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Material Concerns in the Pacific Northwest: Steel versus Reinforced Concrete in Highway Bridge Design in Washington State, 1910-1930

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> *Steel must struggle for precedence with iron somewhat as iron did with wood the past forty years, and it will undoubtedly in the end be as victorious.* (Theodore Cooper, 1879)[1]

> *It is clear that the age of steel, as a universal material, is on the wane . . .* (*The Builder*, 1903)[2]

> *There is no bridge building material which appeals so much to the imagination of the designer as reinforced concrete. It leaves him free to mould the bridge to any structural form which best suits the particular requirements of the site; and although it has been considerably abused, it is perfectly susceptible of beautiful architectural treatment.* (Charles S. Whitney, 1929)[3]

Introduction

The arrival of the motor car in Washington State at the dawn of the twentieth century had an unprecedented impact on the rural and urban environments of this most north-westerly portion of the United States. From the initial handful in the early years - the first two automobiles duly appeared in Seattle and Spokane in 1900, climbing to 763 in 1906 - the rate of increase was phenomenal: by 1915 the number had escalated to 46,000 and by 1920 there were some 186,000.[4] Anticipation of this rising spectre of the automobile age saw the Washington State Highway Department come into being in 1905, based in Olympia, the state capital.[5] Involved from the outset with transforming a medley of primitive, largely unsurfaced, wagon roads to an efficient, reliable network of modern state highways, it was 1909 before things really got moving. The appointment of a new commissioner, Henry Lee Bowlby, in that year marked the onset of a committed, focussed organisation; the 'real beginning' according to a former Bridge Engineer, of the highway department. Formerly an engineering instructor at the University of Washington, Bowlby was instrumental in creating an engineering office 'force' of about six or eight men, and played a key role in expediting the construction of a fairly comprehensive system of state roads and interstate highways during the period 1909 to 1913.[6] The years after this formative period were to see the growth and maturation, by the early 1920s, of a disciplined, forward looking body committed to improving and expanding the key aspect of the State's infrastructure.

The greatest challenge it faced was posed by the physical environment. Washington State is a land of physiographic extremes and variety: rugged mountains, glaciated trenches, extensive basins and broad plateaus dissected by countless rivers and tributaries. Bridges, tunnels, culverts and snowsheds in quantities out of all proportion to those demanded for railways in previous decades were required to traverse these obstacles.

The start of the new century also saw the increasing application of two materials that had already demonstrated their structural prowess over cast and wrought iron in the field of bridgework and building construction. It is widely appreciated that steel and reinforced concrete enabled unprecedented freedom of structural expression permitting new possibilities in form, dimension and constructional technique unimaginable to earlier designers. Perhaps less recognized is the degree of competition that ensued between the two materials, articulated through the mushrooming societies, institutes and publications designed to propagate the use of the material products of the industry to which they, or the authors, were affiliated. In America (and notwithstanding the legacy of a century of refinement in the application of iron in construction) developments in the 1890s in rolling technology and the organisation of practice had possibly already given steel a head start. Most notably, the adoption of standard dimensions for steel shapes in 1895 by many American mills - prompted by an increasing drive towards vertical integration between steelmakers and structural engineering firms - simplified bridge and building fabrication and played a key part in the constructional application of steel in the 1890s. Corporate consolidations further mitigated the change. The amalgamation, in 1900, of 28 of the largest bridge companies into the American Bridge Company (a subsidiary of the recently formed United States Steel Corporation) by Andrew Carnegie resulted in a single company that controlled, for a time, 90 percent of the steel fabrication and bridge erection business.[7]

The arrival of reinforced concrete, however, posed the first serious challenge to metal construction and metallic-minded design. In American bridge building, Melan's system of reinforcing (consisting of a parallel series of steel I-beams, curved approximately to the shape of the shallow arch axis) had already established itself as standard practice by the late 1890s, chiefly through the popularising efforts of Fritz von Emperger, the system's American agent.[8] By 1902, according to one contemporary, over 150 concrete bridges using steel reinforcement had been built, the majority of which were presumably based on the Melan system.[9] By the early 1900s, the leading engineering firms working in reinforced concrete included Ernest Ransome (San Francisco); Julius Kahn (Detroit); Schmidt, Garden and Martin (Chicago) and the Ferro-Concrete Construction Company. Each employed - and promoted - their own variations of the reinforcing techniques developed by an earlier generation of pioneers - Hyatt, Ransome, Wayss, and Hennebique - to construct bold, imaginative structural forms that challenged, through increasingly audacious dimensional feats, territory hitherto the preserve of steel.[10]

The early twentieth century was to see an increasingly fierce debate over the relative merits of the two technologies, *viz.* their relative economy, speed of erection, maintenance and aesthetics. With respect to bridgework, the issue seems to have reached a climax in the late 1920s, with the most vehement argument stemming from the steel 'camp', presumably alarmed by the true scale of competition from concrete in the highway bridge field.[11] Much of this debate was stimulated by the growing experience of many highway departments, counties and cities of considerably lower maintenance costs for concrete structures,[12] the continual 'search' for cheap, durable small span highway bridges,[13] and, quite possibly, by the impact of the first book devoted wholly to the design of reinforced-concrete bridges, published in 1925.[14] Moreover this debate extended across the Atlantic to Europe; one of the leading German engineering periodicals, *Bautechnik*, and its supplements, *Stahlbau* and *Beton u. Eisen*, devoted many pages to the numerous replies received in response to the original and seemingly impartial article on the subject.[15] The issues raised by this debate form the backdrop of this study: to the highway bridge engineer, the choice between steel and reinforced concrete was of great significance, for it had direct bearing on such factors as the cost, efficiency and lifespan of bridges - vital considerations in an era of rapid highway development and increasing vehicular loads.[16]

Economic Preconditions: an ineffectual iron and steel industry and a vigorous Portland cement industry

Despite attempts in the late nineteenth-century to establish an iron and steel industry on the Pacific Coast that could compete with that of the Midwest (let alone the eastern seaboard), all ultimately met with failure. Even the most promising of these, the Puget Sound Iron & Steel Company's small plant at Irondale, near Port Townsend, Washington, soon succumbed to the twin disadvantages of inferior coking coal and excessively high production costs. Indeed, despite early-twentieth-century attempts to resuscitate the latter venture iron and steel production ceased altogether by 1911 and the plant was shut down permanently eight years later. The failure was not attributable solely to inferior coking coal - perhaps Washington's greatest handicap - but also to a whole raft of 'external' factors, including the competition from eastern mills, the effect of railroad rates, and most insidious of all, the United States Steel Corporation's efforts to coerce eastern and European banking houses not to finance iron and steel operations in the west.[17] The success of other integrated iron and steel plants in the far west - Utah, California, Oregon - was similarly short lived and in the west as a whole, only a few survived beyond the end of the First World War. In 1925, of 425 blast furnaces operating in the United States, 415 were east of the Mississippi river, and none were located on the Pacific Coast.[18]

The production of steel on the Pacific Coast did continue, however, but on terms amenable to the giant eastern plants. In at least six of the larger coast cities, steel was manufactured from both scrap and pig iron in basic open hearth furnaces and some of them did produce structural steel in quantity. In Tacoma, which as early as 1914 was forecast as a 'probable steel centre',[19] two of the three largest steel plants - the Star Iron & Steel Company, and the Puget Sound Iron & Steel Company - had structural steel departments, and were supplying their products (which included 'some of the heaviest forms of section') as far as Alaska, the Philippines and beyond.[20] The Star Iron & Steel Company also secured the contract for fabricating the steelwork for the South Fork Newaukum Bridge, one of the bridges discussed below. Nevertheless, these were rare and uncharacteristic success stories. From the outset, local production of structural steel was not destined to have economic significance.

The destiny of reinforced concrete was much rosier. The first plant in the Pacific NorthWest for the manufacture of Portland cement - the prime cementing agent in structural concrete - was built at the small town of Baker (renamed Cement City and later Concrete), Washington, in 1905 by the Washington Portland Cement Company.[21] In the following year the Superior Portland Cement Company was organised, also near Baker. The next decade saw further growth of the industry: in 1911 the Lehigh Portland Cement Company erected a plant near Metalene Falls in the north eastern part of the state; in 1912 the Olympic Cement Company began manufacturing in the city of Bellingham in the north west; and in 1913 the International Portland Cement Company built a plant seven miles east of Spokane. In 1918 the Superior Portland Cement Company purchased the Washington Portland Cement plant, and both plants at Bellingham were integrated. These five plants, all that were built in the state until 1925, were characterized by steadily increasing output and profits: in that year they produced over 3,500,000 barrels which was three times that of neighbouring Oregon.[22]

The other major constituent of concrete, aggregate, was of course virtually ubiquitous in its distribution; for bridge construction it was common practice to simply dredge the gravel and sand from the river bed. Washington was however particularly fortunate in that it had massive deposits of a phenomenally hard gravel termed Steilacoom (from the town of that name) with a compressive strength in excess of 20,000 pounds per square inch. The incorporation of this in concrete greatly enhanced its compressive strength, and was of particular use in the context of the design of superior classes of structural concrete intended for thin and heavily reinforced members, which would otherwise suffer from compressive weakness.[23]

The economies of reinforced-concrete construction, which, all things being equal, compared favourably with steel anyway, were thus accentuated further in Washington, and indeed the far west. Not only did it make use of locally available materials - all the ingredients for the actual concrete were available in bulk, but the actual erection of structures in this material could be performed by relatively unskilled labourers, often convicted prisoners.[24] Steel, on the other hand, required more specialized understanding of fabrication and erection methods, skills that were not traditional to the construction industry in the far west. Furthermore, by building in concrete, a city or county engineer could keep construction funds in the local economy,[25] rather than lose them to the giant bridge departments of the steel producers in Pennsylvania or Alabama. Allied with this was the wider desire for economic independence from the older, established eastern states; Irondale represented one of the first attempts to establish heavy industry in western Washington, an enterprise that the owners (and the local and regional publications) hoped would lead to wealth and power.[26]

Placed in this broad canvas, the evolution of the state highway department in Washington went hand in hand with the development of reinforced-concrete. The great era of the railroads in the region, begun in the late nineteenth century and continuing through to the 1930s, was, in contrast, more intimately associated by tradition with the capital and steel products of the east. Road builders quickly embraced reinforced concrete technology alongside steel, whereas railroad builders maintained a distinct, virtually exclusive loyalty towards steel, since they had longstanding connections with the bridge and structural-steel departments of the giant steel mills. A small number of mass-concrete-arch railroad bridges, with massive full-centred vaults and solid spandrels, were built in Washington, including the Klickitat River Bridge (1908); as were a few reinforced-concrete arch viaducts, such as the Rosalla Railroad Bridge (1915).[27] However, their employment was extremely rare; an unpopularity that in the case of mass-concrete arches was common throughout America on account of their weakness in absorbing the high impact locomotive loadings.[28] The vast majority of twentieth-century railroad bridges in Washington were built in steel.[29]

Bridge Building and the Washington State Highway Department

The second decade of the twentieth century saw, with the accelerating pace of highway construction across the country, the formation or further development of national highway organisations and associations to promote good practice in road and bridge construction. The increasing drive for standards and professionalism in the wider highway engineering field during the 1910s was reflected in developments within the Washington State Highway Department. In 1920 a specific, separate, bridge department was established in Olympia to '*design all bridges according to the best modern practice*.'[30] Until this date there was no recognized position of Bridge Engineer, although by 1918 one person, O. H. Stratton, was acting in that capacity under the Chief Engineer, George F. Cotterill. By 1921 or 1922 there was a team of five or six bridge engineers[31] which had responsibility for the design of all bridges and culverts on the state highway system, and which was also charged with co-operating with the district engineers in supervising their construction and maintenance.[32] (Highway districts were established in Seattle, Spokane, Vancouver, and Walla Walla in 1918, marking the onset of a large scale construction program).[33] The team also provided advice or complete plans for bridges built by the counties from county funds.[34] In common with many highway departments, these specialists represented a new generation of college educated civil engineers who based their economical and efficient designs on an understanding of scientific theory in addition to empirical understanding. In practice though, many of these engineers were frequently involved with the monotonous task of turning out standardized designs that could be easily applied

to a whole array of site conditions. Furthermore, when larger or more specialized structures were required, states tended to contract with private consultants who had expertise in a particular area.[35] Washington was no exception, but its highway department was able to keep the great majority of the work 'in house', even before the establishment of the bridge division. In Iowa, during the 1900s for example, several construction companies were granted blanket contracts on bridge building by various counties, and the state highway commission was powerless to curtail this practice (many of the bridges were inordinately expensive and of inferior quality) because it functioned in a purely advisory capacity *vis-à-vis* the counties.[36] In this respect, the Washington highway department was fortunate in that there was little tradition of private bridge fabricating in the state, at least not on the scale as that endemic to the steel heartland of the east.

The late 1900s -1920s therefore saw the emergence of an increasingly well organised and efficient highway department, intent on creating a comprehensive network of highways throughout the state. The success of this was dependent to a large degree on the delegation of administrative authority between the Highway Department, the counties and cities; legislative changes in the formative years of the Department's existence were intended to impose a strict hierarchical structure. The counties and cities were obliged to offer their designs concerning the construction or improvement of 'permanent highways' for state approval, and good practice was further encouraged by enabling them to obtain, by request, advice or complete plans for the construction of minor roads and their attendant bridges or culverts.

This system, which essentially centralized highway bridge work, was in operation in virtually all the states by the late 1910s, following the passage of the Federal Aid Road Act in 1916, which required the organization of a state highway department before a state could participate in federal aid. Such a system was of course injurious to private practice - it was designed in part to eliminate the exploitation of inexperienced county or city officials at the hands of unscrupulous or inept private engineers or companies, rife in some states - and there was an inevitable backlash. In 1923 bridge companies and private engineers began vehemently denouncing what they saw as a 'paternalistic system' of state bridge engineering, urging the editors of America's leading engineering periodical, *Engineering News-Record*, that a return to the halcyon days of freely competitive practice was in the interests of the public as well as the field of private practice. Their criticisms were directed chiefly at the engineers employed by the states, who, they asserted, were incompetent and lacked experience, and at the bridges they designed, maintaining that they were wasteful of materials. In essence, they argued, entrusted with public money, they could do a better job.[37]

The engineers of the Washington State Highway Department were responsible for the vast majority of bridges built in the state in the ensuing decades, some of which were pioneers of new structural forms or techniques of construction, or which set new dimensional records. These engineers had no monopoly on technological virtuosity however. In order to win those contracts tendered out by the highway department, private engineers and bridge companies had to design increasingly economical, efficient structures since the state bridge engineers were continually striving toward this end, particularly in the short and medium span field. Efficiency and economy in bridge design were of course directly related to the materials of construction - steel or reinforced concrete - and how they permitted particular structural solutions to a given problem.

Steel or reinforced concrete?

The choice facing the early twentieth-century bridge engineer between steel or reinforced concrete was far from straightforward. Either material could claim intrinsic advantages, which in the context of building design have received much attention.[38] Here however, only four factors pertinent to bridges need concern us: relative economy, speed of erection, aesthetic considerations, and corrosion/maintenance.

The chief advantage of reinforced concrete was its cheapness relative to structural steel: for a given structure it typically utilised only about one-third of the steel required in a steel-framed equivalent, and the cost of the concrete was by comparison negligible. Set against this was the speed of erection of the steel frame, the individual components transported direct from the fabricating shop and quickly assembled together on site. The question of aesthetics was a fairly moot one, with advocates of the two techniques fairly evenly balanced. Notwithstanding the stunning examples of structural art that were Maillart's bridges - these and others like them were largely the exception - many engineers saw the humble arch bridge in reinforced concrete as visually far more attractive than the comparable steel truss, and so it was frequently the preferred option for scenic locations.[39] The truss bridge, with its brazen assortment of members bristling with rivets, probably found little support from those engineers with conventional artistic sensibilities. Nevertheless, in terms of sheer grace and power of visual impact, steel unquestionably demonstrated its virtues in the form of the steel arch, steel suspension span, and later the steel cantilever.[40]

The other major factor was that of maintenance and the concomitant expense involved. Steel bridges required painting in the first instance - which added to the initial construction costs - followed by a regular program of re-painting, to maintain adequate protection from rust which could otherwise seriously threaten the structural integrity of the steelwork. Concrete, by contrast, was initially viewed as 'maintenance free' in this respect and it was not until later that it became increasingly apparent that concrete requires attention and upkeep like any other material.

Other factors, specific to bridges, played crucial roles in the decision making process. Bridges had to answer a far greater set of structural design problems, posed not only by the nature of traffic intended for the span and the environmental forces (e.g. wind speed) at work, but by the geological and topographical conditions unique to a particular site. The overriding factor that divided the two materials with respect to their suitability for a given crossing was the length of the intended span. Already by the 1900s, despite the daring designs of Maillart and others that took the structural possibilities of the material to breathtaking limits, reinforced concrete had shown it could not compete in the long-span field. The sheer mass and weight of the concrete necessary for a single long span simply produced intolerable stresses in the superstructure. For very wide crossings, where for various reasons, the construction of intermediary piers was unfeasible or impossible, steel, in the form of arches, cantilevers or suspension bridges was the only choice.

Steel versus reinforced concrete: trends 1900-1960

During the period 1900 - 1960 reinforced concrete rapidly rose to a position of economic superiority in highway bridges in Washington State (Fig 1). This rise was neither entirely steady or predictable. A newly formulated state highway department 'standard' policy enabled a resurgence of the steel truss, during the 1920s, essentially confined to the short and medium span field. In terms of importance, it was these span ranges - and especially the former - that were always the stock in trade of the highway department and counties. By contrast, long span and movable bridges, whilst perhaps individually more vital in terms of bringing regions or even states together, or bridging critical waterways, were always a relatively uncommon requirement. Thus, by the 1950s, reinforced concrete enjoyed a popularity in bridges of total span lengths below 400ft in vast disproportion to the equivalent in steel, and its application in even longer multi-span bridges was on the rise. For the purposes of this paper attention will be focussed on two decades at the start of this saga, the 1910s and 1920s. The first of these decades saw the indisputable arrival of reinforced

concrete in the form of the arch bridge, whilst the next decade witnessed a surprising comeback for steel, with the widespread application of the truss bridge.

1910 to 1919

As early as 1902 the engineer Henry S. Jacoby, in an address before the American Association for the Advancement of Science meeting at Pittsburgh forecast that 'it is the smaller steel structures

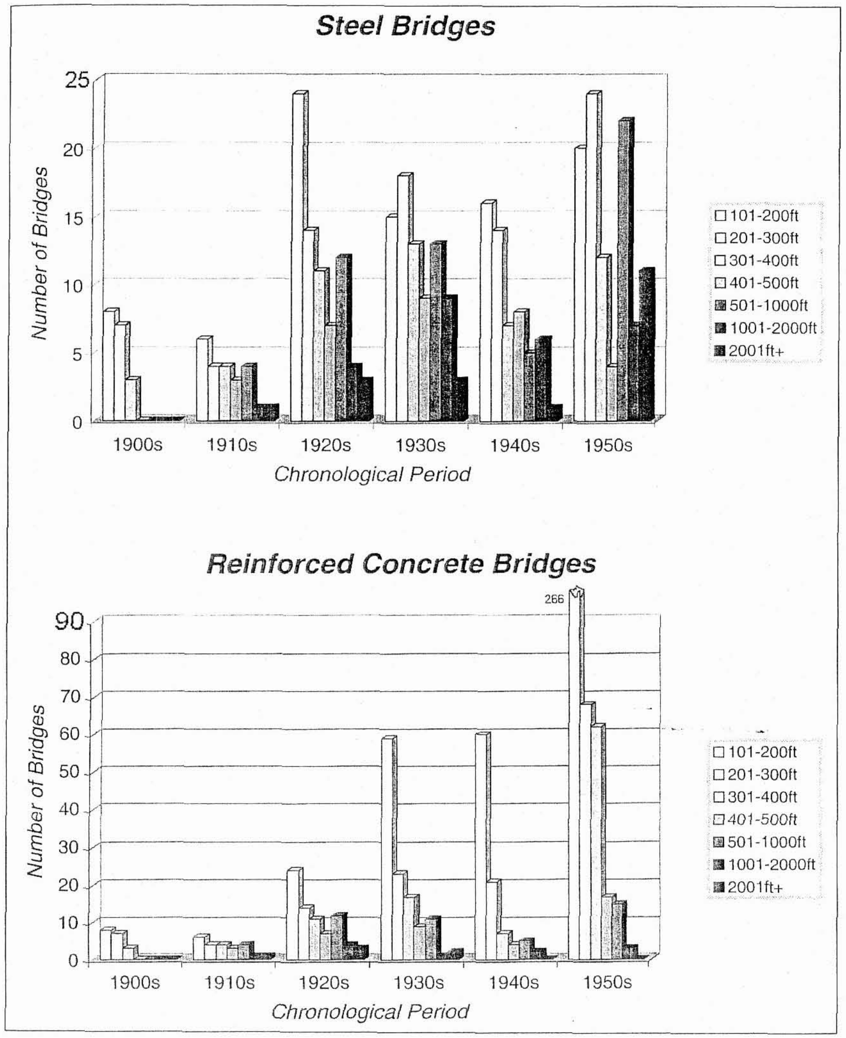


Fig. 1 The changing popularity of steel and reinforced concrete bridges in Washington State, 1900-60

which are destined more and more to be replaced by arches of this [reinforced concrete] material'. The reason, he pointed out, was primarily one of maintenance and longevity:

> *. . . steel bridges require repainting at frequent intervals, constant inspection, occasional repairs and finally replacing by a new structure after a relatively short life, on account of rust and wear, unless it is required even sooner on account of a considerable increase in live load. The concrete arch requires practically no attention except at very long intervals.*[41]

Increasing concentration, speed and dimensions of vehicular (live) loads became matters of growing concern in highway bridge design during the late 1900s and 1910s, and reinforced concrete came to be seen by a growing number of state highway departments and counties as the economical and durable solution. In Cuyahoga County, Ohio, for example, of the twenty steel bridges replaced during the period 1906 - 1913, only three were rebuilt of steel; the remainder were rebuilt in reinforced concrete.[42] In Washington, where, as we have seen, the incentive to use this material was augmented further by local factors, its use in short-span bridges mushroomed during the 1910s - to the detriment of steel. Of the extant steel and reinforced-concrete bridges built in the years 1910 - 1919 having a total span within the range of 101ft - 300ft, over two-thirds are in reinforced concrete, and the overwhelming majority of these are arches.

The Baker River Bridge (1916-17) (Fig 2), an open-spandrel reinforced-concrete deck arch, is one of the earliest surviving examples in the state to herald a move away from the early monolithic arch form in which the steel reinforcing acted more as a binding element than as reinforcing. The only link between the two halves of the town of Concrete, it was built to replace a wooden bridge - condemned by County Engineer A. L. Strong as unsafe and beyond repair. The Skagit County Board of Commissioners favoured a reinforced-concrete arch over a steel truss on the basis of relative costs - especially so after the two local manufacturers, the Superior Portland Cement Company and the Washington Portland Cement Company agreed to donate the necessary cement.[43]

Designed by Bowerman and McClay, Consulting Engineers, of Seattle, the Baker River Bridge consists of a 186ft main span in which the supporting structure is reduced to two narrow parabolic ribs that spring from the base of massive concrete piers, and two short approach spans, each a

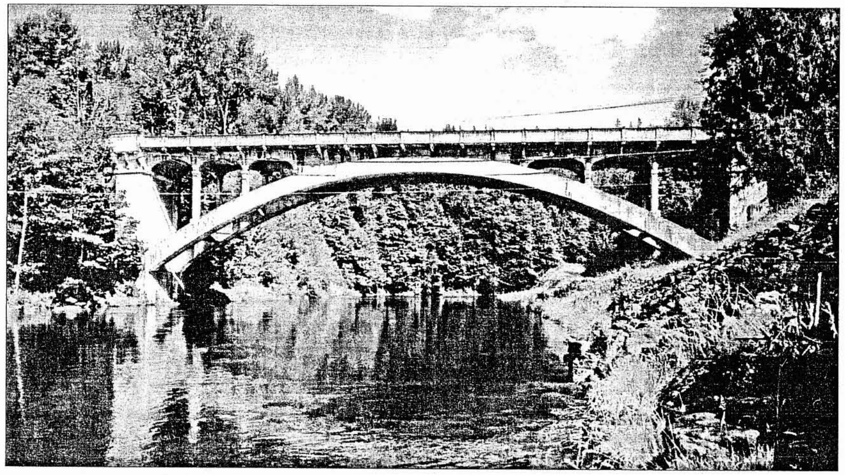


Fig. 2 Baker River Bridge, 1916-17 (Historic American Engineering Record).

reinforced-concrete slab supported on reinforced-concrete girders. The technique of bar reinforcing is not detailed in the few surviving drawings of the structure, but already by the time of its construction, arch bridges employing the Luten system of reinforcing had been built in the state, suggesting this technique may have been used.[44] In this advanced, scientifically-based system, which was introduced to America from Germany about 1900, several bars forming a complete loop were laid transversely through the vault and invert of the arch, and a series of these loops was also laid throughout the length of the structure at regular intervals. The bars were bent to conform to the semicircular section of the vault and the shallow curve of the invert, and were placed near the surfaces of maximum tension under live load.[45] Such a system, using bars distributed only in tension zones, was cheaper and more efficient than the Melan practice of embedding heavy and expensive structural steel sections more or less indiscriminately in the concrete, and pointed to future possibilities for more graceful and attenuated forms which, in Washington, appeared in the 1920s.

Despite the ascendancy of reinforced concrete as the material of choice in the short-span, and increasingly, medium-span field, steel retained overall dominance not only in long-span bridges, but in the specialized field of movable bridges, where high or unlimited vertical clearance for river navigation was required. Two forms of movable span, the vertical lift and bascule, evolved simultaneously in the early 1890s as practical methods of counter-balancing the enormous weight of the span and refinements to the electric motor were perfected.[46]

The earliest vertical lift highway structure remaining within the state is the City Waterway Bridge (1911-13), built to connect Tacoma's business centre with the sprawling manufacturing district on the tidal flats, east of the city (Figs 3 and 4). Built to the designs of the country's premier vertical-lift bridge company, Waddell & Harrington, of Kansas City, Missouri, the bridge was constructed by The International Contract Company of Seattle using non-local materials; the steelwork and machinery for the superstructure were fabricated by the American Bridge Company of New York.[47] The chief component of this mighty structure was the central 220ft Pratt vertical lift span, which could be raised some 75ft to allow tall-masted craft to pass underneath. The unprecedented height of this clearance, coupled with a number of other mechanical and structural features, brought a new level of technological sophistication to the type, which helped ensure that it came to replace the bascule where wider channels were required for navigation.[48] Surviving drawings show Waddell & Harrington did consider a bascule span initially, but their decision to adopt a vertical lift bridge was almost certainly dictated by the economic and practical superiority of this form given the local site conditions. Unlike bascules, vertical lift spans did not have to be raised to the same degree for low-masted craft because the clearance of the lift span in the closed position was that much greater

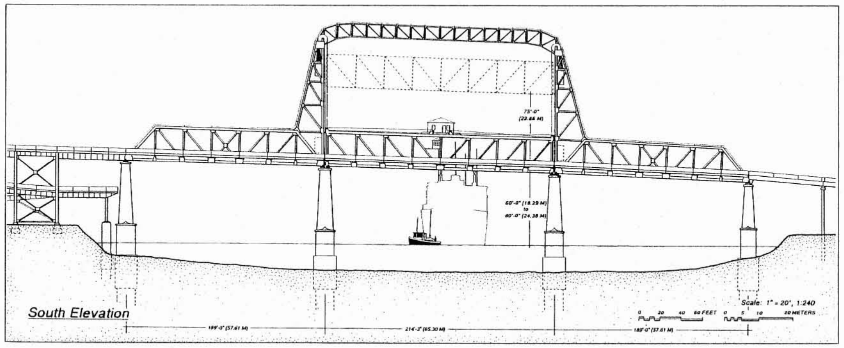


Fig. 3 City Waterway Bridge, Tacoma, 1911-13 (Historic American Engineering Record).

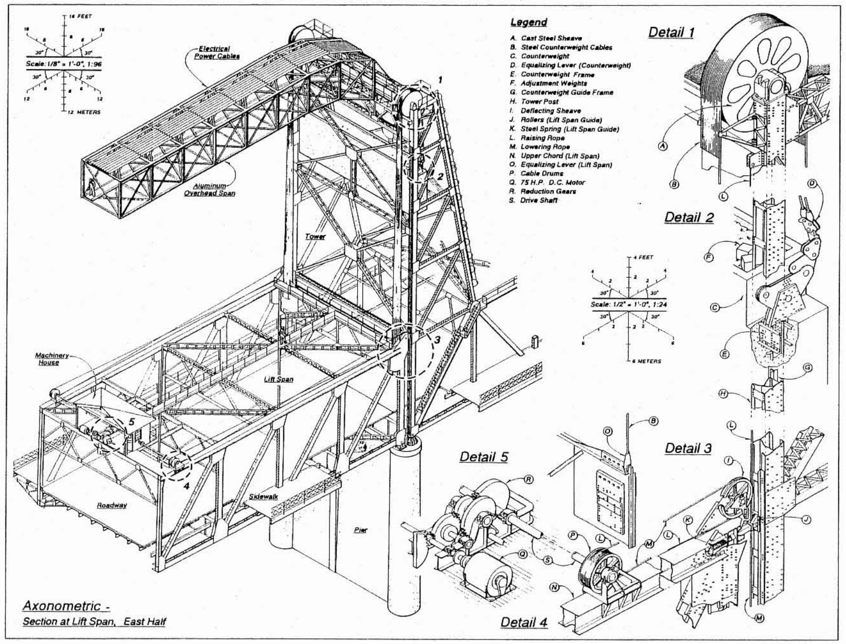


Fig. 4 City Waterway Bridge: Lift span detail (Historic American Engineering Record).

anyway. Also, Waddell argued, vertical lift bridges were more cost-effective in situations where large horizontal clearance was required because of the frequency of passing of large ships.[49]

The eminent practicality of the vertical lift for wide, heavily used waterways probably accounted for its employment in the truly enormous Columbia River Interstate Bridge, (1915-17), also designed by Waddell & Harrington (Fig 5).[50] Built for Clark and Multnomah Counties to span one of America's mightiest rivers, separating the cities of Portland, Oregon, and Vancouver, Washington, this structure has a total aggregate span of over four miles, although a significant portion of this was formed by earthen embankments and continuous plate-girder sections over various islands and sloughs in the crossing. The main channel spans over the Columbia are made up principally of steel Parker-truss forms, with a Pennsylvania (Petit) lift span providing a waterway clearance of 250ft laterally and 150ft vertically.[51] The construction project was so big that the total contract was sub-divided into twelve units. A significant proportion of the 24 contractors who submitted bids were local to Oregon and Washington, and the majority of these were successful on account of the low prices they were able to offer. The steel for the main bridge was fabricated by the United States Steel Products company, whereas the Northwest Steel Company of Portland performed the same task in relation to the slough bridges.

Both the City Waterway Bridge and the Vancouver-Portland Interstate bridge demonstrate the enduring tenacity and eminent suitability of the steel truss as the basic building form for both long-span structures and vertical-lift spans at this time. Used sequentially from pier to pier, steel truss bridges were able to span the longest of crossings (where the depth of the water was not too great) at competitive prices, since the employment of standard sized members, and indeed complete spans, reduced the shop fabrication costs. The various employment of the basic Pratt type and two of its

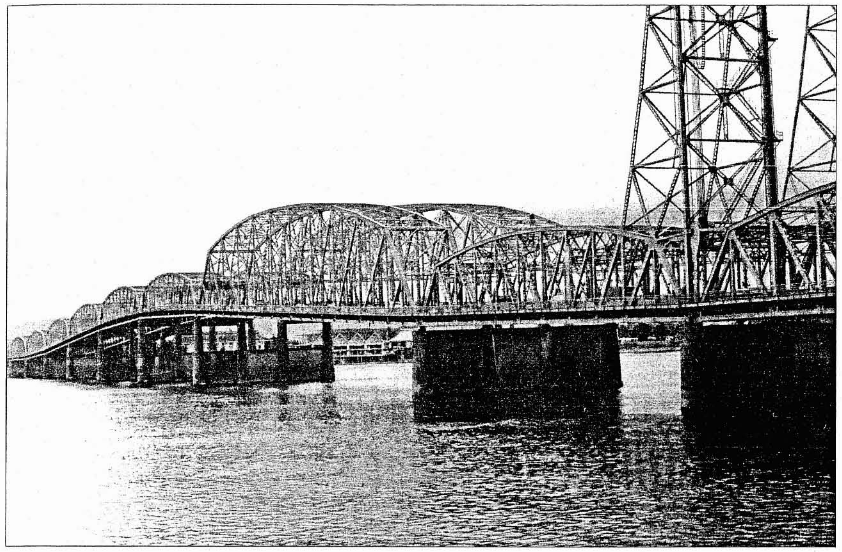


Fig. 5 Columbia River Interstate Bridge, 1915-17

derivative forms (the Parker truss, in which the top chord is built with a polygonal outline; and the Pennsylvania truss, in which the panels are subdivided for further rigidity) in either bridge was typical of contemporary practice in multi-span truss bridge design. All forms were comparatively simple, were economical of steel, and lent themselves well to the connection of the floor and lateral systems (Fig 6).[52] The Pennsylvania (Petit) truss in particular was suited to spans exceeding 250ft or 300ft,[53] and achieved its greatest (multiple) length during the decade in the bridge of the Burlington Railroad at Metropolis, Illinois. Built between 1914 and 1917 under the design and supervision of Ralph Modjeski and C.H. Cartlidge, the almost 3,500ft-long structure was made up of seven spans, of which the channel span had a record length of 723ft.[54] By this stage the continuous and cantilever truss was coming into more general use for long spans, albeit for the railroads, and the next decade was to see its increasing application for highway structures in many states, including Washington.

Nonetheless, the years around 1920 saw developments in reinforced-concrete bridge design further afield which threatened steel's hold on the long span and vertical lift niche. In 1920, both the reinforced-concrete arch and girder forms reached unprecedented lengths for a single span between supports. In Minneapolis, Minnesota, a three-span arch with a central span of 400ft between faces of piers was built across the Mississippi River, surpassing by 62ft Hennebique's Risorgimento Arch across the Tiber at Rome (1911).[55] In Humboldt County, California, a concrete girder highway bridge across the Salt River, composed of two spans, each 142ft between centres of supports, almost doubled the previous span record; investigations by the *Engineering News-Record* showed that hitherto, no reinforced-concrete girder bridge had exceeded 75ft in a single span. In this case steel was not used because of the unavoidable expense of protecting it against the corrosive effects of salt fogs.[56] Both record-breaking bridges demonstrated the future possibilities of building multi-span reinforced-concrete bridges that economised on the number of intermediary supports required.

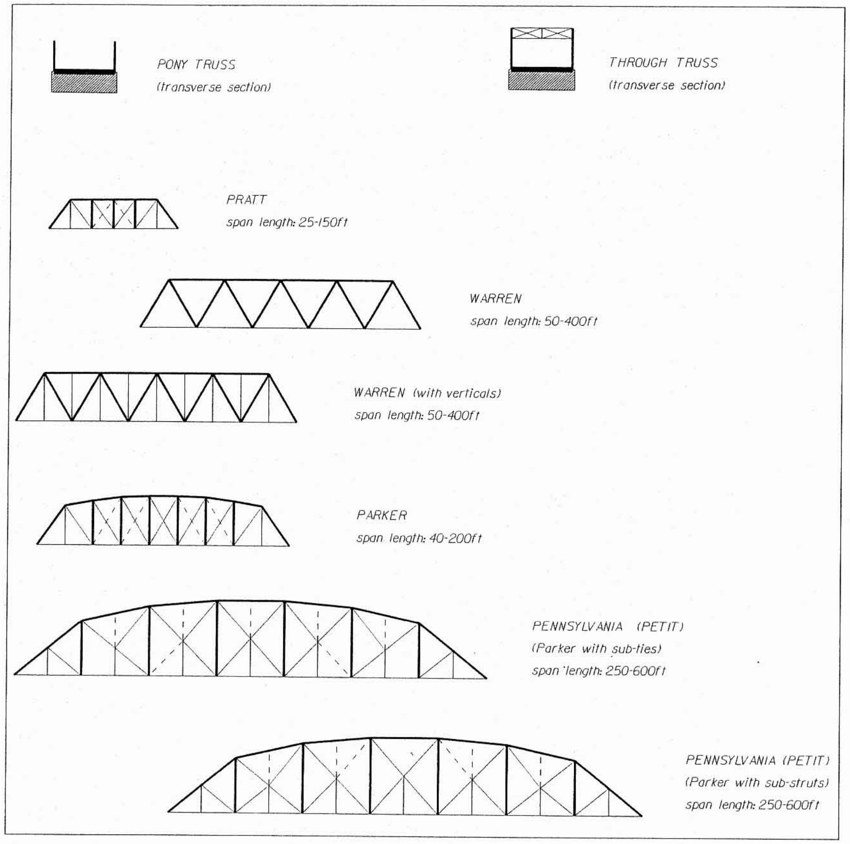


Fig. 6 Diagram showing the principal steel bridge truss forms referred to in the text. The main compression members are shown by a thicker line (after T. Allan Comp and Donald Jackson, 'Bridge Truss Types: a Guide to Dating and Identifying', *American Association for State and Local History, Technical Leaflet 95, History News*, Vol. 32, No. 5, May 1977).

In April 1919, F. H. Frankland, consulting engineer for Waddell's new firm, Waddell & Son Inc., New York and Kansas City, unveiled the firm's design for a vertical-lift bridge with reinforced concrete towers across the Missouri River. Hitherto, because of the weight of the material and the attendant increased vertical reactions on the piers, steel-truss configurations had been used, but in this case the current high cost of structural steel militated against its use. Frankland estimated that by using reinforced concrete instead of steel for the towers, some $4,000 was saved, and also pointed out that '*the advantages from improved appearance and the use of more permanent materials were considerable.*'[57] High structural steel prices during the late 1910s, incidentally, had repercussions in many of the eastern and mid-western states where steel was able to compete with, if not out-compete reinforced concrete, for short-span bridges. The Minnesota State Highway Department for example embarked on a programme of reinforced-concrete bridge design in 1916 for the sake of economy.[58] In November 1916 a steel bridge being constructed for the Pennsylvania Railroad was abandoned, proceeding no further than building of the stone piers.[59]

1920 to 1929

The 1920s saw a marked acceleration in the pace of road building in Washington State as automobile ownership became increasingly popular. The massive demand for bridges required the newly formed State Bridge Department to become increasingly rationalised and efficient in turning out economical and efficient designs. In the first two years of the decade it standardized bridge designs as much as possible, so that preparation and estimates could be expedited at less cost and unnecessary duplication minimised. The floor systems of these standardized designs, and indeed the 'special designs' (ie non-standardized) bridges were designed for two different automobile loadings: class-'A'-, used to withstand 20 tons per axle, for use on the state highway system; and class-'B'-which could accommodate 15 tons per axle, intended for minor (non-state highway) roads. Washington's law specified a maximum vehicular weight of 12 tons per axle at this time, but the Highway Department was cautious about the findings of a committee appointed by the Association of Highway Officials to standardize bridge specifications. This showed that the loading on main highways in many states was frequently in excess of the legal limit.

Reinforced concrete was almost universally adopted for very short-span, up to 40ft, Class-'A'-loading standard designs, with the T-beam and slab forms used predominantly for the larger spans within this range. For small-to-medium sized designs of the same loading, between 90ft and 240ft, steel trusses, with concrete decks, in four span lengths (90ft, 130ft, 140ft, 240ft) were exclusively used.[60] Within two years, the standard T-beam had gained another ten feet in length, whilst the size range of standard trusses had expanded enormously with twelve span sizes comprehensively covering the range 90ft to 262ft. The range of Class-'B'-loading designs also expanded considerably. Originally (1920-22) the only form within this category was the reinforced-concrete T-beam bridge in the span range 20ft to 40ft; by 1922 to 1924 this was supplemented by timber trestles, and, more significantly, by seven sizes of steel truss, with (mostly) timber floors, varying in length from 106ft to 220ft. From this period onwards, the Highway Department did not display its list of standards in its Biennial Reports, although it stated that 'the list of standards is being continually extended as spans of different length are needed'.[61]

With official 'endorsement' from the Highway Department, steel, in the form of the simple truss, thus enjoyed considerable application in the medium-span field during the twenties, successfully staving off the inexorable advance of concrete which had begun in the previous decade. Indeed, of the extant highway bridges in the span range 100ft - 300ft (total length), 10 are steel trusses, used alone without approach spans, and 19 employ steel trusses for the main span. In this span range there are as many steel trusses as there are all forms of reinforced-concrete bridges.

The Highway Department's standard designs do not account for all the truss bridges built in the state during the 1920s, but they were almost certainly the blueprint for a significant proportion. The Dosewallips River Bridge (1923), probably the first bridge to be built to the Class-'A'-loading 240ft standard design, exemplifies why the department relied on the steel truss (Fig 7). Consisting of a 240ft riveted through Petit truss with sub-struts and polygonal top chord (ie Pennsylvania truss) and two 32ft reinforced-concrete T-beam approach spans, it was erected within a 180 working-day contractual clause by Ward and Ward Inc. for just $50,000. Such a feat was possible because of the choice of the Pennsylvania truss as the standard: among a small handful of designs (all derivative of the basic Pratt or Warren forms) that survived an increasingly brutal selection process, this form accomplished the transition to highway use with ease, and adapted readily to advances in riveting technology. Further, it was economical of metal, lent itself well to the construction of the floor and bottom laterals, and required comparatively few shop parts. Indeed, the angles, channels, cover and web plates, etc., used to build up the individual members of the Dosewallips River Bridge were rolled from only five thicknesses of steel (1/4in.; 5/16in.; 3/8in.; 7/16in.; 1/2in.), which was markedly fewer than those required for the more complex, obsolete truss types.[62]

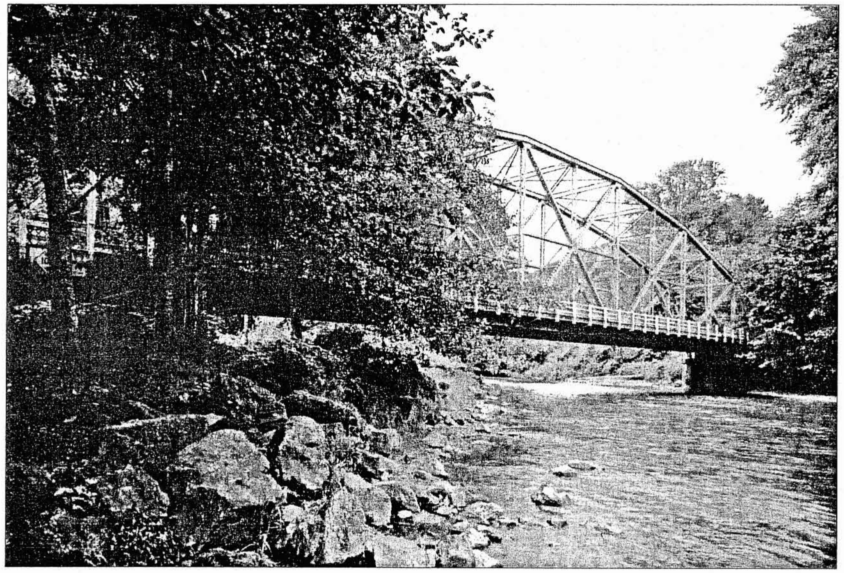


Fig. 7 Dosewallips River Bridge, 1923 (Historic American engineering Record).

This bridge formed part of a program of many improvements and construction projects on the Olympic Highway, a primary route circumnavigating the Olympic Peninsula and now designated as U.S. 101. Because sections of this road passed through the Olympic National Forrest, complete funding for this bridge was supplied from the (Federal) Forest Road Funds of the Bureau of Public Roads. The following year saw another National Forest project: the building of the Bogachiel River Bridge, also along the Olympic Highway. No longer extant, this was a standard 240ft Pennsylvania truss, identical to the Dosewallips River Bridge in all but approaches.[63]

According to Waddell, the use of sub-divided panels in highway bridges where the panels were not much longer than 20ft in length, ceased to be economical for spans under about 225ft to 250ft.[64] At 240ft, and being divided into 12 panels of equal length, it seems likely that the Dosewallips River Bridge, the Bogiachal Bridge and others that were built to the standard Pennsylvania design at this time represented the lower limit for the economic feasibility of this form.

At the other end of the standard size range, the South Fork Newaukum River Bridge (1930), a 90ft Pony Warren Truss with verticals, illustrates that, for the smaller spans also, the Highway Department utilised the other most enduring and successful generic truss type (Fig 8). It is not of a 'true' Warren configuration however, in that the web triangles are not equilateral, and this was frequently the case for there was no structural advantage in making them so. The whole structure is remarkably simple, composed of a parallel upper and lower chord connected by five vertical, and, including the inclined end posts, six diagonal members. Two intersecting diagonals in each panel make up the bottom lateral bracing. Both the top and bottom chords act in compression, whilst the diagonals carry both the compressive and tensile forces acting within either truss. The verticals serve as bracing for the triangular web system formed by the diagonals.[65] The steelwork was fabricated by the Star Iron & Steel Company of Tacoma. Creech Bros, Aberdeen, Washington, erected the bridge, including timber approaches, at a cost of just $15,989 under the supervision of the county engineer, Roy L. Greene.[66]

The simplicity of configuration and economy of metal in the Pony truss form (which does not have any overhead members, unlike the through truss) help account for its immense popularity for short spans in the late nineteenth century and early twentieth century. Despite this, its continued employment was not agreeable to all bridge engineers, least of all Waddell, who objected 'most vigorously' to its use, maintaining that '*under no circumstances [was] it necessary to build them.*' His main objection was that for short spans, plate girders provided a safer alternative, since the determination of the ultimate strength of the partially unsupported top chords of Pony trusses was approximate at best.[67] Nevertheless, their use remained widespread throughout America, and when used in a Warren or Pratt configuration, proved particularly cost effective, because they required only a limited range of shop parts.

Three years earlier, a virtually identical county-funded bridge was constructed over the same river, within five miles of this one, presumably built to the 90ft standard. The principal difference between the two structures was the lacing together of the channels forming the upper chord and end post in the earlier structure: in the later bridge solid cover plates were used to this effect. Despite the cumbersome appearance and greater expenditure of steel in this, possible advantages of using solid plates included ease of riveting and (some) protection against water corrosion, which would otherwise accumulate in the interior of the built-up members.

The compilation of a virtual catalogue of standard designs during the early 1920s enabled the greater part of the work of the bridge department to be taken up with in-house 'special designs'. These were used in situations where the anticipated cost of modifications to adapt a standard bridge arrangement to a site was greater than that involved in designing a 'tailor-made' bridge. In the 1920-22 Biennial Report, the commissioner stated that '*reinforced concrete is used for superstructures whenever feasible, as in the shorter spans and arches, and structural steel with reinforced floors for the longer spans.*' During this biennium, the proportion of steel to concrete bridges of the ten 'special designs' built was evenly matched.[68] But in the following biennium, of

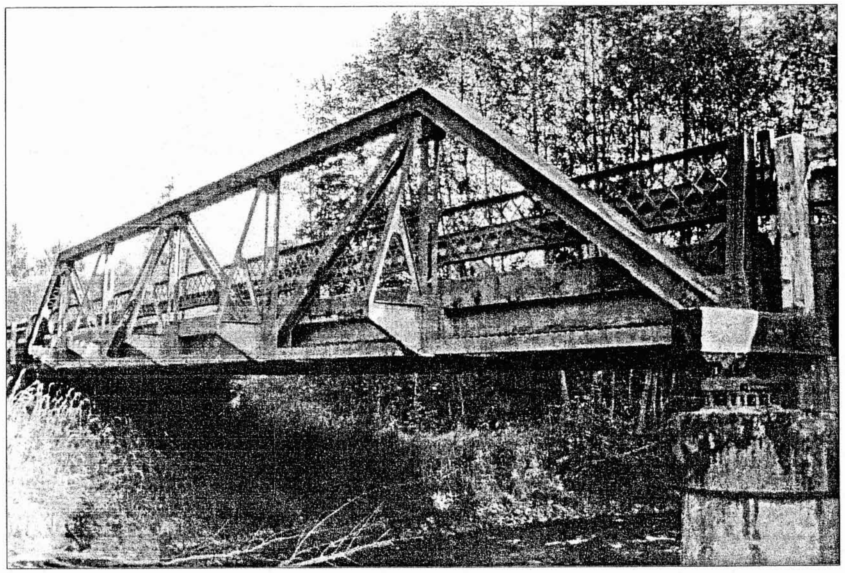


Fig. 8 South Fork Newaukum River Bridge, 1930

the 22 built, 17 were reinforced concrete, three were steel, and two were timber. Eight of the reinforced-concrete structures were arch bridges.[69]

The Indian Timothy Memorial Bridge (1923) was amongst the first to herald the appearance in the state of the through-ribbed or rainbow arch (Fig 9). This open-spandrel form, popularized throughout America between 1915 and 1930 by James Marsh (1856-1936) was both aesthetically pleasing and economical of materials.[70] Located in the arid eastern part of the state, the Indian Timothy Memorial Bridge was designed to resist flash floods, a frequent occurrence in the Alpowa Creek which it spanned. For this reason, it was conceived as a two-span structure rather than one with longer approaches, to provide a greater horizontal clearance under the structure. Both arch spans measure 100ft between skewbacks, and have a rise of just 20ft to the crown. The outward thrust of the arches is counteracted by inclined thrust footings (skewbacks) resting on two massive abutments at opposite ends of the structure, and by a central pier which both spans share. The ribs of the arches - the main compressive members - are not true arcs, for their radii vary at their outer upper surface, centre line, and inner surface. Their minimum dimension, from extrados to intrados, is 2ft3in. at the crown, flaring out to approximately twice that depth near the springing points, while their width remains constant. Whilst lending greater visual sense to the structure, the real purpose of this was to increase the mass of the arch at the skewbacks, to resist the moment forces at these points.[71]

The bridge was built by the Colonial Construction Company of Spokane for $35,120, utilising reinforcing bars supplied by the Pacific Coast Steel Company of Youngstown, Seattle.[72] This last company used a picture of the bridge in a two-page advertisement in the 6 December 1924 issue of the *Pacific Builder and Engineer,* the major contractors' journal in the Northwest. The advertisement claimed that this was the first concrete through arch to be built in the state of Washington, and somewhat paradoxically, it boldly proclaimed that the Highway Department was building large numbers of reinforced-concrete bridges because they required 'NO maintenance'.[73] Presumably, an expanding market in reinforcing bars was to their advantage, since they were

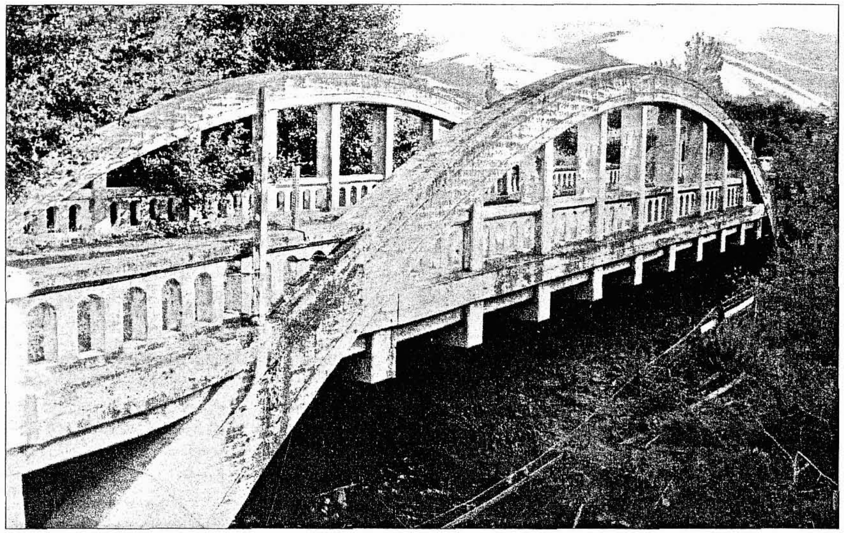


Fig. 9 Indian Timothy Memorial Bridge, 1923.

probably less able to compete in the (more lucrative) steel bridge market. For the highway department's part, low maintenance was an especially desirable quality in this bridge, given its extremely remote, rural location, hundreds of miles from the nearest district office.

The North Hamma Hamma River Bridge (Fig 10) and the South Hamma Hamma River Bridge (both 1923), two identical single-spanned reinforced-concrete rainbow arches spanning different branches of the same river, differ from the Indian Timothy Memorial bridge in three important respects. First, the structure is hinged in three places: at the crown, and at the skewbacks in order to eliminate moment forces at these locations. Second, the arch is tied, meaning that the horizontal thrust is resisted by longitudinal ties which (classically) extend between the hinged springing points (skewback hinges). In the case of the Hamma Bridges, the deck slab itself acts as the tie. The double function of the deck slab was an economical solution, since it partially eliminated the need for massive abutments and foundations to counteract these forces. Third, the ribs were connected by six overhead lateral braces, equivalent to the sway bracing used on through trusses. This was an essential part of the design, given the added flexibility concomitant with the incorporation of hinges, although either structure now functions perfectly well with only four as the end (lower) two braces on both bridges were sawn off in 1977 to increase the vertical clearance for logging trucks.[74]

In other respects, both structures are remarkably similar to the Indian Timothy Memorial Bridge - even to the point of shared dimensions and detailing of some members - suggesting that even in their special designs, the engineers used a great deal of standardization. Another identified bridge, the Goldsborough Creek Bridge, was also markedly similar, and so too, almost certainly, were others built during this decade.

The Hamma Hamma Bridges, each 150ft long between skewback hinges with a rise of 20ft to the crown hinge, are spaced a few hundred feet apart along U.S. Route 101 in the Olympic Peninsula. The length of their span was necessary to provide adequate lateral clearance for driftwood flows, and reinforced concrete was specifically chosen because of the close proximity of both sites to salt water. Like the Indian Timothy Memorial Bridge, the contract for both bridges was awarded to the Colonial Construction Company for a price of $77,838.[75]

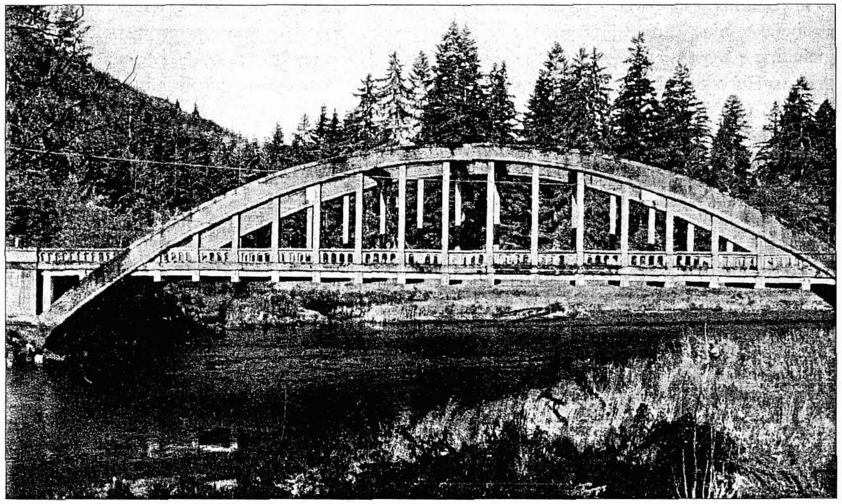


Fig. 10 North Hamma Hamma Bridge, 1923.

In addition to designing both standard and special bridges, for use by themselves, the counties and cities, the Highway Bridge Department was also required to check structures designed by county engineers on 'permanent highways'. Amongst the first executions of this responsibility was in relation to a bridge that had only one forerunner in the state. Designed by E.A. White, Chief Engineer for Pierce County, the Fairfax Bridge (1921) consists of a 240ft three-hinged braced rib deck arch, two 14ft steel towers and timber trestle approach spans. The parabolically curved ribs which spring from massive concrete abutments and support the deck, are hinged at the crown and at the skewbacks. The two skewback hinges comprise fixed pins inside cast-steel shoes, which rest on inclined concrete thrust footings forming part of the abutments (Fig 11).[76] The greater flexibility of the three-hinged form over fixed, single, or two-hinged ensured that they were free from both temperature stresses and almost totally immune from vertical movements in the supporting abutments, both of which could induce material stresses in the superstructure with potentially disastrous consequences. Such factors were probably major considerations *vis-à-vis* the Carbon River gorge, on account of the high annual and diurnal range of temperature, and the nature of the steeply sloping bedrock, which might have been anticipated as posing problems with regard to abutment instability. The principal disadvantage of the three-hinge arch, relative to other more robust forms of steel arch, was its lack of rigidity.[77]

In America, by the 1910s, the three-hinged steel arch had gained overwhelming popularity relative to other types. Even so, steel arches of all types were used sparingly relative to contemporary European bridge building practice; Fairfax bridge is one of only two extant three-hinged bridges in the state. Waddell argued that their extremely widespread use in Europe was partly to do with long traditions of masonry arch building (which continued to influence the way engineers visualized designs in steel), partly to do with the nature of the gorges which had to be spanned, and partly because European designers were as much concerned by aesthetic considerations as they were by economics. By contrast, Waddell argued, American engineers were guided in their designs almost exclusively by questions of economy, simplicity, and occasionally, a need for greater rigidity. Also, the conditions that made the use of an arch economical, or unavoidable - deep, rocky - sided gorges - were not encountered in America to the same degree.[78]

The Fairfax bridge was designed primarily for the structural reasons outlined above. However, aesthetics almost certainly played a role in the design: the use of built-up members throughout, including extensive employment of lacing, produced a structure of extraordinary grace and power that visually complemented the precipitous sweep of the surrounding ravine. Preliminary drawings prepared by White show that he did consider reinforced concrete for framing both the approach spans and the towers (a reinforced-concrete arch, at least in Washington, could not span a gorge of this proportion at this time); whether it was the Bridge Department or his own aesthetic judgement that militated against this monolithic proposal is not known. The bridge, which was jointly funded by both the county and the state, was built by the Union Iron & Bridge Company of Seattle, using steelwork provided by the Minneapolis Steel and Machinery Company.

1930 to 1960

In the 1930s structural innovation in reinforced concrete passed over to the rigid-frame form. Concrete girders, T-beams and flat slabs had been employed from the 1910s and earlier in both the main spans and approach spans, but their use was fairly limited. During the 1930s their employment blossomed, and the T-beam form in particular gained immense popularity. Complementing this was the development of a new rigid-frame form - the hollow-box girder - and daring experimentation in trussed systems of configuration, formerly the (almost) exclusive preserve of steel. The former was destined to achieve immense application in the 1950s, following some pioneering examples of 1936-9, and its endorsement in the superlative, highly publicised Lake

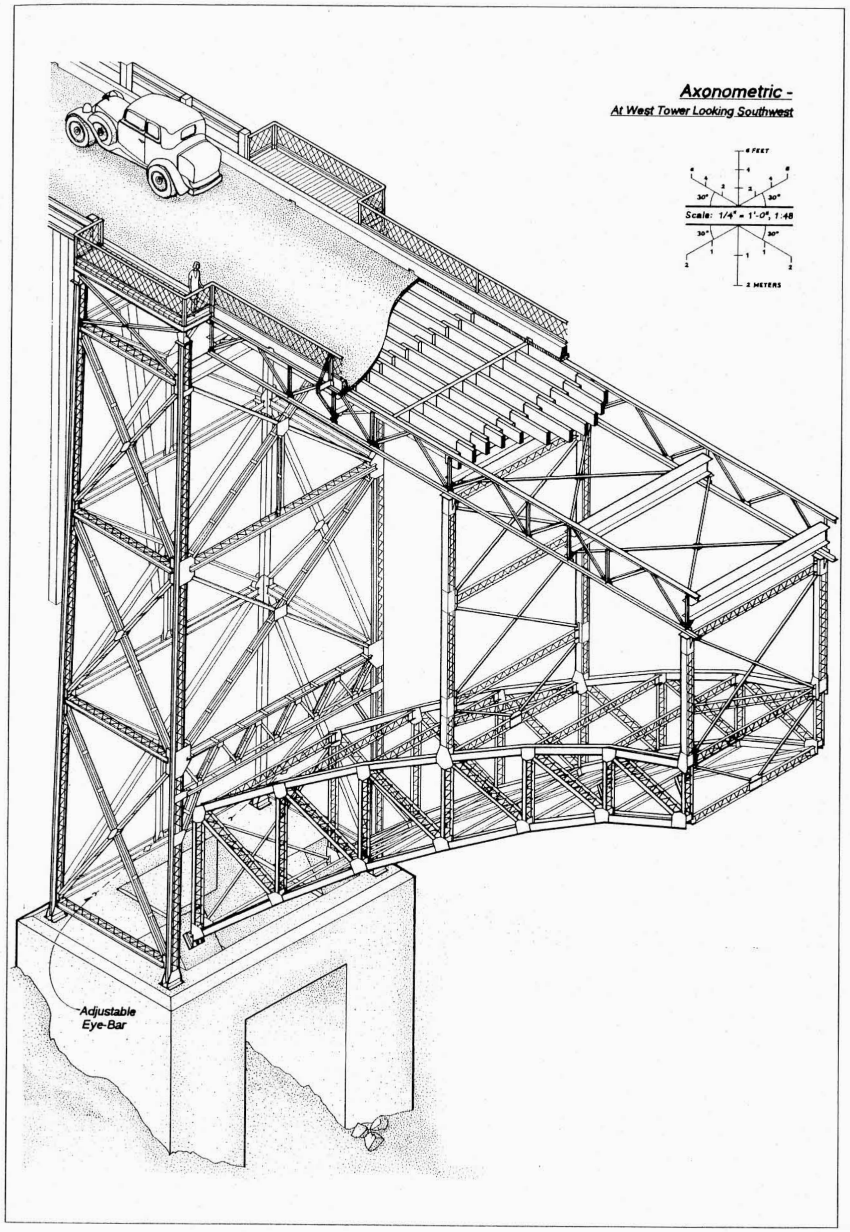


Fig. 11 Fairfax Bridge, 1923: axonometric detail (Historic American Engineering Record).

Washington Floating Bridge - a 7,800ft floating highway, representing the first reinforced-concrete pontoon bridge in the world.[79] The latter, as demonstrated by the McMillin Bridge - a 170ft through-Pratt truss with cambered upper chords[80] (Fig 12) and others like it, was really a structural aberration, but none the less one that demonstrates a growing confidence among designers to test the possibilities offered by the material. The development of these designs, and the widening popularity of earlier forms of rigid-frame construction, was almost certainly enabled in part by higher strength concretes introduced in the early thirties by the Highway Department, and a continuing advancement in even more efficient systems of reinforcing.

The zenith of the rigid-frame bridge was reached in the 1950s, which saw the slab and T-beam forms become virtually the automatic choice for bridges under 200ft, and the box girder become a standard solution for bridges between 200ft and 400ft in length. The widespread adoption of new methods of precast construction aided this process, and already by this decade the first prestressed bridges were appearing in the state. These latter two developments signified the growing importance of speed of construction, alongside traditional concerns of economy and maintenance, as a major factor in bridge type selection. The delayed post-war construction boom meant that highway departments across the country needed rapidly to build cheap and efficient bridges. Precast reinforced or prestressed rigid-frame bridges were the product of a highly rationalized system of virtual mass production, uniquely suited to the tremendous demands of a new era of highway growth.[81]

Developments in steel in the shorter span ranges did continue, albeit less dramatically and with less application. The Chehalis River Riverside Bridge (1939) (Fig 13)[82], and the Cora Bridge over the Cowlitz River (1947) (Fig 14) suggest that the highway department had adopted the Warren truss form in preference to the Pennsylvania (Petit), at least for the 240ft standard specification. Both bridges illustrate refinements to the basic Warren type, including distinctive portal and sway bracing, polygonal upper chords and the employment of punched plates in the built-up members, which both economised on metal and enabled faster erection. Remarkably, and atypically, this period also saw the construction of a diminutive suspension bridge, demonstrating that under certain conditions (in this case the virtual impossibility of erecting falsework), the form could enjoy application where all other forms were unsuitable. The 300ft Yale (Lewis River) Bridge was constructed in 1932 for just $40,000 (Fig 15)[83].

But by this stage steel had relatively little economic significance in the short and medium-span field, having become basically relegated to the longer span field. The remarkable series of steel

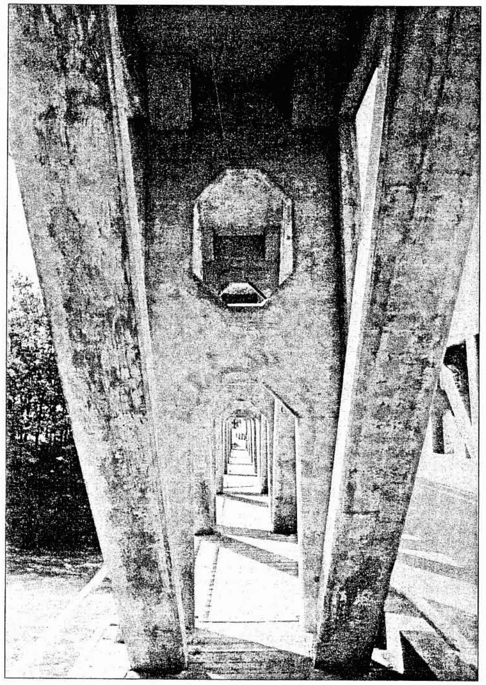


Fig. 12 McMillin Bridge, 1934.

Fig. 13 Chehalis River Riverside Bridge 1939.

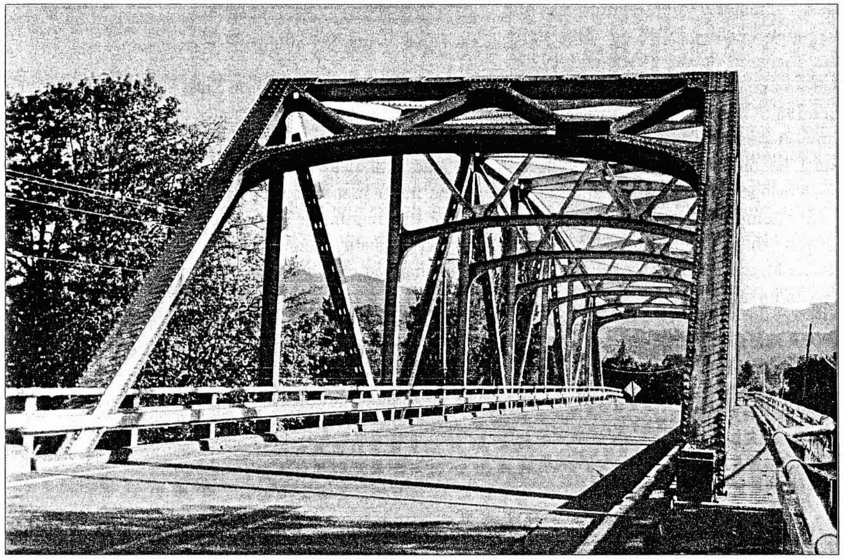


Fig. 14 Cora Bridge, Cowlitz River, 1947

cantilever bridges built from the late 1920s through to the early 1940s is indicative of this, as indeed was the notorious Tacoma Narrows Bridge (1940), and its more successful replacement (1950)[84]. Such milestones illustrate steel's indomitable economic, technological (and, arguably, aesthetic) niche at this time for spanning the widest or most taxing of crossings.

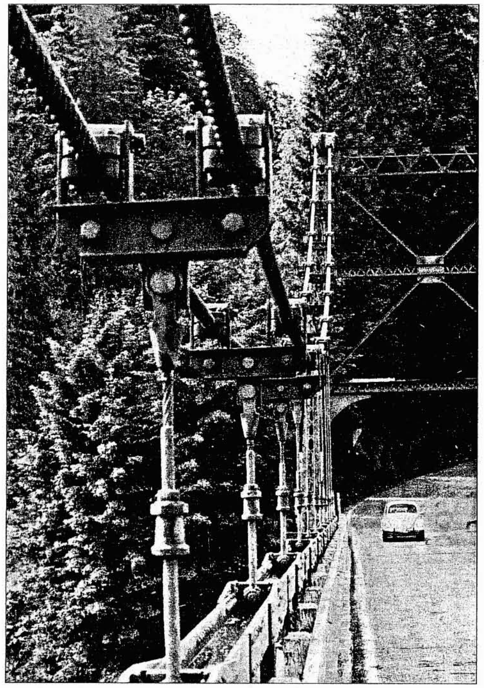


Fig. 15 Yale (Lewis River) Bridge, 1932.

Conclusions

From their introduction in the late nineteenth century, and their ever-advancing application through the twentieth century, steel and reinforced concrete remain the most widely used structural materials at the disposal of the engineer and architect today. For various reasons, including vested interests, a marked degree of competition between the materials accompanied their introduction and adoption. This had a direct impact on their changing application as the twentieth century rolled on. This study has focussed on the 1910s and 1920s, within one field - highway bridge building - and one arena - Washington State. The period saw the coming of age of the reinforced-concrete arch bridge, but also the resurgence of the metal truss, this time in steel. From this formative period however, reinforced concrete ultimately out-competed steel, becoming, by mid century, virtually the automatic material of choice for short- and medium-span bridges, with its application in even longer, multi-span bridges still on the rise.

In attempting to account in general terms for the dominance of reinforced concrete during the period, the single most important aspect was probably the material's virtual monopoly of technological virtuosity. Structural innovations that had repercussions in the short span field came predominantly in the domain of reinforced concrete.

The arch form saw increasingly sophisticated systems of structural arrangement, reinforcement and stress distribution, marked by the appearance in the state of the open spandrel (or 'rainbow arch'), the tied arch, and later, the use of Considère hinges. The attenuated, confident designs of the Baker River, Hamma Hamma Bridges and the Indian Timothy Memorial Bridge, products of the 1910s and 1920s - the real heyday of the open-spandrel-arch form - mark a distinct break from earlier, clumsy exercises in the material that failed fully to exploit the structural possibilities engendered by reinforcing. The massive employment of concrete girders, T-beams and flat slabs from the 1930s, and, later, the introduction of precasting and prestressing essentially sealed reinforced concrete's undisputed ascendancy in the short span field.

The most important and decisive developments in reinforced-concrete bridge design thus came in the first half of the 20th century - alongside the development of highways. In steel bridge design, the basic structural innovations belonged to the eighteenth and nineteenth centuries - whether

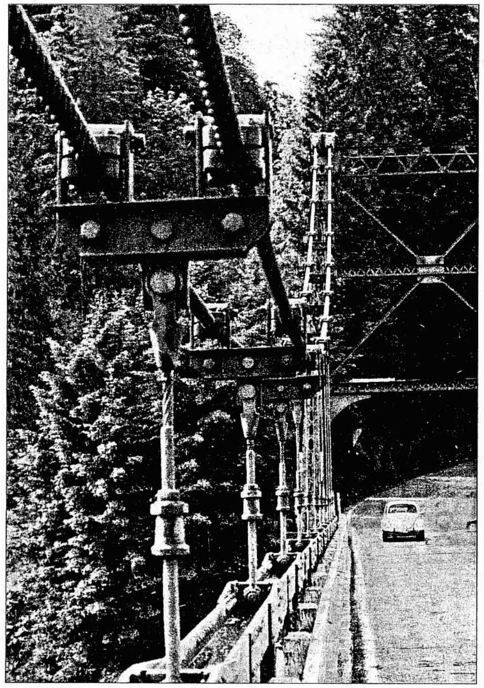
anticipated in wood or iron and translated to steel (e.g., the simple truss), or essentially conceived in steel (e.g., the cantilever truss). All types of bridge-truss, including continuous and cantilever, arch, vertical lift, bascule, suspension and so forth - were born of these centuries; for the most part they were originally designed around the exigencies of the railroads. The vast majority of truss types were unsuitable for the specialized requirements of highway use, and, as has been mentioned, only two generic forms, the Warren and the Pratt, survived the ensuing drastic selection process during the first two decades of the new century. The major change in all these forms was a growing maturity, simplification and streamlining of design - from the elimination of redundant, wasteful truss members, to more efficient mechanical systems in movable bridges. The exclusive employment of the Pennsylvania Petit truss bridge in the Highway Department's longer 'standard' design range during the 1920s demonstrates the economy, efficiency and adaptability of this form. But throughout most of the period, the predominant niche of the steel bridge was for longer spans, technically demanding crossings, or specialized applications, where steel became economically viable or an absolute necessity, given the inability of reinforced concrete to provide an alternative structural solution.

Other changes, including the almost universal adoption of riveting, and the introduction of silicon steel - the latter greatly enabling the full potential of the cantilever form - bolstered steel bridge construction, but two crucial developments lay outside our period. The use of friction grip bolts and the widespread adoption of welding characterized steel construction from the 1960s. These technical advances resulted in far greater use of the rigid-frame bridge in steel for shorter spans - a type anticipated by the comparable form in reinforced concrete. Plate-girder and box-girder forms in steel share many of the advantages of their concrete counterparts: they are lightweight, simple, easily analyzed and rapidly erected. Also, they are frequently used in the decks of cable-stayed bridges, a form which in the last forty years has gained increasing popularity for the longest spans.

Was Washington unique?

Washington State was, of course, only one place where this struggle was played out. Because of conditions specific to the state and the far west, it would seem that it was not typical of the rest of the country. Washington was far from the steelmaking heartland of the east, and despite several ineffectual attempts to produce steel, it entered the twentieth century with no real tradition in this material. Instead, a vigorous Portland-cement industry quickly arose in the first two decades of the century. Other far-west states, including Oregon and California, shared similar preconditions, and the engineers working for or alongside the Highway Departments of these three states were to play a key role in the development of some of the most technologically advanced and elegant American concrete bridges during the early twentieth century. Steel bridges were built in great number, fabricated by both local and eastern firms. Indeed, despite the distance from the steel centres of the east, in most of the examples considered eastern fabricators won the contracts for steelwork, although these were typically for larger or more specialised structures. Further, a significant number of local, or at least western-based fabricators were in operation by the 1920s, mostly competing in the smaller contracts. Nevertheless, the unequivocal ascendancy of reinforced concrete as the principal structural material for standard highway bridges in virtually all states by the 1950s had been anticipated in Washington - and probably other far west states - much earlier.

It seems likely that it was not until the late 1950s that highway departments *across the country* had switched predominantly to reinforced concrete for short-span bridges, given the findings of the *Engineering News-Record's* survey of the impact of prestressing. In 1958 this periodical announced that the nation's structural steel fabricators, faced with a sharp drop in demand or bookings, had embarked on a 'hard sell' campaign. The fabricators and their backing organization, the American cantilever bridges built from the late 1920s through to the early 1940s is indicative of this, as indeed was the notorious Tacoma Narrows Bridge (1940), and its more successful replacement (1950)[84]. Such milestones illustrate steel's indomitable economic, technological (and, arguably, aesthetic) niche at this time for spanning the widest or most taxing of crossings.



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Other changes, including the almost universal adoption of riveting, and the introduction of silicon steel - the latter greatly enabling the full potential of the cantilever form - bolstered steel bridge construction, but two crucial developments lay outside our period. The use of friction grip bolts and the widespread adoption of welding characterized steel construction from the 1960s. These technical advances resulted in far greater use of the rigid-frame bridge in steel for shorter spans - a type anticipated by the comparable form in reinforced concrete. Plate-girder and box-girder forms in steel share many of the advantages of their concrete counterparts: they are lightweight, simple, easily analyzed and rapidly erected. Also, they are frequently used in the decks of cable-stayed bridges, a form which in the last forty years has gained increasing popularity for the longest spans.

Was Washington unique?

Washington State was, of course, only one place where this struggle was played out. Because of conditions specific to the state and the far west, it would seem that it was not typical of the rest of the country. Washington was far from the steelmaking heartland of the east, and despite several ineffectual attempts to produce steel, it entered the twentieth century with no real tradition in this material. Instead, a vigorous Portland-cement industry quickly arose in the first two decades of the century. Other far-west states, including Oregon and California, shared similar preconditions, and the engineers working for or alongside the Highway Departments of these three states were to play a key role in the development of some of the most technologically advanced and elegant American concrete bridges during the early twentieth century. Steel bridges were built in great number, fabricated by both local and eastern firms. Indeed, despite the distance from the steel centres of the east, in most of the examples considered eastern fabricators won the contracts for steelwork, although these were typically for larger or more specialised structures. Further, a significant number of local, or at least western-based fabricators were in operation by the 1920s, mostly competing in the smaller contracts. Nevertheless, the unequivocal ascendancy of reinforced concrete as the principal structural material for standard highway bridges in virtually all states by the 1950s had been anticipated in Washington - and probably other far west states - much earlier.

It seems likely that it was not until the late 1950s that highway departments *across the country* had switched predominantly to reinforced concrete for short-span bridges, given the findings of the *Engineering News-Record's* survey of the impact of prestressing. In 1958 this periodical announced that the nation's structural steel fabricators, faced with a sharp drop in demand or bookings, had embarked on a 'hard sell' campaign. The fabricators and their backing organization, the American

Institute of Steel Construction (AISC), organized a series of regional meetings across the country with state highway officials, consulting engineers and architects to emphasise the point that 'fabricated structural steel can be delivered promptly and when requested.'[85] The prompt delivery of prestressed members was posing perhaps the most serious challenge to steel since the advent of reinforced-concrete framing in the late nineteenth century. The virtues of the material were so manifest and manifold that by the early 1960s it had far outdistanced its nearest competitor in both bridges and buildings.[86] In a wider context, the overall supremacy of reinforced concrete by this decade in both buildings and bridges prompted debate further afield. In 1963 *The Builder* posed the question 'Steel or Concrete?',[87] and in 1968 an increasingly besieged American Iron and Steel Institute (AISI) devoted a whole session of its Autumn General Meeting, entitled 'The Challenge for Steel', to strategies for winning back territory lost to reinforced and prestressed concrete in the field of bridgework.[88] Competition is still very much alive and well; a conference in November 2000 in the steel heartland of the east, co-sponsored in part by AISI and the National Steel Bridge Alliance, devoted one session to 'Steel versus concrete alternatives: Which is economical?'[89]

Although there was probably considerable agreement between the various states *vis-à-vis* the ascendancy of short-span concrete bridges by the 1950s (notwithstanding Washington's comparatively limited application of prestressing at this point), the situation prior to this was almost certainly far more heterogeneous. The intense debate that surfaced in the late 1920s regarding the relative merits of either material for standard highway bridges is indicative of the rising popularity of reinforced concrete across the nation and in Europe. In England, according to an engineer with the London County Council who wrote an article in 1940 advising on the most economical highway bridge types, steel construction held the field until 1935.[90] But in Washington, and in other far-west states, the impact of reinforced concrete was experienced much earlier. There, the rash of concrete arches built in the 1910s accounted for the great majority of short-span bridges of that decade: in eastern states the equivalent span solution was more likely to be the steel truss. The conditions local to Washington - namely the absence of a successful steel industry, and a thriving Portland-cement industry - prompted, almost by default, exploitation of, and experimentation in, reinforced-concrete construction. The engineers of the highway departments of Oregon and California played a leading role in the development of American concrete bridges during the 1910s, 1920s and 1930s, and Washington made its own mark in this western tradition, principally in the form of the box girder and the use of precast/cast-in-situ construction methods.

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