pinnacle of bridge building in the 1920s. Many open spandrel arch bridges have arch rings composed of ribs rather than a full-width rib, resulting in further economy of material.

The South Carolina State Highway Department designed open spandrel arch bridges for a few of the state's prominent river crossings. The 1993 SCDOT inventory identified three open spandrel arches: US 29 over the Pacolet River between Cowpens and Spartanburg built in 1925 and widened in 1974 (4220002901100); the handsome open spandrel arch Gervais Street Bridge over the Congaree River in Columbia completed in 1927 (402000100100); and the US 176 over Broad River bridge built in 1928-30 and widened in 1974 in Columbia (402017600600). [33]

The decline of arch bridge construction starting in the 1930s was due mainly to economic factors. Other reinforced concrete and steel bridge types could be built in the same range of span lengths at less cost using less material, falsework, and labor. Engineers were quick to point out that a disadvantage of arch construction was the "excessive dead load from the massive spandrel fill." Other bridge types, like the T beam, slab, and stringer, could be more easily standardized to fit a greater variety of

[32] Until 1924, county, not state, funds had to be used to match federal funds on federal-aid projects. This is why early bridges on some state highways were built by the county rather than the state highway department. In 1924, the department took over the primary highway system.

[33] Elling and Witherspoon (1993), pp. 22-23, 25.

site and foundation conditions. The arch type continued to be used for culverts and bridges in urban or park-like settings where a traditional arch bridge was desired for aesthetic reasons.[34]

T Beam and Slab Bridges

The T beam and slab bridge types, like the arch, benefitted from advancement in the understanding and application of reinforced concrete during the 1890s and 1900s. Both bridge types relied on the placement of reinforcing bars to accommodate tension (stresses that pull apart) and shear (loads acting across the slab or beam near its bearings). T beam and slab bridges proved ideally suited for standard plans because they could be used in a variety of conditions. The result of their adaptability was that the nation's state highway departments, including South Carolina's, built thousands of nearly identical examples from the 1910s through the 1950s. The State Highway Department phased out both bridge types in favor of prestressed concrete beam bridges starting in the late 1950s. Both were labor intensive to construct, owing to the requisite form work and therefore had high initial construction costs.

Cast-in-place T beam and slab bridges in South Carolina are technologically undistinguishable from those in other states. The earliest documented examples date from 1905 to 1910 when bridge builders first began making use of reinforced concrete as a bridge building material, often modeling their efforts after bridges introduced in engineering magazines, journals, and textbooks. T beam and slab bridges begin appearing in numbers during the late 1910s and early 1920s with the pattern of use reflecting the preferences of the State Highway Department's engineers as they approached the problem of securing federal aid for county bridge projects, and then developing and improving a lengthy state highway system. The Department adopted its first T beam and slab standard plans in 1917 with the goal of bringing uniformity and quality to projects, and making the best use of limited engineering manpower.

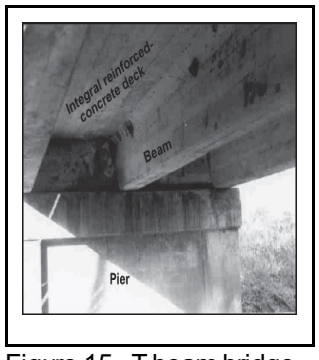

Figure 15. T beam bridge members.

T Beam Bridges

T beam bridges are made up of cast-in-place reinforced concrete beams with integral monolithic flanking deck sections used for spans of 25' to 60' long (Figure 15). The deck thickness and longitudinal beam size and spacing are proportioned to achieve a light, strong, and economical section with low long-term maintenance costs and overall economy of material. The primary reinforcing steel is placed longitudinally in the bottom of the beam stem, and the deck, or flange, reinforcing is placed perpendicular to the stem. Some beams

[34] George A. Hool and W. S. Kinne, Reinforced Concrete and Masonry Structures, 2nd. ed. (New York: McGraw Hill, 1944), p. 478.

have shear details (haunches) at the ends. T beams are almost always supported on reinforced concrete substructures. The basic technology of the T beam bridge did not change from the 1910s through the 1950s, and they were favored by the State Highway Department.

T beam bridges are believed to have been first used in South Carolina prior to 1910 by counties, cities, and railroads, but the 1993 SCDOT inventory did not identify any examples pre-dating 1922. The T beam emerged as one of the most popular of the state's standardized bridge types with the earliest set of standard plans prepared in 1917 (Standard Nos. S-201 to 204). The early state standard T beam bridges consisted of three or four lines of longitudinal beams, but the standards were updated for wider roadways in the late 1920s. The later examples usually consisted of four or more beams. The T beam standards were used ubiquitously through the 1920s and 1930s and continued to be one of the Department's workhorse standards into the 1950s.[35]

Slab Bridges

The slab bridge concentrates reinforcing steel, in the forms of twisted rods or deformed bars, in the lower portion and ends where tensile forces and shear are the greatest. The amount of steel and depth of the slab is predicated on its length and live-load capacity. Slab spans rarely exceeded 30' long, above which other bridge types, like the T beam, were a more economical use of material. The oldest extant slab bridges in South Carolina date from 1905 to 1910.

In 1917, the State Highway Department adopted a standard cast-in-place slab bridge for spans of 10' to 20' long (Standard No. S-102). The standard plan was updated through the 1920s for various roadway widths and live-load capacities. Many of the earliest extant examples are believed to be less than 20' long, and thus they are not included in the pre-1961 bridge survey population. Cast-in-place slab bridges are usually supported on concrete substructures, but the Bridge Division developed a standard slab design of 30' long supported on an economical timber pile substructure (Standard No. SB-101) in 1935.[36]

Precast Slab Bridges

The South Carolina State Highway Department designed a precast, reinforced concrete slab bridge that was fabricated in-house starting in 1947. It was developed specifically to address the pressing need to replace hundreds of deteriorated bridges on the state's secondary road system, which had been established in 1946 and had placed under

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[35] Annual Reports (1917), p. 33; (1924), pp. 62-63; Ellling and Witherspoon (1993), pp. 39-43; Box 43DN, "Very Old Design Notes."

[36] Ibid.

state authority hundreds of deficient county bridges. The slab units, also called planks, were precast at maintenance yards and assembled by state maintenance forces, although private casting companies were contracted to increase supplies of the precast slabs beginning in 1954. The design practice proved so economical and efficient that it placed more than 1,100 precast slab bridges statewide from 1947 to 1961 (Figure 16). Many other southern states, including Arkansas, Florida, Georgia, Mississippi, North Carolina, and Tennessee, followed South Carolina's lead and adopted their own variations of precast designs in the late 1940s and early 1950s.[37]

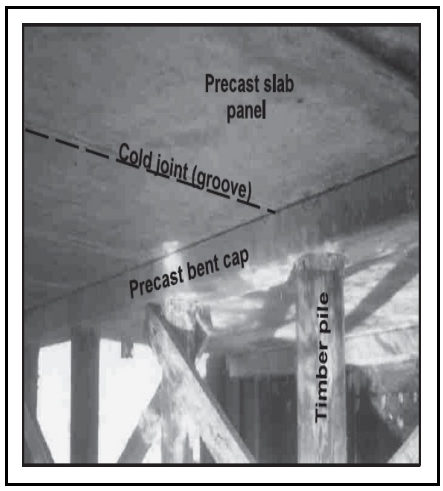

Figure 16. Underside of precast slab bridge used on secondary roads after World War II.

Use of precast reinforced concrete modular units for bridge beams was nothing new. American bridge engineers had recognized from an early date that precast construction was a potentially important means of utilizing the moldable qualities of concrete. During the first decade of the 20th century, engineers realized that precasting offered the potential of manufacturing large numbers of alike structural elements under controlled conditions in factory-like casting yards. After fabrication, the structural pieces could be shipped to construction sites and speedily erected without having to erect formwork or allow time for the concrete to cure. The foremost limit on precast construction was size and weight of the individual units as large structural members are difficult and expensive to move to the site.

The primary benefactors of precast, reinforced concrete, bridge technology during the early 20th century were the railroads. Precast slab bridges offered the advantage of quick erection without restricting traffic. Furthermore, the railroads already had in place the necessary heavy-duty cranes and cars with capacities to handle the precast units. Early examples were a bridge with 16'-long, precast slab spans for the Burlington & Quincy Railroad in Hannibal, Missouri (1909); and a precast slab track elevation of 27'-long spans for the Chicago, Milwaukee & St. Paul Railroad in Evanston, Illinois (1910). Precast slab construction became standard on a few American railroads, like the Delaware, Lackawanna & Western Railroad from the 1910s to 1930s. It is unknown if any of South Carolina's railroads used precast, reinforced concrete bridges. Between the world wars there were few notable examples of precast reinforced concrete highway bridges, although precast components such as piles and railings gained widespread

[37] "Precast Slabs, Curb, and Pile Caps in S.C. Bridges," Engineering News-Record (October 26, 1950), p. 47; C. B. Hunter, "Precast Bridges Replace Wooden Spans in South Carolina Coastal Region," Carolina Highways (April 1950), pp. 8-9.

popularity and were used by the South Carolina State Highway Department beginning in the 1920s.[38]

World War II was a watershed in precast bridge construction. The desirability of using precast reinforced concrete over structural steel or cast-in-place reinforced concrete for short-span bridges had become by the late 1940s a matter of economics rather than technological development. Following the war, the federal and state governments redoubled their efforts to improve the nation's highways with massive infusions of aid, not only for primary highway systems, but also for secondary and local road systems. The expanded highway program in combination with rising costs and shortages of structural steel, as well as increasing labor costs, prompted state highway departments to adapt and seek out the most economical means of building large numbers of bridges to cross small streams on secondary roads. South Carolina was in the vanguard of this effort.

In 1947, C. B. Hunter, who was Bridge Superintendent at the District 7 St. Andrews maintenance shop near Charleston, and M. D. Moseley, who was a bridge design engineer in Columbia, led the effort to find a bridge type that would address replacing secondary road bridges at reasonable costs and with the least possible inconvenience to the traveling public. Their motivation was that creosoted timber stringer bridges were becoming increasingly expensive to build and maintain because of rising material and labor costs. Hunter and Moseley came up with a precast, reinforced concrete 10'-long and 5'-wide slab, or plank with grooves on the sides. Casting beds with metal forms were set up in the shopyard where the bridge sections were cast and cured (Figure 17). Special forms were also used to precast integral curb sections and pile bent cap beams.

Figure 17. Precast slab units stacked at casting yard prior to shipment to bridge site and units being hoisted into place. Note integral curb cast into top beam. *Carolina Highways,* Oct., 1950.

Hunter reported that a six-man crew could handle the entire erection operation of one of the state's precast slab bridges, with the first major task driving the timber piles to support the precast concrete cap beams. Setting the piles took the utmost care as they needed to be precisely spaced to receive the cap beams. After the cap beams were secured to the piles with drift pins, the precast slab sections were set in place using a small crane (Figure 17). The planks were then locked in position and together using transverse tie rods or lag bolts. The joints between the slab sections were filled with mastic grout, and the entire roadway surface covered with a bituminous mix overlay. The initial experiments with the precast slab spans proved so encouraging

[38] J. L. Peterson, "History and Development of Precast Concrete in the United States," Journal of the American Concrete Institute, v. 25, no. 6 (February 1954), pp. 477-496.

that by the early 1950s a second design of 14'-long spans was developed for both H-10 and H-15 live loads. The Department expanded its casting operations, adding a casting yard at the Orangeburg maintenance shop in 1951-52, and then in 1954 contracting with the Carolina Concrete Pipe Company of Columbia to provide even more precast slabs for use in the western part of the state. By the late 1950s, the precast slabs had largely superceded creosoted timber stringer bridges as the bridge type of choice on secondary roads in South Carolina, making a significant contribution to the improvement of the highway system. Maintenance crews became so expert that multiple-span, precast concrete bridges could be literally erected in a day or two.[39]

Based on the successful experience of South Carolina and other states, like Pennsylvania and California, that had led the way in precast construction in the late 1940s and early 1950s, E. L. Erickson, the Chief of the Bridge Branch of the federal BPR, came out in favor of expanded use of precast reinforced concrete throughout the nation in 1953. He cited the proven advantages of standardized precast members as "savings in forms, falsework, and placing of concrete; elimination of a large amount of on-the-job labor; speed of construction; better maintenance of traffic flow; and closer control of concrete mix, placing, and curing, obtained through factory operation and resulting in a better and more durable structure." Precast reinforced concrete research and construction in the late 1940s and 1950s provided the groundwork for a significantly expanded range of precast, reinforced concrete and prestressed concrete structures in the post-1950s era.[40]

PRESTRESSED CONCRETE BRIDGES

The most significant technological advance in bridge building after World War II was the introduction and maturation of prestressed concrete for bridge beams. Introduced in America from Europe in 1949, prestressed concrete came to be the dominant material for primary and secondary road bridges by 1985. Prestressed concrete was developed in Europe in the 1920s and 1930s, but it did not make its appearance in the United States until the 1949-51 Walnut Lane Bridge in Philadelphia, which was built under the direction of Belgian engineers. Following the Walnut Lane Bridge, which received extensive national coverage in the engineering press, many American engineers and fabricators began to look for ways to apply the new material, which produced a substantial increase in the strength as compared to that of a similar non-prestressed beam. Several state highway departments, most notably Pennsylvania and Florida, led

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[39] C. B. Hunter, pp. 8-9; "Pre-cast Bridges Speed Construction Projects," Carolina Highways (December 1954), p. 8; "Maintenance Forces Erect Bridge in One Working Day," Carolina Highways (March 1957), pp. 18-19.

[40] E. L. Erickson, "Precast Concrete Lends Itself to Economical Bridge Construction," Civil Engineering (February 1953), pp. 40-43; J. Roy Fraser, "Precasting Small Concrete Bridges," Proceedings of the Sixth Annual Georgia Highway Conference (February 1957), pp. 27-43.

the way, but by the mid to late 1950s many other states, including South Carolina, had begun using prestressed concrete using beam designs developed and refined in the pioneering states and adopted by national organizations, like AASHO and BPR.[41]

Prestressed concrete is a concrete that is internally stressed in compression, usually by high-strength steel wires or cables, to counterbalance the stresses from bending caused by loads. The advantage is that the designer can make the compressive forces induced into the beam equal to the stresses expected from dead and live loads (that is the weight of the bridge and its traffic), and thus counteract the tendency of concrete to develop cracks from flexing. It is a highly economical use of material, and the beams can be precast in large numbers of like structural elements under controlled conditions in casting yards with savings in forms and falsework, elimination of on-the-job labor, speed of construction, better maintenance of traffic flow, and closer control of concrete mix. The beams can be in a variety of shapes, including I-shapes, T and double Ts, hollow boxes, and slabs. Almost all of these shapes, and a variety of methods for inducing tension in the beams, made their first appearance in the early 1950s. And, as with many new technologies, prestressed concrete went through a period of trial and error prior to becoming a mostly standardized product, but that period was very short as the I beam, double T and box beam designs developed by early adopters of the material proved to be the designs that were standards used nationally by 1960.

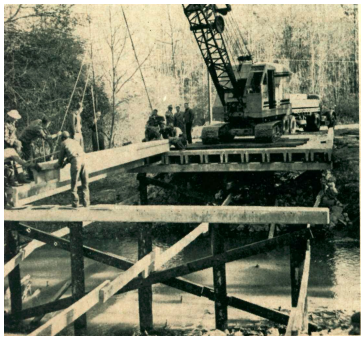

Figure 18. The state's first prestressed concrete double T bridge under construction in 1955. Source: *Carolina Highways*, March, 1955.

The South Carolina State Highway Department built its first prestressed concrete bridge, primarily as an experiment in the use and adaptability, in 1955 on Kilbourne Road (SR 95) over Gills Creek at Columbia (non-extant) (Figure 18). This was the same pretensioned double T beam bridge used in Florida for secondary road bridges starting in the early 1950s. Development of the two stems with an integral transverse slab and shorter cantilevered slabs shape is generally credited to Harry Edwards at LEAP in Lakeland, FL. His original beam was 4' wide and 14" deep. The double T had many applications, from roofing systems to parking decks and bridges. The two stems give the slab support and stability, and the length and depth of the double T beams increased through the 1950s. The Gills Creek bridge beams were 30'-long, 2.5'-wide and in the shape of an inverted U with grooved edges that fit together when the beams were assembled. The bridge was designed for an H-15 load designation, and the beams were manufactured by the South Carolina Concrete Pipe Company of Columbia. The beams were fabricated by placing steel cables under 14,000 lbs. of tension and held at the point

[41] Prestressed Concrete Institute, Reflections on the Beginnings of Prestressed Concrete in America (Chicago: Prestressed Concrete Institute, 1981).

while concrete was placed in the forms around them. After the concrete had set overnight, the tension was released and the excess cable cut off at the end of each channel section. The ends of the sections were then coated in concrete to conceal the ends of the cables. Sections were then cured with steam, which was piped into the forms. The tension induced into the beams gave them a slight camber (upward bot).[42]

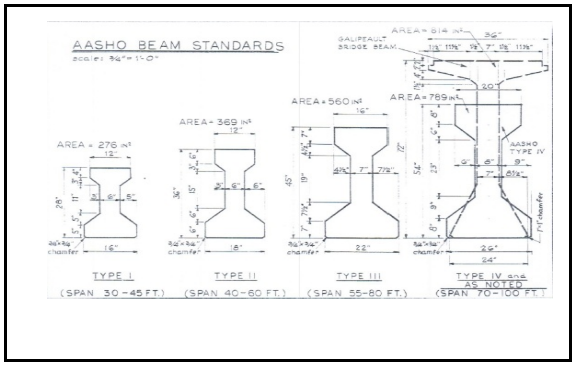

Figure 19. The beam that was developed by the Florida Highway Department in 1950 and first used for the approach spans to the Lower Tampa Bay Bridge went on the become the national standard. It was adopted by AASHO and the BPR in 1957. Many states, including South Carolina, took these designs as their state standards and starting building prestress concrete beam bridges in rapidly increasing numbers thereafter. Source: PCI (1981).

After trial efforts with the channel beam bridges in 1955, the State Highway Department was ready to expand its use of prestressed concrete to bridges on the primary highway system. In 1956, the Bridge Division introduced its first prestressed concrete I beam (stringer) bridges with 35'-to 75'-long beams. Their design was that developed by Florida in the early 1950s and adopted by AASHO and BPR, in 1957. Among the first places nationally that these types of beams were used was for the approach spans on Florida's Lower Tampa Bay Bridge known as the Sunshine Skyway. According to annual reports, the first contracts for prestressed concrete I beam stringer bridges in South Carolina were let in early 1956 for an underpass at Shaw Air Force Base on US 76 in Sumter County and another bridge on US 276 near Simpsonville in Greenville County (both non-extant). One of earliest extant I beam bridges (in 2013) is the 1957-1960 US 21 Business over Beaufort River swing span with I beam approach spans.

The viability and economy of the prestressed concrete I beams was soon proven. Cast in controlled, factory-like conditions, the beams were of high strength and light weight compared to conventional reinforced concrete, and soon made the cast-in-place T beam practically obsolete. By 1960, prestressed concrete stringer and double T bridges were well on their way to becoming the dominant standard bridge types in the state, and both types still dominate today. The introduction of prestressed concrete marked one of the most significant technological changes in standard bridge construction since the early years of the State Highway Department. [43]

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[42] "Department Forces Erect First Pre-stressed Pre-cast Bridge," Carolina Highways (March 1956), n.p.; Prestressed Concrete Institute, op.cit., pp. 92-98.

[43] Annual Report (1956), pp. 42-43; "Shaw Field Bridge Nears Completion," Carolina Highways (January 1957), p. 12. It is believed that the bridge on US 76 near Shaw Air Force Base was replaced about prior to 2010.

Movable Bridges

With its coastal sounds and navigable waterways, South Carolina has a long history of movable bridges dating to the colonial period. Movable bridges are those that can change position to allow the passage of marine traffic. Movable bridge technology dates from ancient times, with the earliest documented examples represented by simple draw bridges that were hinged at one end and lifted at the other end by ropes or cables. The movable bridge remained in its primitive stage, dominated by rude draw and swing spans, until the late-19th century when advances in mechanical and civil engineering resulted in longer, mechanically operated spans that could open and close quickly and provide a wider navigable channel. In the United States, the same need for accommodating greater capacity and span lengths that spawned the railroad's great era of experimentation with metal truss bridges had a similar effect on movable bridge technology. In addition to mechanical operation of swing spans with ever-increasing span lengths and load capacity, several new types of movable bridges were developed, including the bascule (a French word describing raising and lowering using counterweights, like a seesaw), the vertical lift, and the rolling lift favored by railroads. In 2013 there were seven pre-1960 movable highway bridges remaining in the state. Two are o double-leaf bascules in Charleston County, and five thru truss swing spans based on the same basic design and ranging in date of construction from 1935 through 1956.

Swing Span Bridges

A swing span bridge rotates in a horizontal plane around a vertical axis to a position parallel with the marine channel. This permits marine traffic to pass on either side of movable span. When in operation, the movable span is supported by one of two methods: *center bearing* on a vertical pin or pivot, or *rim bearing* on a circular girder called a drum that moves on rollers (Figure 20). The most common swing span design is the lighter and more easily operated and maintained center bearing design with the pivot set on a pier, known as the pivot pier. The rim-bearing design is less common and was used for wider and heavier bridges. All of the identified swing span highway bridges in South Carolina are center bearing. The superstructure of swing span bridges can be a truss or a girder-floorbeam span. The choice of superstructure almost always reflects the prevailing practices of fixed bridge construction with the specific type and design matched to the length and capacity needed at the crossing.

Swing span bridges are rotated by a series of reducing gear sets and a rack and pinion drive. Operators houses and equipment houses that contain the controls and machinery are located adjacent to or on the bridge, depending on its size. Light swing span bridges could be manually operated using a capstan (crank), but larger ones were first powered by steam or gasoline engines and later by direct current electric motors. All of South Carolina’s swing span bridges are modern and are electrically operated.

Swing span bridges were known in Europe since at least the 17th century. Spurred by railroad expansion and the advances in metallurgy and bridge engineering, the bridge type developed most rapidly between 1840 and 1890 in this country. All of South Carolina's surviving swing span bridges are later examples of the well-established but reliable technology that was used through the middle of the twentieth century.[44]

Figure 20. US 21B over Beaufort River 1957-1960 swing span bridge showing elevation of movable span, roadway through the movable span, movable span rotating open, and bridge in the open position to allow passage of marine traffic. TranSystems, 2013.

Bascule Bridges

A bascule bridge rotates in a vertical plane around a horizontal axis, much like a seesaw. Although the bascule dates to ancient times, it was not until the 1890s in the United States that engineers successfully developed innovative bascule designs that produced a balanced system, making large bascule bridges easy to raise and lower. In comparison to swing span bridges, bascule bridges have several advantages, including speed of operation, and thus minimizing disruption of vehicular traffic, and eliminating the obstruction of the pivot pier in the navigable channel. Additionally bascule bridges do not require a clear turning radius that prohibits the construction of docks adjacent to the bridge site, a particular concern at crowded waterfronts.

An influential patented bascule bridge designs was the trunnion bascule developed in 1905 by engineer Joseph B. Strauss (1870-1938), who later became known for his work on the Golden Gate Bridge in San Francisco. South Carolina's oldest bascule highway bridge, the Ashley River Memorial Bridge (US 17 Southbound) in Charleston (1020001730600), completed in 1925, is an example of the Strauss double-leaf, "underneath counterweight" bascule. Strauss's innovation was connecting the counterweight to the bascule leaf by means of a framework consisting of trunnions (or pivots) and linkages. As the leaf moved, the trunnions and linkages swung the counterweight, always maintaining the weight at the tail end of the leaf and using gravity to its greatest effect in assisting with the raising and lowering of the leaf. The

[44] George A. Hool and W. S. Kinne, Movable and Long-Span Steel Bridges (New York: McGraw Hill, 1923), pp. 1-27; Otis Ellis Hovey, Movable Bridges (New York: John Wiley & Sons, 1926), pp. 10-14, 20. J.A.L. Waddell. Bridge Engineering Volume 1 (New York: John Wiley & Sons, 1925), pp. 684-699.

counterweight could be placed in one of several positions, including overhead attached to a tower (overhead counterweight design), attached to the heel end of a truss superstructure (heel trunnion design), or, as in the Ashley River Memorial Bridge, located underneath the roadway (underneath counterweight design). The underneath counterweight design was particularly adapted to locations with ample clearance between high-water level and the roadway. Strauss received a series of patents for his bascule bridge designs from 1905 to 1911 with the basic underneath counterweight design patent filed in 1906. To build his designs and manage the patents, Strauss formed the Strauss Bascule Bridge Company, and by 1920, the company claimed to have designed or licensed more than 300 bascule bridges nationwide. In the national context, the Ashley River Memorial Bridge is a late example of a Strauss bascule bridge, but it is a particularly handsome example noted for its custom, Neo-classical detailing.[45]

[45] Elling and Witherspoon (1993), p. 16; Hool and Kinne, pp. 24-25.

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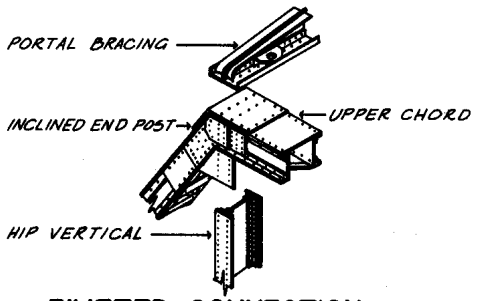
PORTAL BRACING
INCLINED END POST
UPPER CHORD
HIP VERTICAL
RIVETED CONNECTION

Figure 25.