The
METALLURGICAL HISTORY *of* ST. LAWRENCE BRIDGES

AN ONLINE SERIES

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PART 1
THE VICTORIA TUBULAR BRIDGE (1859) — WROUGHT IRON

CIM Bulletin (electronic) (2008), pp. 1-10
www.cim.org

THE VICTORIA TUBULAR BRIDGE (1859) — WROUGHT IRON

Abstract

Despite difficulties with travel and the transportation of goods, especially during freeze-up or spring thaw, there was no bridge across the St. Lawrence until 1859. It was only in this year that railroad development reached a stage that ensured it would be economically successful to build a bridge. Building a long bridge across the non-navigable Lachine rapids was relatively easy for pier construction. The bridge was a wrought iron box girder design, which had been developed recently in England. Wrought iron, which had been economically produced by the puddling of coke-reduced pig iron, was the only material of suitable strength and ductility at the time. It had to be imported from Britain because of very low production in Canada, although there was sufficient pig iron capacity in Canada. The bridge proved a technical success for 50 years, carrying up to 100 trains per day, providing passenger traverse and enabling product delivery that enhanced industrial production in Montreal.

Introduction

In this series of papers, the history of metallurgy is approached through an application of Canadian engineering, namely the construction of bridges about a century ago. These bridges are still in use today by a public that does not realize their historical significance, nor the metallurgical and engineering creativity that made them possible. In the current series, three bridges are considered in as many installments:

1. The Victoria Tubular Bridge (1859) was the first bridge across the St. Lawrence between the Thousand Islands and the gulf (1,200 kilometres), was single-track rail and was constructed out of wrought iron. The bridge provided an important contribution to the evolution of Canadian industry.
2. The Victoria Truss Bridge (1898), built upon the same piers as the Victoria Tubular Bridge, had double rail tracks and also provided roads for pedestrians and carriages. The construction of this bridge highlights the conversion to steel throughout the metallurgical industry and the significance of hot driven rivets, essential for building large structures.
3. The Quebec Bridge (1917) carried both rail and road high above the channel, near the start of tidal brackish water, and allowed for the passage of ocean liners beneath it. This bridge furthered the development of the Canadian steel industry through failure analysis of the initial collapsed bridge and the development of high-strength nickel steel.

The advance of metals technology generally followed incremental improvements that either led up to or followed significant breakthroughs. Such developments had seemingly little impact on social history until they enabled applications that altered people's way of life. One such landmark, the steam-powered passenger railroad, depended on wrought and cast iron combined with more dimensionally accurate machining, thereby reducing leakage between piston and cylinders. Rolled iron sheets were fabricated into riveted boilers and tubes were produced by hot pressure welding; these made possible higher specific power in mobile engines. Increased speeds, loads and travel miles demanded iron frames, forged iron axles, couplings and cast iron wheels (replacing spoked wooden wheels). Iron straps on wooden rails were soon replaced with rolled iron rails of greater strength and wear-resistance. Multi-wagon trains, which required gradual hills and curves, greatly increased the need for longer and stronger bridges.

The need and support for the construction of a bridge near Montreal is discussed in the present paper, as is the site selection of the bridge. In addition, this paper explores the design possibilities for the structure, which were the outgrowth of international developments in bridge technology and were very much dependent on restricted material availability. The significant features of the Victoria Bridge construction are then presented, followed by a discussion of its successful operation and its impact on industrial growth near Montreal.

Reasons for the Bridge

There was general demand for a crossing of the St. Lawrence near Montreal to replace steam ferries that ran in summer and the ice road in winter (Ball, 1987; Victoria Jubilee Bridge, 1898; Hodges, 1860; McQueen, 1992; Ponts du Québec, 1975; Szeliski, 1987; Triggs, Young, Graham, & Lauzon, 1992; Wilson, 1999). The need was greatest during late autumn freeze-up and the spring ice break-up, when crossing was hazardously attempted in hand-rowed cutters that had to be pulled across the ice flows by the crew. Moreover, there was a desire to connect with the network of short rail lines that ran along the South Shore and extend-ed into the Eastern Townships; these rail lines had sprung up to replace the inadequate road system (Boot, 1985). Furthermore, the Inter-Colonial Railroad, which began in the Maritimes, was under construction and would need a link across the St. Lawrence. However, the greatest driving force for the construction of a bridge was the Grand Trunk Railroad, which was intended to connect a line from the Atlantic ice-free port of Portland, Maine, to the western line which ran to Toronto and, later, Chicago (Victoria Jubilee Bridge, 1898; Triggs et al., 1992).

In light of the extensive railroad system that had spread across the United Kingdom and Europe in the period between 1825 and 1850, both the general public and busi-nesses shared the opinion that a continuous rail network was necessary to usher Eastern Canada into the modern world (Triggs et al., 1992). A bridge at Montreal was essential for attracting passengers from the very slow, but interconnect-ing, network of steamboats and stagecoaches. Furthermore, a continuous rail network was needed to hasten freight ship-ments, which were faster than boats across rivers, lakes and canals. These included not only the Lachine and Rideau canals, but also the Erie Canal from the Hudson River to the Great Lakes. In addition, politicians saw gap-free railroads as iron bands that would greatly strengthen the spirit of national unity; this vision culminated in Confederation about a decade later (Triggs et al., 1992).

The site for the bridge was selected by two brothers, T.C. and S. Keeffer, who were later to become prominent builders and founders of the Canadian Society for Civil Engineers (Ball, 1987; Hodges, 1860; Ritchie, 1968). The brothers selected a site at the eastern end of the Lachine Rapids. This location was chosen, in part, to connect with the lines to the ferry terminal, but mainly to avoid any obstruction to ocean shipping into the port of Montreal (Fig. 1). While this loca-tion for a bridge crossing would be quite long (2,010 metres or 1.3 miles), it would have the advantage of secure pier footings on shallow bedrock. The spans could be relatively short and low (Fig. 2), allowing sufficient height for the pas-sage of log rafts from the Ottawa River and for the occasional shallow draft steamers that shot the rapids and carried excursion crowds down river after an ascent via the Lachine Canal (Hodges, 1860; Triggs et al., 1992). A wooden bridge was out of the question because of inadequate durability for railroad service and a stone arch bridge of such magnitude was beyond Canadian skilled manpower capability.

Railroad Bridge Requirements

Rail transportation required extensive bridging and put older technology to severe trials because of the large active loads. In England, multiple arch viaducts of masonry were used if long spans were not needed (in North America, wooden trestles were more common). Wrought iron girders with riveted flanges and ribs were used for bridges up to 9.5 metres (31 feet) in length, but truss design had not been adequately developed. For intermediate spans, arches fabri-cated from cast-iron segments were often suitable; however, many of these failed in railroad service and often resulted in disasters under unexpectedly adverse conditions. For long spans, suspension bridges with wrought iron chain, or eye-bars with pins, filled the need for carriage roads (*Pantydd Menai, The Menai Bridges*, 1980; Plowden, 1974; Rosenberg & Vincent; 1978; Smith, 1964; Steinman & Watson, 1957; Watson, 1975). Conversely, they proved insufficiently stiff for the heavy, swaying, live loads of multi-carriage trains; several suspension spans were shaken to pieces in spectacu-lar disasters. A new design was developed in England around 1848 that would prove suitable for use across the St. Lawrence.

In order to complete a contract by 1850 for a rail line from Manchester across Wales to the port of the Dublin ferry, R. Stephenson needed to span the deep gorge of

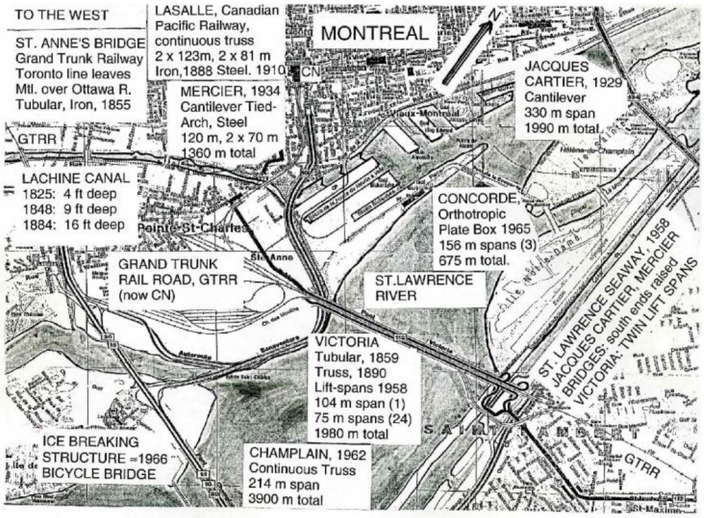


Fig. 1. The site of the Victoria Bridge, at the eastern limit of the Lachine Rapids, was to the west of the Old Port. It was also south of the Lachine Canal, which required several swing bridges; these are seldom opened today, thereby facilitating the present heavy rail traffic. Although there are sev-eral more recent road bridges, the Victoria, which was reconstructed in truss in 1898, is still heav-ily used. Adapted from map of Montreal (2005) published by JDM GEO, les publications Map Art in Montreal.

Fig. 2. Victoria Tubular Bridge, viewed from the northwest, showing the gradual incline towards the centre span and the prows on the piers for breaking ice floes. The thick protective abutment walls were removed when reconstructed in 1898 (Notman photograph, McCord Museum, Montreal; Triggs et al., 1992).

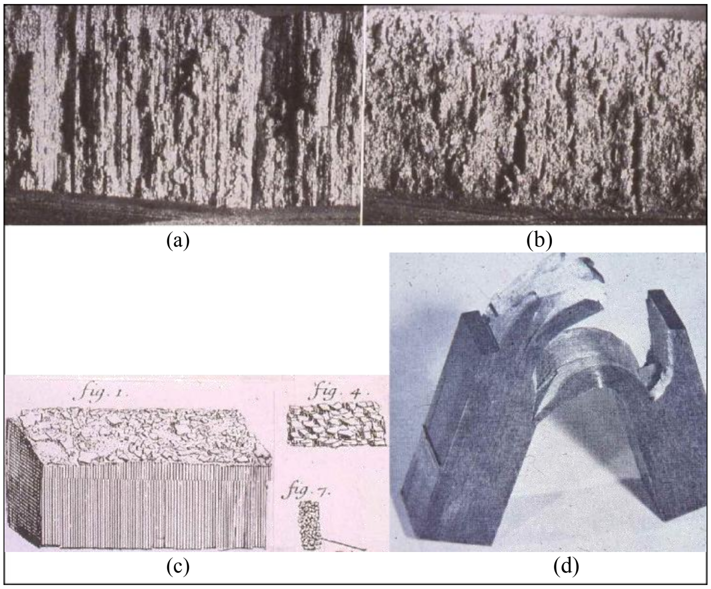
Menai Straits. The gorge was spanned successfully in 1815 by Telford’s suspension road bridge, which was 174 metres long and made of multiple iron eyebars with pins (McQueen, 1992; Plowden, 1974; Rosenberg & Vincent; 1978; Smith, 1964; Steinman & Watson, 1957; Triggs et al., 1992; Watson, 1975). Due to constraints imposed by tall sail-ing ships, arches were out of the question. A convenient cen-tral rock made possible two centre spans of 138 metres and two side spans of 69 metres. With the assistance of a ship-builder, W. Fairbairn, Stephenson tested tubes composed of two ship hulls, one of which was inverted (McQueen, 1992; Rosenberg & Vincent, 1978; Watson, 1975). Wrought iron plates (approximately 2 by 0.5 metres in size) reinforced by ribs of bent angles had been used in hulls for several decades; the riveted joints were beneficial as crack arrestors. Multiple rows of rivets, properly spaced, provided watertight joints due to the high clinching forces developed by hot driven rivets as they cooled (Fisher & Struik, 1974). Large-scale testing over two years showed that buckling in compression regions and fatigue in tension could best be avoid-ed with a rectangular tube, which was reinforced on the top and bottom by a row of six square tubes; the 10 per cent increase in weight more than doubled the load-bearing capacity. This design was so successful that it gave birth to beam theory and provided satisfactory service for much heavier trains. The bridge was only replaced when damaged by fire in 1970 (*Pantydd Menai*, *The Menai Bridges*, 1980). Before considering the transfer of this wrought iron tube design to the Lachine Rapids site in Montreal, the technol-ogy and capabilities of wrought iron are explained in the next section.

Wrought Iron

Wrought iron was discovered to be the only suitable mate-rial in the mid-19th century for long-span bridges because of its tensile strength and ductility, coupled with its econom-ic mode of fabrication. In fact, wrought iron was the materi-al that had introduced the Iron Age in about 2000 BC (Fisher, 1963; Habashi, 1994; Tylecote, 1992). In low-stack furnaces (i.e., the Catalan forge), a mild air-blow upon char-coal reduced the iron oxide. However, because the temper-ature was too low, the iron did not melt, but instead formed a sponge mixed with slag that had to be dug out of the fur-nace. Through hot forging, much of the slag (possibly lique-fied) could be eliminated to produce long strips that consist-ed of bands of iron phase with thin slag stringers (compris-ing approximately three per cent of the strips). Because the slag served as a flux to facilitate welding, the strips could be piled together and consolidated by hot hammering. Such lamination refined both the phases and also redistributed any defects alongside good material. Steel strips of 0.4 to 0.8 per cent carbon (made either by melting in crucibles or by carburizing iron in a forge or in sealed ceramic containers) could be incorporated as a cutting edge reinforced by the tough iron. Because of its good hot workability, iron was used for armor, chains, straps for barrels, reinforcements in farm implements and machine components. For example, iron was used in wind or water mills that sometimes powered forge bellows and tilt, or helve hammers (Fisher, 1963; Habashi, 1994; Smith, 1960; Tylecote, 1992).

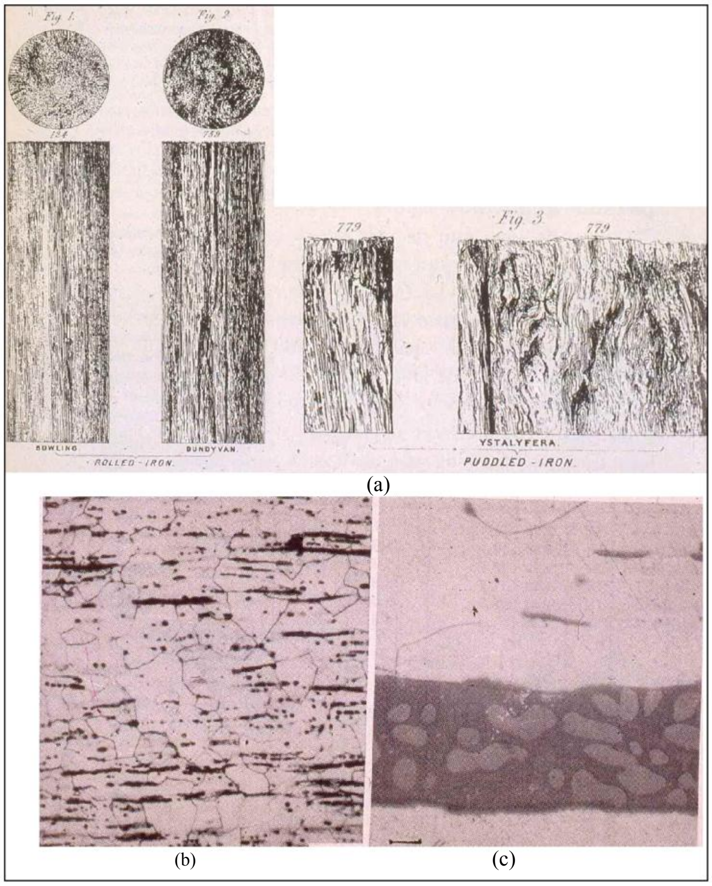
In Europe, during the Middle Ages, liquid pig iron con-taining three to five per cent carbon was produced in improved high-blast furnaces. This inherently brittle mate-rial was readily cast and easily molded during solidification; such products are referred to as cast iron. Cast iron bars could be decarburized by long heating in a forge, or finery, with excess air, and the process could be further accelerated by hammering the iron into thin strips (Fisher, 1963; Habashi, 1994; Samson, 1998). An experienced blacksmith could produce various grades of steel and iron. Different grades of iron could be distinguished by their fracture appearance, which is related to the quantity of combined carbon (Fe_3C, high in white iron) or of free carbon (graphite, grey iron; Smith, 1960). In contrast to the specu-lar (or facetted) fracture surfaces in those brittle materials, wrought iron had a silky appearance related to the forma-tion of voids at the slag that created what are now referred to as dimples (Fig. 3). Such low magnification fractography was the first step in developing an understanding of the microstructure of iron alloys, as introduced by Rèaumur in 1722 in France (Fig. 3a; Metals Handbook, 1987; Smith, 1960) and by Kirkaldy in 1862 in Scotland (Fig. 4; Brick, Gordon, & Phillips, 1965; Smith, 1960). Wrought iron had high ductility in the longitudinal direction due to the duc-tile low-carbon iron grains, as well as to the blunting of cracks by bifurcation along slag stringers; the longitudinal splitting gave wrought iron a failure behaviour, somewhat like wood (Fig. 3c; Brick et al., 1965; Smith, 1960).

In the early 18th century, the industrial revolution essen-tially began with the replacement of charcoal with coke from coal (a technique developed by A. Darby in 1750; Habashi, 1994; Tylecote, 1992). The plentiful supply of harder fuel



(a) (b)
(c) (d)

Fig. 3. Wrought iron fracture surfaces: (a and b) fractographs by optical microscopy (5X; the first is parallel and the second is normal to the slag stringers; Metals Handbook, 1987); (c) sketches drawn by Réaumur in 1722, after C.S. Smith (1960); and (d) macroscopic splitting along the slag stringers in a Charpy specimen (Metals Handbook, 1987).

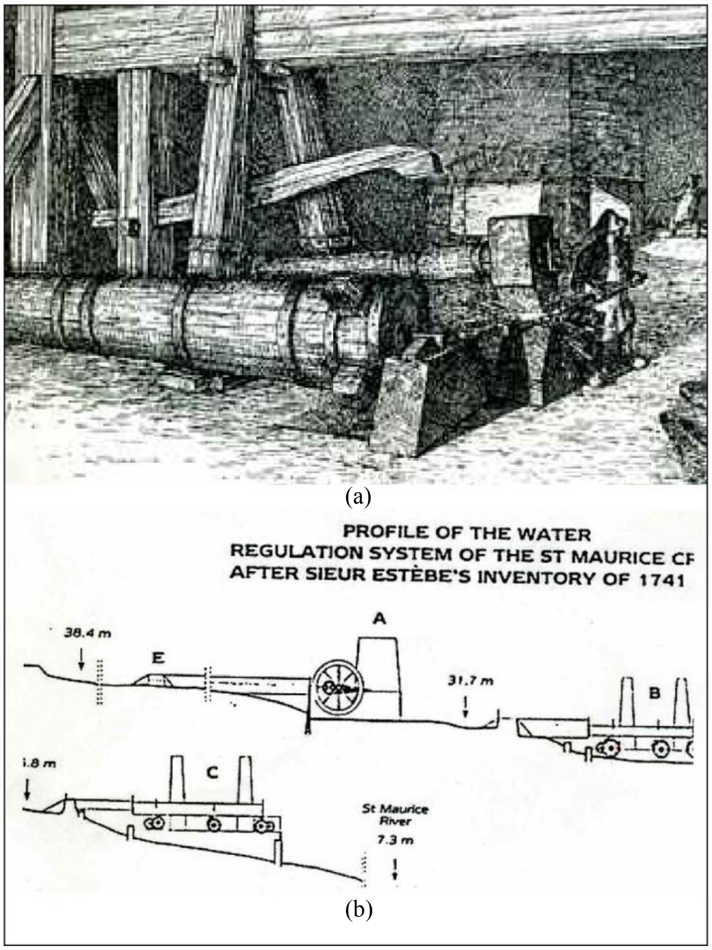


(a)

(b) (c)

Fig. 4. Etched microstructures of wrought iron showing slag stringers: (a) elongated, parallel in rolled bars on left and irregular from primary hammering on right, as prepared by Kirkaldy in 1862, after C.S. Smith (1960); and (b and c) elongated slag first lying between recrystallized ferrite grains (X50) and then exhibiting FeO and Fe_2O_3 (X500, bar 10 Ìm; Brick et al., 1965).

permitted taller blast furnaces and stronger blast, delivered from steam blowing-engines. With these improvements, as well as with the introduction of heated blast air, the output and quality of pig iron were increased and the unit cost was reduced. Later, it became the practice to break the pigs in order to separate them by carbon content and match them with materials most suitable for either foundry use (cast grey or white iron) or for transformation into wrought iron (Smith, 1960; *Making, Shaping and Treating of Steel*, 1957). In about 1780, H. Cort developed the puddling process, in which a mixture of suitable pig iron, slag and mill scale was melted in a reverberatory hearth in which the roof reflected hot gasses from a separate fire box (Fisher, 1963; Gale, 1965; Habashi, 1994; Tylecote, 1992). Air was forced into the liquid as it was being stirred and gradually transformed into solid, low-carbon iron. In about two hours' time, a skilled puddler could gage the reduction in carbon and work the charge into balls of sponge and slag of about 200 kilograms. After rapid transfer to the forging hammers, much liquid slag was ejected in the form of fiery sparks and elongated rectangular muck bars were produced — these were usually finished by rolling (Fisher, 1963; Gale, 1965; Habashi, 1994; Tylecote, 1992; *Making, Shaping and Treating of Steel*, 1957). The muck bars were piled and bound together with wire for further consolidation and reduction of the slag content; the slag was elongated into stringers between the iron grains. To improve the quality, the bars were once more bundled and forge-welded into billets or slabs of suitable dimensions to be used as feedstock for rolling mills (Gale, 1965; Smith, 1960; *Making, Shaping and Treating of Steel*, 1957). Large blooms could be created and manipulated by derricks for the purpose of forging the blooms into large shafts for steam ship engines.



(a)

(b)

Fig. 5. At the Forges St. Maurice, (a) a water-powered shaft with four teeth raised the tilt or helve hammer for beating the slag out of finery iron muck bars and welding them into bundles. Except for the hammer and anvil, the hurst frame was constructed mainly of wood reinforced with iron straps; the projecting horizontal wooden spring safely limited the upward throw of the hammer (Samson, 1998). Similar iron-framed, steam-powered hammers were used up to about 1900; (b) the hydraulic system, as designed by Chaussegros de Lery, drove the bellows for the blast furnace "A" (high-carbon iron) and for the finery furnaces associated with the two forging hammers "B" and "C" to work the low-carbon iron (Samson, 1998).

Mechanical shaping processes were increased in force, speed, shape intricacy and dimensional control by the introduction of steam power and by improved mechanical linkages. Forging hammers changed from the helve type (hinged at one end and raised by a rotating cam; Fig. 5) to the post or C-frame type, which allowed the hammer either to be dropped by a board with rollers after being raised or to be forced down by a double-acting steam cylinder that also raised it (Fisher, 1963; Habashi, 1994; Samson, 1998; Tylecote, 1992). Rolling mills, although steam driven, depended on manual manipulation of the material; in a two-high mill, the plate had to be lifted over the top rolls, whereas, in the three-high mill, less of a lift was required and the plate was pulled in for further size reduction. Due to inadequate transfer equipment, the size of plates was limit-ed to about 2 by 0.5 metres. By pack rolling, up to eight thin sheets could be produced for tin coating, to be used for household implements and food containers (Fisher, 1963; *Making, Shaping and Treating of Steel*, 1957). Grooved rolls were developed for rolling bars, rods for wire drawing, sim-ple shapes and rails. Sheets could be longitudinally slit and bent into angles. Narrow strips (i.e., skelp with beveled edges) could be progressively curled into tubes with longitu-dinal butt seams and hot pressure welded by forcing them through conical dies (or bells; McQueen, 2005).

Iron Production in Canada

In the new colony, iron was always in strong demand, both in cast form for stoves and pots, and in wrought form for plows, axes, scythes and nails. The first, longest running and most successful iron-producing plant was the Forges St-Maurice (1729-1883), which was put into operation by iron master P.-F. de Vezin. This plant had a blast furnace and two forges for finery production of wrought (bar) iron, as well as tilt hammers (Samson, 1998). To reach full production, the engineer, G.-J. Chaussegros de Lery, redesigned the water system to drive the bellows for the blast furnace and forges, as well as to drive the two-tilt hammers (Fig. 5; Berube, 1989; Samson, 1998). A high fraction of the plant's 2,000 ton per year output was converted into bar iron, which was sent to France for the navy; after 1760, the British Navy also recognized the high quality of the iron, but the world mar-ket was in flux. In the century before Quebec changed hands, the iron industry in Britain had been in crisis because charcoal had become increasingly scarce and costly. Iron production there had been reduced to about 17,000 tons, requiring imports from the American colonies of as much as 4,000 tons per year (Fisher, 1963). This demand encouraged the production of over 10,000 tons per year in the American iron industry so that it was able to provide the needed arma-ments for their revolutionary war. Although it suffered much damage, it quickly recovered with improved equipment. The British industry was surging forward because of their conversion to coke (in 1750) and to hot blast in order to pro-duce pig iron and the puddling process for bar iron (in 1780); as a result, Britain became an increasingly strong exporter of iron (Habashi, 1994; Tylecote, 1992). Nevertheless, the American industry underwent renewed growth. By 1840, it was producing 316,000 tons of pig iron and 217,000 tons of bar iron; yet 102,000 tons were still imported from Britain (Fisher, 1963). Compared to what was occurring in Canada, the American production and its ratio to imports were gigantic.

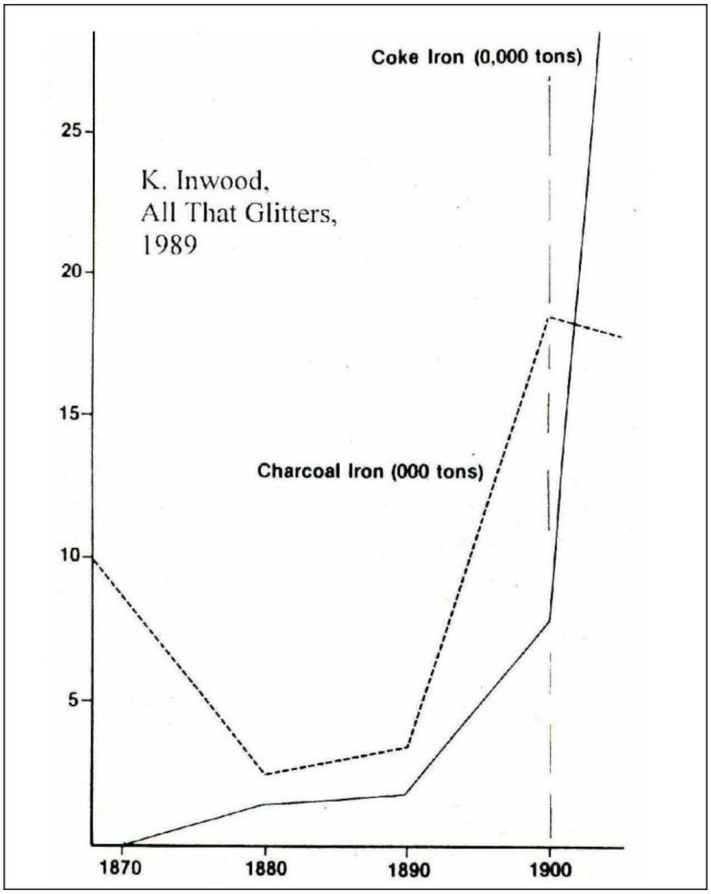


Fig. 6. Canadian production of pig iron was primarily by charcoal up to about 1872; this came to a sudden end in about 1911 due to high costs and removal of tariffs. The utilization of coke for reduc-tion grew rapidly after 1900 (Note that the scale of production for the latter is ten times larger; Inwood, 1989).

Britain's ability to export wrought iron discouraged expansion of iron works in Canada. Between 1793 and 1836, the Forges St-Maurice was leased to a very competent iron master, M. Bell, who turned production increasingly to iron casting, needed by settlers (Berube, 1989; Samson, 1998); its high-quality and steady production allowed it to compete with imports, although new iron works often failed after a brief period of operation. During the two decades following M. Bell's ownership of the Forges, it was sold sev-eral times to not-so-competent entrepreneurs, except for one who rebuilt the blast furnace in 1854 with doubled capacity (4,000 tons per year). Each time the Forges was sold, it eventually reverted to being owned by the Crown (Samson, 1998). In 1863, after a few years of being idle, it was purchased by the McDougall family, who also had a foundry in Montreal. They brought the Forges to a high state of productivity, mostly producing pig iron intended for foundries in industrial centres, as well as some rail car wheels and a limited quantity of finery bar iron for axes (Berube, 1989; Samson, 1998). A big problem was fluctuat-ing demand and prices, which depended on business cycles and changes in tariffs (McNally, 1992). Despite technical success and good productivity, certain loan problems forced G. McDougall into bankruptcy at about 1883; the Forges St-Maurice closed, never to re-open. At the time of the closure, production of charcoal iron had declined to about 2,500 tons per year, while production of coke iron rose to 15,000 tons per year (Fig. 6; Inwood, 1989).

In Canada, between 1760 and 1900, many iron produc-tion facilities were built in locations neighbouring both iron ore natural resources and potential markets (Fig. 7; Andreae, 1989; Gale, 1965; Michael, 1989; Tarassoff, 1989).

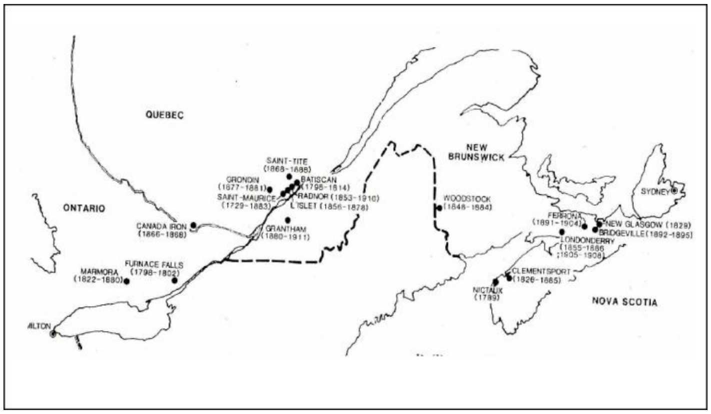


Fig. 7. Map of eastern Canada showing the location of iron works and their dates of operation; the Forges St. Maurice (1729-1883) in Quebec, was the first and the longest lived. Grantham, Quebec, Radnor, Quebec, Londonderry, Nova Scotia, and Ferrona, Nova Scotia, continued production until the end of the charcoal era (Tarassoff, 1989).

Operations were strongly dependent upon waterpower, which was often interrupted by winter freeze or summer drought, and upon the availability of charcoal that general-ly demanded longer haulage when timber was in low supply. The success of iron production facilities was also very dependent on the experience of the iron master and the skills of the workers, who often had to develop quality prod-ucts from raw materials with varying and unmeasured com-positions. Most had short life spans relative to today's stan-dards, such as Marmora, Ontario (Michael, 1989) and Woodstock, New Brunswick, known for its high strength of manganese pig iron (Potter, 1989). The Grantham Iron Works, near Drummondville, Quebec, produced 4,000 to 6,000 tons of pig iron per year under R. McDougall's super-vision between 1853 and 1910 (McDougall, 1989). In this period, much charcoal pig went to foundries to make rail car wheels, as charcoal pig wheels enabled much longer service (approximately 150,000 miles per wheel) than did coke-reduced iron wheels (McDougall, 1989; Samson, 1998). Coke blast furnace production depended upon the easy transportation of ore, limestone and fuel that also provided steam power for the machinery; the production of coke blast furnaces increased rapidly from 1870 to 1910, at which point it surpassed the output of the charcoal furnaces (Fig. 6; Inwood, 1989).

The foregoing account demonstrates that the production of wrought iron in Canada near 1850 to 1855 amounted to only hundreds of tons per year, which was very different from the situation in the United States. Furthermore, there was little production by means of the puddling process (i.e., there were only two furnaces in Montreal; Day, 1864; McNally, 1992); puddling allowed for much larger produc-tivity and by extension, financial growth compared to finery methods. The associated forge capacity was also insufficient. Finally, there was almost no hot rolling capability to produce high-quality plate, nor was there the capacity for slitting and angle bending. The construction of the Victoria Tubular Bridge required 9,000 tons of wrought iron over a period of two years. It is quite clear that Canada was in no position to produce the material for the bridge and that the country could certainly not compete with the experienced and high-capacity construction of the Britannia Bridge (Hodges, 1860; Triggs et al., 1992). Canada never developed such capacity because most pig iron production was devoted to other aspects of railroad technology and because wrought iron was increasingly replaced after 1865 by steel, as explained further in the next paper. Though a rolling mill, Canada's first, was set up in Montreal by M. Holland to roll sheet for nail making, the feedstock was largely imported, except for the little that was produced by the two puddling furnaces (Day, 1864; Kilbourn, 1960; McNally, 1992).

Victoria Tubular Bridge Construction

The Victoria Tubular Bridge required 9,000 tons of wrought iron sheets and angles that were not available from Canadian sources. As called for in the plans, the iron plates were sheared, bent and punched at the same works in England that had fabricated the Britannia Bridge (Fisher, 1963; Hodges, 1860). A tubular bridge like the Victoria was not extraordinary for the time because cov-ered wooden bridges were common; however, the wooden bridges were comprised of simple trusses with a roof and walls for preservation (Harrington, 1976). Under the lead-ership of R. Stephenson, A. Ross transformed the Britannia Bridge design (which had two 138 metre-long spans) to suit the new application of 24 spans of 75 metres each and one central span of l00 metres (Fig. 2). The tube dimensions were reduced to 5.6 metres high by 4.9 metres wide (from the nine metres in height of the Britannia Bridge) and the reinforcements at the top and bottom of the tubes were made of layers of plates that increased near span centres, instead of small square tubes (*Pantydd Menai, The Menai Bridges*, 1980; Hodges, 1860; Plowden, 1974; Smith, 1964; Steinman & Watson, 1957; Triggs et al., 1992). Like the Britannia Bridge, the tube was continuous (rather than comprised of independent spans) in order to decrease deflections. Only one train at a time was permit-ted. Unlike the much shorter Britannia Bridge, the Victoria Tubular Bridge had small diamond or trefoil-shaped windows. Because of the bridge's lower height, a slot was opened in 1870 to let out smoke following the introduction of coal-fired engines.

The box-girder, short span design of the Victoria Tubular Bridge was criticized by Roebling, who suggested that much longer suspension spans be built instead. However, the tubes of the Victoria Tubular Bridge cost only $285 per foot, com-pared to the $375 per foot cost of the Niagara railroad sus-pension bridge. Note that the Niagara deck truss was made of wood, which meant that several extensive strengthenings were required before the bridge was finally replaced in 1883 due to inadequacy (Plowden, 1974; Szeliski, 1987; Smith, 1964; Steinman & Watson, 1957). Though the many piers built near the Lachine Rapids were expensive, simple timber caissons, which were weighted down with stone and which did not require compressed air chambers, reduced the cost (Hodges, 1860; Triggs et al., 1992). In addition, one of the innovations introduced by the site engineer, J. Hodges, was steam-driven excavating and hoisting equipment.

Many Irish ironworkers had initially come to Montreal to work on the construction of the tubular bridge at Ste. Anne, where the Toronto rail line crossed the Ottawa River. For the construction of the Victoria Tubular Bridge, these same workers were responsible for fitting together the pieces and driving in about 1.5 million rivets (270 per day for each team; Fig. 8). Note that this valuable technology is discussed in more detail in the subsequent paper about the Victoria Truss Bridge. Under J. Hodges' supervision (the chief site engineer), the spans were fabricated progressively from both river banks; timber trusses, built efficiently by French Canadian woodsmen, were used to construct the spans (Fig. 8). The centre span was built on a trestle in mid-winter so that material could be transported over the ice (Fig. 9); it was touch-and-go to finish the span before an early spring break-up (Hodges, 1860; Triggs et al., 1992). Out of a work force of 1,000 men, 26 were killed during the three-year construction period. A gigantic boulder lifted from one site is still located on the Montreal approach in memory of the Irish workmen and their families who died from cholera on their passage over.

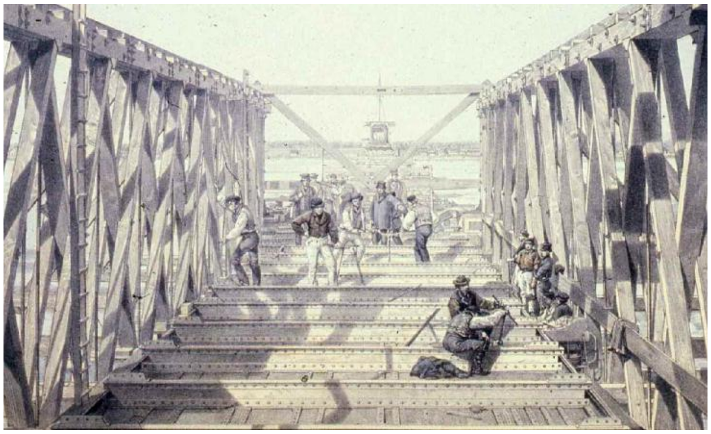


Fig. 8. Laying the floor beams of the tube, workmen are aligning holes in preparation for the rivet-ing team, which is seen standing by the forge at the right. Rivets joining web and flange angles are clearly seen in the lithograph (Hodges, 1860; Triggs et al., 1992).

Fig. 9. Construction of the tubular (box-girder) centre span with a travelling gantry crane on a tem-porary timber truss over winter ice, as captured in a Notman photograph with the South Shore in the distance (McCord Museum, Montreal; Triggs et al., 1992).

The centre piers of the Victoria Tubular Bridge rose 18 metres above normal water level and extended nine metres below it (Figs. 2 and 10). Despite the considerable rise (taller than any building then in the city), the bridge did not appear massive because of its great length (Fig. 7). In 1898, the piers were used, without any reconstruction except widening at the top, for the foundation of the Victoria Truss Bridge (Victoria Jubilee Bridge, 1898). After widening, the piers were 8.5 metres wide at the upper vertical section and had 45 degree prows extending up the river in order to break massive ice floes that could press heavily upon them. A century after construction, the piers were stabilized by pressure grouting during reconstruction to permit passage of ocean ships in the St. Lawrence Seaway (Szeliski, 1987).

Success and Impact of the Bridge

In terms of railway traffic, the bridge fulfilled all the dreams of the builders (Triggs et al., 1992). The transit of up to 100 trains per day led to the need for double tracking, which is examined in the next paper because it took place in the Age of Steel (Victoria Jubilee Bridge, 1898; Szeliski, 1987). The location of the bridge proved suitable over time; heavy rail traffic continues even today as part of the Canadian National Rail Network, which absorbed the Grand Trunk circa 1930.

Another railroad bridge from the South Shore to the island at LaSalle was built by CPR in 1888 in order to con-nect the "short" line from St. John, New Brunswick, through Maine, to the western part of the network (*Ponts du Québec*, 1975; Wilson, 1999). This CPR bridge was a wrought-iron continuous-truss design that was replaced by a stronger steel Pratt truss in 1910. While initially considerable train traffic was comprised of simple passenger trains, the Victoria Bridge would become much more useful in its second gen-eration when roadways were added. These roadways are still heavily used, despite construction of three highway bridges and a tunnel (*Ponts du Québec*, 1975; Wilson, 1999).

Fig. 10. The Victoria Bridge centre span frames Mount Royal and the city as a lumber raft from the Ottawa Valley passes (Notman photograph, McCord Museum; Hodges, 1860).

Table 1. Industrial development from Victoria Railroad Bridge (Ball, 1987; Triggs et al., 1992)

	1852	1861	1871	1881
Montreal population	50,000	100,000		170,000
Industrial employees	9,000	21,000	32,000	
Average number of employees per factory	13	20	30	
Foundries and machine shops with more than 20 employees		12	25	
Metal workers in foundries and machine shops		693	2001	
% of total metal workers in foundries and machine shops		23%	40%	
Shoe making (pairs)				3 million
Garment workers			5,000	
Clothing textile workers (diminishing imports, rising exports)		1,197	3,658	8,941

Notes:

1871: 13 shops > 100 employees, 66 shops <4 employees, 108 in between. Metal working greater than Toronto and Hamilton.

Wood industry grew enormously — saw mills, barrels, boxcars, furniture.

Ste. Anne district in 1871: 5,186 men and women in workshops; more than half of these in one of 13 factories, including Grand Trunk shops with more than 100 employees each.

1875–1878: Lachine Canal widened and locks refurbished.

1880: Francophones total 30 per cent of total workers; 14 per cent of metalworkers at $1.60/hr (many from the Saint Maurice Region.); 13 per cent labourers at $1.00/hr; 35 per cent of carpenters; 52 per cent of painters.

The influx of Irish workers led to the establishment of new residential districts in Montreal: Little Burgundy and Point St. Charles. The Irish immigrants became permanent residents and their numbers grew considerably due to work in the con-tinually extending rail network and in maintenance shops (Triggs et al., 1992). The increased flexibility of transport into and out of the city gave rise to many new industries. The growth in population was very large (as shown in Table 1) and was associated with marked growths in the number of indus-trial employees and in the number of large factories. In 1861, there were 12 foundries that employed 700 persons (23 per cent of all metal workers) and, in 1871, there were 25 foundries that employed 2,000 employees (40 per cent of all metal workers; Ball, 1987; Day, 1864; Kilbourn, 1960; McNally, 1992; Triggs et al., 1992). The foundries utilized pig iron from rural charcoal iron works and were mainly produc-ers of railroad components. The metal-working capacity in Montreal was greater than in either Toronto or Hamilton (Ball, 1987; Day, 1864; McNally, 1992; Triggs et al., 1992).

The box-girder design, in which one of the horizontal flanges (usually the top one) serves as an element of the deck, could not compete with trusses built by riveting. The welded box-girder bridge has been more successful; one such applica-tion is the Concorde Bridge, which runs across the main branch of the St. Lawrence from Montreal to Ile Sainte-Hélène and was built in 1965 (*Ponts du Québec*, 1975; Wilson, 1999). In 1953, a 203 metre-long box-girder of variable height (from seven metres at the piers to two metres at the mid-span) was built in Germany (Smith, 1964; Steinman & Watson, 1957). A box-girder with an air foil section have been used as light, but rigid, decks for suspension bridges across the Severn River in Britain.

Conclusion

The single-track Victoria Tubular Bridge, designed as a box-girder tube and based upon the recent construction of a long-span British bridge, provided a vital link in the Canadian rail network. Its site at the foot of the Lachine Rapids provided good foundation for piers and avoided obstructing ships entering the Montreal harbour. The bridge was constructed of wrought iron, which was econom-ically prepared by puddling from coke-reduced pig iron and shaped by steam-powered forging and rolling. Because of its fibrous structure that contained about three per cent slag, the bridge had great strength and ductility. Relatively small rolled iron plates and angles bent from slit plate were joined by hot-driven rivets into a unified box-girder. In 1859, there was almost no Canadian capacity for puddling or rolling, so materials for the first bridge across the St. Lawrence were fabricated in England. The Victoria Tubular Bridge success-fully carried large volumes of rail traffic, as well as many local passengers from the South Shore, for almost 40 years (Ball, 1987; Triggs et al., 1992). As a critical link for the rail-roads, the bridge contributed to a marked increase in indus-trial production around Montreal.

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