Mr. Rennie concurred in the accuracy of the description of the 'Wellington' Bridge; it presented an excellent example of theory and practice, not only on account of its strict conformity with the principles of equilibrium, but from the correctness with which the works had been executed, as was evinced by the small subsidence of the arch after the centres were struck. Mr. Rennie.

Respecting the theory of the arch, writers were nearly agreed upon the principles established by De la Hire, upon the equilibrium of a loaded chain, or of a series of voussoirs, or wedges, with polished touching surfaces, as shown in his 'Traité de Mécanique,' in 1695.* The subject had been variously demonstrated by writers, but with little effect; architects were forced to select examples at random, for which no precise rules existed; but any person, on examining the actual state of an equilibrated arch of solid materials, or of a substantial chain suspended at its extremities by points, would immediately perceive the difference in the curves, or loads on the extrados, arising from the want of sensibility in the arch, or in other words, from friction and adhesion. Hitherto theory had been unable to comprehend these retarding forces, which had actually been so serviceable to the architect: Perronnet was perhaps the first to throw any real light upon the subject; the experiments which he undertook, on the absolute strength of materials, in the year 1758, previously to the commencement of the celebrated bridge of Neuilly,† and subsequently, those by Gauthey, on the failure of the piers of the church of St. Geneviève,‡ at Paris, were very instrumental in the advancement of the art. It was however, chiefly owing to the good quality of the material, that Perronnet was enabled to surmount the difficulties which arose from the unusual subsidence of the arches, in the bridge of Neuilly. The splaying of the arches, by which a double curvature was given to them, and which had been injudiciously copied in this country, was neither justified by science nor practice. The results of the French experiments were much too slow in reaching this country, and the strength of building materials was but little attended to, until within a recent period.

In the year 1824, the late Dr. Thomas Young having engaged to contribute the article 'Bridge,' to the Supplement of the sixth edition of the 'Encyclopædia Britannica,' applied to Mr. Rennie, to furnish the particulars of the Waterloo and Southwark bridges, then just completed; when, finding the data insufficient, Mr. Rennie under-

* 'Traité de Mécanique.' De la Hire. 12mo. Paris, 1695.

† 'Description des projets et de la construction des Ponts de Neuilli, de Nantes, d'Orléans, &c.' Perronnet. 4to. Paris, 1788.

‡ 'Construction des Ponts.' Gauthey. 4to. Paris, 1809.

took a series of experiments on the absolute and relative strength of materials, part of which he communicated to Dr. Young, and he subsequently published the whole in the 'Philosophical Transactions' for 1818.* The results were then applied to the calculations, on the lateral thrust of the arches of those bridges, perhaps for the first time in this country, and which were more amply applied afterwards to bridges in general by Mr. Ware, and his tables of the relative boldness of brick, stone, and iron bridges, were valuable accessions to our knowledge on this subject.†

As regarded the friction of arches, Mr. Rennie found that the arch stones of Waterloo and New London bridges commenced gliding, or pressing upon the centres, at angles of from 33° to 34°; he believed that soon after the adhesion of the mortar commenced, the centres would have very little pressure on them, even from stones at an angle of 45°.

As to the gliding of the arch stones at the haunches, from the pressure of the upper voussoirs, he had never seen an instance of it; but he had seen the haunches so much eased from the centres, by the lateral action, exerted in driving the stones into the vertex of the arch, as to allow the lagging, or cross bearers above the ribs, to be taken out. This proved the correctness of the rotative system of voussoirs, as shown by experiment.

With respect to adhesion, Mr. Rennie had seen its effect on broken arches of considerable magnitude, among the buildings of Rome, and also in the bridge of Alcantara over the Tagus, where the centre arch, of nearly 100 feet span, had been blown up by the French, leaving the adjoining arches and piers, which were upwards of 90 feet in height, standing perfectly undisturbed.

With respect to the magnitude of arches, M. Perronet expressed himself confident that arches of 500 feet span could be safely executed. The bridge which he proposed to construct, over a branch of the Seine, at Melun, consisted of a segment of a circle of 400 feet. The experience he had derived from the length of the primitive radii of the arches of the bridge of Neuilly, and his experiments on the strength of materials, would appear to justify so bold an experiment.

Mr. Rennie was of opinion, that with our strong magnesian limestones and hard granites, arches of larger span than any hitherto built, might be safely constructed.

There were numerous examples, both in ancient and modern times, of very large arches. The bridge of Narni, in Italy, of Vielle

* Vide 'Phil. Trans.,' 1818, p. 118.

† Vide 'A treatise on Arches and their abutment piers.' By Samuel Ware. 8vo. London, 1809.

Brioude, in France,* and of Alcantara, in Spain, by the ancients; and those of Gignac and of Castel Vecchio, by the middle ages; but the most remarkable example of cylindrical vaulting (the remains of which still existed), was the bridge of Trezzo, over the Adda, in the Milanese.† The span was 251 feet over the chord, and 266 feet over the semicircle. The stone beams in the church of the Jesuits at Nismes, and those between the towers of Lincoln Cathedral, the former equal to the segment of an arch of 565 feet span, and the latter to one of 262 feet span, proved how much could be done with materials of small dimensions.‡

In modern times there were examples of bold vaulting in France, in the bridges of Neuilly, Mantes, St. Maixence, and Jena; in Italy, in the Ponte Sta. Trinita, Turin; in England and Wales, in the bridges of Llanrwst, of Pont-y-tu-Prydd, of Gloucester, of Chester, and those of London and Waterloo over the Thames; independently of numerous arches and viaducts, more recently erected for the use of railways.

The radii of curvature of the centre arch of New London bridge, taken near the vertex, would equal in boldness an arch of 333 feet; and the length of the key-stone, at 4 feet 9 inches, would make the depth only $\frac{1}{70}$th of the whole span.

The origin of the arch had occasioned much controversy. The subject had been learnedly investigated by Dutens, Le Roy, King, and others, but apparently to little purpose, as the invention of the

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* The following dimensions of the Pont de Brioude are given in a letter from M. Seguin to Mr. Rennie (dated Feb. 27, 1827). "The ancient bridge was constructed by the Romans for the use of foot-passengers, pack-mules, and small carts drawn by oxen.

	Metres.		English feet.
Length of the arch . .	56	=	183·73
Breadth ,, . .	5	=	16·005
Height ,, . .	18 to 19	=	59·058 to 61·339

"The arch was a segment of a circle, formed ofvolcanic stone, of little consistence. The bridge gave way in the course of time, but was upheld for fifteen years, by means of buttress walls, 6 metres (= 21·68 English feet) in thickness, and 10 metres (= 32·8 English feet) in height; and also by bars of iron, fixed in the wing wall, and through several courses of the arch-stones. The structure finally fell, and a new stone bridge has been erected upon the same site, of which the following are the dimensions:—"

	English feet.
Opening of the arch, (which is a semicircle) .	150·9
Breadth of ditto	24·7
Height from the stream to the pavement . .	83·7

† A section of this arch is shown in Part 1 of the 'Theory, practice, and architecture of Bridges.' Hann and Hosking. 8vo. Weale. London, 1839.

‡ Robinson, in his 'Travels in Palestine,' mentions the remains of an arch over the valley of Kedron, at Jerusalem, supposed to have been 350 feet span.

arch would now appear to be, with more justice, attributed to the Egyptians, as they seemed to have used it, many centuries before the Christian era.

The researches of modern travellers, particularly those of Sir Gardiner Wilkinson,* proved that the brick arch was known in Egypt in the reign of Amenoiph I., 1540 years B.C., and the stone arch in the time of Psamaticus II., 600 years B.C. "The most remarkable," says Sir Gardiner Wilkinson, "are the door-ways surrounding the tanks of Assassief, which are composed of two or more concentric semi-circles of brick, as well constructed as at the present day, and all the bricks radiate to a common centre."

Mr. Hoskins was of opinion that arches were constructed long anterior to the time of the Ptolemy's; for in the pyramids of Ghebel Birkel and Dunkalie, which were of more ancient date, both round and pointed stone arches were discovered.

Mr. Perring stated that he found at Thebes some remarkably well-formed arches of 12 feet to 14 feet span, built in concentric half-brick rings, the bricks of which were marked with the name of Sesostris; consequently they were upwards of 3180 years old.†

A representation of the tomb of Saqqara and its arched vault of stone, was given in the vignette of the 10th chapter of the 3rd volume of Sir Gardiner Wilkinson's 'Manners and Customs of the Ancient Egyptians.'

The arch seemed to have been known to the Etruscans; and from the representations of their palaces and their sea-ports, the arch appeared generally to have been employed for moles and jetties.

With reference to the knowledge of the arch among the Greeks, opinions were very contradictory. The researches of modern travellers had brought to light many curious remains of Cyclopean or Pelasgic architecture; but in confirming the descriptions of the ancient cities of Mycenæ and Orchomenos, they had left us still in ignorance as to their actual knowledge of the arch.

Mr. Rennie exhibited a series of lithographic prints, from drawings made by the late Mr. Dodwell during his travels in Greece. They displayed the various doorways of Pelasgic fortifications, from the lintel of single stones resting on upright jambs, to the overlapping of the stones until they reached each other, in the form of a triangle, as in the gate of the lions, the entrance into the treasury of Atræus, &c.

But the most remarkable monument was the subterranean chamber, of which Mr. Dodwell's lithographic plate gave an imperfect idea;

* 'Manners and Customs of the Ancient Egyptians.' Wilkinson. 3 vols. 8vo. London, 1837.

† Vide Minutes of Proceedings, Inst. C. E., for 1843, page 170.

complete plans and sections of that extraordinary building were given by Mr. Donaldson in the supplement to the 'Antiquities of Athens,'* from which it appeared, to have been constructed in the form of a parabolic cone, of 48 feet in diameter at the base and 44 feet 6 inches in height, by means of rings of regular masonry, overlapping each other until they reached the apex, where the aperture was closed by a flat stone From this and other buildings of a similar kind, there was reason to infer that the ancient Greeks had very imperfect notions of the arch.

Mr. Kinnard, in his 'Description of the Antiquities of Delos,'† gave a representation of a portal or gateway on the ascent of Mount Cynthus, formed to support the wall of the ancient fortifications. The entrance was constructed with ten large stones inclined to each other, like those at the aperture into the great Egyptian pyramid. It was perhaps the earliest specimen of Pelasgic architecture in Greece, displaying the first step towards the principle of the arch.

That it was known by the Etruscans seemed evident, from the remains of arches and bridges, now existing in the country of the Volsci in Italy; and the researches of travellers in that country, within the last few years, had brought to light many curious examples, anterior to the period of the Cloacæ of Rome, and the tunnel of Albano by Ancus Martius.

Mr. Rennie was of opinion, from his examination of the subject, that there existed no sufficient evidence, to establish the knowledge, or use of the arch among the Greeks.

Mr. Page presented two sketches (No. 3621), made by him of two arches at Cape Crio (Cnidus, Rhodes). These arches were semicircular, built of large stones regularly radiating from a centre, without any mortar in the joints, and stood among Cyclopæan remains, of which they apparently formed a part. He was of opinion, that the Greeks were aware of the properties of the arch. They evidently appreciated its form, for it must have been noticed by all travellers, how frequently the flat lintels were cut out on the under side; several specimens of this existed in the sepulchral remains now in the British Museum. At Athens, he had noticed a very considerable excavation of a regular arched form through solid marble. Mr. Page.

Mr. Rennie observed, that as more useful lessons were given by failures in construction, than by records of successful undertakings, he had caused a large drawing to be made, of the bridge of the Boverie at Liège, showing its state at the time of the report upon it, Mr. G. Rennie.

* 'Antiquities of Athens,' &c. Stewart and Revett. Supplement. Folio. London, 1830.

† Ibid.

by the commissioners appointed by the Belgian Government, when it was condemned, and was ordered to be reconstructed, at the cost of the contractor, which however had not yet been done.

The bridge, which was built of hard, compact, magnesian limestone, consisted of five arches of 78 feet span each, with a versed sine of 8 feet, which was between $\frac{1}{9}$th and $\frac{1}{10}$th of the span. The form of the arch was that of a segment of a circle of 100 feet radius, the angle of the springing was therefore 46° 45′. The abutments at either extremity were of rubble masonry, and were very deficient in weight and dimensions.

The obvious consequence of this want of due proportion was, that the abutments gave way, all the arches sunk at their centres, many of the stones nearly falling out, several of them were fractured in both directions, serious dislocations occurred in each pier, above the springings of the arches, and also down upon the cutwaters, and in spite of all attempts to remedy the defects, the bridge was condemned, and was taken down, although it had cost upwards of £25,000.

It was evident that these flat arches were not well proportioned, and that the abutments were insufficient to support their thrust. It appeared also, from the report of the Commission (of which he presented an abstract, No. 672), that sufficient attention had not been paid to the quality of the workmanship, or in the selection of the materials employed.

Mr. B. Green.

Mr. Green exhibited, and promised a copy of, a design for a stone bridge, of eight semicircular arches, which was proposed to be built over the Tyne, for uniting Newcastle and Gateshead at the high level, instead of as at present descending on one side by steep and inconvenient streets, to rise by as bad an acclivity on the other bank. The injurious effect of this had long been felt, and many designs had been brought forward for remedying it; among others he had, in conjunction with his father, proposed a bridge of four arches of bent timber, to cross the river in the same place.* Cast-iron had also been thought of, and designs were made for using it; but notwithstanding the present low price of that material, it was found that a stone bridge would be as cheap, and he believed that the plan now exhibited would be carried into effect.

Mr. Green presented some specimens of ornamental bricks, which he had used extensively for the decoration of the fronts of buildings; they were made by Mr. Barnes of Newcastle-upon-Tyne, who had found a method of giving them unchanging colours. He also

* A copy of this design (No. 3225) was presented to the Institution by Mr. Neville, in the year 1843. Vide Minutes of Proceedings, p. 37.

promised an account of this manufacture, and of the use of these bricks for ornamental architecture.

Colonel Leake was of opinion, that the arch was known to the Greeks, in very early times. In the remains of Tiræus there were galleries, the roofs of which were formed by stones, meeting at an angle, and supporting each other; they required only a third, or key-stone, to form an arch. Those who were opposed to the belief, that the more ancient Greeks were acquainted with the arch, admitted that the light broke in upon them, in the time of Alexander the Great. They asserted that all masonry, in which arches were found, was posterior to that time. They would not allow the style of masonry, called Polygonal or Pelasgic, to be any proof of an earlier age; affirming that near Rome, Pelasgic masonry was found, of a date as late even as that of the Roman Empire. Colonel Leake believed this to be correct; but he contended, that although the substructure of the Appian Way might exhibit some Polygonal masonry, and although an opulent Roman might have indulged his fancy, by giving a Pelasgic basement to a new palace or villa, there could be no question, that the immense number of Pelasgic fortresses in Greece and Italy, were all anterior to the age of Alexander. Colonel W. M. Leake.

After the conquest of Greece by the Macedonians, a few repairs and additions, might have been made to the fortifications, constructed by the cities in the plenitude of their power; but the greater part of the smaller towns were soon afterwards depopulated, and their old walls were neglected. In Greece, therefore, arches in Pelasgic masonry were, he contended, older than the time of Alexander.

Colonel Leake exhibited a drawing (No. 3639), from sketches made by him, of some arches in the walls of Œnia, or Œniade, in Acarnania, which were described in his "Travels in Northern Greece."* Mr. Mure's "Journal of a Tour in Greece" † contained drawings of other arches at the same place. One of the sketches represented a door at Œnia, which was not formed on the principle of the arch, but might serve, with the others, to show the great variety of ways in which it pleased the Greeks to crown their doorways. In the larger arch, Colonel Leake observed, that the junctions of the stones did not converge accurately to a centre, and he had made the same remark as to other arches, both at Œnia and elsewhere; so that it would appear, that in the solid masonry of the Greeks, the stones having sufficient mutual support, without an accurate convergence, the principle of the arch was not strictly attended to, until ancient solidity gave place to a mode of building

* Vol. iii., page 560.

† Vol. i., page 107.

less solid; a more correct and careful knowledge of the arch therefore became necessary. In Roman buildings, in which ostentation and rapid execution were the leading objects, the arch entered more largely, and this at once accounted for the very rare occurrence of the arch in Greek buildings, compared with the Roman. Another cause of its absence, was the accidental circumstance, that almost all extant Hellênic remains, except fortifications, were those of temples, that there was naturally a great similarity of construction in them, and that the arch was never required in them.

There could be little doubt, that the arches in the ancient works of Volterra and Perugia were, like the Cloaca Maxima at Rome, of the time of the Roman monarchy, or of the early republic; for it was in those times only, that the Etruscans were sufficiently powerful and independent, to build extensive fortifications. After the Roman conquest, no defences at all would have been permitted.

The arts of Etruria were derived originally from the Pelasgi of Greece, and were refreshed by colonies from the same country, in the first or second centuries of Rome, as was confirmed by the similarity of Greek and Etruscan arts and manners, through the whole course of their history.

If existing remains seemed to show that the Etruscans employed the arch more frequently than the Greeks, the difference of materials in the two countries might perhaps be sufficient to account for it; the marbles and hard limestones of Greece, were more suitable to a length of architrave or breadth of opening, than the smaller stones of Etruria.

It was requisite to be cautious, in supposing that there was anything connected with architecture of which the Greeks were ignorant, at the time when they erected the splendid monuments, which still remained. Formerly, it was questioned whether the Greeks possessed the knowledge of making glass; it was now ascertained that the Romans, the Greeks, and the Egyptians, carried it to a degree of refinement, which modern nations had not yet been able to imitate. It was only recently discovered that the Greek architectural word ENTASIS was applicable, and probably applied by the Greeks, not alone for an individual column, but to an entire building.

It was now found, that there was scarcely a right line in the Parthenon, that the pavement on which the columns rested was not level, but convex; that the columns had not only a curved profile, but that they inclined inwards; and that there was scarcely a stone, even of the columns, that would fit any place but its own. The Greeks had lately ascertained this practically, when endeavouring to restore some of the fallen masses to their original situations. The

variety of curves in the architrave and cornice, as ascertained by Mr. John Pennethorne,* was even still more extraordinary.

March 12, 1844.

The PRESIDENT in the Chair.

No. 663. "Account of the Town and Harbour of Pulteney-Town (Wick, Caithness), from their origin in 1803 to the year 1844." By James Bremner, M. Inst. C. E.

Pulteney Town Harbour.

Pulteney-Town and Harbour, situated in N. latitude 58° 26′ 45″ and W. longitude 3° 3′ 56″, are the property of the British Fisheries Society, which was established under Acts of Parliament, for the purposes of extending the fisheries, and improving the sea-coasts of North Britain. They were, under these Acts, empowered to construct this harbour, which, with the town, was planned by Mr. Telford in 1803; both are located upon the property of Sir George Dunbar of Hempriggs, and are separated from the burgh of Wick by the river, which is spanned by a stone bridge of three arches, with a clear water-way of 156 feet: it was built in 1805 by Mr. G. Burn, also from the designs of Mr. Telford.

In the same year, the old or north harbour (Fig. 1), was commenced. With the exception of the pier heads, which were founded by the author, for the contractor, at a depth of 4 feet below low-water mark, the outer walls were all constructed above that level, on a bed of blue clay mixed with stones. The works were of ordinary construction, having behind the face-walls clay puddle, within which, sand was used as hearting. A mass of boulders, whose tops reached the level of half tide, lay outside the pier heads, and protected them from the action of the sea. This harbour was finished in 1811 at an expense of £16,400.

The bed of Wick Bay is sand to a considerable depth; this sand, when disturbed by storms, is driven in great quantities to the head of the bay, where the river empties itself into the sea; with freshes, in easy weather, the river carries the sand thus lodged near its course, towards the harbour entrance.

The north harbour thus soon became nearly filled with sand, from the nature of its situation and the position of its entrance, and owing to this, and the very small rise of tide at this place, the depth of

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* Vide "Pennethorne's Topography of Athens," 2nd Edition, page 573.