THE STRUCTURE AND PROGRESS OF THE FORTH BRIDGE.[1]

As a visit to the works of the Forth Bridge is included in the programme of the present meeting of this Institution, the author trusts that a short sketch of the preliminary proceedings, with a description of the structure and progress, from one engaged on the work from its outset, will prove of interest in explaining the reasons and means adopted for connecting the railways on opposite shores of the Firth of Forth, at the site of the historic ferry and still existing Hawes Inn, whose time-table for the departures of the ferry-boat is so quaintly alluded to in "The Antiquary."

Previous Proposal.—For many years, suggestions for establishing direct communication between the southern railways running into Edinburgh and the Fifeshire lines, with the object of more direct access to Perth and the north, had been frequently considered by the companies interested in that route; but until an Act of Parliament was obtained in 1873 for the construction of a suspension bridge, designed by the late Sir Thomas Bouch, for crossing the Forth at the site of the present works, no proposal gave prospect of successful issue. Although the type of bridge then proposed was not one generally considered applicable for the passage of railway trains, yet no positive objection seems to have been taken to it, inasmuch as a contract was entered into for its construction, workshops were erected at the site, and foundations were started. But after the severe gale at the close of the year 1879, so destructive to a viaduct in an equally exposed position, it was deemed prudent to suspend operations; and the directors of the North-Eastern, Midland, and Great Northern Railway Companies, which each have an interest in obtaining direct access to the eastern and northern districts of Scotland, requested their respective consulting engineers, Mr. T. E. Harrison, Mr. W. H. Barlow, and Mr. (now Sir John) Fowler, to confer together and report upon the possibility of some other plan for making through communication between the existing lines at the point already selected. Tunnelling was out of the question on account of the depth of the water; the proposals therefore took the form of bridges.

Present Plan.—On May 4, 1881, the engineers submitted their joint report, unanimously agreeing that the steel bridge on the cantilever and central-girder system, designed by Sir John Fowler and Mr. Benjamin Baker, was not only the least expensive, but the best suited for the situation. The soundness of this decision has since received confirmation in the fact that seven long-span bridges have been or are now under construction in different parts of the world, and many more are proposed on the principle adopted for the Forth Bridge. For the substitution of this design in place of the suspension bridge contemplated in 1873, the Forth Bridge Railway Company appointed Sir John Fowler and Mr. Baker their engineers, and obtained an Act of Parliament in July 1882. The financial obligations for the construction of the bridge having been undertaken by the railway companies interested in the through route—namely, the North-Eastern, Midland, Great Northern, and North British—tenders were invited for the work, and from the applications received two offers were selected; and with the combined firm of Messrs. Tancred Arrol and Co. a contract was made in December 1882 for the entire execution of the work.

General Dimensions.—The total length of the bridge will be 8300 feet, or 380 feet over one mile and a half. There are two main spans of 1700 feet each, two side spans of 675 feet each, with the ends counterbalanced and anchored to the masonry, and three intervening piers; these together make up about a mile of the total length, and the remainder is composed of fifteen approach spans of 168 feet each, and of masonry arches and abutments. For a length of 500 feet in the centre of each of the two 1700-feet spans there is a clear headway for navigation of 150 feet above high water; the rails being placed at a level 6 feet higher. From the base of the deepest pier to the top of the cantilevers the total height is 450 feet, or only 10 feet less than the Great Pyramid of Egypt.

The cross sections of the main spans are of trapezoidal form, 330 feet in height from centre to centre of the members over the piers, and 33 and 120 feet in width across top and bottom respectively, and tapering towards the ends of the cantilevers, thus giving a form which is eminently suitable for withstanding lateral pressure. The girders carrying the railway are supported at intervals inside the cantilevers, &c., by trestles or cross frames, and a continuous lattice-work parapet $4\frac{1}{2}$ feet above the rails extends the whole length of the bridge.

Load, and Wind Pressure.—In addition to its own weight the bridge is being constructed to support, without exceeding in any member the unit stresses permitted by the Board of Trade, a load equivalent to trains of unlimited length equal to 1 ton per foot run on each line of railway, or passing trains consisting each of two engines and tenders at the head of sixty coal trucks weighing 15 tons each; and also to withstand a lateral wind pressure of 56 lbs. per square foot of exposed surface of train and structure. The magnitude of the lateral pressure may be judged from the fact that over the mile length of main spans the estimated surface exposed to a point blank wind at right angles to the bridge amounts to a little more than $7\frac{1}{2}$ acres; the pressure of 56 lbs. per square foot on this surface would therefore be equivalent to a total of more than 8000 tons. In addition to lateral winds, the direction from any point of the compass has been provided for, even including the imaginary condition of each group of main piers becoming the centre of a whirlwind. Effects of temperature will be provided for in the rails, and at the junctions of the central girders with the cantilevers; and the bearings on both the main piers and under the weighted ends of the cantilevers have provision made for allowing movements due to changes of temperature and to the elasticity of the cantilevers under lateral pressure. The lateral play allowed is limited, so that the whole of the piers may act in concert to resist combined actions of all forces tending to disturb the normal state of rest of the 50,000 tons of permanent load. As a further provision 48 steel bolts of $2\frac{1}{2}$ inches diameter, secured 24 feet down in the masonry by anchor plates, hold down the bed plates with an initial tension of 2000 tons; the nuts and saddle-plates are so arranged as to allow freedom of lateral movement to the skew backs; but any lifting would at once be prevented by the anchorage coming into action, which however could only happen under the assumed circumstances of a wind pressure more than double that already mentioned, acting over the whole estimated surfaces. The maximum pressure on the base of the piers will be a little over 6 tons per square foot.

Forms of Parts.—The enormous forces to be resisted have been met by adopting the most suitable forms of parts for withstanding the stresses. Tubular members are used for compression, and open-braced box-forms for tension. These parts vary in size as required. Though the tubular form has scarcely been used in this country for bridge members since its employment by the late Mr. Brunel, no difficulty has arisen in connexion with its use; even the junctions are dealt with as readily as the generality of the work.

Masonry.—The masonry for the main piers, above the whinstone concrete filling of the caissons, consists of a casing of Aberdeen granite, inclosing and bonded into a hearting of Arbroath stone set in cement, and strengthened by three massive wrought-iron belts built into the stone-work. The deepest pier weighs about 20,000 tons. The remainder of the masonry of the piers and abutments is of a similar class, whinstone being largely used in the interiors.

Steel.—For the principal members of the superstructure subject exclusively to compression, the steel used has a tensile strength of from 34 to 37 tons per square inch, with at least 17 per cent. of elongation in a length of 8 inches; for the other parts 20 per cent. of elongation, with 30 to 33 tons tensile strength. The rivet steel has 25 per cent. elongation, and 26 to 28 tons tensile strength per square inch. The whole of the steel is manufactured by the Siemens process. No sheared edges or punched holes are permitted.

Work started.—No time was lost by the contractors in starting the work. The land was at once entered on; the old workshops were put in order, and the extensive range of offices, stores, workshops, and yards was commenced, which now cover fifty acres. Meanwhile the centre line of the bridge was fixed, and the position of the piers determined. The foundations of those on land were begun simultaneously with the building of temporary jetties for gaining access to the piers that had to be sunk below water-level. These jetties, which are still used for conveying the material, are in themselves no small work; the southern or Queensferry jetty extends 2200 feet from the shore, and is connected with the workshops by an incline worked by a rope driven by a stationary engine. In order that the operations might be carried on continuously day and night when needful, electric light installations, supplemented by lucigens, were laid

[1] Paper read by Mr. E. Malcolm Wood before the Institution of Mechanical Engineers, on Tuesday, August 2.

over the works and piers; and telephonic communication was established between the offices and all the centres of operations. The workshops and yards were rapidly completed, and furnished with tools, of which many are of a special and novel description. Ever since the commencement the work has progressed without interruption, and has gradually assumed the gigantic proportions of the present time. Over 3000 hands have been employed continuously for the last year; and during the present summer months the number has been increased to 3600. The majority find lodgings in the neighbourhood of the bridge; and the remainder make use of a special train service to and from Edinburgh, and a steamer to and from Leith, put on for their use night and morning.

Materials.—The materials for the permanent work have been obtained throughout from producers of repute: Aberdeen granite from Messrs. Fyfe; Portland cement from Messrs. Hilton and Anderson and Bazley White; Siemens steel from the Steel Company of Scotland and the Landore Steel Works. All the steel has been subjected to rigid examination, and has passed the ordeal of specified tests before leaving the makers' works; a few specimens showing its high quality are exhibited. The materials delivered up to the present time have included—

Granite	550,000 cubic feet.
Portland cement	21,000 tons.

The amount thus far erected has been—

Masonry in piers and abutments ...	129,500 cubic yards.
Steel in approaches and main spans	19,000 tons.
Steel for main spans, prepared ready for erection, about	20,000 tons.

By the time the first consignment of steel arrived, the shops were ready for the preparatory operations, and the whole establishment was rapidly organized to deal in the most complete manner with the work to be executed. Hydraulic power is freely used, from the extremely neat form of shop crane to the 2000-ton press for curving the tube-plates. With the exception of the main-pier caissons, made by Messrs. Arrol Brothers of Glasgow, and the superstructure of the approach spans by Messrs. P. and W. Maclellan of Glasgow, the whole of the work has been turned out of the shops at the bridge, their present capacity being an output of 1300 tons of finished work per month.

Shop Practice.—The procedure in the shops may be described as follows. The flat plates and bars are first straightened. The plates to be curved are heated to a uniform red heat in a gas furnace, and while red-hot are moulded in dies under hydraulic pressure to the required form, stacked and coated with ashes, and allowed to cool slowly and equally; any subsequent warping is taken out by placing them again in the press when cold, and giving them a final squeeze into the correct shape. The butts of the bars are cold sawn, and the edges and butts of the flat plates are planed in the usual manner. The ends of the curved plates are planed in a novel form of machine, in which the tool travels in a circular path readily adjusted to the radius of the curved plate. On completion of the planing, the plates are taken to the tube yard, and are built up round the longitudinal ribs and internal stiffening frames, which have previously been fitted together in moulds to the exact diameter required: so that the plating of the framing at once gives the tube its proper form. The plates are in 16-feet lengths, and break joint alternately over the stiffeners at 8-feet intervals. Means are adopted to keep the tubes in line while the rivet holes are pierced by a travelling annular drilling frame, which is mounted on wheels and carries a boiler and engine driving ten drills by cotton ropes. A pair of drills are attached to each bed; and as the beds can traverse the circumference of the tubes, while the drills can traverse the length of the beds, the whole outside of the tube is commanded, and the holes are completed with accuracy to insure their precise coincidence when the parts are rebuilt at the site. As fast as each section of 8 feet length is finished, the machines are propelled along the rails to take up a new position; they thus travel gradually in successive stages over the whole length laid down. The tee and trough-shaped parts are built together in the shops, and the holes are drilled by adjustable vertical and horizontal drills, fitted to a travelling carriage; the power is transmitted to the machines by ropes from the shop shafting. Numerous radial machines are also in use for the secondary parts. For dealing with special parts, many ingenious and somewhat novel workshop appliances have from time to time been brought into use, beyond those here mentioned. All the parts of the junctions are carefully fitted together in the yard in the exact positions they will relatively occupy in the bridge. After each member has been prepared, the pieces are painted, marked, and stored until required for erection.

Founding Piers.—With the founding of the piers below water commenced the more difficult part of the undertaking; but without any sensible delay the whole of the piers have been successfully sunk and completed. The foundations for piers in shallow water were put in either by tidal work or by open cofferdams, and the excavation was carried down to boulder clay or rock. Though these were of individual interest themselves, from the size and difficulties met with, they are dwarfed by the magnitude of the operations connected with the deep-water piers, of which those in the south group are embedded in the boulder clay in one case at 90 feet below mean water-level, while at Inchgarvie they rest on a level bench cut out of the sloping whinstone rock at a depth of 72 feet.

Caissons.—The caissons for all the deep piers are 70 feet in diameter at base; the cutting edges and shoe are of steel, and the upper parts of wrought-iron. They were first built on ways on the south shore, and were launched with sufficient ballast on board in the form of concrete to insure their stability while towed out to their berths at the end of the jetties, where guide piles and dolphins were used to place them in correct position. Temporary wrought-iron cofferdams were built upon the top of the caissons, timber working decks constructed, cranes and concrete mixers fixed, air-pressure connexions made good, and sinking operations commenced with a pressure in the excavating chamber sufficient to drive out the water; the air-compressing machinery was placed on the jetty alongside. The Inchgarvie caissons had to be equipped with all these fittings while moored to the south jetty, so as to be ready for work on arrival over their rocky bed.

The working chamber was illuminated by electric lights; and communication was effected with it through three shafts with air locks on the level of the upper deck. The two shafts for the skips bringing up the excavated material were constructed with horizontal sliding shutters, worked by hydraulic rams, in place of the usual swing doors. The winding drum for bringing up the skip from the working chamber was not in the lock itself, but driven by an engine outside. On arrival of the skip in the lock, the lower slide was shut to, and the blow-off cock opened for releasing the pressure, the top slide drawn back, and the hook of the discharging crane was coupled to the skip by hand. This direct and rapid method of transit for the excavated materials greatly facilitated the sinking; the whole operation from arrival of the skip in the lock to its removal lasted only about three-quarters of a minute in ordinary working, the sequence of the movements being automatically controlled by interlocking gear. The air locks in the third shaft for the men were constructed with a view of rapidly changing shifts, and had double chambers, each capable of holding seven men.

The silt overlying the harder deposit was expeditiously expelled from the working chamber by means of ejection pipes passing into water outside, the air-pressure being sufficient to blow out charges of silt and water mixed in a box which communicated by a valve with the ejection pipes. On reaching the boulder clay, portable steel diggers, actuated by hydraulic cylinders placed between the roof and the implements, were brought into use to break up this hard material.

At Inchgarvie a modification of this system was required for sinking the deep piers into the hard whinstone rock, which had a natural slope of 1 in $4\frac{1}{2}$. Bags of sand and concrete were deposited in two piles on the deeper side of the site to be occupied by the caisson which had been launched with massive timber blocks in the chamber, to rest upon this artificial bed; these blocks and the edge of the caisson touching the rock on the shallower side were the first bearings it took when lowered at the site. The whole of these primary operations required extreme care to provide for differences of weight on the base, due to the depth of water at different states of the tide. Then by means of rock drills and ordinary quarrying operations inside the air-chamber the rock was excavated until the caisson was sunk to a level bench cut out of the sloping rock. In these caissons the full pressure of air due to the head of water was maintained during the sinking, and it was found advisable to change the gangs every four hours; the maximum pressure reached at high tide was 33 pounds per square inch above the atmosphere. The last of these caissons was got down to its final depth in October 1885.

In sinking the southern group of caissons, the air-pressure hardly ever exceeded 22 pounds per square inch, the silt and clay acting as a lute; and the working shifts were of six hours' duration, about twenty seven men being down at a time.

Recovery of Canted Caisson.—With the exception of the north-west pier in the southern group, the whole of the piers were completed with regularity. But the caisson for that particular pier, weighing with concrete some 3000 tons, while ready at the site for placing in its final position, by some means became waterlogged on New Year's Day, 1885, and on the tide falling slid forwards on the mud about 15 feet, and canted over through 25°. After an ineffectual attempt to right it by pumping, regular siege was laid to it; but not until the autumn following, after nine months of incessant work, was a timber jacket or cofferdam completed, which enabled the pumps at last to obtain command over the leaks. The caisson then floated again, and after repair was sunk in position in the ordinary manner, arriving at its final depth in 1886. After the excavation had been completed, the chambers were rammed with concrete and grouted up, the concrete and anchorage and masonry were completed, and the temporary cofferdam was ready for removal.

Men Employed.—No difficulty arose in obtaining a sufficient number of men inured to work under air-pressure, as M. Coisseau, of the firm of MM. Couvreux and Hersent, of Paris, brought his staff of trained excavators from the Antwerp harbour improvement works, and contracted for the work to be executed under air-pressure.

Raising Viaduct Girders.—After the masonry of the approach viaduct piers had been carried up to a convenient height, a temporary stage was built, upon which the girders were erected and riveted up. Steel cross-beams with pairs of hydraulic jacks were placed under the ends of the girders over the piers; and a stage surrounding the piers was suspended from the main girders. From this platform the men in charge of the rams conducted the operations of lifting and blocking up the girders; and the masons afterwards completed the stonework in the vacant spaces. By this plan the girders were raised to their final height in July of the present year. The whole of the ten spans on the south side were lifted simultaneously as soon as they were all riveted up. The materials for the piers were first raised in trucks, by a steam hoist on the jetty, to a tramway laid on beams between the bottom members of the girders, and afterwards lowered into position by winches over each pier, these winches being driven by running ropes from engines on the girders at alternate piers. These approach spans now require only the parapet and a few other details for completing them in all respects, ready for the permanent way.

Erecting Steel Work over Main Piers.—On the completion of the masonry, the operation of erecting the steel work was commenced on the northern piers early in 1885 by riveting up the bed plates, and lowering them into position over the heads of the foundation bolts. Their surfaces were afterwards smoothed by emery wheels, and coated with crude petroleum, to prepare them for receiving the bearing plates of the cantilever bases or skewbacks. These, as already mentioned, have freedom for a limited amount of sliding, and the gauges at present attached show that the sliding movements follow the changes of temperature as anticipated.

The skewbacks, forming the junction of five tubular and five rectangular members over the piers, were then erected, and were connected with the horizontal members at the same level, which had been built together on a stage. After the connexions had been riveted up, a commencement was made upon the upper parts over the piers; these parts have since been erected without any form of fixed scaffolding, and the operation is still in progress over the Inchgarvie piers.

The lifting gear for raising the erecting platforms consists of a pair of plate frames, one below the other, fixed inside each 12-feet pier-column, by pins passing through the wings of the frames and the ribs of the column. The lower frame supports a hydraulic lifting press; and upon the ram rests a through box-girder cross-beam, at right angles to the length of the bridge, passing through voids in the columns, where plates are temporarily left out for this purpose. These cross-beams support lattice-girders in pairs, one on each side of the column, which extend a little more than the full length of the side of the quadrangle formed by the piers. Upon the top of all comes the main deck, furnished with gantries, cranes, oil-heated rivet-furnaces, &c., complete in all respects for carrying on the chief operations of erection. On the bottom level of the girders is a lower deck, with the ends housed in to form temporary shelters for the men. The box and other girders are built up of parts which will eventually be used in the permanent structure. Communication between the level of the jetty and the platforms is made by hoists, drawn up between wire-rope guides by the winding engine on the level of the jetty, which lifts the material by wire ropes to the platform; safety clutches are attached to each cage, for seizing the guide ropes in case the hauling gear were to give way. During lifting operations, access to the platforms is gained by ladders laid up the cross-bracing between the main columns over the piers.

The process of raising the platforms is as follows. Water-pressure at about 30 cwts. per square inch is conveyed from pumps on the jetty to the lifting presses by wrought-iron piping taken up the inside of the columns, and is turned into a cyinder, lifting the load off the series of pins in the top frame. The pins are then withdrawn, and the ram lifts the box-girder, carrying with it the loose frame, until opposite the next series of holes in the ribs of the columns, into which the pins are then inserted; the pressure is released, and the box-girder again rests upon the upper frame. In the return stroke the ram, hanging by its shoulders from the upper frame, by means of its piston form now hauls up the lower frame, from which the pins have been withdrawn; and when this has been repinned, it is ready to support the press for another upward stroke. By this means the platforms have been gradually raised, generally through lifts of 16 feet at a time, until arrived at the summit. On their way up they have been utilized for building the tubular cross-braces and other work; and at the present time those at the southern and northern piers form the stage for erecting the top members between the heads of the main columns. The platforms at Inchgarvie are now only 40 feet below the height to which they will have ultimately to be raised.

In building the pieces together, they are connected by service bolts, until the hydraulic riveters are brought into action. For the open work the riveters are of the gap type; but for the closed tubular work, a special adaptation was devised by Mr. Arrol, by which the rivets are closed in any part of the built tubes. When these machines arrive at the top of the columns, after having completed the riveting on the way up, they are taken apart ready for application elsewhere.

Erecting Cantilevers.—The building out of the first projecting bays of the cantilevers is being conducted on the system just described, with such modification as to suit the altered circumstances. The bottom members are first erected, and have been built by means of overhanging frames in panels, resting upon the completed portions of the tube, and so constructed that, as fast as the work is riveted up by the annular riveting machines, and the forward portions of the cage-like framing are brought into bearing, the back frames can be unshipped and taken forwards to the working face. Upon the top of this framework a movable hydraulic crane is placed for lifting the pieces into position, which are brought alongside from the pier by carriers suspended from a single rail of angle bar. As soon as the limit is reached at which these members can support the projecting work, inclined supporting stays are introduced, which connect the bottom member at this part with a temporary horizontal tie stretching between the main columns at about the level of the cross-bracing; thence the inclined stays slope down again, and are attached to the bottom member on the other side of the pier. After this has been done, platform girders with decks are built at a convenient level to rest on cross-beams carried by rising frames, which are introduced between the corners of the first vertical member of the bridge: this member having been pierced beforehand with a series of pin-holes, in readiness for a lifting action similar to that used in the main columns. The ends of the platforms nearest the piers are raised by suspension bars, by the action of hydraulic rams attached to the main columns at a higher level. From these platforms, as in the previous cases, the erection of all parts commanded by them is carried on as they rise.

The erection of the secondary parts proceeds simultaneously with that of the main members, the railway girders being built by corbelling out from the supports, and the other parts by light stages when the parts themselves cannot serve as a means of support to extend the work. As will readily be understood, the erection of these sections calls for greater nerve and judgment on the part of the men employed than does that of the portions previously described.

In conclusion, the author desires to express his indebtedness to Sir John Fowler and Mr. Benjamin Baker, through whose kindness he has been enabled to place before the Institution the foregoing particulars respecting an undertaking which, as shown by the magnitude of the works now being carried on, constitutes one of the greatest engineering feats ever attempted.

THE MACHINERY EMPLOYED AT THE FORTH BRIDGE WORKS.[1]

THE greater part of the machinery at the Forth Bridge works is original in design and novel in construction, chiefly because of the unusual nature of the work to be carried out. It may be roughly classed under the following heads: hydraulic bending and setting, planing, drilling, erecting, and riveting. In designing the machinery and tools to accomplish these different kinds of work, there had ever to be kept in view rapidity of production, with a very high quality of work in the finished structure. An idea of the quantity of machinery provided to deal with the material passing through the shops may be partly formed from the fact that it is capable of finishing 1500 tons in a single month.

Hydraulic Bending and Setting Machinery.—To bend and twist the large steel plates required in the construction of the tubes and their connexions, a great variety of hydraulic presses had to be provided. The largest of these is capable of exerting a pressure of 1600 tons between the dies. It consists of four 24-inch cylinders, resting on two longitudinal girders bedded in concrete. From each cylinder rise two iron colums, which carry a fixed table overhead. On the top of the rams another table is placed, which can be raised or lowered at will. Between these two tables are placed the blocks which stamp the plates to the desired shape. In most cases this shape is the arc of a circle, but in others the form is very varying, while in some instances the plates are flanged as well as bent or twisted. In nearly every case, after a plate has been set while heated, it requires to be finally adjusted when cooled. To dispense with the heating of the plates gives unsatisfactory work, and is in many cases impossible. In no instance is this plan of bending adopted to any extent without annealing the plates both before and after the work has been put upon them. Much of the final adjusting of the plates is done by presses consisting of a simple ram fixed to the upper of two girders, which are bound together at the ends, the lower girder serving as the seat for the block on which the plate is placed. Numerous other forms of presses are employed for lighter work.

Planing Machinery.—A special class of machinery is employed to plane the edges of the plates. In the case of most of the plates this requires to be done very carefully, because in the structure of the bridge a certain percentage of the stress in compression is taken up by the plates butting, instead of wholly by the rivets as in the tension joints. This statement applies to all plates in the tubes.

The sides are first of all planed on what may be looked upon as an ordinary planing machine. It is provided however with special double side-cheeks, between which are two fixed swivelling tool-boxes, one on each side of the machine. These tool-boxes can when desired be transferred to a special cross-slide, as it is sometimes more convenient to work with one box in the cross-slide rather than with both between the side-cheeks. Both tools act together and cut continuously—that is, during the backward as well as the forward travel of the table. The plate to be cut is fixed upon a curved block, which in turn is securely bolted to the table.

For planing the ends of the curved plates a special machine had to be designed and built, in which the plates are secured to a fixed table, while the tool is made to travel backwards and forwards in a swinging pendulum that receives its motion through a connecting-rod from a travelling saddle. The tool cuts both ways in this instance also, and is fed to its work by hand.

The planing machines employed to finish the rectangular plates for girder work are of the usual pattern for plate-edge planing, but with the addition of an end slide provided with a separate tool for planing one end of the plate at the same time that one of its sides is being similarly treated. This machine finishes a plate at two settings, with the certainty that the ends are at right angles to the sides.

In some machines two saddles are upon the main slide, and in others two tools are in one saddle; both devices have their advantages. The facing of the tees, angles, and other sections is done as a rule by cold steel saws, in order to secure good butting.

Drilling Machinery.—As will be inferred from the varying character of the work, the drilling is performed by various classes of machines. The principle kept in view is that, wherever possible, girders, tubes, &c., should be drilled only while their various parts are temporarily built and held together by bolts in the position they will finally occupy in the finished structure; in this way the highest class of work is obtained.

For drilling the tubes, the machines, each complete in itself, are made large enough to embrace the entire circumference of the tube. They consist of a wrought-iron under-frame or carriage, on which are placed the engine and boiler. On it are also fixed two large cast-iron annular rings or headstocks, embracing the tube, round which ten drilling slides and heads travel circumferentially. The slides are moved around the rings and consequently around the tubes by a worm at each end, gearing into a worm-wheel that forms part of the rings. The motion of the drill-heads on the slides is longitudinal, or parallel to the tubes. These two motions easily permit of the ten drills working at any part of the circumference of the tube comprised between the two annular rings, which embrace a length of 8 feet. When this length is finished, the whole machine is travelled forwards, and is again ready to drill a new length of 8 feet. The tube rests on timber blocks, which are removed from the front and placed behind as the machine travels forwards. In the case of the lighter tubes, the rate of drilling is as high as 12 lineal feet of tube per shift of ten hours; this represents about 800 holes drilled

The booms of all girders are drilled separately on blocks, thus leaving the bracings to be drilled to template, which is done by radial drills at another time. The machines employed to drill the booms are of a wholly different kind from those used for the tubes. They are moved along rails, running on each side of the blocks upon which the booms are built, and parallel with them. They consist of a double carriage with upright columns, connected together by means of a cross-beam and sundry other framing for carrying the shafts, pulleys, &c. To the columns and cross-beam are secured slides, to which the fixed drill-heads are bolted on the front of the machine; while to the back are attached radiating arms, each carrying a single drill. In this way there are both fixed and swinging drills on the two sides of the machine, capable of drilling holes in either a horizontal or a vertical plane. The fixed drills serve for all holes in the regular pitch, while the movable drills take what may be called odd holes, such as those where the struts and ties are to be secured to the booms. All the fixed drills are self-feeding, but the movable ones are fed by hand. The number of drills simultaneously at work varies greatly; at times as many as thirteen have been employed together on a single boom.

Other machines having radials with only single drills are used for a special class of drilling, and are found to work to great advantage. With the exception of a few special tools, all the remaining drilling is done by radials capable of making a complete circle round the column on which they are supported. Tables are placed on each side of these machines, and the work is fixed on one of the tables; and as the drills are placed at a convenient distance from one another, all the drilling required is easily accomplished without a second shifting of the work.

Erecting and Riveting Machinery.—To erect and rivet such large quantities of material at the immense height at which much of it requires to be done demands a large quantity of special plant for riveting and other purposes. The ordinary class of riveting is accomplished by means of small portable riveters, consisting of two arms held apart by links and stays; one arm acts as the holder-on, while the other carries the hydraulic cylinder for supplying the power, the cylinder and arm together forming one casting. For some of the more difficult work, where neither could this form of riveter be employed nor could the work be done by hand, small direct-acting hydraulic cylinders were used; the die for forming the rivet-head was here fixed into the piston. Two 4-inch cylinders were usually employed, held

[1] Paper read by Mr. William Arrol before the Institution of Mechanical Engineers on Tuesday, August 2.