

Discussion.

Mr. am Ende. Mr. M. AM ENDE observed that the first Paper was a great disappointment to him, and he regarded it only as an introduction to a proper Paper on the subject, in which should be given a full description of the bridge, with figured details of at least one of the large spans, strain diagrams, and diagrams of stability of at least one of the large piers. In close connection with the work was an order issued by the Board of Trade, containing certain stipulations respecting the stability of viaducts under loads and under wind-pressure, and he thought that a Paper on the Tay Bridge should contain a full discussion of the relation between that order and the work itself. Such information would be welcomed, not only by the members of the Institution, but by the whole engineering world. Without it indeed it was impossible to call the Paper a complete one, or to discuss it with advantage. The methods adopted to erect the bridge might be investigated, but although they were of great interest they were not important. A knowledge of the structure itself was the essential point; how it was got into position was a secondary matter. This was not an ordinary case; the engineering profession and the public had taken an extraordinary interest in it, and they were entitled to the information which he was asking for, and which he trusted would be forthcoming.

Mr. F. WENTWORTH-SHEILDS thought that Mr. am Ende had been asking for a little too much; because if every detail of a bridge were fully given the Paper would be endless. The construction had been approved by the Board of Trade, and it might be fairly presumed that an engineer of Mr. Barlow's eminence had done the work in a proper way and fulfilled every reasonable condition. There were one or two points, however, on which the information given in the Paper might be supplemented, with advantage to the practical engineer who had such works to design. He did not gather from the Paper the actual amount of pressure upon the foundation of the cylinders, which was a most important point. The foundations were described as consisting largely of silty sand, and the amount of pressure which could safely be put upon such soil, in a large work of that kind, was a point on which fuller information would be very valuable. It would be useful also to have some details of the cost of the bridge. In regard to the construction, it occurred to him that the plated

shafts of the piers were not an improvement upon brick columns. Mr. Wentworth-Sheilda.
If the pier above high-water were constructed of a brick or stone shaft under each main girder, say, 9 or 10 feet in diameter, and these two shafts were connected transversely by a 3-foot wall, so that the horizontal section of the whole should resemble a dumb-bell in outline, he believed the structure would be more stable and rigid, and undergo less vibration from trains passing over the bridge and from high winds acting upon it; and it would be also less expensive. This would no doubt add a little to the weight on the foundations, but the Author had stated that the trial cylinder, which was loaded to 7 tons per square foot, sank very little; that did not show by any means a bad foundation, and he thought a slightly increased weight of masonry might have been very well dealt with. In regard to the girders, a triangulation system with only one intersection of the braces was adopted. He was aware that in large bridges the single-triangulation system, or an approach to it, had been lately adopted to a large extent; but he much preferred lattice-work composed of angle-irons in both directions, which, in his opinion, was more stable and firm than the other system referred to. He could safely say that for a bridge up to 300 feet span, with lattices at an angle of 45° and 6 feet apart, no angle-iron need be used of a greater scantling than 6 inches. Although the weight of the iron in those lattices might be a little greater, there was more simplicity of construction in taking the angle-iron lattices as they came from the rolling-mills, and treating them in no other way except punching rivet-holes in them, than in building up single braces composed of several pieces which involved considerably more work and cost; and the frequent bracing would be more rigid, would tend to connect the top and bottom booms more perfectly, and would be far more effectual in preventing vibration in the structure. The lattices to which he had referred could be readily adapted to receive cross-bracing midway or thereabouts on their depth, when required in very deep girders. With a construction of that kind he had no hesitation in saying that, as the trains ran along in either direction, the vibration was met and stopped better by the array of angle braces, than by single braces of which half the number consisted of flexible flat bars; and thus the structure would be sounder and have a longer life. He would ask, as a matter of information, whether any consideration had been given to the alternative mode of erecting the piers upon elevated scaffolding in a suitable place over the river, and taking them up and laying them in their places by means of the pontoons instead

Mr. Wentworth-Sheilds. of elevating them by hydraulic power, which would have been a more rapid mode of erection; and what were the leading advantages which caused the system adopted to be preferred?

Mr. Berkley. Mr. G. BERKLEY, Vice President, expressed his regret, in which he was sure every member would join, that the Engineer of the work under discussion was confined to his room through serious illness. A description of works of that character was most instructive, and Papers like those under discussion, which gave actual practical experience in the execution of large works, were most acceptable. But the more important the work, the more important it was that the records relating to it should be complete. No information, however, had been given as to the total cost, and there was no division of items. He was, of course, aware that a mere statement of the total cost of a work of that very special character would be misleading, and it would be necessary to divide the cost into various items, and to describe, with some degree of detail, the way in which it had been affected by the special circumstances of the case. For example, some of the girders of the old viaduct were used in the new viaduct. The manner of placing them had been described to him by Mr. Arrol on the spot, on the occasion of a visit, which he had found very interesting. He should like, in the consideration of any large viaduct, to be able to determine whether the span or spans adopted gave the maximum economy. He thought it might be open to doubt, considering the extensive character of the foundations, whether the small spans adopted in parts of the bridge had been the most economical; but, as a question of cost, the fact that certain parts of the old girders were utilized in corresponding parts of the new viaduct was an element for consideration. Nevertheless he hoped the total cost of the work might yet be stated, and divided per lineal foot of the superstructure of the large and of the small spans; also the cost of the foundation works, where laid in a great depth through water, as well as through clay; and where a smaller depth of water had to be passed, there being a rocky foundation. With the information supplied in such a manner engineers would be able to ascertain the actual cost of the work. Having examined the old viaduct, both when it was standing and immediately after it had fallen, and having also examined the present works during construction and when they were completed, he wished to say that a greater contrast could scarcely be imagined. The old work might be represented by the word "fragile," and the new work by the word "substantial," or "robust." The work below the water-line seemed to him to

afford an exceedingly good lesson as to the mode of proceeding Mr. Berkley. under such circumstances. It would be observed that, in the lower part of the work, the concrete within the wrought-iron shell, which might or might not be indestructible, was surrounded by brickwork. This he had heard from Mr. Barlow was composed of excellent and hard bricks set in cement, with a view of casing that concrete in such a way that, if the shell should fail, the case would make a perfectly substantial and sound work without it. The diagrams accompanying the Papers afforded a great deal of information. He might be wrong; but he fancied that the appearance of the piers above the water-line rather resembled masonry work than wrought-iron work. He thought the panic, which undoubtedly existed at the time of the failure of the old bridge, must have led the designers to consider not only the strength necessary for the piers, but also their appearance, so that every one might be impressed with their solidity. Otherwise, it might be open to question whether the form of the upper part of the piers was that which would produce the required strength with the maximum of economy. He was, sure, however, from an intimate knowledge of Mr. Barlow for many years, that he had had full and sufficient reason for whatever course had been adopted.

Sir DOUGLAS FOX said that one or two points had been touched Sir Douglas upon of great interest to those engaged in the construction of Fox. bridge foundations in sand and silt, such as were found in tidal rivers. The effect of the construction of the work upon the scour, as might be expected, was to restore to the river about the same area as that occupied by the piers. Mention had been made of a provision in the contract for filling in with rubble any holes or spaces scoured out during the construction. He should be glad to know what steps were taken where such scour was encountered, and if Mr. Arrol, in the absence of Mr. Barlow, would state what was actually done in any case where the bed of the river was scoured in proximity to the cylinders during their sinking. He concluded that the space scoured out was filled in with rubble, but it was not distinctly so stated. He observed that the larger piers were carried to a depth of 30 feet below the bed of the river, and the other piers to a depth of about 25 feet. Were these the depths from the normal bed before the construction commenced, or were they the minimum depths to which the cylinders were carried below any point to which the bed was scoured? If the depth was from the normal bed of the river, he should like to know what was the greatest extent to which the

Sir Douglas Fox. scour went: in other words, what was the minimum depth between the bottom of any hole scoured round the piers and the bottom of the cylinder. He observed also that great care had been taken to load the cylinders with a maximum weight, and that a record was given of the amount to which they had yielded under the test so given. It would be interesting to know to what extent, when the weight was removed, rebound took place. There was a great deal of force in what Mr. Berkley had pointed out with reference to the construction of the upper piers of the bridge. He thought the use of wrought-iron in a case of that kind was not a course that he would readily adopt, but he was quite sure that Mr. Barlow must have had very cogent reasons for introducing that arrangement. It was not quite evident why the casing of the cylinders was carried up so far. Of late years cylinders had been constructed quite as large as those at the Tay Viaduct, and under similar circumstances, where there was only a cutting edge of iron, and where the outer casing of the cylinders was entirely composed of brickwork in cement; and certainly his feeling would be in favour of not having a perishable material like wrought-iron if it could be avoided. Therefore, he thought, the substitution of a greater thickness of brickwork for the outer casing would be an improvement, unless there was some special reason for the adoption of iron. He should also like to know whether any serious difficulty had been encountered in keeping the cylinders upright during the sinking, and, if so, whether special steps were taken to deal with that particular difficulty.

Mr. Sowerby. Mr. W. SOWERBY said he had carefully studied and made himself acquainted with the construction of almost every system of railway-bridge from the time of the old chain-bridge over the River Tees to the present day. He had also seen most of the large bridges on the Continent, and many of those in India, and he had himself designed many and constructed several bridges. Max Müller had said, "the failures of the past prepare the triumphs of the future," and to nothing was this more applicable than to engineering, for a great deal might be learnt from a failure, when regarded in the light of an experiment. Brunel had remarked, when one of his bridges collapsed, "Ah! I'm very glad, for I was just going to build a dozen of them;" and Murray, when building the Sunderland Docks, remarked, when one of the sea-walls, which had cost £10,000, was washed away by a storm, "Very good, very good indeed, it will help to consolidate the works." Unfortunately such failures were costly, and were sometimes accompanied with loss of life, as in the case of the Tay Bridge. He was well

acquainted with the late Engineer of the Tay Bridge, having first Mr. Sowerby. met him in his native place, Darlington, and he knew something of the difficulties to be contended with in connection with that bridge. One of the principal things he had noticed was with reference to the larger spans. They were of great elevation, the platform was very narrow, and where the spans rested upon the piers, the space occupied was extremely small. It occurred to him that if a force were brought against the structure approaching what he had seen in India the bridge would certainly collapse. Upon one occasion he had seen six of the largest bridges in ruins after a storm and flood; even the piers and abutments of stone and brickwork were completely wrecked. On another occasion he had watched twenty-five spans of a very large bridge swept down by the current; it was a grand illustration of the destructive power of the elements, upsetting all calculations: he had observed the weakness of the same bridge (over the Nerbudda) on a previous occasion during a flood, when it shook like a line of telegraph wires in a gale; and its weakness was very palpable, except to the Engineer-in-charge, who narrowly escaped with his life. The construction of railway-bridges had undergone many changes since they were first introduced in 1825; the suspension-bridge over the Tees at Stockton, after doing duty for twenty years, was replaced by a compound girder-bridge. The old bridge had, almost from the first, to be supported by wooden struts; and the new structure of cast-iron girders and wrought-iron tension-rods had to be similarly supported, for it was on the suspension principle, only of a worse type, and it was proved to be so by the collapse of a similar structure, the Dee Bridge, at Chester. When he was engaged, in 1846, in designing the bridges for the Great Northern Railway, under the late Sir William Cubitt, cast-iron girders were adopted for very considerable spans; wrought-iron ones had not then been introduced. Soon after that time Fairbairn took out patents for wrought-iron girders, but Mr. Sowerby had a book in his possession, dated 1832, in which designs for wrought-iron beams were shown. Amongst the earliest structures of this kind of any size were those on the North-London Railway, at Camden Town, which were strong but very unsightly; next followed the Holyhead box-shaped girders; then the Chepstow Bridge, a kind of compound bridge with suspended platform from circular tubes; then the Saltash Bridge, and, finally, lattice-girders, which were now universally adopted. The construction of the Tay Bridge was on the lattice-girder system, and the exact form of the new one had of course been greatly influenced by the

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Mr. Sowerby. necessity of utilizing the materials of the original structure. There were several points connected with the present structure which appeared to deserve special attention. As a rule, he believed that the piers should be about one-tenth of the span. Some piers that he had seen not long ago in the Scheldt, near Breda, appeared to be like little islands. In the present Tay Bridge, the piers, large and small, were about one-tenth; but he thought that sloping them up in their present direction was not the best method that could be adopted. It might be correct with regard to the lower part of the foundations; but it was different when getting up to a point where they emerged from the bed of the river; at that point the two pillars should be connected together so as to prevent the current forming a swirl, which tended to undermine the piers. This he had noticed in large rivers to a depth of 50 feet. The connection was at a much higher point, and apparently there was no protection at the lower part. Then again, the objection which he saw to carrying up the piers gradually sloping was, that, by not being carried up to the full height, they did not afford a sufficiently broad base for the girders to rest upon. One point of weakness which he noticed in the first bridge appeared to have been partially repeated in the second; the larger girders were what were known as bow and string. The platform was below, and in a manner suspended; and in the other part of the bridge it was over the top of the girders. The distance from the bed of the river to the foundations was 30 feet, and the distance or height from the bed of the river to the top of the girder was 180 feet; so that there was a top leverage of 6 to 1, which appeared to be out of all proportion to ensure stability in a structure subjected to the forces of wind and water it might have to contend against. This was the fatally weak point in the old bridge, and it had apparently been repeated in the new one. Every part of a bridge should contribute to its strength. He had calculated that the amount of dead-weight put upon the girders was nearly 10,000 tons, and it appeared to him that such an arrangement did not contribute to the strength of the bridge. He thought the platform might have been made without so much dead-weight upon it. The bridge over the Menai Straits of necessity had the platform low, and the supporting weight high, because of the compulsory clause in the Act of keeping a certain amount of headway beneath. A square structure of that kind required gussets, stays, and uprights, and there was an immense amount of dead-weight in consequence of its shape. When it was being built, he calculated that 25 per cent. was due to the addi-

tional stays and gussets, in order to complete the triangulation. Mr. Sowerby. If the bridge had been of a triangular shape from the outset, with one side as platform and the apex downwards, this platform would have contributed to the strength of the bridge, and would have saved about 25 per cent. of the dead-weight. The smaller spans of the Tay Bridge might have been all constructed upon that principle. It would have been more difficult with the larger spans, because the headway was of necessity to be 77 feet, and consequently the shape or depth of the girder was somewhat restricted; but the difficulty might have been overcome. In fixing a girder of that description, the chair or saddle for resting it on, or whatever it might have been, would have kept it in position, and a triangular beam would have sent the force of the wind striking out from under it. There was an apt illustration of the same kind of girders, as those adopted on the new Tay Bridge, over the canal near Willesden; whereas, had triangular girders been adopted, the cost would have been greatly reduced, and the structure when fixed would have been quite firm. No wonder the Board of Trade found some difficulty in passing the Willesden bridge; for, although it was a type of bridge very generally adopted, it would probably be in time superseded by the triangular beam bridge, which no other shape could equal in strength, rigidity, lightness, and cost.

Mr. W. SHELFORD stated that he had seen the work once or twice Mr. Shelford. in the course of execution, and he had been much impressed with it. On reading the first Paper he felt, like Mr. am Ende, that it was rather sketchy. It might, at least, have contained more information on certain points of importance. The whole of the bridge was constructed of wrought-iron, except the corrugated floor which was of steel. Like many engineers he had used that floor largely, and it was an excellent thing even when made of wrought-iron, as was usually the case. It was not noisy; when properly constructed it was water-tight, and it distributed the weight remarkably well. It also bore a greater strain than could be easily accounted for by theory. Very little information had been given about girders. The large girders, it was said, were "hog-backed," and Mr. Shelford should be glad to know why hog-backed girders were selected. He presumed it was to economize material. He would suggest whether, if the girders were made with parallel booms, the wind-stresses would not be better provided for by a stiff framing overhead at the ends. It was also stated that the iron-work (evidently the piers) was very strong, and that the mean stress upon the piers was little more than 2 tons per square inch.

Mr. Shelford. Nothing was said as to the stresses in the iron in the girders. It would be interesting to know what rule was adopted as to the stresses upon the iron in different parts of the girders. Was the Board of Trade rule to which Mr. am Ende referred, adhered to throughout—5 tons per square inch for all parts of the girders—and if not, why not? If any one connected with the Board of Trade was present he should be glad to know whether he would pass those girders if 5 tons stress was adhered to uniformly. For himself he doubted it. He believed it was acknowledged that a 5-ton stress might be proper in some parts, but where alternating stresses occurred it was too much. It was stated that “all the girders and wrought-iron piers and cylinders were, in the first instance, built up and fitted together at Messrs. Arrol’s works at Glasgow.” He supposed he should be considered heterodox if he were to suggest that there was no necessity for building up large girders. A gentleman from the Union Bridge Company, of America, was, he believed, present, and perhaps he would say whether that Company would build girders up in the yard, or whether it would make them so accurately that they could be put up on the spot without previous erection. He wished to ask another question with regard to the steel water-pipe, 9 inches in diameter. He happened to know that Mr. Barlow did consider whether he could get drawn steel pipes on account of their lightness for that purpose. Mr. Shelford believed that large wrought-iron pipes had been sent out drawn for the Kimberley Water-works. It would be interesting to know whether those pipes, 9 inches in diameter, were made of riveted material, or whether they were steel drawn? He was sure that any one who had visited the work could not but be impressed with its grandeur and its thoroughly substantial character throughout. He looked upon it as a monument of the skill and experience of the engineer who had designed it, and he believed it would be a credit to the Institution and to the nation.

Mr. Macdonald.

Mr. CHARLES MACDONALD said he should be sorry to criticise a work of such magnitude without having carefully studied it. As he had not seen the bridge, having only just arrived in this country, it would be readily understood why he was reluctant to say anything about it. He would only refer to one or two features that had struck him as being familiar. He had observed in the 145-foot girder a form of truss with which he had had some experience, from the fact that it exactly resembled that adopted for twenty-three spans of 165 feet each, which he had built some years ago for the Pennsylvania Railroad. The form of latticing was the same, except that the connections were all pin-connections.

In the cross section, four trusses were used, whereas in America there were three. The three trusses were identical in strength; all the parts in the shops could, therefore, be made from the same templates, and there would be less liability to error, and less expense in the construction. He believed that form of truss was a very economical one. Whether it was better to adopt the pin-connection or the lattice, was, perhaps, too minute a question to discuss on the present occasion. If he were constructing a 145-foot span, he should prefer the riveted connection, but he should be careful to use the excellent mild steel made in this country rather than iron. He thought the floor was a great improvement upon that put upon the Pennsylvania bridge, which was of timber cross-bearers laid close together. It was believed that, when timber cross-bearers were placed near enough together, and confined by longitudinal guard-rails carefully tapped down upon the cross-bearers, they formed a better floor than a more expensive and rigid one. He had himself known a derailed car dragged 700 feet over a bridge, bouncing upon the timber cross-bearers, and not passing away from the rails any great distance, owing to the guard-rail confining it. The elasticity of the timber cross-bearers had a certain beneficial effect in preventing a jar upon the bridge itself. But he was bound to say that the latest construction adopted by the Union Bridge Company seemed to favour the very form of floor which had been described. One of the latest bridges had that form of floor, except that the plates were not bent cold, but were rolled; they were merely punched and drilled and riveted up without any distortion by bending. As to the form of truss for the 245-foot girder, he should perhaps find some more economical combination than that; but it was a matter of detail scarcely worth consideration at present. The mode of handling the girders upon pontoons was somewhat similar to what had been attempted in erecting a series of 415-foot spans across the Hawkesbury River in Australia. The pontoon, however, was continuous, 315 feet long, 60 feet wide, with the truss overhanging. It was intended to erect each span upon the pontoon, while it was at rest upon a platform at the level of low-water, near the site of the bridge; and, at a suitable height of tide, to swing the completed span into place. That, however, was not yet accomplished, and it would be improper to speak of it in any way of comparison. He was struck with the form of pier, which was rather an expensive one, without combining so much of the element of stability as might be obtained for the same amount of money. He should have preferred a continuous pier, instead of two cylinders connected at the top, and should have liked an oval

Mr. Macdonald.

Mr. Macdonald. or elongated section. In that case the metal portion of the pier could have been so arranged as to distribute the loading upon the foundations, without involving the uncertainty which appeared to be inherent to the present construction.

Mr. Cowper. Mr. E. A. COWPER enquired what pressure of wind had been allowed for? It might be remembered that there had been some discussion about the pressure of wind,¹ and he was requested to design an anemometer to ascertain whether a gust of wind was large or small. He had proposed an anemometer to be placed on each of the piers of the old bridge, with electrical connections, so that at any instant of time the exact pressure of the wind on every pier should be automatically drawn on paper. The plan, however, was not carried out, some objection being taken to placing the anemometer on the piers; but he should be very much interested in knowing what had been the calculated pressure of wind at the new bridge.

Mr. Bruce. Mr. G. B. BRUCE, President, said that Mr. Arrol was present, and the members would be glad of an opportunity of hearing him. They all knew that he was a distinguished contractor, and distinguished for his marvellous ingenuity in designing appliances for carrying out his work.

Mr. Arrol. Mr. W. ARROL observed that the bridge was a very simple structure throughout. Reference had been made to the wrought-iron structure and the caissons; but it would be noticed that the wrought-iron stopped exactly at low-water. As to the caissons being kept perpendicular, there was no trouble at all in that respect. The caisson was kept perpendicular by the rigidity of the pontoon. The pontoon with four legs was strong enough to resist any lateral movement in the large caissons. The caissons were in the first place carried out in sections, and then put together and lined with brickwork. Before being lowered they weighed from 90 to 100 tons. During the time of sinking the caissons there were four guides inside the pontoon, which kept them perpendicular, so that there was no trouble in this matter. The pontoon simply sat on its own four legs, without bracing, or anything of that kind. The shape of the foot of the pontoon prevented any scour taking place. The scour round the permanent structure had been very little. There was a great deal of loose sand round the caissons, owing to their being larger in diameter at the bottom than the top. The hollows scoured out were filled up with rubble to the level of the bed of the river, and there had

¹ Minutes of Proceedings Inst. C.E. vol. lxi. p. 80 *et seq.*

never been any trouble since. The wind-pressure allowed for was Mr. Arrol. 56 lbs. per square foot. The original intention was to build the large girders and rivet them up in their place; but he altered that plan, and built them on shore on a low platform, and then floated them out, and in that way they were of use for building the superstructure. Each span weighed about 520 tons. If he had to do the work to-morrow, he should adopt the same plan, for he had found it very advantageous.

Mr. CRAWFORD BARLOW, in reply, regretted his inability to be Mr. Barlow. present at the discussion on the Paper, owing to his absence from England. Details and diagrams of strains, &c., had been asked for. But in preparing the description he was of opinion that these were unnecessary as no new principle of construction was involved in the design. With regard to the pressure on the foundations, the maximum, where the silty sand occurred, was $3\frac{1}{2}$ tons to the square foot, being all that was considered advisable to impose on that material. The trial cylinder was tested to a gross weight of 7 tons; but that was entirely dead load, whereas one-third of the pressure in question consisted of a live load. The depths of the cylinder-foundations were determined from soundings taken prior to the commencement of the work. These soundings showed that the deepening of the river had been occasioned by the old piers reducing the area of the water-way; the new cylinder-foundations were carried down to at least a depth of 20 feet below such deepenings. Local effects of scour were anticipated round the cylinders in the sandy part of the river, attributable to the operations of sinking them, and in those cases the river-bed had been restored to its original level with rubble; the maximum depth of this scour action was about 10 feet. After the test weights had been removed from the cylinder-foundations, it was generally found that the total subsidence, recorded when they were fully loaded, was slightly reduced. This rebound, which varied with the nature of the substrata, was from $\frac{1}{8}$ to $\frac{3}{8}$ inch. The pontoons afforded such a stable platform from which to conduct the sinking of the cylinders, that little difficulty was experienced in keeping them upright. The cylinders were secured to the well-holes of the pontoon in four places by vertical girders and timber-blocks, which assisted to maintain them in their true position; but where rubble or boulders were encountered, the base of the cylinder often had a tendency to travel out of line. This was remedied by "canting" the cylinder, and sinking it in a slanting position for a sufficient depth to restore it (when it was again brought to the plumb by hydraulic jacks) to its true centre.

Mr. Barlow. The outer wrought-iron casing of the cylinder was only carried up to low-water level. Inside this was a ring of brickwork surrounding the concrete of sufficient thickness to encase it, if the wrought ironwork should perish. The wrought-iron casing was adopted for convenience of construction. The design of the superstructure of the piers was, under the peculiar circumstances of the case, made the subject of much consideration. The relative cost of shafts of brickwork (as suggested by Mr. Wentworth-Sheilds), and of wrought-iron was carefully gone into, with the result that the present design proved the more economical. The wrought-iron plated piers combined great lateral stiffness and rigidity with lightness. During the Board of Trade inspection experiments were made upon one of the highest piers with the view of ascertaining if there was any oscillation, but with four 70-ton engines passing at 30 miles an hour no movement was detected. Professor Ewing, of Dundee, well known for his investigations into the causes of earthquakes, made similar experiments with his seismograph upon the same pier, and he had recently stated, in a lecture on earthquakes before the Royal Institution, that this delicate instrument recorded oscillation immediately on the entrance of a train upon the viaduct (more than a mile away); but the maximum oscillation, indicated as the train passed the spot, did not exceed $\frac{1}{8}$ inch. With regard to the dimensions of the spans, the utilization of the old girders practically settled that point. Hogbacked girders were used for economy; as constructed, ample provision was made for the wind stresses by stiff overhead framings. The question whether the girders had been designed for 5-ton stresses throughout, touched on a very important point, and one which Mr. Benjamin Baker, M. Inst. C.E., brought prominently forward in his address to the Mechanical Section of the British Association at Aberdeen, in 1885,¹ namely, "How far the existing practical rules respecting the strength of metallic bridges are founded on reason, how far on custom, and how far on error." It had long been felt that in girders of small spans where the live load was the prominent one, and in those members of large girders where alternating stresses came into action, 5 tons stress was too much, and consequently a custom had arisen to design these for considerably less stresses. In designing the Tay Viaduct girders this consideration was borne in mind, and in the flooring, and in those parts of the girders where tension altered to compression and *vice versa*, the ironwork had been arranged so that it should have

¹ Report, p. 1183.

no more than 4 tons stress. The suggestion that lattice-work was better than single triangulation in the girders seemed open to the objection of making the scantling in the ties and trusses so light that there would be a liability to vibration with the live loads. The corrugated form of flooring was one that had long been adopted by Mr. W. H. Barlow. It originated in contriving a flooring where headway room underneath a railway was limited, and it was in this respect very economical. The troughs forming the corrugated flooring were bent hot and not cold. He had recently visited the Hawkesbury River Bridge in Australia, and saw one of the 415-foot spans ready for floating; the difference in the operations was that in the case of the Tay Viaduct the girders were floated out at a low level, and raised up to their proper position, while at the Hawkesbury the span was built on a staging on the pontoon of sufficient height to place the span direct on to the top of the piers. This mode of dealing with them, though suitable at the Hawkesbury River, would not have answered in the Tay, where the site was much more exposed and the ultimate height of the girders above the water was almost double. A force of 56 lbs. per square foot had been taken as the basis for the calculations for wind-pressure, and in estimating the overturning effect produced by this force, the parapet and train were treated as presenting a plane surface of resistance; the girder as a surface one and a half time its actual area, and the octagonal side of the pier as a square surface; with these conditions the balance of effects was largely in favour of gravity. The cost was not given because there were exceptional prices for works due to the peculiar circumstances of the case; for instance, in sinking the cylinders the prices included the extra cost involved in sinking through rubble surrounding the piers of the old bridge; and in clearing the bed of the river, at the site of the cylinders, of *débris* of the old bridge. On the other hand, a considerable saving was effected by the use of the old girders, and this greatly affected the comparative cost, as they were used in two-thirds of the length of the whole viaduct. Again, the old bridge afforded great facilities for access, and to a certain extent was used as a staging. The actual cost of the viaduct under these conditions was £670,000, being a little under £64 per lineal foot. The average cost of the river-piers was £4,000 per pier, the foundation work being rather under half that amount. The girder-work of the thirteen large navigable spans cost about £47 per lineal foot, while the cost of the remainder of the girder-work came to about £26 per lineal foot. The 9-inch water-pipe which crossed the viaduct was made of mild steel with

Mr. Barlow. lap-welded seams, the joints being formed with spigots and sockets run with lead.

Mr. Inglis. Mr. W. INGLIS said he had no reply to make, because his part of the programme had not been called in question, the discussion having chiefly related to the design. The only thing to which he need refer was the sinking of the cylinders. The trouble that had been experienced was chiefly with the rubble from the old piers, more than 1,000 tons having to be removed from some of them. The pontoons had answered remarkably well. Considering that the diameters of the malleable-iron cylinders were only 18 inches larger than the brick shafts placed on the top, it was satisfactory to learn that all the seventy-three piers had sunk in their true position.

Correspondence.

Mr. Cunningham.

Mr. D. CUNNINGHAM, who had resided in the immediate proximity of the Tay Bridge during the construction of both old and new viaducts—remarked that he always considered the structure of the piers in the old bridge to be too light, and of unsatisfactory design. When the bridge fell, he was surprised to find that the bases of the piers were not bolted down securely to the brick or masonry substructure; but merely pinned on to the two top courses. He was of opinion, that had an additional £300 or £400 been expended in securing the iron piers to the masonry bases, the old bridge would probably have weathered the storm of the 28th of December, 1879. But the design generally was unsatisfactory; the foundations in particular being too shallow. The method of construction, too, in some particulars, not touched on at the court of inquiry, was very deficient. For instance, sufficient care was not taken, in the construction of the large girders, that the flat-bar tension-ties should be perfectly straight. The result was, that when the girders had attained their position in the structure, many of these flat ties were found to be slack. To remedy this, when girders were bearing their own weight and that of, in each case, half of the roadway besides, these ties were cut across and re-united by plates and rivets, with the most uncertain results as regarded their bearing a fair proportion of the tensile-strain. Mr. Kelsey, the resident engineer of the present structure, though not aware of this fact, anticipated such a difficulty, and made due provision in the construction of the new girders for ensuring the straightness