DUNCAN'S CROSSING POINT.

A model of an improved Crossing Point was exhibited by Mr. Duncan of Leeds; the notch in the rail was shown to be done away with, and the two rails in it were so dovetailed together, as to render any vertical motion between them impossible, thus materially strengthening the crossing.

GREAVES' BLUE LIAS LIME.

A piece of brickwork, set in Greaves' Blue Lias Lime, and which had been kept under water for nine days, was also exhibited. This material was composed of one-third of lime to two-thirds of burnt clay; and it was stated to have been used with great success in the tunnels on the Great Northern Railway, as well as in many hydraulic works, in which it was as durable as cement.

March 12, 1850.

WILLIAM CUBITT, President, in the Chair.

It was announced from the Chair, that copies of the ground-plan of the intended side in Hyde Park, and of instructions for preparing designs of the building for the Grand Exhibition of 1851, had been presented to the Institution, and that, on application to the Secretary, duplicates of these documents would be forwarded to any of the Members who intended to devote their attention to the consideration of this question.

No. 826.—“On Tubular Girder Bridges.”*

By William Fairbairn, M. Inst. C. E.

DOUBTS having been entertained as to the ultimate security of the Torksey Bridge, over the River Trent, the Author has investigated the subject with the utmost care and attention.

A difference of opinion appears to exist,—

1st. As to the application of a given formula† for computing the strength of wrought-iron tubular girders.

2ndly. As to the excess of strength that should be given to a tubular-girder bridge, over the greatest load that can be brought upon it; and,

3rdly. As to the effects of impact, and the best mode of testing the strength, and proving the security, of the bridge.

* The discussion on this paper extended over portions of several evenings, at different periods, but the abstract of the whole is given consecutively.

† *Vide* page 235.

[1849-50.]

These appear to be the chief points at issue: and, as a reply to both parties by whom he has been consulted, the Author has endeavoured to enunciate such views as will, he trusts, settle the question, and prove satisfactory as to the strength and other properties of these important structures. Previous to entering upon the investigation, it may, however, be requisite to offer a few remarks relative to the construction, and other matters connected with the permanency and security of this description of bridge.

Every structure having for its object public convenience and the support of a public thoroughfare, should possess within itself the elements of undeniable security. Bridges and viaducts should especially contain those elements, as they are peculiarly liable to accident; and from whatever cause such accident may arise, the community must be equally interested in the strength and durability of the structure. In the introduction of a new system of construction, comprising the use of a new and comparatively untried material, it behoves the projector, on public grounds, to be careful and attentive to the most minute circumstance directly, or indirectly affecting the security of the bridge. In those of the tubular construction, considerations of this kind are of primary importance, as much depends, not only upon the principle of construction, but upon the quality of the material employed and of the workmanship introduced, which in every case should be of the very best description.

In the construction of tubular-girder bridges, the Author has endeavoured to apply these principles; and having a strong conviction of their great superiority in strength, durability, and cheapness, for traversing large spans, he has not hesitated to advocate their introduction. It, however, becomes necessary, from time to time, to submit them to a rigid examination, and before opening such bridges as public thoroughfares, it is essential to subject them to severe and satisfactory tests. These tests and examinations have been various and frequent, and it may safely be affirmed, that in no case, where tubular-girder bridges have been duly proportioned and well executed, has there been the least reason to doubt their security.

The first idea of a tubular-girder bridge originated in a long series of experimental researches, and during their first application to railway constructions, the utmost precaution was observed in the due and perfect proportion of the several parts. These proportions were deduced from the experiments made at Millwall, upon the model of the Britannia Tubular Bridge; and, after repeated tests upon a large scale (full size), the resisting powers and other properties of this kind of bridge were fully established. From these

experiments a formula was deduced, for calculating the ultimate strength of every description of bridge, from 30 feet up to 300 feet, or even to 1000 feet span; and as that formula is now before the public, it is believed, that it may be relied upon as perfectly accurate. To relieve it, however, from anything like ambiguity, it will be well to state, briefly, certain points which should be taken into consideration in its application.

It has already been determined by experiment, that in order to balance the two resisting forces of tension and compression in a wrought-iron tubular girder, having a cellular top, that the sectional area of the bottom should be to the sectional area of the top, as 11 to 12; which being the correct relative proportion of those parts, it then follows, that by any increase to the one, without a proportionate addition to the other, the bridge will be rendered weaker; inasmuch, as increased weight is given to the girder by the introduction of a useless quantity of material, which, in this instance, is totally unproductive. This being the case, it is of importance to preserve, as nearly as possible, the correct relative proportion of the parts, in order to ensure the maximum of strength in the two resisting forces of tension and compression—an arrangement essentially important in these structures, and also in the application of the formula to determine the ultimate strength of the girder. If, for example, an excess of material was given to the bottom of a girder, the formula, $W = \frac{a d c}{l}$, would not apply, as the top and bottom areas would be disproportionate to each other, and that in excess would have to be reduced to the due proportion of 11 to 12; or, in other words, the additional strength must be omitted from the calculation, in computing the strength of the bridge. The same reasoning will apply, where the excess of area happens to be in the cellular top, although in this case the formula, $W = \frac{a d c}{l}$, still applies, as the excess cannot be considered in the calculation of the strength of the girder.

Assuming, however, that these proportions are maintained, the above formula furnishes a correct principle, on which to estimate the strength of wrought-iron tubes of this description, whatever may be their depths, or their relative dimensions.*

* Mr. Tate, an eminent mathematician, remarks upon the formula—

1st. With respect to $W = \frac{a d c}{l}$, where a is the area of the section of the bottom, and $c = 80$, the constant deduced on this supposition, will apply to all

In the case of the Torksey Tubular Bridge, of 130 feet clear span, the following are the dimensions of the girders in the middle, as given by Mr. Fowler (Plate 11):—

SECTIONAL AREA OF THE TOP.

	Ft.	In.	In.	In.	In.
Longitudinal plates	2	$8\frac{3}{8}$	$\times 2$	$\times \frac{3}{8}$	$= 24\cdot47$
Vertical plates	1	$1\frac{1}{4}$	$\times 3$	$\times \frac{5}{16}$	$= 12\cdot42$
Angle iron	0	$4\frac{3}{4}$	$\times 9$	$\times \frac{5}{16}$	$= 13\cdot35$
Area of cellular top as given by Mr. Fowler					50·24
Ditto, as given by Capt. Simmons					51·72
Mean					50·98

SECTIONAL AREA OF THE BOTTOM.

	Ft.	In.	In.	In.	In.
Longitudinal plates	2	9	$\times 2$	$\times \frac{5}{8}$	$= 41\cdot25$
Centre strip	1	0	$\times \frac{3}{4}$		$= 9\cdot00$
Packing strip	0	$3\frac{3}{4}$	$\times 2$	$\times \frac{1}{8}$	$= 4\cdot68$
Area of the bottom					54·93

Here there is an evident want of proportion, the bottom being greatly in excess of the top, which renders a reduction of the area of the bottom of the girder from 54·93 to 46·76 absolutely necessary. Hence, by the formula, $W = \frac{a d c}{l}$, or, $\frac{46\cdot76 \times 120 \times 80}{1560} = 287\cdot7$ tons, or 288 tons the breaking weight in the middle. From this is given $288 \times 4 = 1152$ tons, as the breaking weight, equally distributed over one of the spans of the Torksey Bridge, neglecting the weight of girders, ballast, rails, chairs, &c., which are differently estimated, but must be deducted from the breaking weight of the bridge.

Mr. Fowler estimates an equal distribution of the load on the Torksey Bridge, of a span of 130 feet, as follows:—

depths of the tube, within short limits of error, where such depths, or a are large in proportion to the depth of the cells, and the thickness of the plates.

2nd. With respect to the formula $W = \frac{a d c}{l}$, when a is the area of the whole section, and $c = 26\cdot7$, then the tubes should be similar in all respects, but a slight variation in depth, from that of similar form, will not produce much error, especially where the depth is considerable. At the same time it must be observed, that both formulæ apply with great exactness, where the tubes are similar.

	Tons.	Tons.
Rails and chairs	8	} = 177
Timber platform	15	
Transverse beams	27	
Ballast, 4 inches thick	35	
Half the weight of the four girders, which are each 46 tons in weight (it should have been the whole weight when equally distributed) }	92	
To this must be added the rolling load, as agreed upon between Mr. Fowler and Capt. Simmons		} = 195
Total load	372	Tons.

Now as the ultimate strength of the bridge is 1152 tons, it follows, that 177 being a constant will reduce its bearing powers to $1152 - 177 = 975$ tons, as a resisting force to the heaviest rolling load that can be brought upon the bridge, being in the ratio of 975 to 195, or 5 to 1.* These appear to be the facts of the case; and although the principal girders do not attain the standard of strength which the Author has ventured to recommend, as the limit of force; they are, nevertheless, sufficiently strong to render the bridge perfectly secure. In the calculations for estimating the strength of bridges of this description, it is always assumed, that the proportions of the top and bottom of the girder are not only correct, but that the sides are sufficiently rigid to retain the girder in shape. It is further assumed, that the whole of the plates are in the line of the forces, and that the workmanship and riveting are good.

On the excess of strength that should be given to girder bridges, there is a difference of opinion. The Author, however, entertains a conviction that no girder bridge should be considered safe, unless it be tried under four times the greatest load that can be brought upon it; and in wrought-iron tubular-girder bridges, the breaking weight is computed at 12 tons to the lineal foot, inclusive of the weight of the bridge, or about six times the maximum load.

On this calculation, the Torksey Bridge should have been constructed according to the following tables, which exhibit the

* It is considered by some engineers, as very important to the strength of these bridges, that the girders should be continuous, or extending over two, or more, spans. This is, no doubt, correct to a certain extent, and although the fact is admitted, yet this consideration is nevertheless purposely neglected, in these calculations; any auxiliary support of that kind acting merely as a counterpoise. It is considered safer, to treat the subject on the principle of compassing each of the spans with simple and perfectly independent girders.

strengths, proportions, and other properties of the girders, which are recommended in structures of this kind, and for spans from 30 feet up to 300 feet.

The first column gives the length of the clear span from pier to pier.

The second, the breaking weight of the bridge in the middle.

The third, the area of the plates and angle-iron of the bottom of the girder.

The fourth, the area of the cellular top; and

The last column, the depth of the girder in the middle.

TABLE showing the Proportions of TUBULAR GIRDER BRIDGES,
From 30 to 150 feet span; where the depth of the girder is $\frac{1}{15}$ th of the span.*

Span.		Centre Breaking weight of Bridge.	Sectional Area of bottom of one Girder.	Sectional Area of top of one Girder.	Depth at the Middle.	
Feet.		Tons.	Inches.	Inches.	Feet.	In.
30		180	14.63	17.06	2	4
35		210	17.06	19.91	2	8
40		240	19.50	22.75	3	1
45		270	21.94	25.59	3	6
50		300	24.38	28.44	3	10
55		330	26.81	31.28	4	3
60		360	29.25	34.13	4	7
65		390	31.69	36.97	5	0
70		420	34.13	39.81	5	5
75		450	36.56	42.67	5	9
80		480	39.00	45.50	6	2
85		510	41.44	48.34	6	7
90		540	43.88	51.19	6	11
95		570	46.31	54.03	7	4
100		600	48.75	56.88	7	8
110		660	53.63	62.56	8	6
120		720	58.50	68.25	9	3
130		780	63.38	73.94	10	0
140		840	68.25	79.63	10	9
150		900	73.13	85.31	11	6

* The Author has generally taken the depth of the girders at $\frac{1}{15}$ th of the span; but in cases where the span does not exceed 150 feet it has been found more economical to adopt one-thirteenth of the span. For spans above 150 feet it is, however, more convenient, on account of the great weight of the girder, to adhere to the original proposition of one-fifteenth, in order to keep the centre of gravity of the girder as low as possible, and to prevent oscillation under a passing load. In situations where it is objectionable to increase the depth of the girder, it then becomes essential to increase the sectional areas of the bottom and of the cellular top, in the ratio of the depths.

TABLE showing the Proportions of TUBULAR GIRDER BRIDGES,
From 160 to 300 feet span; where the depth of the girder is $\frac{1}{15}$ th of the span.

Span.	Centre Breaking weight of Bridge.	Sectional Area of bottom of one Girder.	Sectional Area of top of one Girder	Depth at the Middle.
Feet.	Tons.	Inches	Inches.	Feet. In.
160	960	90.00	105.00	10 8
170	1,020	95.63	111.56	11 4
180	1,080	101.25	118.13	12 0
190	1,140	106.88	124.69	12 8
200	1,200	112.50	131.25	13 4
210	1,260	118.13	137.81	14 0
220	1,320	123.75	144.38	14 8
230	1,380	129.38	150.94	15 4
240	1,440	135.00	157.50	16 0
250	1,500	140.63	164.06	16 8
260	1,560	146.25	170.63	17 4
270	1,620	151.88	177.19	18 0
280	1,680	157.50	183.75	18 8
290	1,740	163.13	190.31	19 4
300	1,800	168.75	196.88	20 0

In these tables, the breaking weights of all the girders are calculated from the formula $W = \frac{a d c}{l}$; as for example:—Taking from the table a bridge similar to that at Torksey, 130 feet span; W = the breaking weight, a = area of the bottom 63.38 inches, d = 120 inches, the depth of the girder, c = 80 the constant deduced from the experiments, and l = the length, 1560 inches, between the supports.

Hence $W = \frac{63.38 \times 120 \times 80}{1560} = 390 \times 2 = 780$ tons, the breaking weight of the bridge in the middle, or 1560 tons equally distributed over the surface of the platform of the bridge.

From this it will be observed, that after deducting the permanent load of the Torksey bridge (177 tons), there remain 1383 tons, as resisting force to the travelling load of 195 tons, which, according to calculation, is rather more than seven times the greatest weight that can be passed over the bridge,* 12 tons per lineal foot

* Since the Table referred to above was completed, and which has been closely adhered to in the calculations of the strengths and proportions of wrought-iron tubular girders during the last 18 months, 1 ton per lineal foot has been taken as the permanent weight of bridges, from 40 feet up to 100 feet span, and the rolling load as 2 tons per lineal foot; and in spans varying from 100 up to 300 feet, the permanent weight of the bridge is estimated at $1\frac{1}{2}$ tons per lineal foot, and the rolling load also at $1\frac{1}{2}$ tons per lineal foot. For practical purposes these proportions are found to be perfectly safe; although in spans above 300 feet, where the permanent weight of the structure becomes

being assumed as the measure of the strength of a tubular girder-bridge, for a double line of rails, and which will cover all contingencies, either as regards the weight of the bridge, the permanent load, or the forces by which it may be assailed.

Another subject of importance is the force of impact and the effects of vibration, on bridges of this description; and although it is only recently, that the Author has had the advantage of reference to the highly valuable Report of the Commissioners appointed to Inquire into the Application of Iron to Railway Structures, he is nevertheless of opinion, that the principles upon which he has endeavoured to establish the construction of these particular bridges, ever since their first introduction, is perfectly secure, and may be relied upon as being calculated to meet all the requirements and the conditions of railway traffic.

He cannot agree with the Commissioners in some parts of that Report, as several of the experiments therein referred to, do not appear to bear out the fact of increased deflection at high velocities. In several carefully conducted experiments on tubular girder-bridges, of spans varying from 60 feet to 100 feet, the deflection was found to be, as nearly as possible, the same at all velocities; and although the experiments at Portsmouth (at some of which the Author was present) are highly valuable, and exceedingly interesting, he is nevertheless of opinion, that there must be a considerable difference in the effects of a weight, rolling over a cast-iron bar, 9 feet long, and that over a bridge 60 feet long. It is true the Commissioners, in their Report, have qualified the results obtained from these experiments, by others made upon existing cast-iron railway girder-bridges, where the deflection was reduced from an increase of the statical deflection, amounting to $\frac{1}{10}$ ths of an inch, as produced upon the 9-feet bars, at a velocity of 30 miles an hour, to $\frac{1}{10}$ th of an inch upon a bridge of 48 feet span, at a velocity of 50 miles an hour; thus clearly showing, that the larger the bridge, and the greater the rigidity and inertia of the girders, the greater will be the reduction of deflection to the passing load. In the tubular girder-bridges, composed of riveted plates, it must be observed, that the Commissioners had no experience, nor were they acquainted with the strength, rigidity, and other properties of girders, composed of wrought-iron riveted plates. The deflection due to the passing load, appears to be the same at all velocities, and unless there exist irregularities and

a large proportional of the load, it becomes necessary to introduce into the calculation new elements as regards strength, as may be seen in those for the Britannia and Conway Tubular Bridges.

inequalities on the rails, tending to cause a series of impacts, it may reasonably be concluded, that the deflections are not seriously, if at all, increased at high velocities.

On the effects of impact, the Author perfectly concurs in opinion with the Commissioners, that the deflections produced by the striking body on wrought iron, is nearly as the velocity of impact, and those on cast iron greater in proportion to the velocity.* These experiments and investigations are extremely valuable.

The mode of testing bridges is a part of the inquiry which requires consideration, and in order to maintain unimpaired the elastic powers of the structures, the tests should not exceed the greatest load the bridge is intended to bear at high velocities; in fact, the Commissioners are correct in assuming, that the flexure of the girders should never exceed one-third of their ultimate deflection. In wrought-iron girders, the effects of reiterated flexure are considerably less, in a well-constructed bridge, of similar proportions to those given in the table, than those of cast iron. The deflection produced in these constructions, by the greatest load, will not be more than one-sixth of the ultimate flexure of the girder. On this subject, the effects of impact and the resistance of tubular girders to a rolling load, were strikingly exhibited, in the experimental tests made on the first construction of this kind, erected for carrying the Blackburn and Bolton Railway across the Liverpool and Leeds Canal, at Blackburn.

That bridge is 60 feet clear span, and three locomotives, each weighing 20 tons, coupled together, so as to occupy the entire span, were made to pass over, at velocities varying from 5 miles to 20 miles an hour, producing a deflection, in the centre of the bridge, of only $\frac{1}{10}$ ths of an inch. Two long wedges, 1 inch in thickness, were then placed upon the rails in the centre of the span, and the fall of the engines from this, when at a speed of 8 miles to 10 miles an hour, caused a deflection of only $\cdot 420$ inch, which was increased to $\cdot 54$, or about $\frac{1}{2}$ an inch, when wedges $1\frac{1}{2}$ inch in thickness were substituted. These were severe tests, and such as would not be generally recommended, as the enormous strength of these girders is now well understood, and they may safely be considered fit for service, after being subjected to the heaviest rolling load, or one-sixth of the breaking weight, taken at high velocities.

The paper is illustrated by a model and by diagrams, showing the construction and dimensions of the bridge, from which Plate 11 has been compiled.

* *Vide* Report of the Commissioners appointed to Inquire into the Application of Iron to Railway Structures. Folio. Plates. London, 1849.

TUBULAR GIRDER BRIDGES.
TORKSEY BRIDGE.

ELEVATION.

P L A N .

Scale of Feet.

HAY & SON, LINCOLN TO THE QUEEN.

SECTION AT CENTRE OF OPENING.

Scale $\frac{3}{4}$ Inch to a Foot.

SECTION AT CENTRE OF PIER.

Scale $\frac{3}{4}$ Inch to a Foot.