compound had been adopted. Mr. Whyatt's experience with tar-varnish appeared to have been unfortunate; and it suggested that the material was either faulty or improperly applied, for the Author has used it extensively for many years on outside work, such as iron piers, bridges, etc., with great success. Before selecting the material to be used to coat the structure, he had a dozen wrought-iron plates, 12 inches square, covered with two coats of different compounds, and suspended them about 50 feet above some chemical-works in the district for 3 months; this was a severe test, as the atmosphere was heavily laden with chemical fumes. From the results obtained, he decided upon the paint or compound to be used for the various parts of the structure. The longitudinal movement of the stiffening-girder was checked, as stated in the Paper, by the adoption of raking guys $3\frac{1}{4}$ inches in diameter, fixed between the centre pin and the cables. The Author.

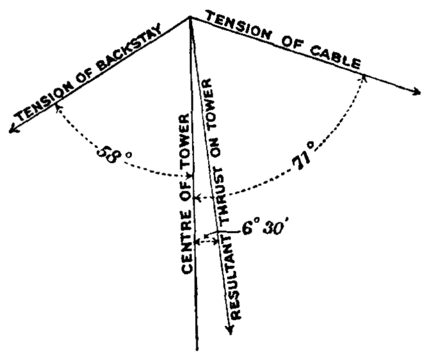
The PRESIDENT remarked that deposits corresponding in appearance with the one alluded to in the Paper were found in many places in the neighbourhood of lakes and estuaries, especially in the north of Ireland. The material had the appearance of clay, but was entirely composed of diatomaceous material; it was used largely in the preparation of explosive compounds such as nitro-glycerine, also for non-conducting covering for boilers. The President.

## Correspondence.

Mr. F. ARNODIN, of Châteauneuf-sur-Loire, observed that the Widnes and Runcorn transporter-bridge was a remarkable work in more than one sense. The fact that this bridge was the longest suspended span in the United Kingdom rendered it the more regrettable that in its construction the improvements realized in transporter-bridges erected in other countries had not been introduced. In the following critical examination of it questions of details and cost of construction would be neglected, and only defects which might have an influence on the security and life of the work would be considered. Judging by Fig. 1, Plate 1, the back-stays were inclined at an angle of 58° to the vertical, while the tangent to the parabolic cable was inclined at an angle of 71°. The resultant force due to the tensions in these two directions acted along the bisector of these combined angles, that was Mr. Arnodin.

Mr. Arnodin. to say, along a line inclined at 6° 30′ to the vertical (*Fig. 33*). As this line passed outside the base of the towers, it followed that these were subjected to an overturning tendency towards the river, and that the supports on the river side were stressed much more than those on the land side. In order to remedy this the saddles which carried the cables (Fig. 2, Plate 2) had been placed on an oscillating sector, and the cables rested in a groove on the saddles, where they were clasped by jaws in order to prevent them from slipping. This was not a happy arrangement, for the single cable was composed of nineteen elementary strands, in contact at points of the circumference, which left between them very appreciable voids. The grouping of these elements could not then be considered as forming an immovable and incompressible whole. By the tension as well as by the dilatation, the points of contact were indented under the pressure, and the jaws lost little by little the energetic grip which in principle should hinder the slipping. It followed that the slipping was always to be feared, and if it occurred it might bring about the ruin of the whole structure. Besides, the back-stays being more inclined than the cables suffered an extra tension of about 12 per cent. As the cables were of uniform section

*Fig. 33.*

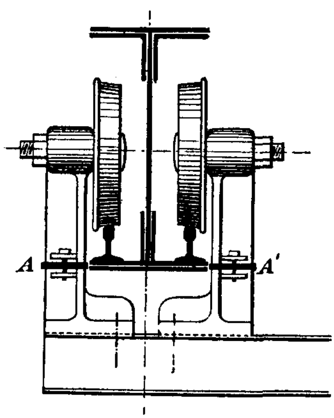



throughout their entire length, the back-stays were subjected to a stress 12 per cent. in excess of that in the parabolic portion. From this it appeared that there was either insufficient section in the back-stays or excess of section in the parabola. It was to obviate these two inconveniences that in all the other suspended transporters in the world a junction had been made over a gudgeon on the top of the pillars, in such a way as to prevent absolutely all possible slipping, and to enable different sections to be adopted for the back-stays and cable, so that they might sustain the same stress. Fig. 7, Plate 2, showed that the elementary strands, to the number of nineteen, were grouped in hexagonal form and surrounded with a common envelope serving for protection against oxidation. Experience had proved that in this kind of cable, whatever steps might be taken, there always existed interior voids wherein rain-water accumulated by percolating through imperceptible fissures in the envelope. The water flowed in these voids as in so many tiny canals, carrying deterioration into the centre of the bundle. This deterioration might not begin for several years if the preservative coverings had been applied with the greatest care; but when it began it made rapid progress, for as it was hidden from inspection it could not be counteracted, and a cable of this kind was thus doomed to comparatively rapid destruction. It was for the purpose of avoiding this defect that in France it was now the practice to keep the cables separate from one another, in order to be able to inspect and paint them when necessary. In connection with the preservation of large suspended works French engineers had gone farther, and the French Minister of Public Works prescribed in the regulations for new works the principle of "interchange" which Mr. Arnodin had introduced into all his suspension-bridges. This principle consisted in arranging the members in such a way that it was possible to displace any piece whatever, repair it or change it for a new one, and replace it in its original position, without being obliged during the operation to displace the neighbouring pieces, or even to interrupt the normal service of the work, the strength of which was quite sufficient when depending on the fellow-members of that which had been displaced. For this purpose members of the same kind were built in multiple, there being at least three side by side. According to this principle of interchange, when a cable deteriorated in the course of a number of years, it would be replaced by a new one without having to demolish anything; and by repeated replacement it would be possible to make the suspension-bridge last indefinitely, just as a railway was maintained. The Newport transporter-bridge, which was now being constructed by Mr. Arnodin in collaboration with the borough engineer, Mr. R. H. Haynes, was the first work in the United Kingdom constructed on this principle, although it had been applied in France for the last 10 years. In Figs. 24 and 26, Plate 3, the trolley from which the transporter-car was suspended was shown running on rails placed on the side of the lower flange of the main girders. This was a bad arrangement, for it developed in the girders an unsymmetrical stress which tended to tilt the girder, and when the girder became inclined the wheels tried to leave the rail. This might cause a grave accident, for the flanges of the wheels were insufficient to prevent derailment. In the transporter-bridges which had been recently constructed, *e.g.*, those at Rouen, Martrou, Nantes, Marseilles, care had been taken to put symmetrically on each side of the web of the girder a double line of rails, as in *Fig. 34*, in such

Mr. Arnodin.

Mr. Arnodin. a way as to exert only symmetrical stresses, and not to produce any tendency to distortion, whatever might be the load carried on the transporter-car. There was a gain in having the wheels in duplicate for the suspender from the car, for it permitted the removal of either of the wheels even when working, without any fear of the corresponding cable being slackened. By placing small horizontal wheels at A and A′ an arrangement was obtained which absolutely resisted any tendency to derailment. The conditions were then superior to those of ordinary wagons on a railway, which were liable to be derailed, and whose wheels it was impossible to replace during their normal work. There was an advantage in putting a number of wheels to bear the transporter-car in order to obtain a relatively light load on each; and in order not to fatigue the angles of the main girders which carried the rails, the length of the car and the obliquity of the suspenders which supported it necessitated the extension of the framework of the trolley to a considerable length. It followed that if axle-motors had to be employed it was necessary to use many, otherwise the motor-wheels would slip on the rails without causing movement. Under normal conditions the four motor-axles provided at the Widnes and Runcorn bridge were probably sufficient for the traction, but when a gale was blowing, or when the car was heavily loaded, the traction would be difficult; for, as the weight in the car increased, the flexibility of the suspension-bridge increased, and the resistance to traction became very appreciable. Now, as the motor-axles were placed at one-quarter and three-quarters of the length of the trolley, it resulted from the deflection of the bridge under the load that the extreme wheels carried proportionally more than those of the motor-axles, and the latter were consequently more liable to slip. Lastly, the slipping of the motor-wheels wore them more than the free wheels, and this wear still further diminished their power of adhesion. These different phenomena had been well understood by the constructors of all the other transporter-bridges in

*Fig. 34.*



Mr. Arnodin. the world, including that at Duluth, Minn., for all of them had preferred to haul the trolley by means of a cable, with wheels turning freely on their axles. All the wheels were then in the same condition of rolling as those of a wagon hauled by a locomotive. Besides affording security of travelling during stormy weather, this arrangement had the advantage of requiring less motive-power.

Mr. Colson. Mr. C. H. Colson observed that it would be interesting if the Author could describe more in detail the methods adopted to form the cable from the separate strands, and to ensure that each strand took its proper share of work and was in exactly its right position. The reasons which had led to the steelwork in the anchorage being coated with "several coats" of tar-varnish were not clear. The numerous experiments made during the last few years on the corrosion of steel when embedded in cement concrete had proved fairly conclusively that clean steel embedded in non-porous concrete was quite unaffected by corrosion, and that even if the steel were slightly rusty before being placed in position, no ill-effect was to be feared. The protective action was said to be due to the formation of a silicate of iron; but if the steel was painted or covered with tar-varnish before being placed in the concrete, this silicate could not be formed; hence if the tar or paint coating was at any time destroyed, a void would be left into which water might penetrate and set up the corrosive action that would have been prevented had the concrete been in actual contact with the iron. For this reason it appeared to be unfortunate that the anchorage-links had been coated with any paint or tar composition. In Mr. Colson's practice the steel bars when brought on to the works were reasonably cleaned of all rust and coated with thick cement grout applied as paint; this appeared to stop further corrosion and to keep the bars in good condition. It was perhaps doubtful whether the concrete in the cylinders was sufficiently rich in cement to ensure its being water-tight. Some time ago he had the opportunity of inspecting the remains of ferro-concrete piles which had been cut off during the construction of a jetty and left for 5 or 6 years on the foreshore, covered by the sea at every tide. On breaking open the pile-ends it was found that, where covered by the concrete, the bars were in quite good condition, whereas the ends projecting outside the concrete were almost eaten away by rusting. In view of the small size of the tower-cylinders it would be useful to know what considerations had governed the selection of the pneumatic process for sinking them instead of the method of excavating under water inside the cylinders by grabs. The latter method would have been cheaper and would have allowed of continuous working.

Mr. Duryea. Mr. EDWIN DURYEA, jun., of San Francisco, whose experience with suspension-bridges consisted of about 6 years' work in various capacities in connection with investigations for, or the design and construction of, several large suspension-bridges, including the Williamsburg bridge, New York City, of 1,600 feet span, the old Brooklyn bridge, of 1,596 feet span, and the proposed Hudson River bridge, at 59th Street, New York, of 2,850 feet span, remarked that the discussion of the Paper might be divided into two parts; first, the uses for which the bridge should have been or had been built, and the completeness with which the special structure under discussion provided for them; and secondly, the structural features of the bridge. In respect of its object, which was to provide for pedestrian and vehicular traffic only, the bridge was similar to one recently completed in the United States at Duluth, at the head of Lake Superior.[1] In that case the only object secured had been pedestrian and vehicular traffic between the city of Duluth and Minnesota Point, a narrow spit of land more than 6 miles long and only a few hundred feet wide, separating Lake Superior from the Bay of Superior, which included Duluth Harbour. A much more important object, that of giving direct railway connection between the mainland and Minnesota Point, thus adding 6 miles of much needed dock-room to the harbour, had been entirely neglected; though the building of a tunnel about 2 miles down the Point, the subsequent dredging of a canal over this tunnel from the lake to the harbour, and, finally, the filling-in of the present canal (all of which had been suggested some years ago) would at the same time have given this additional dock-room and greatly improved the harbour in other ways. It was not apparent, however, that any such additional benefit could have been secured in the case of the Widnes and Runcorn bridge by a more positive connection of the two sides of the river; and if no such larger need really existed, the present structure should serve all purposes. At the same time, as a permanent carrier of general traffic a transporter-bridge was at best only a makeshift, in comparison with an unbroken roadway; the cost of the structure was £133,000, or about $650,000, which was a large sum; and fuller explanation seemed necessary to show why the additional cost of a bridge or tunnel with an unbroken roadway would not have been well expended, or why the unbroken roadway might not even yet be needed in the near future to provide for increase in traffic, or for classes of traffic which could not be adequately served

[1] C. A. P. Turner, "The Ferry Bridge across the Ship-Canal at Duluth, Minnesota." Trans. American Society of Civil Engineers, vol. lv, p. 322.

by a transporter-bridge. With regard to structural design, the choice of a suspension-bridge seemed a wise one in view of the comparatively long span (1,000 feet), the rock anchorages which were economically available, and the very light moving loads. Although the Author did not state it clearly, the maximum total moving load on the span—the transporter-car with its trolley, hangers and traffic load—might be inferred to be only 120 tons, or only 269 lbs. per foot of span. The Author was to be commended for his choice of a suspension-bridge, but not for his treatment of the subject in his Paper. The most severe criticism on the Paper, from the standpoint of an engineer who had had to do with suspension-bridge design, was that it dealt principally with details, and almost entirely neglected to treat the methods used in the design. These were of special interest in connection with suspension-bridges, as no standard methods of design and computation for such structures seemed yet to have been agreed on by the few engineers who had had to deal with this form of construction. The value of the Paper would be greatly increased if much fuller data were given as to loads, methods, assumptions, formulas, and results. At present it contained very little which dealt with the actual design of suspension-bridges. The characteristic elements of a suspension-bridge were the cables, the anchorages and the stiffening-trusses. The towers were of equal importance, but had no special relation to the suspension principle. The platform and its suspenders were subordinate features. The ideal suspension-bridge, it was believed, should have as few cables as practicable—preferably only two, unless they would then become too large—and should have only two stiffening-trusses. The tower at each end of the span should have not more than four posts, or preferably only two, and these arranged to rock at the base. Cables should preferably be "straight" in the shore spans, but if it was desirable or necessary that the shore spans should carry loads, their cables should then be anchored near midspan by anchor-bents to limit the deformations of the cables. In general, it was unnecessary and unadvisable to cradle the cables. The bridge under discussion conformed to some of the above requirements, but to others it did not. The sag of the main cable was about 84 feet, or about one-twelfth of its span. This ratio was too small for bridges of longer span and carrying heavier loads, the economical proportion for these being about one-eighth, equivalent to 125 feet for the Widnes bridge. The small sag here used seemed advisable, however, because of the (for a suspension-bridge) short span and the very light loads. The effect of the smallness of the sag was to increase the changes in sag arising from variations in temperature and stretch, and to decrease Mr. Duryea.

Mr. Duryea. the deformations of the cable from moving loads and thus lessen the duty which must be performed by a stiffening-truss. It would be of interest to learn how fully the changes in the cables from variations in temperature and from deformations and stretch caused by moving loads had been considered in the design of the structure. In the cables a detail which differed from what was considered good practice in America was the fastening of the ends of each strand to the anchor-chain by means of sockets. In America, good practice had always been thought to require that the wire in each strand should be continuous, except for unavoidable splicing, and that the strand should be directly connected to the anchor-chain by a loop. Numerous tests should of course show whether socketing was safe and could develop the full strength of the strands, but the feeling among American engineers had always been against the use of sockets. No large or important American bridges had them in cables, and the best practice did not sanction their use even in suspenders. The use of a centre hinge in the stiffening-truss was very commendable. Its safe use, however, entailed some provision to limit the bending in the cables above the hinge, from changes in sag. This could easily have been accomplished by supporting the suspenders at the centre of the span on a special casting of somewhat large radius, resting on the cable. The cradling of the cables seemed advisable in this case to resist the wind-pressure, because the light weight of the structure and its small width (35 feet) compared with its span, gave it but little power to resist the wind. It did not, however, seem advisable generally to cradle cables, as the complications in the structure which resulted were not usually justified by the comparatively small good effects thus secured. The saddles at the top of the towers were unusual in only two features, neither of which was entirely new, but both of which were good. One was the use of segmental rollers, and the other was the adoption for the back cable of a different angle with the horizontal from the main cable. The last feature had been proposed by Mr. Joseph Mayer in connection with his designs for a bridge of 2,850 feet span over the Hudson River; as had been also the positive connection of the cable to the saddle, and of some of the suspender-clamps to the saddle by an auxiliary cable. The wisdom of the Author's adoption of a steeper slope for the back cable seemed doubtful, however, as greater stress in the back than in the main cables was thus caused, and hence the size of the cables was increased throughout their whole length. It would be interesting to learn whether the saving in length of the back cables and the possibly better conditions at the anchorage-pits fully compensated for the increase in cost of cables due to the steeper

Mr. Duryea.

back angles. The anchorages were of a usual design and simple and effective. The filling of the pits with concrete around the lower ends of the anchor-chains at once, followed later by the complete filling of the anchor-chain tunnels, was a very advisable feature and one which had been adopted in the best American practice. The eight posts at each end of the span in the Author's design had been used in America, but these were unnecessarily complicated and were adverse both to a clear determination of stresses and to economy of construction. The use of a two-post tower rocking on its base, at each end of the span, would have served all purposes, greatly simplified the structure, and saved a very appreciable part of the cost of the towers and foundations. If the rocking tower was not considered desirable, much simplification and saving in cost could still have been effected by using a four-post instead of an eight-post tower. One of the most characteristic elements of a suspension-bridge was the stiffening-truss. The design of stiffening-truss used by the Author was believed to be wise in including a central hinge, but no advantage had been taken of that hinge to adopt rational and economical proportions for the stiffening-truss. With a central hinge it was practicable to adopt the economical proportions, which were approximately those of other trusses, say a height equal to one-ninth of the span with a curved top boom, or perhaps one-twelfth with a horizontal top boom. The span here meant was one-half the cable-span, or the distance from the central hinge to either tower, namely, 500 feet. The economical height of truss would then be perhaps 56 feet with a curved top boom, or 42 feet with a horizontal top boom. The uniform height of the truss as built was 19 feet, only one-twenty-sixth of the half cable-span. If a definite degree of stiffness was to be provided by the stiffening-truss, this could have been secured much more economically by a higher truss; or with the same expenditure as for the lower truss, much greater stiffness would have been provided by a higher one. This question had been treated thoroughly and mathematically by Mr. Mayer,[1] and also, without mathematics, by Mr. Duryea.[2] It was questionable, however, whether the degree of stiffness already provided in this bridge was not unnecessarily high. In view of the unprecedentedly light moving load and the small sag of the cables, it would seem that local stiffening only might be sufficient, and the larger function of the stiffening-truss (the dis-

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[1] "The Stiffening System of Long-Span Suspension Bridges for Railway Trains." Trans. American Society of Civil Engineers, vol. xlviii, p. 371.

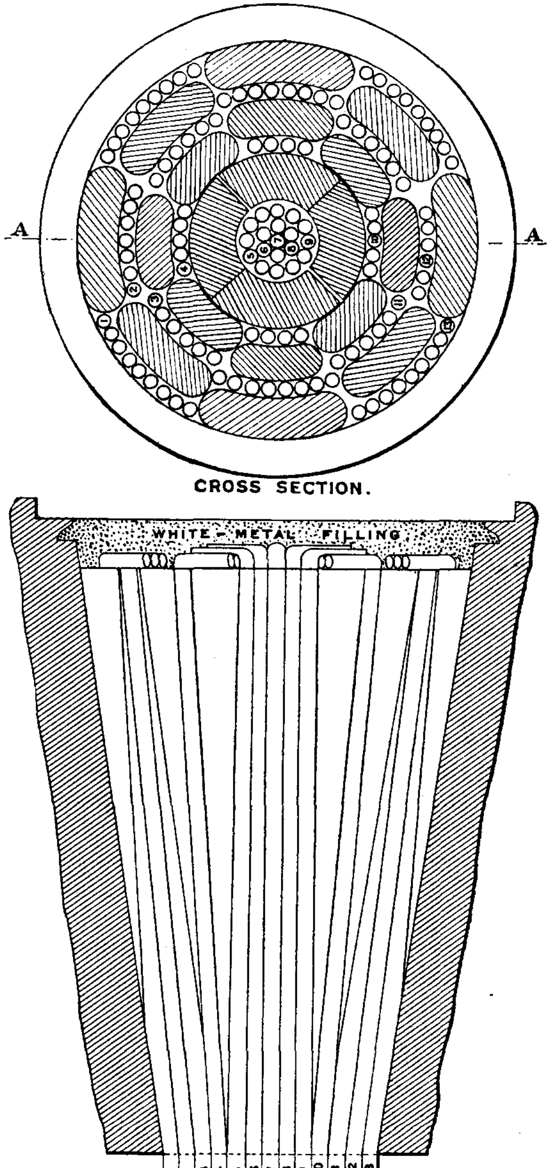
[2] *Ibid.*, p. 442.

Mr. Duryea. tribution of local loads over the whole cable-span) unnecessary. However, the light fixed loads, due in part to the absence of any platform or floor, tended to make the necessity for the true stiffening-truss distribution more probable. The mathematics of suspension-bridge design dealt principally with the relations between cables and stiffening-trusses, and if the Author would include a full treatment of this in his reply great value would be added to his Paper. The single, definite, short, moving load made the problem unusually simple and definite, and permitted of accurate treatment to an unusual degree. With regard to the specification, the requirements for Portland cement were lower as to both strength and fineness than those usual in ordinary American practice, and Portland cement of the qualities specified would not usually be acceptable in first-class American engineering work at the present time. The proportions specified for concrete showed the use of rather richer mixtures than were usual in American works, but the specifying of cement and aggregates only, without giving the proportions of sand and of stone or gravel in the latter, made the two practices rather hard to compare. In general, the most common American practice on first-class concrete work was 1 part cement, 3 parts sand and 5 parts broken stone or 6 parts gravel (packed volumes)—the richest perhaps 1 : 2 : 4, and the poorest perhaps 1 : 3 : 7. The specifications, as given, did not permit of machine mixing of concrete. Machine mixing was now almost universally used in America, and was believed to be in England, not only because of its cheapness, but also because better concrete was believed to result from it. The minimum elongation specified for the steel was somewhat low according to American ideas. Examination of the abstract of contract prices indicated that in general the prices for the Widnes bridge were higher than the prices would be for corresponding work in America. This might be partially due to the small quantity of each kind of work in this bridge. Mr. Duryea's general impression was that the total cost of the Widnes bridge was unduly high in comparison with the somewhat limited service, which was all that could be given by a transporter-bridge. His ignorance of local conditions, however, might render this view erroneous.

Mr. Glover. Mr. W. J. Glover, who had been responsible for the manufacture and erection of the steel cables, observed that in his opinion the design adopted for the cables presented many advantages over the selvagee form of cable, constructed by laying parallel wires together. In that form the uncertainty of obtaining uniform tension on all the wires would be increased by the action of the wind during adjustment, and any slackness appearing on compressing the separate bunches of wires could not then be eliminated before lowering them into their final position. The aggregate loss in strength in the selvagee form of cable when tested under the most favourable conditions in a carefully prepared straight length, amounted to 3 per cent. of that of the individual wires. This loss was inevitably increased when dealing with bunches of 127 wires, as movement was unavoidable in bringing the separate wires into position after adjusting their deflection. A distinct advantage was manifest in erecting the machine-laid section of cable, by avoiding the necessity of sending men across the span, however great. The 127-wire section, when laid in the form adopted by the Author, lost only 6 per cent. in strength, although the margin allowed in the Paper was set at the safer figure of 10 per cent. The total number of wires appearing on the surface of the cable-sections was 28 per cent., and when grouped in the saddles and clips, 18 per cent. only were visible before covering with the waterproof sailcloth double serving. Experiments upon the limit of elasticity of cable-wire, recorded by Mr. G. C. Henning, showed the remarkable figure of 95 per cent. The original specification for the first East River bridge wire called for a limit of elasticity of 47 per cent., although actual deliveries showed fairly uniform results of about 85 per cent., which was the limit accepted as obtainable on steel cable-wire of 200,000 lbs. breaking-stress per square inch of section. The difference was doubtless accounted for by results obtained with the special recording-apparatus referred to by Mr. W. Hildenbrand, and not by any increase in the elastic limit of wire produced since the first East River cables were made. It would be interesting to hear the outcome of the Author's further correspondence on this subject with Mr. Hildenbrand. The erection of the main cable-sections had been successfully accomplished by the arrangement described by the Author. The carriers were mounted on the Blondin rope and fixed to the hauling-rope, but ran free on the section of cable to be passed across the span. Upon the leading end being pinned down to the opposite anchorage, the endless hauling-rope was reversed, thus withdrawing the running clips and leaving the erected cables free. The method of fitting the sockets to the ends of the strands and the arrangement of the wedges was shown in *Figs. 35.* It consisted of a symmetrical arrangement of the smallest number of wedges to ensure an unyielding grip upon the whole of the 127 wires. By this method the wires were disposed in regular form between mild steel wedges of sufficient proportions to permit the wedges to be driven home simultaneously, and finally by the application of a drift and a heavy hammer. The ends of the wires Mr. Glover.

Mr. Glover.

*Figs. 35.*




CROSS SECTION.

LONGITUDINAL SECTION ON AA.
Scale: Half Size.

were lastly turned over the back ends of the wedges, and the whole socket was run with white metal. It should be noted that the white metal was not depended upon to take any of the strain, but merely to retain the wires and wedges in their positions, and to prevent the ravages of the atmosphere. Mr. Glover.

Mr. Robert H. Haynes, of Newport, Mon., remarked that the system of propulsion described in the Paper was entirely novel so far as its application to the working of transporter-bridges was concerned, and only experience could demonstrate whether it was likely to be as reliable under service conditions as the older and theoretically less perfect methods previously adopted in continental structures, which, except in one instance, had been uniformly satisfactory. These might be described as main- and tail-rope haulage systems, which in the three earlier examples were worked by steam-power supplied by a power-house erected at one end of the bridge. In the later structures electricity had been adopted as the motive power, the control being effected from a pilot-house erected on the transporter-car. In one instance the ends of the rope were fixed in the towers, the rope being passed thence along the underside of the bridge-platform to pulleys in the centre of the truck or trolley, the bight being in turn carried down to and wound around a drum erected on a lattice structure placed over the car-roof. The drum was driven by two 25-HP. motors with series-parallel control, the latter involving the use of only two electrical leads overhead. Electrically this method had worked well, but mechanically it had not been an unqualified success, as in the event of the rope breaking the car must be hauled to one side or other by hand. The arrangement, although inexpensive, was not likely to be repeated. In the Nantes and Marseilles bridges the winding-apparatus, which consisted of a frictionally-driven drum worked by two motors, each of 30 B.HP., was fixed at one end of the bridge, the necessary electrical leads being carried along the underside of the platform. The current was taken by under-running trolley collectors and insulated conductors down to duplicate controllers placed in the operator's cabin. Series control was adopted in these cases. Six feeder- and control-wires were used to permit of the reversal of the motors and to control the braking. There were two hauling-ropes passing over and under the bottom bracing of the girder structure, both ropes being attached to a swan-neck in the centre of the trolley and again secured to the drum in such fashion that when one rope was wound on, the other was unwound. At Nantes the original hauling-ropes were still in use after about 18 months' service, and during this period no trouble had been experienced. A maximum speed of Mr. Haynes.

Mr. Haynes. 10 feet per second was obtainable. A system which obviated the use of rope-haulage appeared preferable at first sight, but whether sufficient adhesion would be obtained between the driving-wheels and the rails during frosty and snowy weather, particularly during high winds, had yet to be proved. It might be found necessary to introduce sanding-apparatus to prevent slipping. The position of the motors high up over the trolley was not an ideal one, as renewals of working parts and the replacement of armatures, which must sooner or later be done, would probably be found a tedious task involving the use of special tackle. The track-rails would doubtless have a shorter life than where rope-haulage obtained. The braking-arrangements were more simple and adequate than with rope-haulage, and in this respect the system was advantageous. Rope-haulage was being adopted for the Newport bridge. A comparison of the results of the two methods after an extended trial under ordinary conditions would enable a more definite opinion to be expressed as to which was the better. The plan of the Widnes car differed greatly from that adopted on the continental bridges, which had cars of greater width in relation to their length, it being considered that loading and discharging were facilitated by the wider car. Where vehicles drawn by tandem teams were chiefly in use in any particular locality, the longer car was more convenient. No general rule could be laid down, as each district needed special treatment. Continental designs provided for great flexibility in the stiffening-girders and a considerable increase in the number of parts, particularly in the cables and suspension attachments, the chief objects sought being facility of erection, great range of adjustment, and comparative ease in renewal, should such become necessary. The reasons given by the Author for the adoption of single cables with a minimum number of attachments were unanswerable. The extremely moderate cost of the Widnes bridge was a matter for comment; the satisfactory nature of the foundations had doubtless in part brought this about. Speaking generally, transporter-bridges had been erected in situations involving foundation-works of a troublesome and expensive nature, the expenditure under this head representing a considerable portion of the total cost.

Mr. Henning. Mr. Gus C. Henning, of New York, considered that the structure designed and erected by the Author was very interesting and practical for its purposes, in its place; but that it would have been designed with parallel-wire cables instead of cabled ropes, had the proper information been available. The tests of cables accepted by the Author as correct and satisfactory were very misleading, because those who had made them had not been sufficiently accurate and particular about such matters. It had been repeatedly demonstrated in America that cables of parallel wire were much more reliable and stronger than those built up of spiral wire ropes. At p. 97 the Author stated that "experiments were made at the United States Arsenal at Watertown, Mass., in 1895, with four ropes made of parallel wires and four laid with twisted wires, each rope being constructed of thirty-seven wires of No. 8 gauge." In the reports nothing was stated about the construction of the parallel-wire cables. Careful inquiry had brought out the fact that these parallel-wire cables were held in the ordinary sockets, jammed and held in place by steel wedges driven between the wires into the lead poured in between them. As the construction of the cables was all-important, and should be precisely similar to that adopted in bridges, these wires should have been laid, under absolutely uniform stress, around two shoes, like those which connected the wires to the anchor-bars, and the two ends of the continuous wire then fastened. Pins passed through the shoes, and by these pins they should be held in the testing-machine. As this had not been done, the results of the tests could not be considered to represent correctly the properties of parallel-wire cable. The report stated, in fact, that some of the wires pulled out of the sockets, an accident which could never happen when a test was properly prepared for and carried out. It was stated in the Paper that "the results showed that the wires were much more uniformly strained in the twisted ropes than in those with the straight wires." This was a misleading statement, which would not have been made had the cables been properly constructed. Again, the statement that the modulus of twisted-wire ropes was 25,000,000 lbs. per square inch against 27,000,000 lbs. for the straight-wire rope was incorrect and contrary to experience. The stretch of twisted-wire ropes was very great, showing an apparent modulus of elasticity of not more than 20,000,000 lbs. per square inch; while that of parallel wires, when all were acting together, was between 29,000,000 lbs. and 30,000,000 lbs. per square inch, according to repeated tests. The proper sectional area to be used for calculation was that based on the total weight of wire from anchor to anchor, compared with the number of wires contained in any cable. Careful examination of twisted-wire cables and also of those built up of parallel wires, had always shown that the latter were much more uniform and reliable. This was proved by the fact that in tests of twisted-wire ropes, single wires broke first, long before the entire rope failed. Mr. Henning had never seen a twisted-wire rope fail otherwise than piecemeal, as was clearly indicated at p. 98 by the words: "In making the tests of the Mr. Henning.

Mr. Henning. rope, it was found that the outside wires always broke first, which is no doubt due to their firmer grip in the sockets, those in the centre drawing slightly." This very action made it impossible to determine the modulus of elasticity of twisted-wire rope, which was possible in the case of parallel-wire cables. The stretch observed and measured when testing the former was very considerable, and was mainly due to the rearrangement of the wires in the several strands, the outside wires being forced into the inner ones: it was not the determination of purely elastic changes of length from which alone the modulus could be determined, as was possible in properly made test samples of parallel-wire ropes. Tests made of No. 7 or No. 8 wire suitable for bridge-cables showed, as stated at p. 98, a modulus of elasticity of over 29,000,000 lbs. per square inch, with a tenacity of 90 tons to 110 tons. The yield-point, as determined by a recording instrument, was found to be at least 85 per cent. of the tenacity, and had, in hard wire, been found to be as high as 95 per cent., without showing brittleness, but with an elongation of 5 to 6 per cent. in a 12-inch length.

Mr. Hildenbrand. Mr. WILHELM HILDENBRAND remarked that the whole construction of this bridge coincided so much with his own views on suspension-bridges, that he could find nothing to criticize, but everything to praise. In fact, the plan as a whole and in detail appeared to him as if it had been designed by himself, which in the eyes of the profession might be no compliment to the engineer of the bridge, but which was certainly the best compliment that Mr. Hildenbrand could express. The proportions of the bridge were harmonious and pleasing, and the towers, while giving an impression of stability and strength, were graceful and of simple beauty, without showing any pretence or effort at producing an architectural effect. The designer of the towers and approaches had abstained from encumbering them with useless ornaments, and he had succeeded in making the structure an ornamental landmark merely by aesthetic outlines, correct distribution of masses, and good proportions. The principal features of the structural details agreed, as a whole, with Mr. Hildenbrand's practice in the construction of suspension-bridges. For instance, in embedding the anchor-chains in cement, the Author had departed from the usual European custom and had followed American examples, which was much to the advantage of the structure. To make anchor-chains accessible for inspection was an alluring illusion of safeguard, but experience had shown that the easier the access was, the less were anchor-chains inspected, the more they were exposed to corroding influences, and the quicker they became decayed. He had had occasion to open anchorages which had been standing over 50 years, and he had found all anchor-bars embedded in cement, though only imperfectly covered with paint, in a perfect state of preservation. When building the Cincinnati suspension-bridge over the Ohio river in 1895-9, he covered all anchor-irons with a layer of paraffin in addition to two coats of red lead, and he believed that the former obviated any anxiety about oxidation going on unobserved. In order to test the protective qualities of paraffin, he had placed two pieces of steel—one painted, the other covered with a coat of paraffin —in a pot of concentrated hydrochloric acid. The first piece was destroyed and vanished in a few hours, while the second piece, after having been immersed for 6 weeks, did not show any effect of the acid on the paraffin or the steel. Of course, where exposed to the sun, or where appreciable motion took place, paraffin was not lasting; but underground, or embedded in masonry, paraffin was, in his opinion, the best protection that could be put on metal subjected to oxidation. In the cradling of the cables he recognized another familiar feature of American suspension-bridges. It was first introduced by Mr. John A. Roebling, the pioneer of cable suspension-bridges in America, in a cable aqueduct over the Allegheny River, built in 1844. Different engineers had tried to prove theoretically that cradling the cables was of no advantage to a bridge, but whoever had had opportunity to make practical observations would be convinced that the lateral stiffness of the floor was decidedly increased by drawing the cables into inclined planes. He noticed that the back cables of the Widnes and Runcorn bridge formed a larger angle with the horizontal than the main cables, which caused the stress in the former to be about 14 per cent. higher than in the latter. It was therefore a question whether it might not have been more economical to socket some of the wire ropes at the towers and to continue them from there to the anchorages with heavier ropes for supplying the back cables with the needed additional strength, without wasting material in the long span. Probably the Author had considered this question, and if he had found that the extra trouble and expense of socketing was not considerably less than the cost of giving the whole cable the required strength of the back cables, he had done well to make all ropes continuous from anchorage to anchorage. Any kind of splice was always an element of weakness which should be avoided, and one of the advantages of wire cables consisted in their continuity without intermediate splices, which advantage should not be abandoned without the best of reasons. For a structure of the magnitude of the Widnes and Runcorn bridge, Mr. Hildenbrand would probably have adopted cables of parallel

Mr. Hildenbrand.

Mr. Hildenbrand. straight wires in place of twisted ropes. While there was no objection to wire ropes, it was known that parallel lines would require 10 per cent. less material, and they certainly made a more compact and better-looking cable. The end connection of straight-wire strands with the anchor-chains was perfect, while that of wire ropes was at best clumsy, and introduced an element of weakness. The tests made at Watertown in 1895 were, to his knowledge, made with socketed ropes and strands, which were very different from a large wire cable, made in place and carefully adjusted. There was an unjustifiable prejudice among many engineers against wire cables, on account of the supposed difficulty and "impossibility" of adjusting thousands of wires to the same tension. Such a supposition was erroneous. He had had experience in the construction of large wire cables after the spin-in-the-air process, and did not hesitate to say that the wires in a cable could be more accurately adjusted than any other aggregate of bridge-members in ordinary structures; for instance, the number of eye-bars forming the bottom chord of a truss, or the diagonals of the web system. The accuracy of such bridge-members depended on the workmanship and on measurement, which were never perfect. No matter how rigid the inspection might be, there were always discrepancies, and the engineer could only trust that the stress in several tension-members pulling in the same direction was equal; he did not know it, and had no means of proving it. It was different with a wire cable. There the engineer could see the tension in each wire, and by only ordinary diligence and attention the stress in the different wires would not vary by $\frac{1}{10}$ lb., or less than 0·05 per cent. For instance, in a cable of 1,600 feet span and 150 feet deflection, a No. 6 wire, when first suspended, would have a tension of about 210 lbs. If it were given only 209 lbs. tension, it would sag 10 inches below the other wires, which was a discrepancy so great that the regulator could not help seeing and correcting it. As a matter of fact, the wires were regulated within $\frac{1}{4}$ to $\frac{1}{2}$ inch, which was between 0·0125 and 0·025 per cent.; but to allow for some want of care, and for the difficulty of regulation in windy weather, he had placed the maximum variation of tension in the single wires at 0·05 per cent. In no other kind of bridge-work was the same accuracy even supposed to exist; and further, the accuracy of the tension in the wires of a cable was not imaginary, but was just as real as the weight of any piece of steel read on a pair of scales. In conclusion, he wished to congratulate the Author and the other engineers on the successful completion of this structure, which would be a lasting monument of their engineering skill and good taste.

Mr. R. S. Scholefield inquired whether there had been any tendency for the rockers under the saddles to jam, as the distributing-girder was being built gradually in its position. Had not the increasing weight pulled the saddle over towards the centre of the span, or had the clamps that were attached to the back-stays and the saddles been successful in preventing all movements of this nature? Had any special carriage or other provision been made for the painting and maintenance of the cables and other steelwork? Were the strands of the cables tied together at shorter distances than the 6-foot spacing of the soft-steel wire bindings, and had the weather found its way within the strands of the cable between the places where it was bound? Was it not difficult to make certain that all the suspending rods of the car carried their proper proportion of the load, and would not the over-screwing of some of the nuts, or the under-screwing of others, by careless workmen, have thrown an over-strain on some of the suspenders? **Mr. Scholefield.**

Mr. C. A. P. Turner, of Minneapolis, considered that the Paper could be best appreciated by those who had worked out the details of a structure of this general character. The artistic treatment of the towers and approach-spans was very pleasing indeed, and many of the features of the design for the type selected seemed to be worked out in the most creditable manner possible. The arrangement of the track on the outside of the chord of the stiffening-truss appeared to him to be somewhat open to criticism from the structural standpoint, in that the load was applied eccentrically, which could, he thought, have been readily avoided by the adoption of the expedient he had used for the transporter-bridge at Duluth, Minneapolis; and it seemed to him that the usual English practice of having riveted connections for the stiffening-truss would have resulted in greater rigidity. On the question of wind-pressure, his view was that if a structure possessed a fair degree of stiffness, the cumulative effect of gusts of wind need not be considered. In connection with the car suspended by ropes with sway-cables, the Author did not state the amount of the weight transferred to the windward side by these cables in a gale, nor did he state his experience in working the car under severe wind conditions. In designing the transporter-bridge at Duluth[1], Mr. Turner had selected the double-system, Warren type of stiff, riveted construction throughout, because the site was exposed to severe gales, and it was necessary to have continuous service. The **Mr. Turner.**

[1] C. A. P. Turner, "The Ferry Bridge across the Ship-Canal at Duluth, Minnesota." Trans. American Society of Civil Engineers, vol. lv, p. 322.

Mr. Turner. traveller was also of stiff riveted construction, so that the total lateral sway amounted to barely ½ inch in a 60-mile gale, and was practically imperceptible. In executing the work, the contractors had not seen fit to follow his details of truck-bearings, and the cheap substitutes furnished did not stand the wear more than a little over 3 months, when they were replaced by others. With this exception, the bridge had been an unqualified success. To prevent shock to the traveller the car was suspended from its foot by links, and was received by a buffer-platform, backed by pneumatic cushions. Similar cushions were also provided to receive the traveller at the top. The clearance required in this case was 136 feet, which would render the sway with a rope suspension much greater than would be the case with the Author's design. The cost of the bridge had been approximately £23,000. In calculating the action of the wind, the live load had been considered as transferred entirely to the windward truss, and on the leeward side upper rails were provided for the uplift. The span was approximately but two-fifths of that of the Widnes and Runcorn bridge, and hence was more suitable for a simple span. He had, however, made preliminary estimates for a stiff braced structure of 1,000 feet span, with a clearance of 175 feet, and a stiff traveller with a live-load capacity of 150 tons, at an estimated cost of £120,000. Whether this estimate would be inconsistent with market-prices and labour-conditions in England he did not know, but it would seem that where such an excellent example of rigid construction of long span as the Forth bridge had been erected at so reasonable a cost, there should be no difficulty in putting up a 1,000-foot span in competition with the cable-suspension type, from the commercial standpoint; and a discussion by the Author of the relative costs of the suspension and the braced construction would be interesting and valuable. In the case of the Duluth bridge, a proposition had been submitted for a bridge of suspension type, with a capacity equal to one-third of the live-load of his design, at the same price, and naturally it had received but scant consideration, in view of the fact that its operation was guaranteed under wind-pressure but one-quarter of that for which the rigid type was designed.

The Author. The AUTHOR, in reply, observed that as Mr. Arnodin had designed all the transporter-bridges built before the one described in the Paper, his remarks were of special interest. The Author did not agree, however, with all Mr. Arnodin's statements, believing that several of them were not founded upon facts; he also failed to see the cause for regret that the improvements realized in other transporter-bridges had not been adopted. Before designing the structure, the construction of existing bridges was carefully studied, and what appeared to be defects were avoided; this had led to the design of a bridge which was entirely different in many details from any that had been previously erected. With regard to the difference between the angles of the back-stay and the main cable, in the first place, the sharp angle of the back-stay was not due to design, but was governed entirely by the circumstances of the site, and could not possibly be avoided. In the next place, Mr. Arnodin's diagram (*Fig. 33*) certainly did not show the actual resultant pressure on the towers; for, by the adoption of saddle and rollers, the resultant pressure was made absolutely vertical; and the only possible use the diagram could be was to illustrate an elementary principle in mechanics. It was very necessary that the cable should be firmly gripped to the saddles, or there was undoubtedly danger of its slipping; and as the load increased during erection, care must be taken to follow up the diminution in the area of the cable due to the squeezing of the strands and of the individual wires, by screwing down the cable-grips as the work proceeded; for if by the carelessness of the engineer in charge this should be neglected, the result might be serious. With proper care there was not the slightest danger. When the cable and back-stays were continuous there was of course an excess of weight in the cables; but the extra cost of this excess in section was far preferable to, and cheaper than, multiplying the connections at the top of the towers. Mr. Arnodin's objection to the single cable, and his preference for a number of smaller ones, was founded upon the possible deterioration of the cable by percolation of water, and the impossibility of examining it; but surely, it was just as impossible to examine the inside of a cable 4 inches in diameter as it was that of a 12-inch cable, and the inspection was not assisted in the slightest degree by having a number of small cables. The great objection to the multitude of cables was the much larger surface which was exposed to the atmosphere; and as the atmosphere at Widnes was heavily charged with chemical fumes, it was very desirable that the surface of the cables should be exposed as little as possible. With ordinary care, the cables would last as long as, if not longer than, any part of the structure; and it was difficult to see, not only the advantage of the "principle of interchange" but the practicability of it; for it would be interesting to know how the various sections of the booms of the stiffening-girders, or the tower-legs could be interchanged. Even the cables would present many difficulties, on account of the many connections to the suspenders and to one another; in fact, in the Author's opinion, no such "interchanges" The Author.

The Author. would ever be made. The running of the trolley-wheels on one side of the flange of course produced eccentric loading; but certainly not with ill effects to the extent mentioned by Mr. Arnodin. Central loading was no doubt preferable, but the plan advocated by Mr. Arnodin and shown in his diagram (*Fig. 34*) had not been adopted because of the following grave defects:—As the wind-pressure was the most important factor in the consideration of the stresses, by adopting the proposed method there would be an additional distributed load of about 80 tons to be allowed for; which, for a span of 1,000 feet, was a serious item. The girder carrying the rails was entirely unsupported laterally, and the wind-pressure on the car, the reversal of the stresses, and the fatigue of the web next the angle-bar, would eventually produce serious results. The plan advocated necessitated the adoption of small wheels, which was a disadvantage. The four trolley-wheels on the same centre being rigidly connected with the trolley-framing, it would be next to impossible, with the varying deflection, for all the four wheels to bear alike on the rails; and the supposed evil of the rail on the outer flange would still exist. The supposed advantage of "interchange" of the wheels was imaginary; for a wheel could now be changed in less than 7 minutes. With reference to the question of propelling the car by cable or by direct traction, this had been carefully considered, and it had been decided that the latter had most advantages. With cable-traction, the two cables, of about 1,600 feet each, would have to be supported at short intervals, and would be a source of constant trouble in many ways, especially during a gale; the application of the brake to the car-trolley would present difficulties, and more power would be required to drive the car—not less power, as stated by Mr. Arnodin. Rope-traction had long since been abandoned for direct traction; and in travelling cranes, the conditions of which more nearly approached those of the transporter, rope-traction had not been adopted for many years and had been superseded by direct traction. With reference to the slipping of the driving-wheels, if the bridge were constructed according to the design of the Widnes bridge, with the rails having an ascending gradient at each end, there would be no fear of slipping, even during a gale, if the rails were not allowed to become greasy. The wear of the driving-wheels did not decrease their power of adhesion, as stated by Mr. Arnodin, for they adjusted themselves automatically to the changed diameter. The wearing of the wheels and of the rails was not such a serious matter as the wearing of the cables, pulleys, guides, adjusting-gear, etc., nor attended with such serious risks of breakdown: and

The Author.

with rope-traction, if the ropes were to break, the car would be stranded. In reply to Mr. Colson, the strands forming the cable had been capable of adjustment at each end during erection, by means of the screws, and it had been easy to see when they had the correct versed sine and when they were in their place; then the temporary binding clips were put on. With individual wires this might be difficult; but with large strands it presented no further difficulty than that of the engineer being hung up in mid-air to make the inspection. The anchor-bars had been coated with tar-varnish in order to protect them not only during transit and erection but also after they were in position; for more than 12 months elapsed before they could be covered with the concrete, and in the meantime the pit was often full of water. Cement grout could be and was often used as a paint with advantage; but it required to be carefully put on, and the tar-varnish was inexpensive and easily applied. The concrete in the cylinders was practically hermetically sealed with the rock at the bottom and almost neat cement at the top, so that it might be considered to be perfectly water-tight. The erection of the cylinders had been carried out by a very experienced contractor, and he, knowing the condition of the site, had no doubt considered the plan he adopted to be the best; this matter had been left to the judgment of the contractors, and had not been specified by the engineers. The remarks of Mr. Duryea were interesting, but the Author could not agree with all his statements, nor with what he considered to be canons of good practice. As to Mr. Duryea's statement that it was unnecessary and unadvisable to cradle the cable, experience of the Widnes bridge had proved quite the contrary. Before the stiffening-girders met at the centre of the span during construction, a heavy gale sprang up; and but for the cradling of the cables, the results might have been serious, for the girders were not stayed in any way; as it was, the movement did not exceed 7 inches. If the versed sine of the cables had been one-eighth of the span instead of one-twelfth as suggested, the horizontal bracing of the girders to resist wind-pressure would have had to be considerably increased. Socketing the cables, if efficiently carried out as described in the Paper, was a very satisfactory device; and in the experiments made, the cable always broke outside the socket. With reference to the suggestion that stiffening-girders should be 56 feet deep instead of 19 feet, neither mathematically nor "without mathematics" could such a suggestion be satisfactorily upheld. Mr. Duryea's impression that the cost of the structure was unduly large, was not supported by the statements of many engineers and contractors of wide experience. Mr. Glover's remarks about the

The Author. construction of the cables formed a valuable addendum to those in the Paper. The question raised by Mr. Haynes about the comparative advantage of ropes and direct traction had been answered in the foregoing reply to Mr. Arnodin; his objection to the motive power being so high above the ground applied to both systems, but the driving-gear of the Widnes bridge was very accessible for any position of the car. The plan of the car had been made to suit local conditions, and was found to be very convenient; the broad car adopted on the Continent was necessary in order to obtain the required deck-area without projecting too much into the waterway; it was not such a convenient arrangement as that adopted at Widnes, which had two defined tracks for vehicles and ample space for foot-passengers. Mr. Henning had had considerable experience in the testing of cables and wires, and his opinions should have weight; but the Author was of opinion that further experiments on an extended scale, with large ropes, were necessary before the question of the relative advantages of parallel wires and twisted strands could be determined, and the result of the Author's experiments certainly coincided with those obtained at Watertown. If the stretching of the rope was "due to the rearrangement of the wires in the several strands" they would not have recovered when the load was taken off; and as the observations were taken near the working-load of the cables, after a load nearer the breaking-load had been applied, the modulus of elasticity obtained should be fairly accurate. Mr. Hildenbrand, who had had great experience in suspension-bridges, and had been associated with the design and construction of many of the largest well-known structures, asserted that there was no difficulty, as suggested by the Author, in arranging the parallel wires in their proper place and with the correct sag. If this were so, the best form of construction of the cable, for reasons mentioned in the Paper, was no doubt to have the individual wires laid parallel. In reply to Mr. Scholefield, the safe travel of the rollers was 8 inches, and as the travel of the rollers due to the extension and straightening of the back-stay during construction was about $10\frac{1}{2}$ inches, the load was taken off the rollers by means of hydraulic jacks, and the rollers were set back during construction. The strands of the cables were temporarily clamped in position during erection at varying intervals, not always the exact 6 feet. The method of ascertaining whether all the suspension-rods had the correct tension was described in the Paper; and there was no reason why any one should be either under-screwed or over-screwed. The plan adopted by Mr. Turner in the Duluth bridge for carrying the trolley-wheels did not appear to be a wise one; for the wheels and the bearings, being inside a box boom, must be very difficult of access. The Author could not agree with Mr. Turner's ideas of the cumulative effects of wind; for no amount of stiffness of the structure would prevent them. The amount of vertical pressure on the booms of the girders due to a horizontal wind-pressure of 30 lbs. per square inch on the car, was about 8 tons, and the car worked perfectly well during a strong wind, the amperage of course being considerably increased. In the Duluth bridge, the longitudinal rigidity of the car-trolley was an undoubted mistake; for on account of the deflection of the girders with the travelling load, the end wheels of the trolley would carry at times most of the load; and it was probably more owing to this arrangement than to the defective "truck-bearings," that the trouble in working the car arose. It was absolutely necessary for the car-trolley frame to be flexible longitudinally. The Author.

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13 March, 1906.

Sir ALEXANDER RICHARDSON BINNIE, President, in the Chair.

The discussion on Mr. John J. Webster's Paper "The Widnes and Runcorn Transporter-Bridge" was continued and concluded.

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