The construction of the Forth Road Bridge

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La construction du pont-route sur le Firth of Forth

Der Bau der Straßenbrücke über den Firth of Forth

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The economy in design and lightness in weight of the Forth Road Bridge gave rise to unique problems in erection. These difficulties were enhanced by the fact that the site is in latitute 56° North — much further North than any major suspension bridge in the world — and notorious for its high winds and gales. Much of the pattern of erection of the bridge had to be changed on account of these two factors.

When it was opened in September, 1964, the 3,300-ft. main span of the bridge was the fourth longest in the world — exceeded only by the Golden Gate, Mackinac and George Washington Bridge in the U.S.A. Since then the mighty Verrazano-Narrows Bridge with a span of 4260 ft. has been completed at the entrance to New York Harbour, and work is well advanced on the Tajo Bridge of 3,323 ft. span in Lisbon, which is scheduled for opening in 1966.

The erection of the Forth Road Bridge superstructure fell into three distinct phases. First was the building of the two steel towers 505 ft. high on either side of the river; second, the spinning of the two main cables which passed over the tops of the towers and are anchored on either shore; and the final phase, the erection of the suspended deck which is hung from the cables and carried the roadways, cycle tracks and footways high over the river to connect with the new systems of approach roads on either shore.

Erection of Towers

Unlike the Forth Railway Bridge, where the steelwork was erected plate by plate by means of little 30 cwt cranes — and riveted in position as in ship-

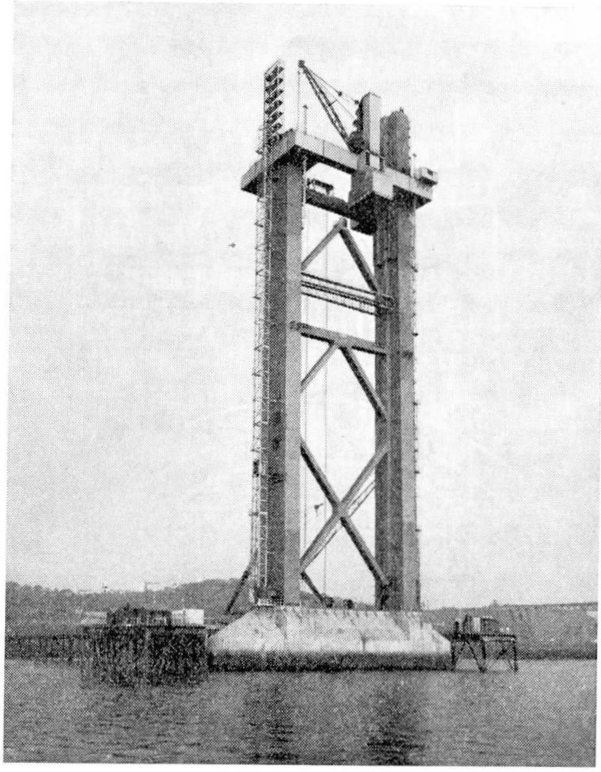

Fig. 1. North Tower under construction. Note climbing structure and temporary lift shafts.

building — the towers of the Roadway Bridge were erected in large all-welded boxes weighing 32 tons each and site-connected by high-strength bolts.

The fabrication of the structural steelwork of the bridge, although shared amongst a number of different shops, presented no unusual features except for the towers. Here the 33 huge welded steel boxes in each tower leg, each box measuring about 47 ft. high, up to 12 ft. wide and 5 ft. deep, with machined butts at each end, presented a major achievement in precise fabrication. Apart from ensuring that the towers were truly vertical, the purpose of this machine finish to butting plates was to ensure perfect load transmission between sections. Made in high tensile steel to BS 968: 1941, these boxes were delivered to the base of the tower by road, along a causeway from the shore. They were lifted into place by means of a 32 ton derrick mounted on a climbing structure which weighed some 240 tons. This completely encircled the tower and was raised up on it stage by stage by means of hydraulic jacks as erection proceeded.

The hydraulic jacking equipment used to raise the climbing structure from one working level to the next — a height of some 47 ft. — was installed in the four corner compartments. Whilst being lifted, the structure was suspended on four steel links, perforated at 18 inch centres, which hung from two temporary steel girders bolted across the top of the tower sections previously erected. At each of its eleven working levels, the weight of the climbing structure was carried by four thick steel shear plates welded to the side of the towers. Other shear plates and corner clamps provided resistance against possible uplift and lateral forces respectively. Each 18 inch lift of the climbing structure took about 10 minutes, so that the whole 47 ft. lift could be completed in a day. The climbing structure was designed to act as a safe working platform and carried bolting up stages and gantries which gave protected access wherever necessary. It was also equipped with a men's hut and store room. Temporary lifts were provided for men and materials up the outer face of each tower leg to every level at which the platform halted.

Compressed air lines and electric power cables were housed in the lift shafts which subsequently gave access throughout cable spinning and all other operations to the temporary platform at the tower top. Numerous special safety precautions, including anti-freezing devices, rope combs to prevent the ropes from threshing around in high winds, and an additional hand trip gear in each lift cage, were installed. Whilst each box section of the towers was lifted from the horizontal to the vertical position, the lower end travelled on a bogie into the plumb position. After each section had been landed on tapered dowels to position it exactly on top of the section below, it was connected by means of verticle high tensile steel tie rods and high strength bolts.

The three boxes making up each section of tower leg were inter-connected by bolted cover plates. The normal time taken to erect one complete lift of the tower with bracing, including moving the climbing structure and extending the lift shafts, was about eight working days. The North and South towers were erected in twelve months, from June 1960 to June 1961. The steelwork of each tower including bracing amounted to about 3,000 tons.

The effects of the remarkable slenderness, lightness and economy of the bridge first manifested themselves when the North tower was free-standing and had nearly reached its full height. In quite light cross winds it repeatedly developed an aerodynamic oscillation which amounted to 7 ft. 6 in. sway at the tower top with a period of $4^1/_2$ seconds. The bolted butt joints between the base and section I were opening a measured amount of 0.09 to 0.12 inches. No such phenomenon had occurred before on any major suspension bridge. Steel erectors were thrown about, brused and even became "sea sick". Remedial measures were urgently designed and within a week the movement of the tower was checked by an ingenious damping device. This consisted of a 16 ton weight, tied to the tower top by means of two lengths of steel wire rope, free to move up or down on rails inclined at a slope of 45°. The ropes were tied down to the ground at 100 ft. intervals to keep them taut. Any swaying of the tower top of more than about 8 inches then had to pull the weight up the slope — and the loss of energy due to the friction of the weight on the rails sufficed to damp out the oscillation. It must be emphasised, of course, that these movements only occurred during erection; once the main cables were assembled across the river and bolted to the tower tops, they became perfectly steady. Moreover, the oscillations only occurred in very light and steady

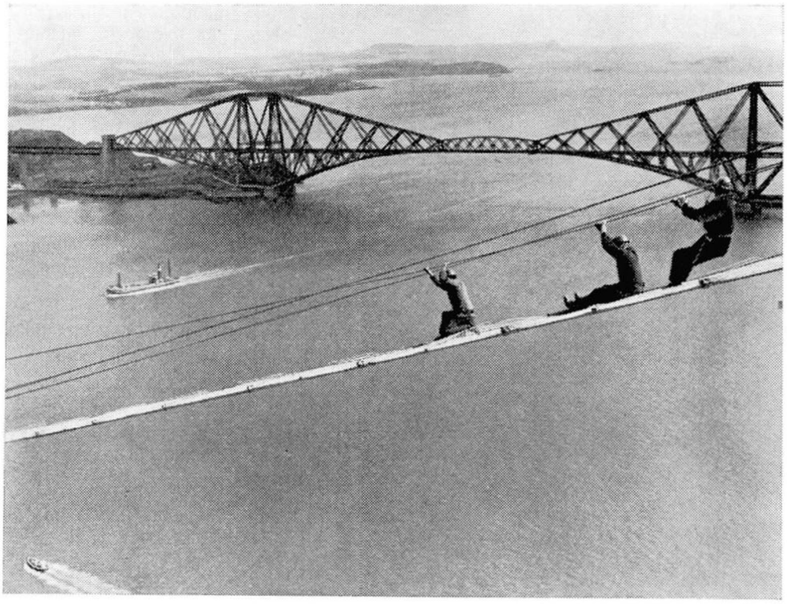

Fig. 2. Erecting panels of wire mesh on catwalks.

cross winds of 20—25 m.p.h. In a wind of 70—80 m.p.h. so much turbulence and eddies were set up that the tower merely shuddered a few inches.

Mr. C. Scruton of the Aerodynamic Division of the National Physical Laboratory, Teddington, has pointed out that for a rectangular shape the aerodynamic oscillation built up very rapidly at a certain reduced wind speed but that at higher wind speeds it began to reduce, and not until a wind speed of about 5 times that initially causing excitation was reached, should serious oscillation occur, either of galloping nature in the fundamental mode, or vortex-excited in the first harmonic mode. As the free-standing Forth Bridge towers first oscillated at 25 m.p.h., it might require a wind speed of at least 125 m.p.h. to cause it to oscillate again — and this would of course far exceed the range of steady winds.

Erection of Cables

The two main cables of the bridge are each made up of 11618 parallel wires of galvanised high tensile steel 0.196 inches (5 mm) in diameter with an ultimate strength of 100 to 110 tons per square inch. Experience in the U.S.A. has shown that this is the most suitable diameter to use. If the wire were drawn thicker its breaking strength would be reduced and it would become too stiff to bend readily round sheaves and strand shoes. If it were drawn thinner its ultimate strength would be increased but there would be a greater length to spin. The 30,000 miles of wire used in the cables of the Forth Road Bridge — weighing 7,450 tons and sufficient to go one and a quarter times round the world — was all manufactured by the Wire Department of Dorman

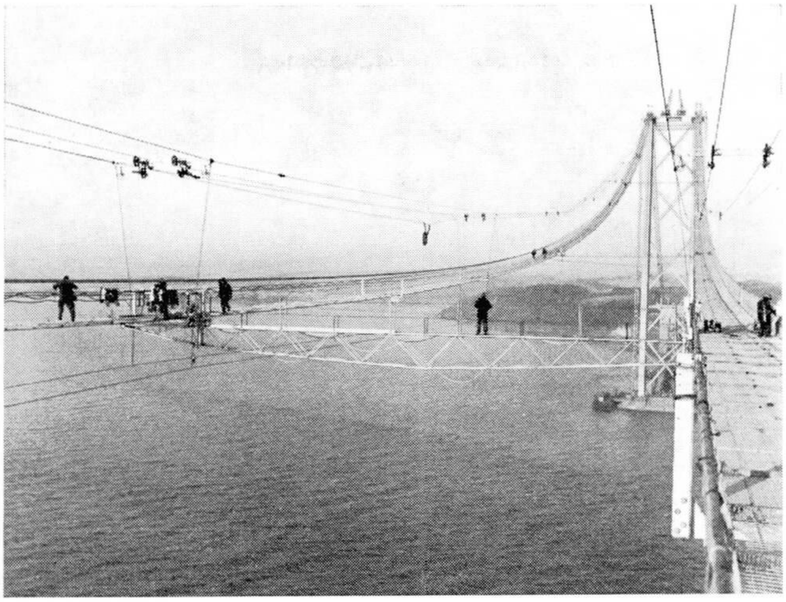

Fig. 3. Start of cable spinning. Note catwalks, cross bridges and spinning wheel.

Long (Steel) Limited, Middlesborough. It was delivered by rail in coils of about 9 cwt to the wire store and reeling shop at the South end of the bridge. Here the coils were spliced together by means of cylindrical steel nipples in a press and wound onto large 6 ft. diameter drums of which 90 were available. For this operation the coils were mounted successively on horizontal swifts or turntables from which the wire was led through a tensioning device and "fleeter" onto the electrically-powered drums. After each drum had been loaded with seven tons of wire it was moved out of the shop on bogies and transferred to the unreeling area behind the South anchorage from which all the cable spinning was done.

Meanwhile, two temporary catwalks or footbridges for use in spinning the cables had been erected right across the span from anchorage to anchorage about four ft. below the level where the main cables were to be. Each catwalk was 9 ft. 2 ins. wide, floored with wire mesh and supported by 10 galvanised wire strands one inch thick — eight of which were spaced out and ran parallel beneath the floor, and the other two supported the tops of wire mesh parapets 3 ft. 6 ins. high on either side. Seven light tubular cross bridges were provided, to inter-connect the catwalks, and storm systems of 1 in diameter wire ropes were assembled beneath in an inverted parabola to keep them secure in winds of gale force. The footbridge strands were clamped every 100 ft. throughout their length to transverse steel beams with rigid posts at either end. With all their vital structural parts made of steel, the catwalks were thus not only very light and strong, but provided the maximum degree of safety and freedom from fire risk whilst offering the minimum obstruction to the wind. In the bitter gales of the Forth, which on occasion bellied the catwalks out 70 ft. sideways at mid-span, they proved their worth.

The 20 footbridge strands 6,100 ft. long between side towers, were erected by unreeling them one at a time on to the bed of the Forth, from a drum on a pontoon that was towed across from North to South. After the free end of the strand had been hauled up and connected to the top of the North side tower, the strand was paid out across the river and over the top of the staging at the base of each pier, until the other end could be connected to the top of the South side tower. In good weather two strands could be laid per tide. After all shipping had passed, they were slowly lifted by the tower top derricks, and previously marked points on each strand were clamped in position on the tower tops. In spite of fast-running tides and winds exceeding 30 m.p.h. all the strands were erected and adjusted in four weeks. The amount of adjustment necessary to bring all the strands to exactly the same sag in the main and side strands proved to be well within the 18 ins. allowed.

The centre cross bridge in the main span was then lifted to the South tower top and hauled out along the strands by means of winch lines from the North tower. The first journey out to mid-span was made by a gang of men in a work car also slung from the footbridge strands to bolt the cross bridge in position. Panels of wire mesh flooring in 10 ft. lengths, complete with parapets and timber treads, were then laid out in trains up to 400 ft. long, loosely fastened to the footbridge strands, and hauled out towards mid span and down the side span. Gangs of men went out in the work cars to raise the parapets and secure them and the floor mesh firmly to the strands. During the course of mesh erection, which was kept roughly balanced as between main and side spans, each of the cross bridges was assembled at the appropriate time. The storm system was then laid on the footbridges, the vertical ties connected, and each parabolic rope festooned over the sides and the ends of it connected and tensioned at the tower bases. The two tram support strands, $1^3/_8$ in. diameter and 15 ft. 6 ins. apart, were then hauled into place about 21 ft. above each catwalk. These strands, which passed over temporary portal frames or "goal posts" which had been erected at the main and side towers and the splay saddles, carried 58 transverse steel beams spaced at 200 ft. centres throughout their length. These beams, complete with all their fittings, including the rocker and pulley sheaves which supported the tramway or endless hauling rope, were slid into position along the strands. When in place, each cross beam was secured to the catwalks by means of tensioned ties so that the support strands shared the weight of the footbridge with the footbridge strands.

The endless hauling ropes that carried the two spinning wheels over each catwalk were each made up of two 1 inch diameter wire ropes 8,000 ft. and 7,000 ft. long respectively. After being hauled out on the footbridges, these ropes were spliced together in situ and tensioned to about 6 tons by means of a bogie at the north anchorage. Two spinning wheels were clamped to each hauling rope, one at the North and one at the South anchorage. Grooved to carry four bights of wire each, the wheels were supported in such a way that

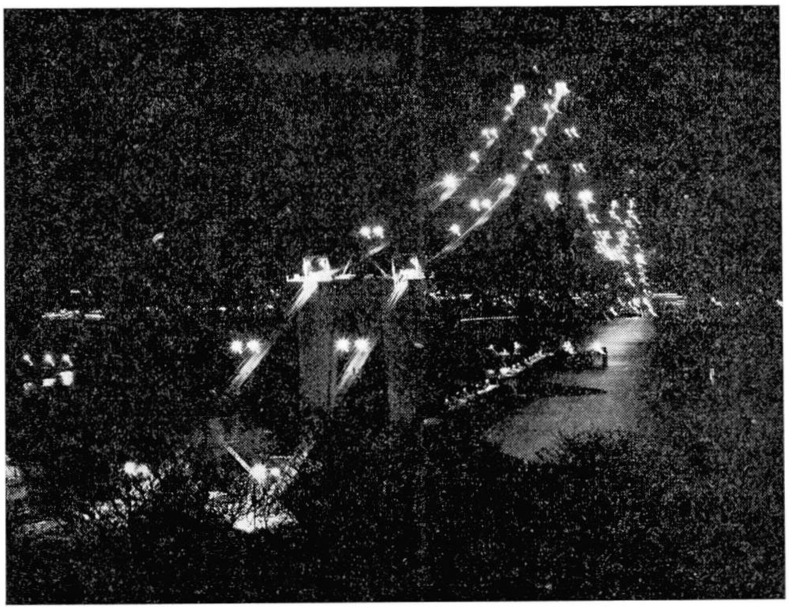

Fig. 4. Cable spinning by night.

Fig. 5. Cable spinning nearly completed — the last spinning wheel leaving the South anchorage.

they could readily negotiate the sheaves that carried the endless tramway ropes and so pass without difficulty through the "goal posts" at the various saddles. It should be noted that the back leg of the spinning wheel carriage was shorter than the front to avoid excessive deformation of the tramway rope which would otherwise have ridden out of its sheaves.

The method of spinning parallel wire cables adopted on the Forth Road Bridge was of course essentially the same as that developed and patented many years ago by John A. Roebling, and used by him on the Grand Trunk

Bridge at Niagara (1855) and the Brooklyn Bridge (1883). Through the years, and particularly in the cable spinning on the George Washington Bridge (1931), this method had been enormously improved and speeded up by new techniques and mechanisation. It had never, however, been used outside the U.S.A. because no bridge of sufficient span to warrant its use had been built elsewhere. Today it is a highly complex process, involving the design and use of many specialised machines, such as reeling and unreeling plant, tramway drives, compacting and wrapping machines and expert knowledge and experience of how to put them to the best use. The contractors for the Forth Road Bridge therefore decided to seek advice from John A. Roeblings Sons Corporation, Trenton, New Jersey, rather than embark on spinning the cables for the fourth longest span in the world without any previous experience of what was involved. This decision proved to be absolutely right and, not only in the design of the plant but also in the detailed organization of the site work, the Roebling Bridge Division and their engineers gave invaluable assistance.

The method of cable spinning is basically a simple one, loops of wire being carried over the span on a grooved spinning wheel by means of a tramway drive or aerial ropeway until they reach the far anchorage. Here the loops are pulled off the spinning wheel by hand and placed round a semi-circular strand shoe which connects them to the anchorage. At the near end the loops of wire are also placed by hand around a strand shoe at the near anchorage. So the spinning proceeds as the wheels shuttle to and for across the river. Each wire has to be adjusted for level in the main and side span to ensure that all wires have the same sag. Each cable is made up of 37 strands with an average number of 314 wires per strand. All the wires in one strand are connected to the same shoe, 37 strand shoes being provided at each anchorage. At the saddles and at the anchorages, the strands maintain their identity, but throughout the rest of their length the wires are compacted together so that the cable assumes a circular cross section of tightly bunched parallel wires.

At the start of cable spinning in November 1961, the drums of wire from the reeling shop were mounted in turn on eight electrically-powered unreeling machines which had been installed behind the South anchorage. From these, four ends of wire were passed through a high counterweight tower and thence looped by hand around the four grooves on the spinning wheel and led back to one of the strand shoes on the face of the anchorage to which they were temporarily connected. When the "despatcher" in the control office gave the order to start, the four unreeling machines immediately paid out the wires and at the same time the tramway drive machine set in motion the endless hauling rope to which the spinning wheels were attached. The speed of these machines had to be kept in conformity — but any small variations were taken up in the counterweight tower, which also ensured equal tensions in all the wires. In delivering four bights of wire to the far anchorage, the spinning

Fig. 6. A general view taken on last day of cable spinning.

wheel had laid ten miles of wire across the span. As it returned empty to the South side, the other loaded wheel was carrying another ten miles of wire across. When the spinning of each strand, with an average number of 314 wires, was completed, the wires of the last trip were spliced to the four ends that had been temporarily connected to the strand shoe at the start of it.

The speed of the spinning wheel, which was of course variable, attained a maximum of 700 ft. per minute. Of the eight wires placed each trip, the four first connected to the South anchorage were stationary or "dead" wires and were placed in hooks at the side of the catwalk. The other four, known as the "live" wires, which were travelling at twice the speed of the wheel, were hooked down by groups of men stationed at 400 ft. intervals along the foot-bridge and placed under live wire sheaves on the same side of the walks. To assist in identification of the wires, they were patch painted with a spray gun in different colours as they were unreeled, and the wires laid by each spinning wheel were temporarily housed on different sides of the walk.

The elaborate electrical installation on the footbridges included lighting systems throughout their length; 20 small winches for adjustment of individual wires by means of remote control; signal lights, 61 telephones and 34 hand trip switches that would immediately stop the spinning wheel in the event of emergency. In addition, there were no less than 272 pairs of "live" wire sheaves and 272 "dead" wire hooks, along the length of the catwalk; and 16 wire clamps installed at the saddles for use during the spinning of each strand.

The spinning was started in December 1961 — in what proved to be one of the worst winters ever known on the Forth. The steel erectors had to be trained in the work, which necessitated groups of men stationed at intervals of 400 ft., high over the Forth, working in intelligent cooporation, without

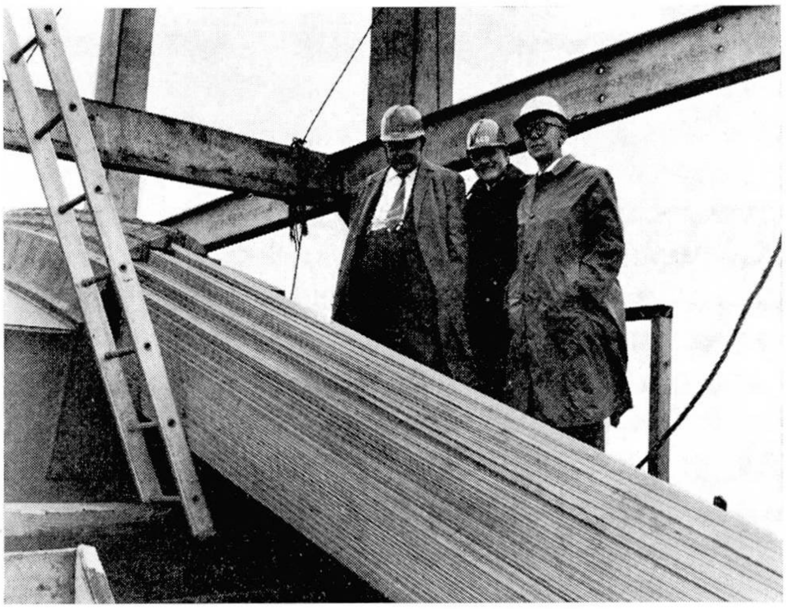

Fig. 7. Prof. Stüssi, President of IABSE, with Mr. W. Henderson, Bridge Engineer of the Scottish Development Department, and the Author, at the Saddle on the South tower top.

meal breaks or shelter, in two shifts from eight in the morning to midnight, adjusting the cable wires to the correct sag. Months passed before persistent high winds allowed two consecutive days of uninterrupted work. Roeblings' chief engineer who visited the site on several occasions, was appalled by the conditions which had to be faced.

In February, 1962, the site was hit by two terrific storms which blew for hours on end and gusting to over 100 m.p.h., at a time when only four or five strands had been spun on each footbridge and the work was in a most vulnerable stage. In the North-West side span the cables ultimately broke loose from their rope lashings to the catwalk and threshed around smashing up the intricate electrical installations and battering down 1,000 ft. of the parapet. Progress was brought to a standstill for six weeks while all the elaborate temporary installations of telephones, signal lights and sheaves on the catwalk were replaced and the parallel wires of the cables, which had become almost inextricably crossed and tangled, were combed out straight again. No damage was done to any of the permanent material.

After these initial difficulties, the men learned the job so well that they could lay more than 500 miles of wire in a good day. Nevertheless, the delays due primarily to wind amounted to 33%, compared with a normal loss in the United States of some 5%. Work was carried on in conditions of extreme cold and exposure. Low temperature halted work when ice on the cat walks made them dangerous.

Individual wires were each adjusted during spinning in the side spans and the main span. After each group of four strands had been spun they were untied one at a time and the wires shaken out throughout their length. A variation of 14 ins. in the sag at mid span of the high and low wires was considered permissible — any wires exceeding this tolerance were corrected. The final adjustment for level was carried out at night, by means of hydraulic jacks at the anchorages, as soon as each group of four strands was completed. The cable strands were then clamped in position in all the saddles — i. e. those at the tops of the main towers and the side towers and the splay saddles at the anchorages. The saddles at the tops of the main towers were fixed but the others were on rockers — the bases of the side tower saddles being jacked forward in three stages during erection of the suspended structure, so that they were finally vertical under dead load at mean temperature.

The main cables were then conpacted into a circular cross section throughout their length between the saddles, in which, of course, they maintained their hexagonal form. This was done by means of four specially designed conpacting machines which encircled the cables and travelled along them, squeezing the wires at intervals throughout their length, so that the ratio of voids was reduced to 21%. Working 24 hours a day in three shifts, the compacting was completed in three weeks.

The tramway support beams, storm systems and spinning equipment were then removed and the catwalks slacked off and hung at intervals from the main cables. Then at night, the positions of the suspenders were carefully measured and marked off on the cables so that the 192 cable bands could be bolted in place. Carried out on work cars running on the tram support strands, the two halves of each cable band were assembled in position and clamped together by bolts tensioned well into the plastic range.

Each suspender was made up of two bights of steel wire rope, which were laid in grooves formed for them on top of the cable bands, and terminated in two sockets at the lower end, which were bolted to the top of the panels of deck steelwork. No means of adjustment for length was provided and it is to the great credit of Messrs. Bruntons of Musselbourgh, who suppledi, prestretched, measured, socketed, and reeled all the suspendors, that no correction whatever was needed.

The suspenders were unreeled in turn on the platform at the tower top and pulled out along the catwalks by means of two work cars. The socketed ends were then lowered over pullies temporarily fixed at the cable band until the bights of rope landed in their seatings. The connection of the sockets to the deck proved very difficult near the tower because of the very tight clearances and the necessity to pull the cables down and the end of the deck up about 30 ins. in order to bring them together. As the distance from the tower increased, so the connections became easier. On account of the close spacing of the two suspender ropes that terminated in a common socket, permanent spacers had to be fitted at the mid-point of all suspendors longer than 150 ft., in order to prevent them from clashing together in storms or wind. Nearly all the painting of suspenders was carried out by four sets of "mucket" equipment used on

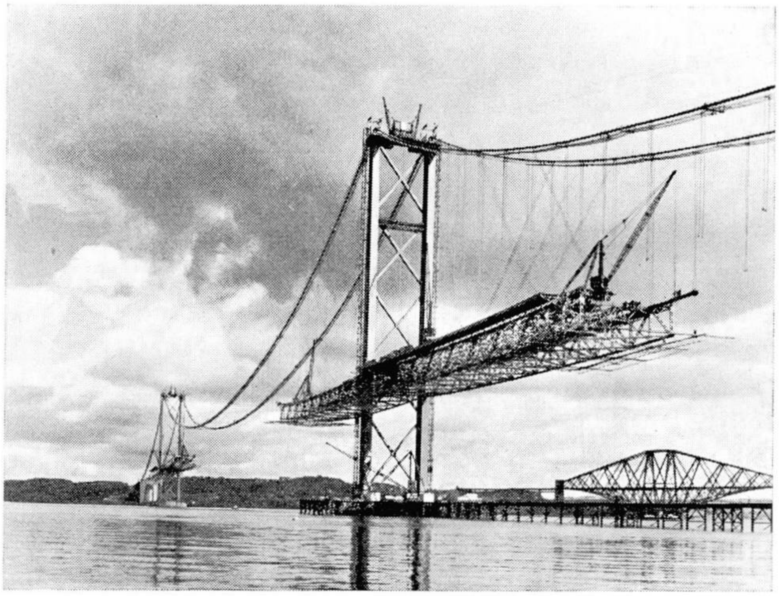

Fig. 8. A view during erection of suspended structure. Note temporary upward deflection of steelwork.

Fig. 9. Prof. Stüssi, Mr. W. Henderson and Author on the South "battledeck".

air-operated stagings, which were lowered from the cable downwards. The muckets consisted of small paint containers which could be split and reconnected around each suspender rope. As the muckets moved down the ropes, paint was fed into them under pressure and an even coat thereby applied and forced into the interstices of the surface of the rope. By using four muckets simultaneously in a cradle, a coat of paint could be applied to all four ropes at a speed of about 10 ft. per minute.

After compaction, the cables were wrapped around throughout their length between cable bands and/or saddles with 0.147 in diameter galvanised wire under a residual tension of about 400 lbs. Wrapping was started on the backstays because they are nearly straight and not subject to any subsequent distortion which might disturb the wrapping wire. In the side span it was begun as soon as the side span steelwork was erected; and in the main span as soon as the deck steelwork had been joined at mid span. Two large and intricate wrapping machines were used which weighed about 4 tons each and were designed for the purpose. Each consisted of twin wire reels and a power-driven "flyer" or revolving ring, which was concentric with the cable and supported on it. As the "flyer" revolved, the wrapping wire was pulled off the reels and laid round the cable, the last turn being held tightly against previous turns by means of four spring-loaded fingers. The drums which encircled the cable were split at the bottom and hinged at the top so as to enable them to pass the cable bands. The machine hauled itself along the cable and was capable of wrapping whilst travelling up or down hill. Ahead of the wrapping machine, the temporary straps round the cable were removed and the surface painted with a thick red lead compound. The joints between the wrapping wire and the edges of the cable bands were sealed with adhesive filler and the surface of the wrapping wire was finally given four coats of paint. The speed of wrapping was about 1 foot per minute which should enable the machine to wrap about 90 feet per day including all operations.

After the wrapping of each cable was completed, a permanent inspection walkway was made along the top of it, the two hand strands at the top of the parapets on the catwalks being transferred for this purpose. The job of dismantling the wire mesh from the footbridges proved one of the most potentially dangerous. The greatest care had to be excercised and the use of safety harness was made compulsory. It was done by eight gangs of men working up and downhill from the middle point of the side spans and the quarter points of the main span. After the ten foot panels of mesh had all been lowered to the deck by means of winches, the catwalk strands were disconnected at the side towers and lowered by the tower top derricks onto the footways and removed.

Erection of Suspended Structure

A very careful study had to be made to determine whether the 14,050 tons of steelwork in the deck should be delivered piece small, lifted to deck level and erected by travelling derricks working outwards from the towers; or whether panels of steelwork should be pre-assembled in a yard adjacent to the site, floated out on pontoons and lifted into place from the water. Other factors affecting the decision were the necessity to set up a big grit-blasting and metallizing plant for the protection of the steelwork and the provision of a large area with good rail and/or road access where steelwork could be stored whilst awaiting erection. In the event, the matter was settled by the absence of any suitable yard near the site and the very great cost of establishing one; and the offer by the Scottish Development Department of the use of part of their Bridge Depot at the disused air field at Drem, East Lothian, about 30 miles from the South end of the bridge, where good communications by road and rail existed and hangers and ample storage space could readily be made available.

The two stiffening trusses, which are 30 ft. deep and spaced 78 ft. apart, are inter-connected by cross girders at 30 ft. centres and have systems of lateral bracing in the planes of the upper and lower chords. The suspenders are at 60 ft. centres, so that the deck is divided into 55 panels of 60 ft. in the main span and 22 panels in each side span. The dual roadways, each 24 feet wide and 10 feet apart, are carried on stringers spanning between the cross girders and are approximately at the level of the top chords of the stiffening trusses. The footways and cycle tracks are carried on cantilevered extensions which project beyond the line of the main cables. In the main span, where the lightest possible type of construction is desirable, the roadways are of steel "battledeck" construction i.e. orthotropic plates stiffened on the underside by means of welded steel trough sections and transverse stiffeners. In the side span, however, where additional weight is an advantage, the roadways are formed of reinforced concrete slabs 60 ft. long and about $8^1/_2$ ins. thick. Steel curbs, surmounted by open grillage crash barriers, are provided on each side of each carriageway and all-welded steel parapets on the sides of the footways and cycle tracks.

Before the start of deck erection, the contractors had a series of wind tunnel tests carried out under the direction of C. Scruton at the Aerodynamics Division of the National Physical Laboratory, to ascertain how much of the steelwork could safely be erected in the first pass. At this stage, it was known that the connections in the lower chords of the stiffening trusses and the lower lateral system would necessarily have to be left open until after the two halves of the deck had been joined at mid-span. The original intention had been to erect the full 24 ft. width of both battledeck carriageways, without the cantilevered footways and cycle tracks, in the first pass. The wind tunnel tests, however, showed that if this were done, there would be severe aerodynamic instability under winds of 50 m.p.h. and upwards which would have built up uncontrollably until the deck tore itself to pieces. If, however, only a 16 ft. width of each carriageway was assembled in the first pass, leaving a 26 ft. wide longitudinal gap between them, and no cycle tracks or footpaths, the deck would be stable in winds up to 100 m.p.h., which was the maximum

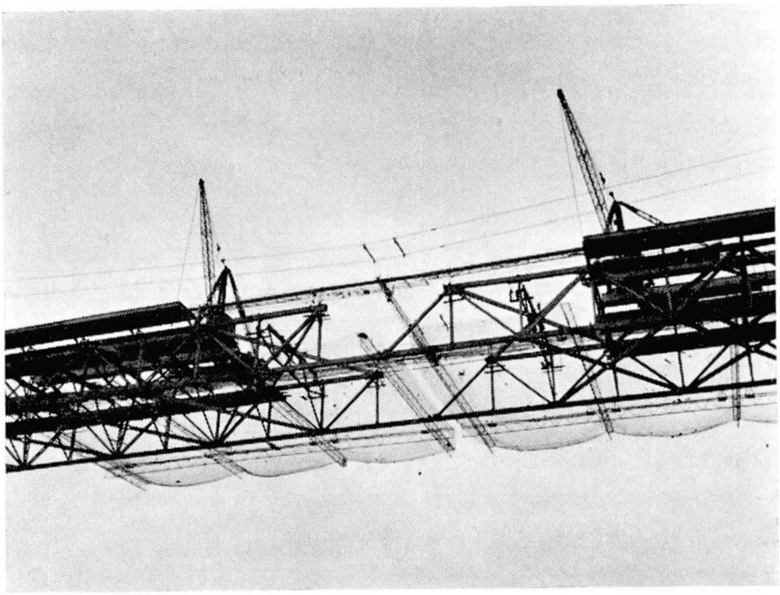

Fig. 10. Closure at mid point of main span. Note two sets of safety nets below steelwork.

wind speed employed in the tests. After trying various other possible arrangements, this solution was adopted as giving the most stable condition.

The first 90 ft. lengths of deck were cantilevered out from each side of each tower and the 15 ton travelling derricks assembled on them before the end of cable spinning, so that there would be no delay in starting deck erection. As soon as each panel of steelwork had been connected to the suspenders, the temporary crane tracks were extended and the derrick moved out to the end of the panel in order to erect the next one. The work in main and side spans was kept in balance until 18 panels had been erected on either side of each tower. Owing to the fact that the main cables, which were clamped in the saddles at the tower tops, had to stretch some 18 feet in their length of 7,000 feet between anchorages as the deck was erected and its dead load came onto them, the tops of the towers were at this stage deflected back a maximum of 30 ins. to the shore and the side spans were temporarily humped up. For this reason erection had then to be discontinued in the main span until the side span steelwork was completed. Concreting of the roadway panels in the side spans was then begun, the work being organized so as to spread the load as uniformly as possible along their length, whilst steel erection in the main span was completed. The gap at mid span before closure was $8^1/_8''$ in the top chord and $8^5/_8''$ in the lower chord which agreed within quarter inch of the calculated figures. Junction was then brought about by releasing the ends of the deck from the towers and so allowing the two halves to meet for connection at mid-span.

Before this occurred, the lower chord joints which had been opened began to close and were completed as soon as possible. Many connections in the middle of the side spans closed at much the same time and sometimes out of

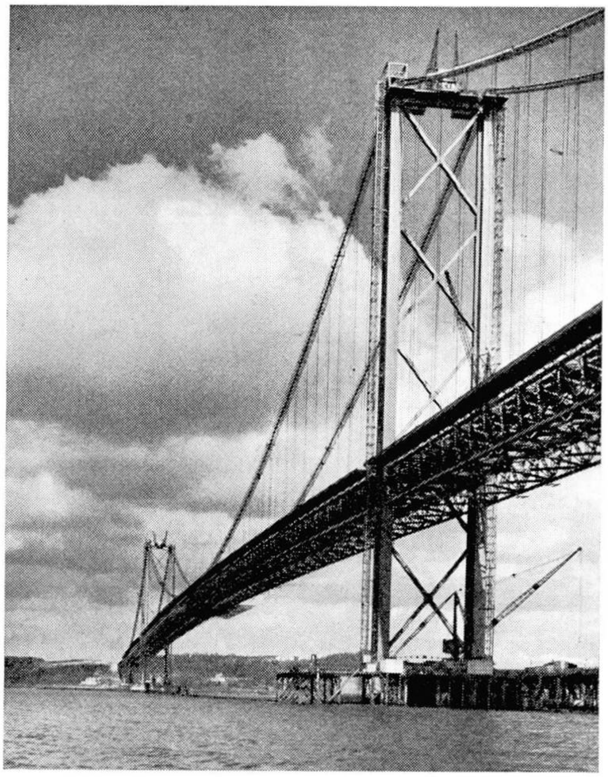

Fig. 11. A view of the bridge after junction of deck steelwork at mid span.

alignment, because the cover plates had to be temporarily left off to prevent risk of damage. Hydraulic jacks of 50 ton capacity had to be used to open the butts and drawing gear to bring the chords into line. The permanent painting stages had unfortunately not been designed at this stage and a prodigious amount of temporary staging was required for all this work beneath the deck where access was very difficult. In spite of giving it the highest priority, some three months elapsed after closure before all the lower chord connections could be made. Much time would have been saved if some provision had been made in the design for bringing the chord joints automatically into alignment as they closed.

The second pass erection in the main span was carried out by means of two gantries specially designed at the site, which moved from the towers towards mid-span, assembling the remainder of the deck steelwork. As junction had by then been effected at mid span and the majority of the bottom chord joints were completed, there was no further risk of aerodynamic instability and the whole of the "battledecks" could safely be assembled. Designed narrow enough to pass inside the suspenders, these gantries had hinged cantilevers at the ends which could be raised for the erection of the footway cycledeck panels. They enabled assembly and welding in the second pass to start three months earlier than would otherwise have been possible and, after quickly completing their work in the main span, were used to erect crash barriers and grillages in the side spans.

In order to resist lateral wind forces during erection of the first six panels of deck, the ends of the stiffening trusses were connected by temporary links to the legs of the towers, and the wind shear was resisted by the permanent longitudinal expansion joints provided on the centre line of the bridge. For erection of the sixth to the twelth panels, the expansion bearings in the main and side spans were temporarily clamped together at the towers, the temporary links at the ends of the stiffening trusses were removed, and sets of temporary diagonal wire rope cross bracings were used between the deck and main cable at the end three panel points. From the twelfth panel out to mid span the suspenders were shorter in length and better able to offer resistance to lateral wind forces, so that the cross bracings were no longer needed. No such bracing appears to have been necessary on any of the big suspension bridges in the U.S.A., and the need for it at the Forth was probably due to the exceptional lightness in weight and relative bulkiness of the suspended structure and "battledeck" panels and the exceptionally windy conditions obtaining at site. Even with this bracing in use, lateral deflections of the working fronts up to 13 feet or more were observed under winds of 60 m.p.h.

All the site connections in the suspended structure — apart from the joints between "battledeck" panels and connections of crash barriers and parapets — were made with high strength friction grip bolts, tightened by means of impact wrenches. All other connections were site welded. From mid 1963 to completion, a peak force of 25 welders under three foremen was fully employed, together with erectors who assisted in preparing the steelwork by means of *Z*-pieces, wedges and hydraulic jacks. The welds between adjacent panels of "battledeck" were carried out by means of two runs, using automatic Fusarc machines, no difficulties being encountered through distortion. Nothing was provided in the design of the grillages or parapets to assist in their assembly or alignment and a great deal of tedious and costly work was thereby involved.

During the whole of the deck erection, four huge assemblies of safety nets, measuring 196 ft. × 145 ft. in plan, were provided and moved out beneath the four working fronts. Made of terylene or nylon chord, the nets were supported on light tubular steel structures and cost more than £ 20,000. Throughout construction safety measures for the workmen were considered of prime importance. These included the compulsory wearing of safety helmets by everyone on the steelwork (which saved a number of lives), the provision of safety harness for any man requiring it and the appointment of the three senior engineers and foremen (including the Agent) as safety supervisors. No safety officer was employed as such because the job was too complex and it was considered better to charge all engineers and foremen with the responsibility for safety in their sectors, and by means of regular meetings to keep it in the forefront of their minds. Decisions to provide safety appliances which cost many thousands of pounds have to be made at a high level and designs for them prepared months before they are needed at site.

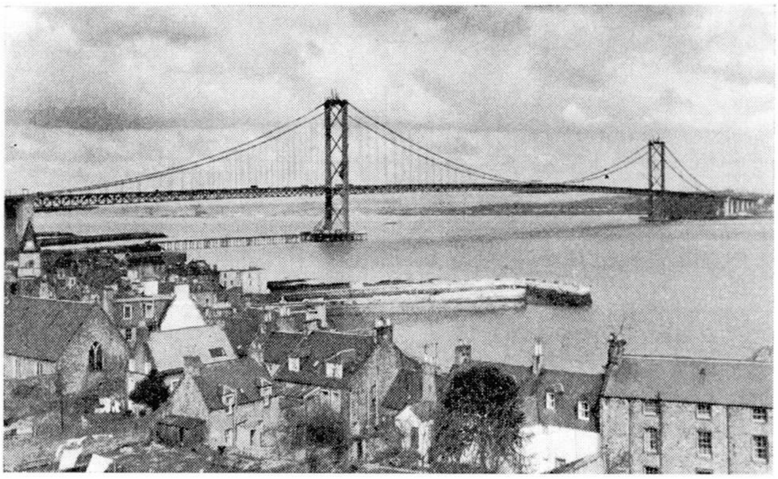

Fig. 12. General view of bridge nearing completion.

The contractors' staff was made up of engineers and foremen with world-wide experience of bridge building. The labour force reached a peak of 400 men during cable spinning and deck erection and working agreements laying down fair comprehensive rates of pay keyed to production and taking into account the arduous considitions, were hammered out in meetings on the site. Good labour relations are largely a matter of psychology, patience and understanding. The management's endeavour was to build up a team and their measure of success can best be judged by results. In nearly five years work there was no official strike at all, and unofficial strikes occupied less than 2% of the time of one trade only.

Concreting of the deck slabs in the side span roadways was begun in October, 1963, and completed during the six winter months. Three sets of shutters for the full width of each panel, more than 60 ft. long, and heated underneath when necessary, were used. The concrete was heated at the mixer and poured at not less than 45° F. The shutters were moved from panel to panel on rollers running on the lower flanges of the stringers; they were jacked up to the correct level when in place and had the edges of the formwork sealed against the stringers by means of rubber Ductube inflated from $1^1/_8''$ to $1^3/_4''$ diameter which effectively retained the grout.

Expansion joints of rolling leaf design, developed and patented by Demag A.G., were provided in the deck on either side of each main tower. These permitted longitudinal movement of the suspended structure as well as a degree of rotation in the horizontal and vertical planes. Sliding plates sufficed for the expansion bearings in footways and cycle decks.

To protect the "battledeck" panels and form the running surface on the carriageways of the main span a layer of mastic asphalt $1^1/_2''$ thick was laid by hand. It was found that much better adhesion was obtained if the steel-work was newly grit-blasted before the asphalt was laid. In the side span a similar thickness of hot rolled asphalt was machine-laid on the concrete. The surfaces of all footway cycle decks were thinly coated with rubberized bitumen and spread with fine granite chips.

Protection of Steelwork

The grit-blasting, metallizing and painting of the fabricated steelwork was nearly all carried out in a purpose-designed plant installed in available hangers at Drem Airfield. One of the hangers was extended to house a huge grit-blasting chamber and zinc-metallizing machine together with all necessary transporting and handling gear, and a second hanger converted for use as a painting shop. A 35 ton Goliath crane on 500 ft. tracks was used for lifting heavy pieces, such as sections of the towers, and mobile cranes for the lighter lifts. All the heavy steelwork was treated at Drem, where the peak labour force over four years amounted to 66 men, some of whom had to work on night-shift and the total internal and external areas treated, including painting, reached a figure of more than 10,000 square yards per month.

Acknowledgments

The Consulting Engineers for the whole Forth Road Bridge project were Messrs. Mott, Hay and Anderson with whom were associated Messrs. Freeman, Fox and Partners for the main bridge and approach viaduct. The foundations and anchorages were built by John Howard & Co. The contract for the supply and erection of the main span superstructure was awarded to the A.C.D. Bridge Company, a consortium formed by three major bridge construction firms — Sir William Arrol & Co. Ltd., The Cleveland Bridge and Engineering Co. Ltd. and Dorman Long (Bridge and Engineering) Ltd. On a job such as the erection of the superstructure of the Forth Road Bridge, costing some nine million pounds and involving many imponderable risks from weather and other causes, contractors cannot fairly be asked to quote firm prices except for the supply of materials. For this reason a form of target contract was worked out which allowed fair payment to the contractor for his site and other costs, while at the same time ensuring that the client would not be called upon to pay heavily for risks which might not materialise. The target contract also provided a strong incentive element which ensured that the work was completed as economically and quickly as possible.

It gave the engineers on site great pleasure to welcome Prof. Stüssi, President of the IABSE, when he paid a visit to site during erection of the suspended structure — and also when he and Mrs. Stüssi accepted an invitation to attend the opening of the bridge by H.M. Queen Elizabeth II on 4th September, 1964.

Summary

The Paper describes the erection of the superstructure of the Forth Road Bridge, which was opened to traffic in September 1964, and was at that time the longest single span in Europe and the fourth longest in the world. The work fell into three distinct phases. First was the building of the two steel towers, 505 ft. high, on either side of the River. Second, the spinning of the two main cables which pass over the tops of the towers and are anchored on either shore; and finally, the erection of the suspended deck, which is hung from the cables and carries dual 24 ft. wide roadways and the cantilevered cycle tracks and footpaths.

The economy in design and lightness in weight of the Bridge gave rise to unique problems which were enhanced by the extraordinarily adverse weather conditions encountered at the Site, which is in latitude 56° North — much further North than any major suspension bridge in the world. These are fully discussed, together with the effects of aero-dynamic action during erection of the towers and suspended structure, and the measures taken to obviate them. Details are given of the supply and erection of the parallel wire cables, the temporary footbridges and the many specialised machines required for the spinning, compacting and wrapping of the cables.

In conclusion, particulars are given of the labour relations, the emphasis on safety precautions, and the target contract adopted which operated very fairly to both client and contractor, and ensured that the work was completed as economically and quickly as possible.

Résumé

L'auteur décrit le montage de la superstructure du pont-route sur le Forth, qui a été livré à la circulation en septembre 1964 et, à cette époque, représentait la plus grande portée simple d'Europe et la cinquième du monde. Les travaux comprennent trois phases distinctes. On a construit d'abord les pylônes métalliques, hauts de 154 m. On passa ensuite au filage des câbles principaux, reposant sur les pylônes et ancrés sur chaque rive. Pour terminer, on monta le tablier suspendu aux câbles et qui porte deux chaussées de 7,3 m ainsi que les postes cyclables et les trottoirs en encorbellement.

La conception très économique et le faible poids du pont ont donné lieu à des problèmes sans précédents, aggravés par les conditions météorologiques extrêmement défavorables rencontrées sur place, à 56° de latitude Nord, beaucoup plus au Nord que ce ne fut jamais le cas pour un pont suspendu important. L'auteur traite à fond de ces problèmes ainsi que de l'effet des phénomènes aérodynamiques pendant le montage des pylônes et du tablier et il présente les mesures prises pour y parer. On donne des détails concernant

les câbles à fils parallèles, avec leur montage, les passerelles provisoires et les nombreuses machines spéciales pour le filage, le serrage et l'habillage des câbles.

Pour terminer, l'auteur donne des détails concernant les conditions de travail, l'ampleur des mesures de sécurité et le contrat adopté, qui a donné pleine satisfaction au maître de l'œuvre comme à l'entrepreneur et a garanti une exécution des travaux aussi économique et rapide que possible.

Zusammenfassung

Es wird die Montage des Überbaus der Forth-Straßenbrücke beschrieben, die im September 1964 dem Verkehr übergeben worden ist und zu jener Zeit die längste Einzelspannweite in Europa und die fünfte der Welt darstellte. Die Arbeiten können in drei Phasen aufgeteilt werden. Zuerst wurden die zwei 154 m hohen Stahlpylonen errichtet. Hierauf folgte das Spinnen der Hauptkabel, die auf den Pylonenköpfen aufgelagert und an jedem Ufer verankert sind. Schließlich wurden die Versteifungsträger montiert, die an den Kabeln angehängt sind und zwei je 7,30 m breite Fahrbahnen sowie die auskragenden Rad- und Gehwege tragen.

Die Wirtschaftlichkeit des Entwurfs und das leichte Eigengewicht der Brücke führten zu einmaligen Problemen, die zudem vergrößert wurden durch die außerordentlich ungünstigen Wetterbedingungen an der Baustelle; diese befindet sich auf 56° nördlicher Breite, also viel nördlicher als jede andere große Hängebrücke der Welt. Diese Probleme werden ausführlich besprochen zusammen mit den aerodynamischen Einflüssen während der Montage der Pylonen und der Versteifungsträger sowie den Maßnahmen, die zu deren Vorbeugung getroffen wurden. Es werden Einzelheiten über die Paralleldrahtkabel und deren Montage, über die provisorischen Laufstege und die zahlreichen Spezialmaschinen angegeben, die für das Spinnen, Pressen und Umwickeln der Kabel benötigt wurden.

Abschließend bespricht der Verfasser die Arbeitsverhältnisse, den Umfang der Sicherheitsmaßnahmen und den für diesen Bau abgeschlossenen Vertrag, der sich sowohl für den Auftraggeber als auch für die Unternehmer günstig erwies und eine möglichst wirtschaftliche und rasche Ausführung der Arbeiten gewährleistete.

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