GRAND TRUNK RAILWAY COMPANY OF CANADA.

VICTORIA BRIDGE.

LETTER

TO THE

SHAREHOLDERS OF THE GRAND TRUNK RAILWAY OF CANADA,

BY

ROBERT M'CALMONT, ESQ.,

EX-DIRECTOR.

WITH A REPORT TO HIM BY MR. LIDDELL,

ON THE BEST AND CHEAPEST MODE OF BRIDGING THE ST. LAWRENCE AT MONTREAL.

TOGETHER WITH

COUNTER-REPORTS BY MESSRS. R. STEPHENSON, I. K. BRUNEL, EDWIN CLARK, AND A. M. ROSS;

AND

REPLIES TO EACH BY MR. LIDDELL.

LONDON:

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1856.

LETTER FROM MR. McCALMONT TO THE SHAREHOLDERS OF THE GRAND TRUNK RAILWAY OF CANADA.

3 *Crown Court, Philpot Lane,*
London, April 30, 1856.

GENTLEMEN,

HAVING for some time past endeavoured to enlist my Co-Directors in an inquiry as to whether such an expenditure as £1,400,000 for a connecting link in your railway system across the Saint Lawrence be unavoidable; and failing to obtain from them that cordial and energetic co-operation which I believe the case to deserve, my feeling of responsibility compels me to make known to you the steps which I have considered it right to take in furtherance of your interests.

I now, therefore, beg to lay before you a letter dated 29th March, from Charles Liddell, Esquire, Civil Engineer, of No. 24 Abingdon Street, Westminster, to myself, together with Correspondence and Reports, to which it refers, on the subject of the Victoria Bridge across the Saint Lawrence at Montreal.

These communications between Mr. Liddell and me, were preceded by the refusal of Mr. Stephenson, to confer with him on the subject, when invited, at my suggestion, on behalf of the Board to do so. It seemed to me intolerable that an inquiry should be thus eluded by the exclusion of the Company from professional opinions beyond those of Mr. Stephenson's selection, in which he would naturally seek support for the conclusions to which he had committed himself.

It will be in your recollection that at the Public Meeting, held at the City of London Tavern in July last, when your sanction was obtained to certain concessions made to the Contractors, it was announced that they had consented to a modification of the contract for the Bridge;—that the works on it were to be almost suspended for some time;—(partly on financial grounds, but also in conformity with an assurance from Mr. Stephenson, that until the plans of the Bridge should be reconsidered, the progress of the works was to be strictly confined to those portions, such as the approaches, which would be common to whatever structure might be eventually adopted—an assurance, by the way, strangely irreconcileable with paragraph 70 in his Report, and paragraph 20 in the Report of his assistant, Mr. Clark;)—and you were assured of the existence of "an opportunity for consideration whether some plan of " construction may not be devised whereby all the advantages to be derived from

" completing this important link in the great chain of communication may be " obtained at a less charge upon the undertaking."

I am constrained to express my opinion that any expectation of such a result, although obtainable, will prove a delusion, unless an unreserved and candid inquiry into the subject be insisted on. As regards the plans, an overwhelming preponderance of authority, as well as demonstration, will be found in favour of a more economical construction than that prescribed by Mr. Stephenson; and, as regards the contract, which, according to the Prospectus, is founded upon estimates framed by Messrs. Stephenson and A. M. Ross, I affirm that, fraud being out of the question, these estimates are based on error.

The documents now laid before you may help to suggest a future course. They deserve your attentive perusal and consideration.

Surely amongst the Shareholders there must be many gentlemen competent to form a correct judgment on the matter; and I trust that some of you will come forward and organise a Committee to grapple with the subject. What is to be insisted on is INQUIRY—uncompromising, straightforward inquiry—with a determination to arrive at a knowledge of the true merits of the case, and so to be in a position to deal with whatever circumstances may arise.

The Board is in the dark, and is consequently unqualified to negotiate intelligently with the Contractors either under existing circumstances or probable contingencies. Pending such consideration of the subject as I trust you will institute and insist upon, all expenditure upon the Bridge ought to be arrested.

In the hope that a suitable inquiry may be instituted by you, I will abstain from comment upon the reckless manner in which the Company are being heretofore led on blindfold in regard to this Bridge.

Before concluding, I beg to acquaint you that as the exercise of that reserve which may become a Director is incompatible with my sense of my duty to you, I have, in order to qualify myself for addressing you as I now do, judged it expedient to withdraw from the Board, and I have accordingly tendered my resignation as a Director.

I am, Gentlemen,

Your obedient Servant,

ROBERT M^c^CALMONT.

GRAND TRUNK RAILWAY OF CANADA.

VICTORIA BRIDGE.

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CORRESPONDENCE AND REPORTS.

24, *Abingdon Street, Westminster,*
March 29th, 1856.

VICTORIA BRIDGE, MONTREAL.

To R. McCALMONT, Esq.

A Director of the Grand Trunk Railway of Canada.

Sir,

I have received the Reports of Mr. Stephenson, Mr. Ross, Mr. Brunel, and Mr. Clark, in reply to my Report to you of September 22nd, 1855, on the subject of the Victoria Bridge.

It will be in your recollection that when you first applied to me, I advised you against receiving any Report *privately*. I recommended you rather to urge the Board to institute an inquiry from such Engineers of repute *in this Country and America*, as would enable them to set the question, which you had raised respecting the cost of it, satisfactorily at rest.

It will also be in your recollection that on the point of cost seemed to turn the question whether the Bridge could be carried out or not, for its great cost made doubtful, and perhaps still makes doubtful, to some at least, its commercial advantage to the Shareholders.

I was afterwards requested by the Directors, through you, by your letter of 9th August, 1855, to report my opinion on the subject. I did so, and a copy of my Report is appended hereto. But when that Report was placed before them, they refused to receive it, excepting from you, as a private Report made to you; and so the address was altered, and stood as it now stands in the printed copy which follows.

My Report was, it appears, when given in, placed in the hands of Mr. Stephenson to answer; and this he has done in the Reports above referred to.

The Reports of these Gentlemen have been now again sent to me by you *privately*: and if it were not that the statements against my Report contained in them, if unanswered, might place you in a false position, I should certainly not notice them further. The manner adopted of conducting an inquiry of such importance is so repugnant to my ideas of business, and so little calculated to elicit truth, that I re-enter most unwillingly upon the subject, and only for the reason above given.

After having read and carefully considered the four Reports, I have no reason to withdraw any statement I have made, and still believe that "a permanent and substantial Railway Bridge across the St. Lawrence at Montreal" may be erected for less than £400,000 sterling, including all contingencies, instead of the contract sum of £1,400,000, with a contingent increase of £100,000.

In none of the Reports is there a word in justification of the prices implied in the Contract sums, viz., the price of £56 a ton, *i. e.* 6*d.* a lb. for ironwork; and the price of 36*s.* 6*d.* *a cubic foot* for ashlar-work in foundations on rock in 8 feet average depth of water, *i. e.*, nearly three times the price of the granite masonry of the Skerry Vore lighthouse.

By calculating the work in detail as far as is possible from the prices given, it is evident that the estimated cost, viz. £1,400,000, has no true relation to the work to be done, and in none of the Reports is there any attempt to show that it has such relation.

In fact this sum appears to be, as Mr. Brunel expresses it, a sum "*assumed as the cost.*" For the Bridge, for which this sum was the *original contract price*, is now reduced more than *one-sixth* of the length and nearly *one-fifth* of the height of the *original designs* as specified; and yet £1,400,000 appears to be assumed throughout as the cost of the Bridge so reduced, notwithstanding that the proportionate value of the reductions is above £200,000.

As regards the details of the construction suggested in my Report, Mr. Brunel has ventured to condemn Concrete in foundations as worse than a bed of gravel. Mr. Stephenson has asserted that even encased in iron its "*use would be futile;*" and that, if "practicable" to use it, there would be danger in "trusting the superstructure upon it." But neither of these gentlemen have given the shadow of a reason for their dicta, which are, I maintain, inconsistent with the best experience.

All the Reports condemn any other superstructure than tubes as unsuited to "*this particular case*," although there are extant only three examples of Tubular Bridges in the world, unless it be on the Grand Trunk Railway, and the practice of Mr. Brunel is diametrically contrary to his present recommendation; indeed, in examples of great spans for Railway Bridges, in this and other countries, I find that universally other systems have been preferred to that of the tube. But in truth the conflicting statements in these very Reports, prepared to support the Tubular Bridge system, afford the best proof against its economical application.

In short, instead of serving to guide the judgment of a Board of Directors, the general tenor of the Reports is to divert attention from the main question at issue, viz., *the cost of a permanent and substantial Bridge* across the St. Lawrence at Montreal. Lengthy disquisitions are given on Foundation-work and Ice-breakers, and on the theory and practice of Girder Bridge construction; disquisitions abounding in strong assertions, and full of misconception. The foundations, ice-breakers, and superstructure, are, of course, very important points for consideration, and I have given you my views upon them in great detail; but they sink into insignificance compared with the question whether £600,000 is not sufficient to carry out the very Design proposed, and whether the Contract Sum is not a Million in excess of what is necessary to make a Permanent and Substantial Bridge.

I submit that on these essential points there is no question of opinion. There can only be question of fact. To understand the difference in the estimates requires no knowledge of engineering science, but only the application of common sense to make fair deductions from the indisputable facts of the case. The necessity for lengthened scientific discussion has arisen solely from my having to expose the fallacies involved in the authoritative dicta of Mr. Stephenson and Mr. Brunel.

On what must be considered matter of opinion—viz., the general Architectural appearance and Picturesque effect of the Bridge, I venture to assert that an Open Structure, such as I propose, would be found far to excel the Tubes in these respects, besides obviating the annoyance to travellers of passing through a mile and a third of noisy dark tunnel.

I subjoin copies of my first Report and of the four Reports above alluded to, which for the sake of convenience I have had printed *in extenso*, with my replies and remarks in the margin, each in the form of a separate letter to you.

I have the honour to be, Sir,

Your very obedient Servant,

CHARLES LIDDELL.

London, 9*th August*, 1855.

CHARLES LIDDELL, Esq.

My dear Sir,

As I am leaving Town this P. M. for a few weeks, I am disappointed at not finding you at home. My object in calling is to say that I have been requested by the Grand Trunk Board to ask you to submit to them a Report of your opinion as to the most economical mode of constructing a permanent and substantial Railway Bridge across the Saint Lawrence, at Montreal.

I am aware that you are tolerably well informed as to the peculiarities of the site, and also of the plan of the Bridge already commenced, and the progress of which may possibly be found to conflict in some degree with the full adoption of any new plan that might now be proposed. It would, however, depend upon circumstances how far what is now commenced might be reconciled with the modified adoption of new proposals.

You will please combine with your Report any suggestions that may appear to you appropriate and tending to that economy which the Shareholders would appreciate.

It is desirable that as little time as possible should be lost in your stating your ideas, and it will then be seen whether your assistance is likely to be availed of in making complete plans.

Please to send your report to Wm. Chapman, Esq., Sec. G. T. C., Broad Street.

Yours truly,

(Signed) ROBERT McCALMONT.

24, *Abingdon Street, Westminster,*
September 22nd, 1855.

~~To the Directors of the Grand Trunk Railway of Canada.~~

R. McCALMONT, Esq.

~~Gentlemen,~~

Sir,

At your request, that I would "submit to you a Report of my opinion, as to "the most economical mode of constructing a permanent and substantial Railway "Bridge across the Saint Lawrence, at Montreal," I have the honour to place before you the following statement:—

From the information I have been able to collect regarding the physical features and phenomena of the Saint Lawrence River, near Montreal, it appears to me that the building of a Railway Bridge across it will be an Engineering work of vast extent, but involving no peculiar difficulties, nor any necessity for unusual expenditure.

Were it not for the phenomena which occur at the "taking" and breaking up of the ice, the task of Bridging the Saint Lawrence on the site proposed would present only the most ordinary character of Engineering work; and these phenomena may, I think, be provided against, as I shall afterwards state more fully, by independent Ice-breakers, without departing from such ordinary character of work.

The bed of the river being a uniform shelving rock, a secure foundation is at once obtained; the depth of the water is inconsiderable, being only 10 to 12 feet at the deepest during the season when masonry work could be carried on, and for about one-half of the whole length of the Bridge not more than 6 feet. The depth does not vary more than 18 inches from April to December. Again, by the physical formation of the bed of the river, the main current is confined to a Channel through the Sault Normand, not exceeding 1,200 or 1,500 feet in width. The velocity through this channel is not more than 4½ miles per hour; about the same as that of the Thames, at London Bridge, at half ebb. Throughout the remainder of the width of the river, the velocity is very much less, and from the south shore to the central channel the stream is very sluggish.

Under the conditions above described, the construction of the Bridge requires that means should be devised for executing a vast quantity of common work in a short time, rather than any very special Engineering contrivance.

But the question now arises as to what provisions have to be made against the ice phenomena, so graphically described by Mr. Logan.—(*See Trans. Geo. Society, London,* 1842.)

In the first place, it is evident that the Superstructure of the Bridge must be raised beyond the possibility of its being reached by the ice; and as the water is said to rise not more than 25 feet above summer-level, when the damming by ice in Saint Mary's current takes place, and it is during this rise that the piling of the ice takes place, it is probably quite sufficient to fix the height of the abutments at 35 feet above such level. The fact for determining this height I take from Mr. Logan's papers, and shall adopt it for present purposes.

The phenomena of the "packing and shoving of the ice," as they affect the form and dimensions of the Piers, may next be considered.

When the ice packs, it is in consequence of meeting with some obstruction; single pieces of no great size strike against the obstruction with a certain momentum, in consequence of which, the pieces slide over and under each other, and get packed. But at the season of packing, this ice is brittle and friable, being new-formed and mixed with snow, and its momentum is chiefly consumed by crushing in the act of packing, so that the momentum of large masses of this ice will be of infinitely less power against the Piers of a bridge than what might arise from the direct shove or pressure of a field of hard ice. But to counteract the greatest weight of ice and dammed water that can possibly press at once upon the bridge in the site in question, I am convinced requires only a moderately-sized Pier of good masonry.

To facilitate the disruption of ice fields coming against the Piers, the latter must, of course, be provided with substantial Ice-breakers, against which the floating ice may be broken up. Thus the Piers will be protected from its direct action, and packing at the bridge prevented.

This risk of packing at the bridge itself indicates that the spans must be made large, and for the purposes of navigation also large spans are necessary.

Without more local information than I possess, however, it is impossible to determine precisely what spans and what number of piers would form the most economical bridge. I will assume 220 ft. clear waterway for 24 side spans, and 330 ft. for the centre opening, to be sufficient for all purposes.

These appear to be the number and dimensions of openings shown on the published lithographed drawings, and by the model exhibited in Paris of the proposed Victoria Bridge. I have made the height of the bridge also the same as shown on them, viz., 70 ft.

First, with respect to the building of the Piers. As I have before stated, I see no reason to apprehend any difficulty in protecting them in the manner usual where exposed to the influence of ice.

The foundations are naturally quite solid, and the under-water portion of the Piers is at so small a depth that their construction can be no great expense.

The chief point for consideration seems, in fact, to be, how to construct this part in the shortest possible time. For the best manner of accomplishing this object, I advise that the Piers, up to the ordinary level of water, should be formed of rough stone concrete with cement, laid in an iron casing; the upper portion of the Piers to be built upon this in the ordinary way. I am decidedly of opinion that, in this manner, if proper Ice-breakers are added, sufficient resistance will be provided to meet the only force that can be exerted against the Piers, viz., the weight of ice and of the water dammed back at the bridge.

As to the Ice-breakers, my opinion is, that they should be built as *an annex* to the piers, and formed of wood and iron, in the manner commonly used by American Engineers in the rivers affected by heavy floating ice.

On this plan of construction, I think that the Piers will be thoroughly protected, and readily relieved, and the Ice-breakers can be renewed from time to time, as they may require it, at little cost.

In making my estimate for the Piers, I have calculated them for a double roadway. Such provision will require but a small additional cost; for, as a certain mass is required to resist the weight of the ice and dammed water, it may as well be disposed in such a form as to carry a double line.

My estimate for the 24 piers and 2 abutments, built in the manner recommended, with Ice-breakers for each, and for the Embankments at each end of the Bridge, amounts in the whole to £220,000. I have in this estimate adopted prices of work far above the English, in accordance with my information regarding the rates of skilled labour in Canada.

Secondly, as regards the Superstructure, four forms suggest themselves to consideration, for crossing the Saint Lawrence: the Suspension Bridge; the Tubular Girder Bridge (Britannia Bridge type); the plain Girder Bridge; and the Trussed Girder Bridge.

Of these, the first may be put out of the question, not from any incompatibility of the form with all the requirements of a railway bridge, but because, in this case, large spans are totally unnecessary for any reason of excessive cost of foundations, or height of piers, or in reference to the navigation; and it is only where such considerations are paramount, that the Suspension Bridge is to be recommended.

Tubular Girder Bridges (of the Britannia Bridge type) for moderate spans, such as 220 feet, cannot be recommended on account of their great cost, and, also, because they form a disagreeably noisy and dark tunnel, without any countervailing advantage.

Plain iron **I** shaped Girders are much less costly than Tubular Girders, are excellent in most respeets, but they are more costly than Trussed Girders; and I have arrived at the conclusion, that wrought-iron Trussed Girders are the best adapted for bridging the Saint Lawrence, for reasons of economy, as also for providing the permanency and substantiality required.

I have lately been putting up a large bridge with what are known as Warren's Trussed Girders (in spans of 150 feet each). From the experience obtained in the execution of that work, I am able to speak precisely as to the cost at which such Girders can be erected; and, satisfied as I am of their being good and substantial, I have no hesitation in recommending them, though there are other forms of Trussed Girders that are equally good in all respects.

I have taken the Equilateral Triangle Trussed Girders (Warren's) as the basis for comparing the three forms of wrought-iron Girders, and have put the calculation into a tabular form for facility of comparison.

In this table, the calculated strain on the iron is the same, and the price is taken at £24 per ton for all. But it must be observed that, in making this comparison, the Tubular Girders are calculated on a construction which gives, theoretically, equal strains with those applied to the other Girders, but which cannot be recommended in practice. In fact, it appears to be necessary, in order to obtain sufficient stability in Tubular Girders of such spans as 220 feet, to make them about 70 per cent. heavier than the weight given in the table:—

COMPARATIVE TABLE.

—	24 Spans of 220 ft. clear, with length added for piers.		1 Span of 330 ft. clear, with length added for piers.	
	Tons of Iron.	£.	Tons of Iron.	£.
Warren's Girders . .	3,360	80,640	472	11,328
Plain ditto	3,686	88,464	561	13,464
Tubular ditto . . .	6,105	146,520	928	22,272

The cost of carriage of the materials to Canada, and the erection there of tubular and plain girders, I cannot reckon at less than £12 per ton, whereas the Trussed Girders could be carried out and put up for £8 per ton.

My estimate for the superstructure, on the plan I have recommended, is £123,000, and for the piers £220,000; and the total estimate for the bridge, with an allowance of 10 per cent. for contingencies, amounts to £377,000. For this sum of £377,000, I feel confident that responsible contractors would readily come forward in public competition to tender for the execution of the work, on the plans I shall be ready to prepare, should you honour me with further instructions in the matter.

I append three photographic views of the Crumlin Viaduct, alluded to in this Report, as illustrating my experience of the application of the Triangular Trussed wrought-iron Girder.

I have the honour to be,

Sir, ~~Gentlemen,~~

Your obedient Servant,

(Signed) CHARLES LIDDELL.

GRAND TRUNK RAILWAY OF CANADA.

VICTORIA BRIDGE.

REPORT OF MR. STEPHENSON, WITH REPLY.

MR. STEPHENSON'S REPORT.

To the Chairman and Directors of the Grand Trunk Railway of Canada.

GENTLEMEN,

1. HAVING learnt that some doubts have been expressed respecting the fitness of the design for the Victoria Bridge, across the St. Lawrence at Montreal—that it is more costly than necessary, and that other systems of structure less expensive, yet equally efficient, might with propriety be adopted, I feel called upon to lay before you, in some detail, the considerations which influenced me in recommending the adoption of the design which is now being carried out. In doing so, I beg to assure you that the subject was approached in the outset, both by Mr. Alexander Ross, your engineer in Canada, and myself, with a thorough consciousness of the enormous expense which must inevitably be involved, whatever description of structure might be adopted,—also of the large proportion which this cost must bear to the entire outlay of the undertaking of the Grand Trunk Railway of Canada. We were, therefore, fully alive to the imperative necessity of studying the utmost economy in every part of the work, consistent with our notions of efficiency and permanency.

2. It will be my endeavour, in the following remarks, to satisfy you, and those interested in the undertaking, that these objects have been kept steadfastly in view.

3. It would evidently be unreasonable to expect that, amongst professional men, an absolute identity of opinion should exist,

REPLY.

To Robert M'Calmont, Esq., one of the Directors of the Grand Trunk Railway of Canada.

VICTORIA BRIDGE.

SIR,

I HAVE read Mr. Stephenson's Report on "the fitness of the design for the Victoria "Bridge," which, though not professing to be a direct answer to my Report to you "on the "most economical mode of constructing a per- "manent and substantial bridge across the St. "Lawrence at Montreal," is nevertheless so in fact, as is apparent, not only from internal evidence, but also from the fact that it is accompanied by Reports from Mr. Clark, Mr. Brunel, and Mr. Ross, written at his request on my Report.

The following is my reply to Mr. Stephenson's views and statements.

That the bridging of the St. Lawrence at Montreal is no light work few will be disposed to deny. Whether it be built on the cheapest system of American lattice bridges at a cost of £200,000, or on a system of ashlar work and iron tubes at an expenditure of £1,400,000, it is in either case a costly work.

That to recommend a bridge of $1\frac{1}{2}$ mile in length, of a height above the bottom of 72 feet in the middle, and of 35 feet at the abutments, involves heavy responsibility is very certain; and it may well justify the extreme caution with which Mr. Stephenson describes himself to have been influenced in approaching the consideration of it; for upon the care and judgment with which the case is considered the nice adjustment of the means to the end upon which the outlay is to be made, and the sufficiency of the structure when made, must depend.

The question which has been raised is exactly

MR. STEPHENSON'S REPORT.

either in reference to the general design, or in many of the details of a work intended to meet such unusually formidable natural difficulties as are to be contended with in the construction of a bridge across the St. Lawrence.

REPLY.

upon these points, viz., whether it is necessary to incur so heavy an expenditure as £1,400,000 to bridge the St. Lawrence at Montreal, or whether a substantial and permanent bridge, all sufficient for the purpose, cannot be put up at a much smaller cost.

In reporting to you as I have done in favour of this latter supposition, I was well aware of what I was undertaking in opposing my opinion to that of Mr. Stephenson. I was well aware that, from his professional position, his authority is not lightly to be disputed; and if I had not carefully considered the question, when urged by you to report upon it to the Board of Directors, I should not have advocated the opinions put forward in my Report, nor should I now defend them. But, retaining those opinions, as I still do, I shall endeavour to uphold them in my reply to Mr. Stephenson, and to the three other Reports which he has obtained and put in to support his own. I shall endeavour to show that, as I conscientiously believe it to be the case, neither in the cost of the work as designed, nor in the design if executed at *reasonable rates*, has economy or sufficiency without excess been studied.

4. You will remember, that at the time I first entered upon the consideration of the subject, these difficulties were deemed by many, well acquainted with the locality, and publicly stated by them, to be—if not insurmountable—at all events of so serious a character, as to render the undertaking a very precarious one.

Against this statement I have only to remark, that designs and estimates had been made for a bridge by eminent American engineers for this very place prior to the formation of the Grand Trunk Company; and that the matter had been treated by them as presenting no very extraordinary difficulties to engineering skill.

In the Report of Mr. Keefer to the Hon. John Young, Chairman of Committee of the Montreal and Kingston Railroad, he says, "A "wooden bridge, properly constructed and protected, will last at least half a century, and, "if it were not for the contingency of fire, would be all that is needed. This risk of "fire should not, however, operate against the construction of a bridge of wood, if the "more expensive structure be unattainable." He afterwards gives his estimate for a bridge, with a centre span of 400 feet of iron, and 22 arches of wood of 300 feet span, with piers of stone, protected by enormous shoes of crib-work, and leaving a clear waterway of 240 feet between each, at £400,000 currency (£320,000 sterling), and he evidently considers the chief difficulty was that of obtaining funds.

In all works of unusual magnitude difficulties are imagined insuperable, and the same kind of objections are taken; and though I by no means seek to make light of the difficulties of this work, yet on the other hand it is desirable to free the consideration of it from all exaggeration.

5. The information I received respecting these obstacles, when my attention was first drawn to this project, was so striking that I reserved forming an opinion until I had visited the spot,—had well considered all the detailed information which Mr. Alexander Ross had collected during several months' previous residence in the country,—and had heard the opinion of many intelligent residents, regarding the forces exhibited by the movements of the huge masses of ice during the opening of the river in spring.

6. The facts gathered from these sources fully convinced me, that, although the under-

As a matter of fact, the contract and the specification referring to the designs were signed on the 3rd March, 1853. Mr. Stephenson did not go to Canada till September of that year, and left it in November of the same year: he did not himself witness any of the phenomena of the ice, and in any judgment he has formed must, therefore, depend entirely upon the information derived from others.

I shall have occasion in my reply to Mr. Brunel's report to quote at length from the best authorities on the subject of the ice phenomena, and the provisions usually to be made against the forces, some of which authorities Mr. Stephenson has used in support of his

MR. STEPHENSON'S REPORT.

taking was practicable, the forces brought into action by the floating ice, as described, were of a formidable nature, and could only be effectively counteracted by a structure of a most solid and massive kind. All the information which has been collected since I made my first Report has only tended to confirm the impressions by which I was then guided.

7. For the sake of clearness and simplicity, the consideration of the design may be divided into four parts—*first*, the approaches;—*secondly*, the foundations;—*thirdly*, the upper masonry;—and *fourthly*, the superstructure or roadway.

8. The approaches, extending in length to 700 feet, on the south or St. Lambert side, and 1,300 feet on the Point St. Charles' side, consist of solid embankments formed of large masses of stone, heaped up and faced on the sloping sides with rubble masonry. The up-stream side of these embankments is formed into a hollow shelving slope, the upper portion of which is a circular curve of 60 feet radius, and the lower portion or foot of the slope has a straight incline of three to one; while the down-stream side, which is not exposed to the direct action of the floating ice, has a slope of one to one. These embankments are being constructed in a very solid and durable manner, and from their extending along that portion of the river only, where the depth at summer level is not more than 2 feet 6 inches, the navigation is not interrupted, and a great protection is, by their means, afforded to the city, from the effect of the "shoves" of ice, which are known to be so detrimental to its frontage.

REPLY.

views, drawing from the passages quoted conclusions which in my opinion cannot be justified, whether those passages be read by themselves or with the context; but I will make no further remark here upon what seems to me a tendency to overrate the difficulties.

About the approaches I shall say little, excepting as to the cost. I think it is abundantly clear, from the fact that quay-walls and crib-work jetties at Montreal stand against the ice-pressure, and also from the very nature of the forces in action, and from the position of the embankments, that there can be no possibility of damage to an embankment of rough stone, at slopes of 2 to 1, without any facing of masonry. From Mr. Logan's paper I find, that since the revetment-wall was built at Montreal, the dangerous action of the shove of the ice has been stopped, although it was formerly known to have been piled up against a house distant more than 200 feet from the margin of the river, so as to break in at the windows of the second floor. Mr. Keefer states, "that though probably there is no "point where the ice strikes with greater "force than against the long wharf at the Bon "Secours Market, yet this *crib-work* has re-"sisted the shock, and forced into the air a "broken heap of fragments." But, as to the cost, it is quite inconceivable how embankments of such dimensions as those given, viz., 2000 feet length by some 30 feet height, together with abutments only 35 feet high in 2½ feet depth of water, though 240 feet long, can cost such a sum as £200,000. The embankments, taken at 12 yards high throughout, with slopes of 2 to 1, and 11 yards top, contain only 280,000 cubic yards, which, at 2*s.* 6*d.* a-yard (a very full price, one would say, for stone quarried close at hand), would amount to no more than £35,000. The abutments, taken of the dimensions given by Mr. Ross, as nearly as I can follow them, and at his own price (2*s.* 6*d.* a-foot), would only amount to about £56,000. This sum, together with the cost of the embankments, making a total of £91,000—*i. e.*, less than half of the estimate for the same work given in Mr. Stephenson's report, viz., £200,000.

That foundations in 2½ feet water do not require "*any extraordinary means for their* "*construction*" is very certain, and from that partly I argue that the estimate given above, on Mr. Ross's price for masonry, is sufficient. The cost of damming back the water of 2½ feet depth may safely be included in this price for work of such dimensions, if the masonry of the piers can be done at such a rate.

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9. For further details on this subject, I beg to refer you to the Report made by Mr. Ross and myself, on the 6th of June, 1853, to the Honourable the Board of Railway Commissioners, Quebec.

10. Advantage has also been taken of the shallow depth of water, in constructing the abutments, which are 240 feet in length, and consist of masonry of the same description as that on the piers, which I am about to describe, and, from their being erected in such a small depth of water, their foundations do not require any extraordinary means for their construction.

11. The foundations, as you are aware, are fortunately on solid rock, in no place at a great depth below the summer level of the water in the river.

12. Various methods of constructing the foundations suggested themselves, and were carefully considered; but, without deciding upon any particular method of proceeding, it was assumed that the *diving bell*, or such modifications of it on a larger scale as have been recently employed with great success in situations not very dissimilar, would be the most expedient. The Contractors, however, or rather their Superintendent, Mr. Hodges, in conjunction with Mr. Ross, after much consideration on the spot, devised another system of laying the foundations, which was by means of floating "coffer-dams," so contrived that the usual difficulty in applying "coffer-dams" for rock foundations would be, it was hoped, in a great measure obviated. When in Montreal, I examined a model of this contrivance, and quite approved of its application, without feeling certain that it would materially reduce the expense of construction below that of the system assumed to be adopted by Mr. Ross and myself in making the estimate. In approving of the method proposed by Mr. Hodges, I was actuated by the feeling that the Engineers would not be justified in controlling the Contractors in the adoption of such means as they might consider most economical to themselves, so long as the soundness and stability of the work were in no way affected. This new method has been hitherto acted upon, with such modifications as experience has suggested from time to time during the progress of the work; and, although successfully, I learn from the Con-

REPLY.

The specification for the construction of the bridge sets forth, that "the *masonry of the* "*piers being built in from* 8 *to* 12 *feet water* "*must necessarily be set by means of the* "*diving-bell.*" Mr. Stephenson seems also to have *assumed* it as the best plan, but without, as far as I can discover, giving any reasons for doing so. This plan, *assumed as the best* in one instance, and as *the necessary mode* in another, has now, it appears, been abandoned, and the system of caissons (spoken of, by the way, as if it were some new discovery) is adopted, though Mr. Stephenson doubts its advantage in point of economy. Mr. Stephenson adds:—"I learn from the contractors that the "bed of the river is more irregular than was "supposed, presenting, instead of tolerably "uniform ledges of rock, large, loose frag- "ments, which are strewed about, and cause "much inconvenience and delay. They are "consequently necessitated to vary their mode "of proceeding to meet the new circum- "stances." What mode of proceeding? To change the diving-bell for the caisson, or the caisson for something else? And if the latter, for what else? Then he goes on:—"*And it* "*may be stated, that all observations up to* "*this time show the propriety, notwithstanding* "*the difficulty with dams, of carrying the* "*ashlar masonry of the piers down to the* "*solid rock, and that any attempt at obtain-* "*ing a permanent foundation by means of* "*concrete confined in caissons would be utterly* "*futile.*" By what process of reasoning this result is arrived at it is impossible to guess. Assuredly it does not flow from the statements above given; at least I cannot suppose Mr. Stephenson to imply that the newly-contrived caisson of Mr. Ross, contrived for a temporary purpose, is in any way analogous to the system of Bêton foundations, so largely used in France.

This conclusion then, "that any *attempt to*

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tractors that experience has proved the bed of the river to be far more irregular than was at first supposed, presenting, instead of tolerably uniform ledges of rock, large loose fragments, which are strewed about and cause much inconvenience and delay. They are consequently necessitated to vary their mode of proceeding to meet these new circumstances; and it may be stated, that all observations up to this time show the propriety, notwithstanding the difficulty with dams, of carrying the ashlar masonry of the piers down to the solid rock, and that any attempt at obtaining a permanent foundation by means of concrete, confined in "caissons," would be utterly futile; however, if it were assumed to be practicable, there would be extreme danger in trusting such a superstructure of masonry upon concrete confined in cast-iron "caissons" above the bed of the river; indeed, considering the peculiarities of the situation, and the facts which have been ascertained, this mode of forming foundations is the most inappropriate that can be suggested, as it involves so many contingencies, that to calculate the extreme expense would be utterly impossible.

13. These considerations lead me, therefore, to the conclusion that the present design for the foundation is as economical as is compatible with complete security.

14. We are now brought to the question as to whether the upper masonry is of a more expensive description than necessary, or whether it can be reduced in quantity? This question is exceedingly important, since the cost of the masonry constitutes upwards of 50 per cent. of the total estimated cost of the bridge and approaches. The amount of the item of expenditure for the masonry is clearly dependent upon the number of piers, which is again regulated by the spans between them.

15. The width of the openings in bridges is frequently influenced, and sometimes absolutely governed, by peculiarities of site. In the present case, however, the spans, with the exception of the middle one, are decided by a comparison with the cost of the piers;

REPLY.

"*obtain a permanent foundation by means of*" "*concrete confined in caissons would be utterly*" "*futile,*" is one of those authoritative dicta which I, for one, cannot accept without proof; and I believe that by no reasoning, or proof from practice, can it be sustained. "*If it were*" "*assumed to be practicable,*" however, Mr. Stephenson goes on to say, "there would be extreme danger in trusting such a superstructure of masonry upon concrete confined in cast-iron caissons above the bed of the river." This is another absolute assertion. The whole idea is condemned without one single reason or fact to justify the condemnation.

And, indeed, the assertions are in direct contradiction with extensive experience derived from engineering works in this and other countries.

The Pont du Carrousel in Paris is built on concrete foundations, confined in *wooden* casings, reaching 9 to 13 feet above the bed of the river. The Pont du Souillac is built on concrete foundations, extending 6 to 8 feet above the bed of the river, confined in wooden casings.

The *piers* of the great Bridge of Narva on the Narowa, a river with a current of 5 to 7 miles an hour, and more than 30 feet deep, are of *bêton.*

The Bridges of Rouen, Langon, Asnières, and many more besides, are built on *concrete foundations, extending above the bed of the river*, and each of these foundations has to endure a pressure per square foot of its area equal to or greater than the Victoria Bridge. What reason then has Mr. Stephenson for the above assertions of "futility" and "extreme danger?" There *can* be no reasonable doubt that where masonry in caissons is "practicable," properly-made bêton would be as practicable. Bêton is, in fact, the material eminently suited, independently of economical considerations, for the foundations of the piers of the Victoria Bridge.

In paragraph 13 follows:—"these *considerations* lead me therefore to the conclusion, that the present design for the foundations is as economical as is compatible with complete security:" *i. e.*, having ruled authoritatively, that to obtain permanent foundations by means of concrete confined in cast-iron caissons "would be utterly futile," and that if practicable, they could not be trusted to bear the superstructure, he jumps to the conclusion, that "*the present design is as economical as is compatible with security.*"

Mr. Stephenson in the latter part of his report states the cost

	£.
Of the piers to be . . .	800,000
Of the superstructure .	400,000

In considering the statement, that the cost

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for it is evident, that as soon as the increased expense in the roadway, by enlarging the spans, balances the economy produced by lessening the number of piers, any further increase of span would be wasteful.

16. Calculations based upon this principle of reasoning, coupled to some extent with considerations based upon the advantages to be derived from having all the tubes as nearly alike as possible, have proved that the spans which have been adopted in the present design for all the side openings, viz., 242 feet, have produced the greatest economy. The centre span has been made 330 feet, not only for the purpose of giving every possible facility for the navigation, but because that span is very nearly the width of the centre and principal deep channel of the stream.

REPLY.

of the openings of the bridge "are "decided by comparison with the cost of "the piers," it is necessary to bear the above figures in mind. There are 24 spans of 242 feet, and the average cost is about £15,500 each. There is one of 330 feet, costing £28,000. The 25 spans therefore make the total of £400,000. There are 24 piers, and they average £33,666 each, making the total of £800,000.

With so great a difference between the cost of piers and superstructure as two to one, it is clear that the true proportion of spans has not been arrived at. Indeed the true proportion is only arrived at when the cost of the superstructure, for a given strength, is equal to that of the piers.

Now if the calculation be made in reference to piers which cost £33,666 each, and spans of 242 feet which cost £15,400 each, it will be found that the true proportion of span to pier, without adopting the principle of continuous beams, would be about 365 feet, and this would result in a saving of about £100,000. If the principle of continuity were adopted, the spans would have to be still further increased to give the true proportion, and with a still further saving. This calculation, however, is made on the assumption of a uniform price per ton for the iron-work, which ever span is adopted; for which, perhaps, some slight allowance would have to be made.

My object *here*, however, is not so much to show what would be the best span to adopt with a tubular bridge, as to point out inconsistencies which pervade the design taken in connection with the amounts of Mr. Stephenson's estimates. I need not, therefore, at present, pursue this subject into a question of a cheaper kind of superstructure. I shall have to speak again on the subject.

17. The correctness of the result of these calculations obviously depends upon the assumption that the roadway is not more costly than absolutely necessary; for if the comparison be made with a roadway estimated to cost less than the tubular one in the design, then the most economical span for the side openings would have come larger than 242 feet, and the amount of masonry might have been reduced below what is now intended. In considering the quantity of masonry in the design, you must, therefore, take it for granted for the moment that the *tubular roadway* is the cheapest and best that could be adopted, and leave the proof of this fact to the sequel of these remarks.

18. It may perhaps appear to some in examining the design that a saving might be effected in the masonry by abandoning the inclined planes which are added to the up-side of each pier, for the purpose of arresting the ice, and termed "ice-breakers."

The postulate put by Mr. Stephenson in paragraph 17 should therefore stands thus, "*you must take it for granted that the tubular* "*roadway is the cheapest and best that* "*could be adopted,*" *and cannot cost less than* £400,000 (for he has elsewhere stated £400,000 to be the cost), "*and leave the proof of these* "*facts to the sequel.*"

Now, as from the sequel of Mr. Stephenson's Report, we gather that the total weight of iron in the proposed tubular roadway will be about 7,200 tons, Mr. Stephenson here wishes it to be taken for granted, that a tubular roadway, at £56 per ton, or 6*d*. per lb., is the cheapest that can be adopted.

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19. In European rivers, and I believe in those of America also, these "ice-breakers" are usually placed a little way in advance, or rather above the piers of the bridges, with a view of saving them from injury by the ice shelving up above the level of (frequently on to) the roadway.

20. In the case of the Victoria Bridge, the level of the roadway is far above that to which the ice ever reaches; and as the ordinary plan of "ice-breakers," composed of timber and stone, would be much larger in bulk, though of a rougher character than those which are now added to the piers, I have reason to believe that they would be equally costly, besides requiring constant annual reparation, it was therefore decided to make them a part of the structure itself, as is now being done.

REPLY.

In most of the great stone bridges over European rivers, viz., the Elbe at Dresden, the Moldau at Prague, the Danube at Linz, and Pesth, there are no ice-breakers beyond the regular cut-waters of the piers. In American bridges the ice-breakers generally abut against the pier, although the raking timbers of which they are composed are not united so as to form an integral part of the piers. They are not "altogether detached from and a little way above the piers," *i. e.*, placed in the manner of dolphins, as such separate structures are technically termed. In stone bridges in which the pier-heads are formed into ice-breakers, as in the manner of Mr. Stephenson's design, they appear to be always faced with timber and iron.

There can of course be no sort of objection to a stone ice-breaker executed at 2*s.* 6*d.* a-foot for ashlar work above water; the only questions are, whether it is necessary to go to such expense as 2*s.* 6*d.* a-foot where crib-work or good range-work properly protected with timber and iron can be put up for less than half the cost; and whether such an outlay for foundations as that estimated by Mr. Stephenson and Mr. Ross cannot be replaced by a cheaper and equally-efficient mode of construction. Of these comparative costs I have to speak hereafter.

21. To convey some idea of the magnitude of ordinary "ice-breakers" placed on the upside of the pier, and to enable you to form some notion of their cost, I cannot do better than quote the following, from the excellent report, addressed to the Honourable John Young, by Mr. Thomas C. Keefer, whose experience in such matters from long residence in the country entitles his opinion as to the proper character of such works to confidence:

"The plan I have proposed contemplates "the planting of very large 'cribs,' or "wooden 'shoes,' covering an area of "about one-fourth of an acre each, and "leaving a clear passage between them of "about 240 feet, a width which will allow "ordinary rafts to float broadside between "them. These 'islands' of timber and "stone will have a rectangular *well* left "open in the middle of their width, to-"ward their lower ends, out of which will "rise the solid masonry towers, support-"ing the weight of the superstructure, and "resting on the rocky bed of the river. "This enclosure of solid crib-work, all "round the masonry, yet detached from "it, will receive the shock, pressure, and "grinding of the ice, and yield to a cer-"tain extent, by its elasticity, without "communicating the shock to the masonry "piers. These cribs, if damaged, can "be repaired with facility, and from their "cohesive powers will resist the action of

In proposing to convey "*some idea of the magnitude of ordinary ice-breakers*," Mr. Stephenson has not done justice to Mr. Keefer's Report. Mr. Keefer describes no "*ordinary ice-breakers*," but special contrivances designed to meet special circumstances minutely described in his Report, and distinctly alluded to in the last sentence quoted by Mr. Stephenson, and which I have had printed in italics. The bridge as designed by Mr. Keefer was to consist of timber *arches*, the springing of which was necessarily "the lowest and most "exposed part." In order to prevent the ice from "reaching *the springing of the arches*," Mr. Keefer proposed to "apply to the sides of "the piers the same system of protection "which has proved successful in the construc-"tion of ice-breakers in the large rivers of "North America." Now Mr. Keefer's proposed construction, instead of being placed on the upside of the pier as is to be inferred from Mr. Stephenson's Report, was completely to surround it, "forming an enclosure of solid "cribwork all round the masonry.

"During the construction they were to serve "as coffer-dams, *out of which the solid-masonry towers were to rise*; and being formed of "the cheapest materials," he considered they would be useful "as service grounds or plat-"forms," for carrying on the works. Mr. Stephenson, therefore, in speaking of "*ordinary*

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" the ice better than ordinary masonry. " During construction they will serve as " 'coffer-dams,' and being formed of the " cheapest materials, their value as service- " ground or platforms for the use of ma- " chinery, the moving of scows, &c., during " the erection of works, will be at once " appreciated. *Their application to the " sides of the piers is with particular refer- " ence to preventing the ice from reaching " the spring of the arches, which will be " the lowest and most exposed part of the " superstructure if wood be used."*

22. In the first design for the Victoria Bridge, ice-breakers very similar to the above, described by Mr. Keefer, were introduced, but subsequently the arrangement was changed, partly with a view of gaining the assistance of the whole weight of the bridge to resist the pressure of the ice, before it became fixed, and partly for the purpose of obviating a considerable annual outlay.

23. I have not data at hand to estimate correctly the cost of the ordinary ice-breakers as described, but I have little or no doubt that, as I before stated, they would have required to have been large and substantial masses of stone and timber, which in amount of cost would be scarcely less than, if not equal to, the inclined planes of masonry which have been added to the upside of the piers. On this point, however, as well as upon others in reference to some reduction in the quantity of masonry in the piers and abutments, I intend to address Mr. Ross, who, being on the spot, will be able to determine with more accuracy than I can the amount of actual saving which can be effected in the masonry.

24. It is now necessary for me to say a word or two upon the style of the workmanship: it consists simply of solid ashlar, and considering the severe pressure and abrasion to which it will be subjected by the grinding of the ice, and the excessively low temperature to which it will for months be periodically exposed, I am confident that it is not executed with more solidity than prudence absolutely demands; and considering the difference of the rates of wages in Canada and this country, I believe the price of the work will come out nearly the same as any similar work let (here) by competition.

REPLY.

" *ice-breakers*" and in comparing the shoes proposed by Mr. Keefer with those proposed by himself, however little he may have intended it, is certainly putting forward a statement which can only mislead as to the quantity of work required for an *ordinary American ice-breaker*. If any comparison is to be made it should embrace ***the whole foundation-work and ice-breakers on Mr. Stephenson's design as well as in that of Mr. Keefer's.*** Mr. Keefer's estimate for the cribwork shoes, the piers, the abutments, and embankments, altogether amounts to less than £208,000. On Mr. Stephenson's design the work, preparatory to placing the first foundation-stone in the piers, is, according to Mr. Ross, 55 or 60 per cent. of the whole cost, *i. e.*, it amounts to £440,000—£480,000 of the £800,000 which the piers are stated by Mr. Stephenson to cost; and if the cost of the foundation-work of the piers, of the ice-breakers, the abutments, and the embankment, is all taken together, it amounts to no less a sum than one million sterling,—£1,000,000 against £208,000, Mr. Keefer's estimate. In point of fact, Mr. Stephenson, in suggesting ordinary ice-breakers of the magnitude of Mr. Keefer's cribwork shoes, is suggesting the addition of nearly one-half of Mr. Keefer's bridge to his own. Mr. Stephenson himself states (paragraph 21) that Mr. Keefer's " experience, from long residence in the country, " entitles his opinion as to the proper character " of such works to confidence." He also quotes a passage to show Mr. Keefer's opinion that cribwork is better suited than masonry " to " receive the shock, pressure, and grinding ***of* " *the ice*, and if damaged, can be repaired with " facility;" but he omits to quote the experience of Mr. Keefer as to cost, which I have shown to be so largely at variance with his own estimates, although it was the ***cost*** that he proposed at the outset to illustrate, and it is this that is the essential matter in discussion.

Mr. Stephenson proceeds on the assumption that the cribwork shoes of Mr. Keefer are " ordinary ice-breakers as described," and leaves to Mr. Ross a not very difficult proof, viz., that the bridge being built as designed, with the exception of the " inclined planes of " masonry, which have been added to the " upside of the piers," the inclined planes of " masonry" will not be more expensive to add than the " ordinary ice-breakers, ***as described***." It is evident enough that all other parts remaining the same, the addition of the mere ice-breakers in ashlar would not be so much as the islands proposed by Mr. Keefer. But if masonry of ashlar work in Canada is not more than 2*s*. 6*d*. a foot, which may be taken as about the price of similar work in Britain, and if the foundations are in water never exceeding 12 feet, and the average not more than 8, with a rock bottom, how can an average expenditure for the masonry of the piers of 10*s*. a foot be justified? Such is, as nearly as I can calculate, the estimated price, including every cost. What is there in the situation to cause such an excess of expenditure? It is clear from their reports, that neither Mr. Keefer nor Mr. Gay, Transatlantic engineers of eminence, and employed by the Committee of the Montreal and Kingston Railroad in 1851 to report on the subject of a bridge across the St. Lawrence prior to Mr. Stephenson's engagement on the work, estimate such a price as necessary. It is clear from estimates of the cost of work in similar situations in America, that no American engineer would dream of such an expenditure.

Excluding the foundation-work and masonry up to summer water-level, and taking the ashlar stone-work at 2*s*. 6*d*. a foot, the piers amount to about £160,000, and the cost of that part of the work does not, comparatively speaking, much affect the case. The abutments, at 2*s*. 6*d*. a cubic foot, and embankments at 2*s*. 6*d*. a cubic yard,—

Amount to about	£92,000
Masonry of piers above water	160,000
Superstructure as designed and of the weight stated, if taken at £36 a ton to	260,000
	£512,000

This sum I believe to be considerably more than the work would cost. I believe that it could be sublet by the contractors, with a good margin of profit on this amount.

In order to test the accuracy of these statements it would be easy to obtain estimates from builders and manufacturers for the work complete, say for doing 1,250,000 cubic feet of ashlar in piers, above summer-water level; 450,000 cubic feet of ashlar in abutments; 280,000 cubic yards of embankment of rough stone, including all scaffolding, plant, and material necessary for the execution of the work.

The only question then, in which there is really any room for doubt as to the *cost* is that of the foundation work. From the figures given by Mr. Stephenson and Mr. Ross themselves, may be estimated tolerably correctly by any one the value of the work above water in the piers and abutments. No one will venture, I think, to assert that iron tubes cannot be put up at £36 a ton, the price allowed in the above estimate, including every expense, either of lifting or erecting them in their place: and, indeed, the facility of getting materials to the site, and the low cost of timber for scaffolding, appear to me to render such an estimated price far more than enough. The subject then being stripped of all other considerations, we have the important question left as to what are the best kind of foundations, and what would be their cost in addition to the amount above given for the above-water part of the structure.

Now the quantity of masonry above summer-water level, as shown by the specifications, is about 1,250,000 cube feet; and as the cost of the piers, as stated by Mr. Stephenson and Mr. Ross, is £800,000, and the price of the ashlar work above water is also given by Mr. Ross at 2*s*. 6*d*. a foot, it follows that the amount due to the below-water work, including coffer-dams, &c. &c., is about £640,000.

Now is such a sum at all necessary for securing a solid and permanent foundation? If the *ashlar work cannot be put in on Mr. Stephenson's and Mr. Ross's plans*, at a less sum than £640,000, that is £1. 16*s*. 6*d*. *per cubic foot*, is it not possible to apply some other equally efficacious mode of construction?

Now an almost solid mass of cast-iron might be sunk on to the rock for such a sum of money. The masonry of the Skerryvore Lighthouse, built on a storm-beaten rock in the Atlantic, off the north-west coast of Scotland, 11 miles from the island of Tyree—the nearest land—an island destitute of any shelter for shipping, to which everything had to be brought, labouring under all the disadvantages of remoteness from markets, inaccessible shores, and stormy seas;—the masonry in that work, every stone of which had to be carried in steamers to its place *as weather permitted;* every stone of which was granite of expensive form, chiselled to the finest possible joints and beds—so finely fitted, dowelled, and cramped, as to make the structure almost a monolith,—the masonry in that work, certainly executed under the greatest difficulties on record, and in a manner I believe as expensive as any on record, cost but 12*s*. 6*d*. a cube foot. I might go on to compare the work with that of the Eddystone and Bell Rock Lighthouses, in both of which the cost of masonry was considerably lower than in that of Skerryvore; with the foundations of the London Bridge, the cost of masonry in which, up to high-water level, including coffer-dams and all expenses, did not exceed 12 shillings per cube foot, though on piles the *heads* of which are in water of 23 feet depth at low tide, and with a rise of tide of 19 feet, *i.e.* 42 feet below high-water level, or five times the average depth of the Victoria Bridge foundations on solid rock. I might go on to compare the work with innumerable other examples, all telling the same tale, and the nearer they approach in similarity of position, telling the tale with more effect.

Is it not then preposterous to talk of spending £1. 16*s*. 6*d*. a foot for even ashlar foundations, placed on the solid rock for the Victoria Bridge?

If, however, "*it is assumed*," as Mr. Brunel says, that the money "*is to be spent*," if the foundations at £1 16*s*. 6*d*. PER CUBIC FOOT, amounting in all to £640,000 must be adopted; and if we add this sum to the amount of £512,000 for the remainder of the work given in the preceding account (page 9), which account is chiefly made up on the prices supplied by Mr. Ross, the resident engineer of the work—we still have a total sum of only £1,152,000, *i.e.*, there is still a surplus to be accounted for of £248,000, to make up the £1,400,000, at which this work is estimated.

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25. The description and style of the masonry is precisely similar to that adopted in the Britannia Bridge; the material is the same, and the facility of obtaining it is not in any important degree dissimilar.

In taking the price given by Mr. Ross, of 2*s*. 6*d*. per foot, for the Victoria-bridge masonry, I am confirmed as to its correctness by the statements made in this paragraph; for from Mr. Clarke's book on the Britannia and Conway bridges, I find that the average cost of the masonry for those bridges was 2*s*. 1*d*. and 2*s*. per cube foot respectively.

26. The next point to be discussed is the construction of the superstructure or roadway, and here, owing to the misconception which seems to exist on this subject amongst some Engineers, I am compelled to enter somewhat into technical details in reference to the treatment and construction of beams.

27. The matter has already been debated before the Institution of Civil Engineers, at great length, arising out of a paper read by Mr. Barton, on the construction of the bridge over the river Boyne, erected under the direction of Sir John Macneill.

28. In the design of this bridge the Engineer has adopted what is technically termed the "trellis" system of beam, or girder, for the avowed purpose of saving material, as compared with the plain tubular system, adopted in the Britannia, and now proposed for the Victoria Bridge.

29. It has been already stated that the design and cost of masonry materially depend upon the comparative expense which may be incurred in the construction of the roadway,

In order that you, and others who may read these observations, may understand exactly the conception I have acquired on the subject of such a superstructure or road-way of a bridge as we are now considering, I propose here to set forth the principles which guide me in proportioning the parts of beams and girders—what, to use Mr. Stephenson's words, are "the "simple principles" which I conceive "*should* "*govern the arrangement of every beam-* "*bridge*;" and I use the term *conception* not vaguely to express an "impression" or feeling of the mind, but that definite knowledge which is derived by induction from observed facts.

The strength of an engineer's work depends upon its *proportions*, the *materials of which it is composed*, and the *manner of putting them together*.

The *strength of materials* depends upon their physical constitution, viz., form, texture, elasticity, ductility, cohesion.

The resistance of materials in beam and girder bridges, and other engineering structures, is exposed to various strains—compression, extension, detrusion, deflexion and fracture under a cross strain, and this resistance can be since the spans or openings adopted are really governed by this item in the estimate. It is, therefore, doubly necessary that this part of the proposed design should be analysed with great care.

30. Notwithstanding the discussion which took place at the Institution of Civil Engineers, as to the comparative merits of constructing beams in almost every variety of detail, it certainly appears, as far as I am able to form a judgment, that much error still prevails regarding the simple principles that should, and indeed must, govern the arrangement of every beam bridge.

31. The tubular system is openly declared by some to be a wasteful expenditure of material for the attainment of a given strength; in short, that in the scale of comparative merit it stands at the lowest point. This, if it were the fact, would not be extraordinary, since it was the first proposed for carrying Railways over spans never before deemed practicable; but in the following remarks I hope to convince you, in the simplest manner, that (except in particular cases), whilst it is not a more costly method of construction, it is the most efficacious one that has hitherto been devised.

32. There are three distinct classes of beams (including that to which the present design belongs), between which I shall make comparisons. They are as follows:—

FIRST.—*The Tubular Girder*, or what is sometimes called the *box girder*, when employed for small spans, with which may also be named the *single-ribbed girder*, both belonging to the class known as "boiler-plate girders."

SECOND.—*The Trellis Girder*, which is simply a substitution of iron bars for the wood in the trellis bridges, which have been so successfully employed in the United States, where wood is cheap and iron is dear.

THIRD.—*The Single Triangle Girder*, recently called "Warren," from a patent having been obtained for it by a gentleman of that name.

33. Now, in calculating the strength of these different classes of girders, one ruling principle appertains, and is common to all of them. Primarily and essentially, the ultimate strength is considered to exist in the top and bottom,—the former being exposed

determined by direct experiment alone for each material.*

In the earlier period of the application of the principles of science to determining the proportions of the parts of engineering structures and especially of iron (to which material these observations are confined), the resistance of materials was measured not only by its final cohesive force, *i.e.*, was not referred to the strain producing *fracture* alone, but to a strain with which materials might be loaded without overstepping the *limits of their elasticity*, called by workmen "settling or taking a set," and which practical men, without reference to scientific principles then provided against by great excess of strength.

About fifteen years ago, however, Mr. Eaton Hodgkinson proved, by the results of a long course of careful experiments, what M. Vicat's experiments on iron wire had already indicated, that *no material* is so elastic as to recover itself perfectly from even very small loads *allowed to act for a considerable time*, and that, therefore, the notion of fixing by experiment a "*limit of elasticity*," or a strain under which the metal does not alter, is not admissible. This "defect of "elasticity" is greater in cast iron than in wrought iron and steel, but pre vails in all materials experimented on. Mr. Hodgkinson's results demonstrate, in short, that the strain producing fracture is the only phase in their resistance which we can fairly adopt for establishing practical rules for the strength of materials.

Another important result of Mr. Hodgkinson's experiments—those made in 1846 for Mr. Stephenson, and those in 1848 for the Royal Commission appointed to inquire into the application of iron to railway structures—is the information afforded by them of the properties of many denominations of iron made in different districts, or at different ironworks in the same district, which have got into common use. In such cases as nothing precise had been ascertained, engineers had been forced to adopt a *mean* or very low *value* of their resistance: or, in the case of any important work, to make special experiments for themselves, in order to determine the proportions of the parts of the structures in which any particular iron was to be employed. So completely did the Royal Commissioners appreciate the result of their inquiries in this respect, that they report as

* For a clear and philosophic exposition of this much of the subject, I beg to refer to Dr. Thomas Young's Lectures on Natural Philosophy, Lecture XIII. London, 1801.

to a compression force by the action of the load, and the latter to a force of tension; therefore, whatever be the class or denomination of girders, they must all be alike in amount of effective material in these members, if their spans and depths are the same, and they have to sustain the same amount of load.

34. On this point, I believe there is no difference of opinion amongst those who have had to deal with the subject. Hence, then, the question of comparative merit amongst the different classes of construction of beams or girders is really narrowed to the method of connecting the top and bottom *webs* (so called). In the tubular system, this is effected by means of continuous plates riveted together; in the trellis girders, it is accomplished by the application of a trellis-work, composed of bars of iron, forming struts and ties, more or less numerous, intersecting each other, and riveted at the intersections; and in the girders of the simple triangular, or "Warren" system, the connection between the top and bottom is made with bars—not intersecting each other, but forming a series of equilateral triangles: these bars are alternately struts and ties.

35. Now, in the consideration of these different plans for connecting the top and bottom *webs* of a beam, there are two questions to be disposed of; one is,—which is the most economical? and the other,—which is the most effective mode of so doing? But while thus reducing the subject to simplicity, it is of the utmost importance to keep constantly in mind, that any saving that the one system may present over the other, is actually limited to a portion, or per centage, of a subordinate part of the total amount of the material employed.

36. In the case now under consideration, namely, that of the Victoria tubes, the total weight of the material between the bearings is 242 tons, which weight is disposed of in the following manner:—

		Tons.
Top of tube . . .	76	
Bottom of tube . . .	92	—158
Sides of tube		84
Total tons . . .		242

37. Assuming that the strain, per square inch, in the top and bottom is the same for

their first general conclusion, "*that it appears* "*advisable for engineers in contracting to* "*stipulate for iron to bear a certain weight* "*instead of endeavouring to procure a certain* "*mixture or quality.*"

As a first *principle*, therefore, my *conception* is, that the ultimate resistance to fracture is the property of iron which I have to consider, and that within certain limits I can command iron of the strength required at the market price. To adopt any other principle on these points is to refuse the light of the knowledge we have acquired on the subject so far; and to recur to the idea of a fixed value for the resistance of all irons is a retrograde step.

But the *form* into which the materials of a beam or girder (I shall now confine my observations to this kind of *structure*) are put, is even more important than the judicious choice of the material itself.

Now in the first place, as to the *form* in which the iron is *produced at the ironworks* for application in *beam* or *girder* bridges, viz., *bars* and *boiler-plate*.

The ultimate tensile strength of bar iron has been determined experimentally or the products of the different iron districts, in this and other countries; and from the results obtained at various times, on bars varying from 1 square inch to 9 square inches of section, the following may be given, as obtainable *with certainty* on an engineer's specification, at a small increase beyond the general market price of the day:—

	Tons per Sq. Inch.
Welsh Iron	24 to 28
Staffordshire Iron . .	24 to 28
Scotch (Govan) . . .	24 to 29
Yorkshire, Low Moor	26 to 32
Scrap (Howard & Co.)	26 to 32

The ultimate tensile strength of *boiler-plate*, deduced from experiments made on specimens of only *half a square inch of sectional area*, so that the strain was insured to be perfectly diffused over the whole metal, is—

	Tons per Sq. Inch.
Shropshire	22½
Staffordshire	20¼
Derbyshire	20⅛
Yorkshire, Low Moor . .	25½

And boiler-plate always bears a higher price in the market than bars, however selected, excepting the highest quality of *scrap-iron*.

Experiments made at the Britannia Bridge, reported in Mr. Clark's book, page 376, give 19·6, say 20 tons per square inch as a mean every kind of beam,—say four tons of compression in the top and five tons of tension in the bottom,—the only saving that can by any possibility be made to take place, being confined to the sides, must be a saving in that portion of the weight, which is only about 34 per cent. of the whole. How, therefore, can 70 per cent. of saving be realized (as has been stated) out of the total weight, when the question resolves itself into a difference of opinion upon a portion which is only 34 per cent. of such weight?

38. I am tempted to reiterate here much that has been said by several experienced Engineers on the subject, during the discussions already alluded to, at the Institution of Civil Engineers; but the argument adduced on that occasion could only be rendered thoroughly intelligible by the assistance of diagrams of some complexity; and I think sufficient has been said to demonstrate, that no saving *of importance* can be made in the construction of the roadway of the Victoria Bridge, as it is now designed, by the substitution of any other description of girder. Yet, lest this should be considered mere assertion, permit me to adduce one or two examples, where the close-sided tubular system and the open-sided system may be fairly brought into comparison with each other in actual practice.

(22 the highest, and 18 the lowest) of the qualities delivered by different makers in Staffordshire, Derbyshire, and Shropshire.

Now, in order to make a *tie* of bar-iron, such as the bottom web of a trussed-beam or girder-bridge, the *same strength throughout* the entire length can always be secured by an addition of 10 per cent. to the weight; while, to make a *continuous tie* of boiler-plates, to insure the same strength throughout, the additional weight required in the most perfect system of riveting, viz., chain-riveting, is 15 per cent. increase of weight required for reduction of strength by the perforations for rivets; and 15 per cent. for the requisite covering-plates of the system, if chain-riveting be adopted.

Hence the importance of substituting the best bar-iron for boiler-plate wherever the tensile strength is called into action.

The absolute resistance to crushing of wrought-iron bars has been seldom determined; but besides the older experiments of Duleau, there are three experiments of Mr. Eaton Hodgkinson, which show that $23\frac{1}{2}$ to $27\frac{1}{2}$ tons are sustained without fracture or much flexure, though the length was considerably reduced, whilst $9\frac{1}{4}$ tons produced no sensible change: and by selecting the iron for the work it has to do, it is unquestionable that we may with certainty calculate on a resistance of 25 tons per square inch of section, to strains of compression.

The importance of the form in which the material is presented to strain in girder-bridges of different "patterns," may now be pointed out.

From Mr. Hodgkinson's experiments, made for Mr. Stephenson, "it appears that the "resistance of plates of the same length and breadth, but varying in thickness, is nearly as "the cube of the thickness. Thus a plate of *double* the thickness of another would "resist buckling or flexure with seven or *eight times* the force applied in the direction of "its length."—*Royal Com. Rep.*, *App.* (A.A.), pp. 119, 120.

Hence the great importance of choosing a "pattern" in which thick plates or bars can be used under compression.

In the course of the same series of experiments, it was proved, that "in the crushing "of rectangular tubes, the strength, instead of being nearly as the third power of the thick- "ness (that is, for twice the thickness, eight times the strength), as was found to be "the case in bars, is so much reduced, that to produce *double* the strength, *four times* "the thickness of the metal is required."

Hence, again, the great importance of choosing a "pattern" in which thick plates are subjected to compression.

It also appears, that when the thickness of the plates of the tubes is the same, the strength of the smaller ones is greater than that of the larger. Thus, in a rectangular tube of $\frac{1}{16}$ inch metal, 8″ × 4″ (10 feet long), the strength per square inch of section was 6·79 tons; in an 8-inch square tube of the same metal, it was only 5·9 tons; *and in a 4-inch square tube it was 8 6 tons.*

Hence the great importance of disposing the "effective material" in the most efficient or strongest *form*.

The weight per square inch of *greatest resistance* is the essential element for calculation in all ordinary circumstances, but in tubular and other girders where iron is employed in a hollow-square form to resist compression, an extremely important result of the experiments made for Mr. Stephenson is, that the weight of greatest resistance to ***wrinkling***, ***corrugation***, or ***buckling***, was ascertained, and that after buckling had begun, destruction under increased weights ensued rapidly.

On this subject we find, amongst others, the following experiments on tubes of $\frac{1}{16}$ inch metal, in *Royal Com. Rep.*, p. 162.

Dimensions of Tube.	Length.	Weight under which Buckling began.	Weight per Square Inch at which Buckling began.
Inches. Inches.	Ft.	Lbs.	Tons.
8·17 × 4·1	10	13,209	3·85
8·1 × 4·1 divided by a cross-piece into two of 4" × 4".	10	37,401	8·857
8·1 × 8·1	10	15,897	3·428 Or more observable with 4·267
8·1 × 8·1 divided by a star partition into 4 tubes of 4" × 4".	10	56,630	7·119

By these experiments, the extreme importance of the form and disposition of the effective material is most strikingly proved.

The facts above adduced are, probably, sufficient to prove that it is, to say the least, very vague and unprecise to state, "whatever be the class or denomination of girders, they "must all be alike in amount *of effective* material in the top and bottom members or "*webs*." For, a broad thin plate is very much weaker than a narrow thick one; and a large thin cell is very much weaker than a small thick one in the top member. And even Yorkshire plates would be a very sorry substitute for Howard's bars in the bottom, in whatever point of view they be compared. But I must now illustrate and prove the importance of the *form* in which material is employed in beam and girder bridges still more directly.

The experiments, above quoted, show that the boiler-plate begins to corrugate or buckle with a much less strain than would be required to tear it asunder. In prosecution of the inquiry into the best form of tube to be adopted for the Britannia and Conway Bridges, a grand series of experiments was made, on the resistance to fracture under cross strains, of tubes of various sizes and proportions, as to the thickness and disposition of metal in the top, bottom, and sides.

In the course of these experiments the ***cellular top*** was devised to overcome the difficulty of the tendency of plates to become crippled or wrinkled on the top or compressed ***web*** of tubular bridge girders. For it was found, that what is called the coefficient of resistance to compression and extension (*i. e.* to fracture under a cross strain), and which in questions on the strength of materials is a constant for material of the same quality,—it was found, I say, that this coefficient is "variable in ***tubes***, and represents "their power to resist crippling. ***It depends on the thickness of the iron in the tubes*** "***when the depth is the same, or upon the thickness divided by the depth when that varies.***" [Royal Com. Rep. p. 117.]

This difficulty had to be got over by finding a form and dimension of top such that the resistance of the metal to corrugation would be greater than to tension, and the solution of the difficulty was deemed to be found in the ***cellular top*** above alluded to. In the experiments with a tube measuring 75 feet between supports, and in its other proportions intended to be a *model* of the Britannia Bridge (to a scale of 1-6th), the resistance was higher than had been obtained by any other form of tube experimented on, save one or two of the medium size made of 3-4***th inch plates in top, bottom, and sides***, and in which, of course, the strains or resistances are ***subjected to different laws from those in the beam or girder bridge now under consideration.***

Now the final result deduced from the experiments on the large model was, "that a "cellular top similar to that in the model, will fail with 14·8 tons per square inch of "compression, and the bottom with 18·6 tons of tension." This value of the resistance to tension is a *mean* of *three* experiments, varying from 16·6 tons to 20·3 tons. Adopting these results without comment, I conceive that we take the *highest value* admissible for the constants in the formula for calculating the strength of tubular beam or girder bridges.

But, if instead of a bottom *web* of boiler-plate, 16 feet wide, I can use two sets of bars concentrated within a compass of a square foot for the bottom; and if, instead of a *web* or cellular structure of thin boiler-plate extending over 16 feet in width for the top, I can use thick bars or beams of metal rolled, of the quality and to the shape required for giving the strongest form to resist compression, it is evident that the amount of "effective "material" in the two forms of girder bridge for the same strength, would require to be, for the top, 14·8 square inches in this form to 25 in the tube: and for the bottom, 18·6 square inches to 26 in the tube. For these figures represent the inverse proportion of the ultimate breaking weights of the materials, arranged in the form in which they present themselves in a tubular-girder bridge and a Warren-girder bridge respectively.

And that the "*strength*" of a structure depends upon its ultimate resistance to fracture, and that the safety and permanence of a structure is measured by the degree in which its ultimate resistance exceeds the greatest loads that may come to strain it, is proved by the evidence of practical men, confirmed by the approbation of the scientific and practical men who were on the Commission appointed to inquire into the Application of Iron to Railway Structures.

"In girders for railway bridges, Mr. Brunel stated that he allows the *load* to be "*one-third* to *two-fifths* of the *breaking* weight; but he considers that the rule he adopts "for calculating the dimensions of the girders gives more than the usual strength. "Mr. C. May considered *one-third* to be sufficient. Mr. Rastrick, Mr. P. W. Barlow, "Mr. R. Stephenson, and Mr. Joseph Cubitt, adopt *one-sixth;* Mr. Hawkshaw prefers one-"seventh, *except in cases where great care is exercised in the selection of materials* and "workmanship, when a smaller proportion would suffice."—*Royal Com. Rep., App.* 265. The Royal Commissioners, in reference to cast-iron girders, came to the conclusion, "that "to allow the greatest load to be *one-sixth* of the breaking weight, is hardly a sufficient "limit for safety, even upon the supposition that the beam is perfectly sound."—*Royal Com. Rep.*, p. xi.

The principle, therefore, of "assuming that the strain per square inch in the top and "bottom *web* is the same for every kind of beam" is an erroneous one, sanctioned neither by reason nor practice; and I find that in the following notable bridges of *boiler-plate*, the strain per square inch and the Factor of safety attributed to the structures, in no way justify any such assumption.

Ratio of the depth to the length.	BRIDGE.	Weight per Foot run, Single Way.	Working Load per Foot run.	Tons per Square Inch.		Factor of Safety.	REMARKS.
				Tension.	Compression.		
		Tons.	Tons.				
1/15·5	Britannia, centre of great tubes, considered as a continuous beam.	3·38	1·	4·01	3·85	3	The strains on the Britannia Bridge, considered as *independent* tubes, are—
1/15·15	Ditto, on top of the centre pier, considered as a continuous beam.	..	..	5·9	4·0		Tension . . 7·68 tons. Compression 7·13 ,,
1/15	Conway, at centre of tube.	2·78	1·33	6·08	5·06	3	
1/13 65	Torksey, centre of span, considered as a continuous beam.	0·7	1·33	..	4·67	?	
	Ditto, on centre pier . .	0·7	1·33	..	6·9	?	
1/10	Asnières, throughout whole length.	0·45	1·25	3·75	3·75	6	The Pont d'Asnières was the first boiler-plate bridge erected in France.
1/14.4	Clichy	0·44	1·25	4·5	4·5	5	
	Langon	0·7	1·25	4·5	4·5	5	
1/11	Aire Ferry	1·07	1·	7·0	4·1	?	

REPLY.

For the selection of the best form of beam or girder bridge, I think it important also to determine the strain on every part of the structure according to the principles of calculation which apply to it.

For a tubular bridge I adopt the formulas and constants given by Mr. Clark in his work on the Britannia Bridge, in the absence of more experience or better theory to guide me in the calculation of the area of top and bottom webs at the centre.

For Warren and trellis girders I adopt the rules deducible from the elementary principles of statics, by which I can determine with mathematical precision the strain on each and every element of the structure.

For plain girders I adopt the principles laid down by Young and Navier, and Tredgold, with constants derived from the experiments of Fairbairn, Gouin, and others.

By the formulas given by Mr. Clark, deduced from the model, the area of the sides of tubular girders would amount to only *two-ninths* of the whole sectional area; and if this proportion could be carried out in practice, the close or boiler-plate *sides* would be as good as could be adopted. But in the Conway tube it was deemed necessary to stiffen the plates deduced by that formula by additions, rendering the weight of the sides *one-third* of the weight of the girder. In the large tubes of the Britannia the weight of the sides was nearly *two-fifths* of the total weight; and in the Aire Bridge the weight of the sides is nearly *one-half* of the whole weight.

For proportioning the sides of the tubular-beam bridges, it thus appears that there is no rule of practice; and as it is admitted that they are not intended to bear any part of the horizontal strain, there is no general mechanical consideration by which their thickness can be decided, so that in designing a tube, engineers are left much to their own judgment in the matter, and to their reliance on very limited *precedents*. All that I can learn from Mr. Clark's book is "that it is evident that the sides should be as thin as possible, "consistent with the strain to which they are subject." And that we are to interpret this maxim by the principle, "that it is not considered prudent to *expose a thinner than a* "*½ inch plate* to the action of time and the weather." And even then "the precautions "requisite for maintaining deep sides in shape become very formidable. The T irons and "gussets and stiffening plates for this purpose, in one of the Britannia tubes, weigh 215 "tons, or upwards of one-third of the whole weight of the sides."

Now as to the sides of Warren and trellis girders, as I have said, ***the exact strain on every part can be determined with mathematical precision.*** The thickness of metal to support this strain in bridges, above 100 feet span, is such as to exempt them from all fear of want of permanency, without any superfluity; and after we reach a span of 200 feet, there need not be an ounce of superfluous material in any part to adapt it perfectly to the function it has to perform.

I will conclude this part of the subject by referring to Mr. Barton's paper, read before the Institution of Civil Engineers, April 1855, containing a very distinct and practical exposition of the work which the sides of a beam or girder bridge have to perform; of the manner in which this work is performed in each kind of girder bridge; and on the relative practical value of each kind of side in those bridges; merely calling particular attention to the fact that Mr. Barton, in stating 27 per cent. as the excess of material in the sides of a tubular beam beyond that in a Warren beam, has not taken into consideration the *prudential maxim*, "*that in such bridges a thinner than half-inch plate should not be* "*exposed to the action of time and the weather.*" Nor has he alluded to the proportionate increase of the weight of every *part of a beam* from an excess of *dead weight* in any one part.

From the Report of the discussion which took place at the Institution of Civil Engineers on Mr. Barton's paper, as given in the 'Civil Engineer and Architects' Journal,' May and June, 1855, I observe that certain speakers, ignoring or forgetting the fundamental ideas on which our conception of the forces at work in a beam under deflexion depend, boldly asserted the identity of the considerations which apply to the calculation of the strength of a solid beam (or prismatic solid body) with those applying to a framed or trussed girder; saying that "one simple rule, or principle, is applicable to every form of "beam that has been devised, commencing with the simple square bar, through all "modifications of form, up to beams with open trussed sides."

REPLY.

Another speaker following on the same *side* says, *the forces supposed to be called into play* (in a beam under strain) *are invariably assumed to be in horizontal lines.*

Now, according to all elementary treatises on the strength of materials and on applied mechanics, the forces are invariably assumed to act *in vertical and horizontal* lines *in the plane of the beam's depth.* And the reasoning, therefore, of both these speakers was inconsistent with all our positive knowledge on the subject, and was completely answered by a speaker who, in the *discussion* of the 1st of May, 1855, clearly *demonstrated* their inconsistencies; and, as far as I can judge from the report of the discussion, the general voice of the meeting was against receiving the notions of the speakers who advocated Tubular Bridges.

Besides, as the Institution of Civil Engineers, like other scientific societies, does not come to a vote,—as the Society is not answerable for the individual opinions expressed by the members, as the papers do not even go through the formality of an examination by a Committee to report their merits,—I hold it very unsuitable for Mr. Stephenson to have alluded to these discussions in a question of the nature now before us; for it gives an air of additional authority to what Mr. Stephenson considers " sufficient to *demonstrate* that " no saving *of importance* can be made in the construction of the roadway of the Victoria " Bridge." With respect to subjects of speculation and science, the existence of an *agreement* of the persons assumed to be qualified as authorities in matters of opinion on technical questions is most important. Mr. Stephenson's allusion to the discussions at the Institution of Civil Engineers might leave the impression that all or most of the able and honest men who have diligently studied this subject were satisfied with his *demonstration* of the economy of the proposed Victoria Bridge tubes—an impression which I beg to warn you against receiving.

The strength of plane girders depends on distinct considerations from that of either tubular-bridge girders or trellis girders. These latter are considered in the light of *trusses*, or *framed beams.* The strains and proportional dimensions of the parts are determined on the principles applicable to such constructions. In the plane girder the strength of the vertical web is an important part of the whole. Instead of making the " plates as thin as possible," they are made of the thickness that will insure permanence. The stiffening is arranged with the express object of causing the plates to do their work advantageously; or in the manner *assumed* in the formulas applied for determining their relative strength. The sides are attached to, and closely combined with, the top and bottom web, so that there is no inherent weakness, causing them to buckle, as there is in the sides of tubes; and thus the moment of their resistance to horizontal strains may be utilised in the *total resistance* of such girders to the extent of one-third of the whole strength of the girder, their weight forming little more than two-fifths of the whole weight. This form of girder-bridge has been extensively used in France for large spans; and whilst its great advantages over the *tubular* girder-bridges are there deemed ascertained, its inferiority, in point of economy, to the triangular braced girder is recognised.

No bridge of any importance has hitherto been constructed of plane girders except on the *principle of continuity;* and why this principle has not been adopted in the proposed design for the Victoria Bridge, it seems to me difficult to reconcile with any " practical " reason."—(See paragraph 54.)

I believe that I have now shown that, according to the principles " which *should* govern " the arrangement of every beam-bridge,"—

1st. There is a misconception on the part of Mr. Stephenson and of the engineers whom he has called upon to support him in his views of the merits of tubular-bridge girders, in the fundamental ideas of the use of materials, and of the principles of construction usually accepted in reference to the construction of girder bridges.

2nd. The tubular-bridge girder is the most costly, and therefore the most inefficient method of construction of beam that can be applied.

3rd. That the Warren or trellis-bridge girder must necessarily cost less for the same strength; and the proportion of the diminished cost, while it depends to some extent on the notions of the designer, cannot reasonably be less than 50 to 60 per cent., and may be much more.

4th. That the saving is *not* "limited to a portion or per centage of a subordinate part "of the total material employed;" but has reference to *each and every part of the Tube, top, bottom, and sides,* in all of which *the weakest and most expensive iron is employed in the weakest form.*

I believe that I have also shown that what Mr. Stephenson is pleased to call a *demonstration* of the impossibility of making an important saving in the construction of the roadway of the Victoria Bridge, is no demonstration at all, but merely his *ipse dixit*, unsupported by reason or precedent.

MR. STEPHENSON'S REPORT.

39. The most remarkable parallel case which occurs to me, is the comparison of the Victoria Tubes, under consideration, with a triangular or "Warren" bridge, which has been erected by Mr. Joseph Cubitt, over a branch of the River Trent, near Newark, on the Great Northern Railway.

40. The spans are very similar, and so are the depths. In calling your attention to the comparison, you must bear in mind that all possible skill and science were brought to bear upon every portion of the details of the Newark Dyke Bridge, in order to reduce the total weight and cost to a minimum.

As Mr. Stephenson has been misinformed as to the depth of the Newark Dyke Bridge, he has NOT brought the "open-sided system" *fairly* into comparison with either the Victoria Tubes, or their type, the Aire Ferry Bridge. The Newark Dyke Bridge is 16 feet deep, not "an average of 19 feet," nor is there any apparent lavishness in the thickness of the side plates of the Aire Ferry Bridge, seeing that the plates are *only half-inch thick.* For what I believe to be a *fair comparison of these bridges*, I beg to refer you to my reply to Mr. Clark's report, paragraphs 11 to 15.

41. The comparison stands thus:—

Victoria Bridge, as being erected.—Span, 242 feet; weight, including bearings, 275 tons, for a length of 257 feet.

Newark Dyke Bridge, as erected.—Span, 240 feet 6 in.; weight, including bearings, 292 tons, for a length of 254 feet, which shows a balance of 17 tons in favour of the Victoria Tubes.

42. The Newark Dyke Bridge is only 13 feet wide, while the Victoria Tube is 16 feet, having a wider gauge railway passing through it.

43. This is a very important case, as the spans and depths are all but identical, and it will therefore enable you to form a judgment upon that point which has caused so much controversy at the discussion alluded to. It is true, that in the Newark Dyke Bridge a large proportion of the weight is of cast iron—a material I have frequently adopted in the parts of tubular bridges subjected to compression only; but from its brittle character, I should never recommend it for exportation, nor for the parts of a structure that are liable to a lateral blow.

44. It has been suggested, that there is much convenience in the arrangement of the trellis, or "Warren" bridge, as it may be taken to pieces, and more conveniently and economically transported overland than "boiler plates." This may be correct under some circumstances; but it cannot hold good for a work like the Victoria Bridge over the St. Lawrence.

45. I am aware that girders upon the "Warren" principle have been adopted in India, and I am not prepared to call in question the propriety of these applications in certain cases; but what I have been aiming at in these observations is, to prove to you, that no economy over the plain tube can be effected in the case of the Victoria Bridge. I may add, that it has sometimes been urged that the workmanship in trellis, or "Warren" girders, is of a less expensive character than that required in tubes. I am bound to confess my utter inability to understand such a statement; for after many years of practical experience, as a manufacturer of iron-work of every description, I do not know any class of workmanship that bears so small a proportion to the value of the material as "boiler-plate" work.—If there be any difference in the cost, it ought certainly to be in favour of tubular beams.

MR. STEPHENSON'S REPORT.

46. Another example may be mentioned of a tubular beam, somewhat similar in dimensions to the last described, and one which is actually erected on a continuation of the same line of railway as that on which the Newark Dyke Bridge is situated, namely, over the River Aire at Ferry Bridge.

47. Although the similarity is not so great with this as with the Victoria Tube, yet I believe it is sufficiently so to form another proof that the advantage is in favour of the solid side.

48. As before.

Newark Dyke Bridge.
Span, 240 ft. 6 in. Weight, tons 292.

Ferry Bridge.
Span, 225 feet. Tons, 235.

49. The difference between these weights is more than sufficient to compensate for the difference of span; besides which, in the Ferry Bridge—made according to my designs and instructions—I was lavish in the thickness of the side plates, and the bearings, which are included in the above weight, were stiffened by massive pillars of cast iron.

50. For a further example, let me compare the Boyne Trellis Bridge (held by some to be the most economical) with the present Victoria Tubes.

51. The Boyne Bridge has three spans, the centre one being 264 feet, and the height is $22\frac{1}{2}$ feet. It is constructed for a double line of way, and is 24 feet wide. The total load, including the beam itself, the rolling load at 2 tons per foot, and platform rails, &c., amount to 980 tons uniformly distributed.

52. The bridge is constructed upon the principle of "continuous beams," a term which signifies that it is not allowed to take a natural deflection due to its span, but being tied over the piers to the other girders, the effective central span is shortened to 174 feet: in fact, this *principle* changes the three spans into five spans. Now the effective area given for compression in this centre span is $113\frac{1}{2}$ inches, which gives a strain for the 174 feet span of nearly six tons to the inch in compression.

53. The Victoria Tubes are so dissimilar in form and circumstances to the Boyne Bridge, that it is a troublesome matter to reduce the two to a comparative state. However, the Victoria Tubes are known to be 275 tons in weight, 242 feet in span, and of 19 feet average depth, the strain not being more than four tons per inch for compression, with a uniform load of 514 tons, which includes its own weight, sleepers, and rails, and a rolling load of one ton per foot.

REPLY.

The comparison, in these paragraphs, of the Victoria Tubes, with the Boyne Bridge it will be observed, is limited to some general statements of weights and loads, and even in this comparison Mr. Stephenson is again misinformed as to the facts he pretends to compare. The effective area given for compression in the middle of the centre span of the Boyne Bridge is $113\frac{1}{2}$ square inches in *each girder*, or 227 inches in the two girders—and, therefore, the strain on the iron is under 3 *tons* per square inch, not 6 tons, as stated by him. Starting then as he does with a blunder, it seems almost unnecessary to follow the comparison further.

In paragraph 53, Mr. Stephenson asserts that, "*the Victoria tubes are known to be 275 tons in weight.*"

In paragraph 36, he gives the weight of the tubes *between* the *bearings* as 242 tons, viz.,

Top of Tube . . .	76 tons
Bottom of Tube . .	92
Sides	84
The sum of which is .	252 tons,

not 242 tons as Mr. Stephenson states. Now with this weight *between the bearings*, we have only 23 tons left for the iron in the bearings, which is only $3\frac{1}{4}$ tons above the average weight per foot run of the tube, for the strengthening and supporting the ends of the tubes on the piers—and it may, judging from any precedents, reasonably be questioned whether this is sufficient, *if* the weight of the tubes is *known to be* 275 *tons*. In short, there are some discrepancies in these figures which render them not altogether reliable for the purpose of comparison.

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54. The Victoria Bridge has not been designed upon the principle of "continuous "beams" for various practical reasons, including, amongst others, the great disturbance which would be caused by the accumulated expansion and contraction of such a continuous system of iron-work, in a climate where the extremes of temperature are so widely apart, otherwise the principle alluded to was first developed in tubular beams, namely, in the Britannia Bridge.

55. But since we are now only discussing the merits of the sides, let the Boyne Bridge be supposed to have sufficient area in its top to resist four tons per inch (the proper practical strain), and let the spans be not *continuous*, it will be found by calculation that the area required at top will be 364 inches, instead of 113½ inches, and the weight of the span would be found by calculation to come out little short of 600 tons: whereas, it is now 386 tons; and if we suppose the Victoria Tube to carry a double line of way, and 24 feet wide, with a depth of 22½ feet, even if we double the sides in quantity, the whole amount of weight will be certainly very little more than 500 tons for 242 feet span.

56. It will be necessary to conclude my remarks with some further observations relative to the comparisons under our notice, which are of vital importance in considering the design of such a bridge as that to be erected for the Grand Trunk Railway of Canada.

57. Independently of the comparative weights and cost, which, I believe, have been fairly placed before you, the comparative merits as regards efficiency have yet to be alluded to.

REPLY.

Why Mr. Stephenson, who had an opportunity of appreciating the value of the principle of continuity at the Britannia Bridge, should have so lightly abandoned it in this case it is difficult to conjecture. A saving of about 40 per cent. of material can be effected by this principle in trellis, triangular, and plain girders, and the stiffness of the bridge be greatly increased. Mr. Stephenson indeed says, that it is a "troublesome matter" to make the calculations necessary to compare a continuous beam with an independent one. Can it be that Mr. Stephenson considered the saving of some 2,000 tons of iron not worth the trouble of adjusting the dimensions of his tubes to meet the case of continuity? or is the practical reason for not making the Victoria Bridge on the principle of continuous beams that already as independent beams the thickness of the metal is reduced as far as is consistent with permanency, and that therefore no important saving can be effected by its adoption? As I have already said, those assigned among the "practical reasons" for not adopting continuity, seem to me to be wholly insufficient.

The action by gravity on a gradient of one in 132 may surely be provided against by tying the girder in the middle of a continuous length to its pier; for the effect of gravity for a length of continuous beam of 4 spans would only amount to 5 tons, supposing the beam fixed at the centre; and if no means were taken to obtain resistance to the dislocation of the masonry beyond its friction on its own bed, one course of ashlar one foot thick covered with a bed plate of the width of the pier and the breadth of the tube would not be moved by it. There was no necessity for making the whole "one continuous system of iron work," to obtain the economy of material above mentioned. The whole length might have been divided into four lengths, as proposed by Mr. Brunel, or say five lengths of about 1,300 feet each, made within themselves, on the principle of continuity. These would then have presented no greater "disturbance by accumulated expansion and contraction" than the tubes of the Britannia Bridge which form for each single line a continuous system of iron work of 1,237 feet, weighing 4,680 tons, or three times as much as the single line of the Victoria Bridge, and are yet arranged so that no "disturbance" arises from the freedom to dilate their accumulated expansion and contraction to each end.

Mr. Stephenson leads us here (paragraph 55) to expect a *discussion* of "the merits of "the sides," that is, of the relative weights of materials required in the sides of the Boyne Bridge, and in his Victoria tubes.

For this it was only necessary to have stated—

The Boyne Bridge is 264 feet clear span, and has a double line of way. The weight of the sides between the piers is 82 tons. The Victoria Bridge is 242 feet clear span, and is designed for a single line of rails, and if we take two Victoria tubes to carry a double line of way, we have double the quantity of material in the sides that is designed for

1 tube or 168 tons between the points of support, and if we increase this quantity in proportion to the spans, viz., as 264 to 242, we have 183 tons; and if we again increase this in the proportion of the depth, viz., as 22½ to 19, we have the final result of 216 tons for the sides of the Victoria tube enlarged so as to be fairly compared with the Boyne Bridge, *i. e.*, the weight of the iron in the sides of the Victoria Bridge would be to the weight of the iron in the sides of the Boyne Bridge as 216 to 82 or 2½ to 1.

But instead of this simple and true statement, we have a quasi "discussion," in which are given "the area required for the *top*," and "the *weight of the span*" of the Boyne Bridge as they would be by some processes of calculation of his own, for which Mr. Stephenson has not given the data by which to test their correctness.

MR. STEPHENSON'S REPORT.

58. You may be aware that, at the present time, theorists are quite at variance with each other, as to the action of a load in straining a beam in the various points of its depth; and the fact is now known, that all the received formula for calculating the strength of a beam subject to a transverse load require remodelling;—therefore, at present, it is far beyond the power of the designers of *trellis* or *triangular* bridges, to say with precision what the laws are which govern the strains and resistances in the sides of beams (girders of simple solid rectangular sections have not yet been properly valued);—yet one thing is certain, which is, that the sides of all these "trellis" or "Warren" bridges, are useless, except for the purpose of connecting the top and bottom, and keeping them in their position: they depend upon their connection with the top and bottom webs for their own support, and since they could not sustain their shape, but would collapse immediately they were disconnected from these top and bottom members, it is evident that they add to the strain upon them, and, consequently, to that extent reduce the ultimate strength of the beams.

I must here call attention to Mr. Stephenson's assertions (paragraph 58), that "one "thing is certain, which is that the sides of "trellis and Warren bridges are useless," &c., coupled with this (paragraph 61),—"and yet "we are aware that from their continuity and "solidity the sides of a tube *are* of value to "resist horizontal and many other strains, inde-"pendently of the top and bottom."

As an assertion that the unnecessary amount of material in the sides of a tubular-bridge girder adds, or may add, in some degree, to the strength of the beam, there is some truth in this latter remark; but to say that "the sides "of all these trellis and Warren girders are "useless *except* for the purpose of connecting "the top and bottom, and keeping them in their "proper position," seems to me equivalent to saying that the keystone of an arch is useless except for the purpose of separating the two halves of the masonry of the arch, and keeping them in their proper position. Most assuredly sides constructed of the strength of those of the Aire Bridge, if *disconnected from* the top and bottom, could not sustain their shape, but would collapse immediately. It may, however, be fairly reproached to the close or plate sides, that not only would they collapse "if discon-"nected from the top and bottom members," but that if it were not for the vertical columns and stiffeners, they would collapse under the action of the top and bottom, without being disconnected from them at all.

That in the same Report should be enunciated two propositions, both in the same authoritative manner,—in the one *that primarily and essentially* the ultimate strength is considered to exist in the *top* and *bottom* of the different classes of girders, and in the other that in tubes the sides, from their continuity and solidity, *are* of value to resist *horizontal* and many other strains *independently of the top and bottom*,—seems to me to be a strange inconsistency, and strongly to indicate that the material in a tube is badly disposed for its work. As the essential elements of strength in tubular-bridge beams are the top and bottom webs, surely that construction of girder which concentrates the greatest amount of material in the top and bottom webs, removing it from the sides must be the best. Now in the theory of the Warren girder, the whole horizontal strains arising from the weight of the bridge and its load are resisted by the top and bottom web; and the diagonal bracing is only adapted to absorb the resultants of these horizontal forces and the vertical forces arising from the load, and necessary to hold the top and bottom web in position. They form the keystone of the arch, and can only be said to depend for their support upon the top and bottom webs, in exactly the same manner as the top and bottom webs depend upon *them* for *their* support. The whole together form a mutually-dependent system of bracing the simplest that can be contrived.

To illustrate the extent to which the sides of tubular beams "*are* of value to resist horizontal and other strains," I shall take Mr. Stephenson's model tube, and the last or ***decisive*** experiment upon it, reported in Mr. Clark's book, pages 178 to 185.

Depth to centre of top cells 51 inches.
Half length . . 450 ,,
Sectional area of top . 26·5 square inches.

Let f = the resistance per square inch to destruction by compression. The strength of the top = $26 \cdot 5 f$.

$$\therefore 51 \times 26 \cdot 5 f = 1351 \cdot 5 f = \text{moment of forces of the top plates:—}$$

The sum of the thickness of the sides being $2 \times 0.1 = 0 \cdot 2$ inch, and their depth 21 inches; the moment of the strength of the side being f times the breadth multiplied by the square of the depth divided by 6, when the bottom offers equal resistance with the top—

$$\frac{f \times \cdot 2 \times 51^2}{6} = 86 \cdot 7 f.$$

Therefore the sum of the moments of the bottom and sides—

$$1351 \cdot 5 f + 86 \cdot 7 f = 1438 \cdot 2 f,$$

and this is equal to the half length multiplied by the half breaking weight, viz., 89·24 tons,

$$\text{or, } 450 \times 44 \cdot 62 = 1438 \cdot 2 f. \quad \therefore f = 13 \cdot 96, \text{ tons.}$$

And the value of the sides to resist horizontal strains is therefore about $\frac{1}{17}$th part of the whole, or about 6 per cent.; and this on the assumption that the ***coefficient*** for the plates is the same as for the cells.

In reference to Mr. Stephenson's remark, that "at the present time theorists are quite at variance with each other as to the action of a load in straining a beam in the various points of its depth," although the subject broached appears to me somewhat irrelevant, I have to observe that as a question of analytical physicial science the usual theory of the strength of materials is certainly unsatisfactory; for while the equilibrium of forces in space is generally represented by six equations, three of components and three of moments, the ***usual*** theory of the mutual action of the parts of a prismatic solid body is represented by two equations between the external force applied and the vertical and horizontal forces in the vertical plane of the beam, neglecting the mutual lateral action of the fibres on each other.

But, I am not aware, nor can I learn, that theorists are quite at variance with each other as to the action of a load in straining a beam in the various points of its depth; and I shall be exceedingly astonished to find that the generally received theory of these strains is inconsistent with fact, though their mathematical representation is known to be extremely difficult if not impossible with existing analytical means.

Can allusion be here made to the results of Mr. W. H. Barlow's investigations "on the existence of an element of strength in beams subjected to transverse strains, arising from the lateral action of the fibres or particles on each other, and named by him the Resistance of Flexure?'"—*Trans. Roy. Soc. London*, 1855.

Mr. Barlow's experiments on beams formed of two parallel bars, separated at given intervals by vertical ribs, proved that there is an element of strength depending on the degree of flexure to which the metal forming the bars is subjected; or that, with the same deflection and the same length of bearing, the resistance to fracture is greater when the depth of metal in the beam is greater.

The results obtained confirm the best theory, and are valuable additions to our practical knowledge of the strength of materials. They prove conclusively, that it is neglecting true theory to attempt to carry the material of resistance to the extreme distances from the neutral axis, as is done in the Aire-ferry Tubular Bridge, and apparently in the proposed Victoria Tubular Bridge. They afford another evidence of the advantage of the Warren,

REPLY.

trellis, and plain girders, by reason of the depth given to the top and bottom bars of the trussed beam; and they render the abandonment of the cellular or deep top and bottom webs in tubular girders very questionable engineering.

Founding upon the generally received theory, engineers who have employed the continuous beam have theoretically determined with perfect accuracy the points of contrary flexure and the extent of deflection for all the varying positions of the passing load that occur in practice, and have had striking practical demonstration of the truth of the theory during the testing of their bridges. Who can read the details of Mr. Barton's experiments on the Boyne lattice-girders and doubt the soundness of his theory; and who can read paragraph 57 of this Report of Mr. Stephenson's, and doubt his confidence in the theory, seeing that he contrasts the deflection, *calculated* to the tenth part of an inch, that the Victoria tubes *will* undergo when tested, with the ascertained deflection of the Boyne trellis under the tests of the Inspector of the Board of Trade.

Although there is a certain complication and uncertainty in applying the usual theory to calculate the resistance of plane sides of thin boiler-plate stiffened by vertical pillars, &c., the same reproach cannot be made to the theory applicable to the trellis and triangular braced girders. In these, the simplest principles of statics are applicable with absolute certainty to determine exactly the strain on every part, and that under a greater variety of assumed load than in practice is usually taken into account in settling dimensions. Therefore, in designing a trellis or triangular-braced girder, not only the laws which govern the strains and resistances in the sides are known, but their application is so *simple* that there is no excuse for not availing curselves of them to proportion the parts so as to ensure the greatest efficiency from a given *weight* of materials.

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59. In the case of the Newark Dyke Bridge, when tested to a strain of 6¾ tons to the inch, its deflection was 7 inches in the middle, and when tested with its calculated load of 1 ton per foot run the deflection was 4⅝ inches. The deflection of the Victoria tubes by calculation will not be more, with the load of 1 ton per foot, than 1·6 inch; and we have had sufficient proof of the correctness of this calculation in existing examples. That of the Boyne Bridge, with a uniform load of 540 tons, was 1·9 inch, with the spans shortened in effect as described.

60. Many other bridges of similar spans to those above named have been constructed upon the open side or truss principle, which are (in every sense of the word) *excellent* structures; but since no comparison of economy between them and the Victoria tubes has been offered, it would be improper to class them with those (already named) which have actually been put forward as examples of economy, to a large extent, over the tubular system.

61. As an argument in favour of the trellis beams it has been stated that no formula has been used to value the sides of a plate beam for horizontal strains; and, therefore, since the sides are thrown away, except for the office they perform in connecting the top and bottom webs, it is asked, why should more material be placed in the sides than sufficient for that purpose. Now I admit that there is no formula for valuing the solid sides for strains, and that we only ascribe to them the value or use of connecting the top and bottom; yet we are aware that, from their continuity and solidity, they are of value to resist horizontal and many other strains, independently of the top and bottom, by which they add very much to the stiffness of the beam; and the fact of their containing more material than necessary to connect the top and bottom webs is by no means fairly established.

62. It is also said that the trellis and "Warren" beams are usually made deeper in proportion to their span than the tubes, and, therefore, the strain being less, a less quantity of material is employed in the top and bottom webs. It is important to observe, in replying to this, that the advantage named is not (theoretically speaking) peculiar to "trellis" or "Warren" bridges; on the contrary, it is well known that a change of proportion of the depth of any beam to its span changes the effect of the load in straining its top and bottom webs; and if the strain per inch is to be the same, such a change in the proportions as alluded to will cause a change in the weight of the beam itself, as the horizontal strains in the top and bottom webs of a beam of a given span depend upon the distance between them. Such beams are said to vary in strength directly as their depths and

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inversely as their spans. With regard to tubular beams, a practical rule has been established, which determines that the depths shall not be less than 1·15th of the span; but although this is the minimum depth given, there is no reason to consider it the maximum depth; indeed the tubular bridges just named are of a greater depth than that proportion would give; for instance, the depth of Ferry Bridge is 1-11th of its span, and that of the Victoria tubes next the centre opening is 1-12th of the span. These proportions are, I believe, very similar to those that are usually adopted for "Warren" or trellis beams.

63. It is well known that the diagonal 'struts' in these latter systems (when under pressure) deflect as if they themselves were beams; and any increase in the depth of the sides would be an increase of length in the diagonals, which in the "Warren" must be compensated by an increase in their sectional area; and in the trellis beam, if they are not increased in area, they must be in number, so as to make more intersections; therefore, an increase in depth of the sides of these systems would not only be a proportionate increase in their weight, but would be an increase per square foot of their surface. Now the sides of a tube (from their nature) may be increased in depth up to a reasonable practicable limit without any increase in their thickness.

REPLY.

There is no doubt that the dimensions of the connecting vertical bracing in trussed girders must be proportional to those of the top and bottom chord, and also proportional to the depth. In reply to the statement as to the sides of tubes, I cannot do better than to direct your attention to the following extracts from Mr. Clark's work on the Britannia bridge, on this very point (pages 577 and 789).

"The material in the sides of one large "tube is distributed in the following man- "ner:—

	Per cent. of the whole.
"Plates acting as sides . . .	40
"Plates, &c., acting as covers	19
"Pillars and stiffeners . . .	27
"Knees and gussits	7
"Rivet-heads	7
"Total	100"

From this it will be seen, that 26 per cent is required to connect the plates together and for rivet-heads, and that 34 per cent. of the whole weight of the sides is consumed in stiffening them, *i. e.*, 60 per cent. of the whole is needed to render efficient the ***plates acting as sides;*** and as Mr. Clark gives this law, *viz*, "the weight of a larger structure "will increase as the cube of its length, but it would also require a much larger per "centage of stiffening-plates in the sides; ***for as the pillars increase in height, the weight "increases as the cube of the length, while the strength is only as the square.***" It is evident that though "the sides of a tube may be increased in depth up to a reasonable "practical limit, without any increase in the *thickness*" of the plates composing them, yet the ***weight*** of the sides of tubes increases in a rapid proportion to their depth.

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64. Having given you my views with respect to the comparative merits of the different kinds of roadway consisting of beams that may be adopted in the Victoria Bridge, I now proceed to draw your attention to the adaptation of the "suspension" principle, similar to that of the bridge which has been completed within the last few months, by Mr. Roebling, over the Niagara River, near the great "Falls."

65. You are aware, that during my last visit to Canada, I examined this remarkable work, and made myself acquainted with its general details. Since then Mr. Roebling has kindly forwarded to me a copy of his last Report, dated May 1855, in which all the important facts connected with the structure, as well as the results which have been produced, since its opening for the passage of railway trains, are carefully and clearly set forth.

66. No one can study the statements contained in that Report without admiring the great skill which has been displayed throughout in the design: neither can any one who has seen the locality

fail to appreciate the fitness of the structure for the singular combination of difficulties which are presented.

67. Your engineer, Mr. Alexander Ross, has personally examined the Niagara Bridge since its opening, with the view of instituting, as far as is practicable, a comparison between that kind of structure and the one proposed for the Victoria Bridge ; and as he has since communicated to me, by letter, the general conclusions at which he has arrived, I think I cannot do better than convey them to you in his own words, which are subjoined below.

" I find from various sources that considerable pains have been taken to produce an impres- " sion in England in favour of a suspension bridge, in place of that we are engaged in con- " structing across the St. Lawrence at this place. This idea, no doubt, has arisen from the " success of the Niagara Suspension Bridge, lately finished by Mr. Roebling, and now in use " by the Great Western Railway Company, as the connecting link between their lines on " each side the St. Lawrence, about two miles below the Great 'Falls,' of the situation and " particulars of which you will no doubt have some recollection. I visited the spot lately, " and found Mr. Roebling there, who gave me every facility I could desire for my objects. Of " his last Report on the completion of the work, he also gave me a copy, which you will " receive with this. I have marked the points which contain the substance of his statement. " I also enclose an engraved sketch of the structure. Mr. Roebling has succeeded in accom- " plishing all he had undertaken, viz., safely to pass over Railway Trains, at a speed not " exceeding 5 miles an hour: this speed, however, is not practised, the time occupied in " passing over 800 feet is 3 minutes, which is equal to 3 miles an hour. The deflection is " found to vary from 5 to 9 inches, depending on the extent of load, and the largest " load yet passed over is 326 tons of 2000 lbs. each, which caused a depression of 10 inches. " A precaution has been taken to diminish the span from 800 to 700 feet, by building up " underneath the platform at each end about 40 feet in length, intervening between the " towers, and the face of the precipice upon which they stand, and struts have also been " added, extending 10 feet further. The points involved in the consideration of this subject " are, first, *sufficiency ;* and, second, *cost.* These are in this particular case soon disposed of ; " —first, we have a structure which we dare not use at a higher speed than 3 miles an hour ; " in crossing the St. Lawrence at Montreal, we should thus occupy three quarters of an " hour, and allowing reasonable time for trains clearing and getting well out of each other's " way, I consider that 20 trains in the 24 hours are the utmost we could accomplish. When " our communication is completed across the St. Lawrence, there will be lines (now existing, " having their termini on the South Shore), which, with our own line, will require four or " five times this accommodation. This is no exaggeration. Over the bridge in question, " although opened only a few weeks, and the roads yet incomplete on either side, there are " between 30 and 40 trains pass daily. The mixed application of timber and iron, in " connection with wire, renders it impossible to put up so large a work, to answer the " purposes required at Montreal, we must therefore construct it entirely of iron, omitting " all perishable materials ; and we are thus brought to consider the question of cost, in " doing which, as regards the Victoria Bridge, I find that, dividing it under three heads, it " stands as follows :—

	£.
" FIRST.—The approaches and abutments, which together extend " to 3,000 feet in length, amount in the estimate to . .	200,000
" SECOND.—The masonry forming the piers, which occupy the " intervening space of 7,000 feet between the abut- " ments, including all dams and appliances for their " erection	800,000
" THIRD.—The wrought iron tubular superstructure, 7,000 feet " in length, which amounts to (about) £57 per lineal " foot	400,000
" Making a total of	£1,400,000

" By substituting a suspension bridge, the case would stand thus:—The approaches and " abutments, extending to 3,000 feet in length, being common to both, more especially as these " are now in an advanced state, may be stated as above at £200,000.

" The masonry of the Victoria Bridge piers ranges from 40 to 72 feet in height, averaging " 56 feet ; and these are 24 in number. The number required for a suspension bridge, " admitting of spans of about 700 feet, would be 10 ; and these would extend to an average " height of 125 feet. These 10 piers, with the proportions due to their height and stability, " would contain as much (probably more) masonry as is contained in the 24 piers, designed "for the Victoria Bridge; and the only item of saving which would arise between these would "be the *lesser* number of dams that would be required for the suspension piers. But this, "I beg to say, is more than doubly balanced by the excess in masonry, and the additional "cost entailed in the construction at so greatly increased a height. Next, as to the super- "structure, which in the Victoria Bridge costs £57 per lineal foot. Mr. Roebling, in his "Report, states the cost of his Bridge to have been 400,000 dollars, which is equal to £80,000 "sterling. Estimating his towers and anchor masonry at £20,000, which I believe is more "than their due, we have £60,000 left for the superstructure; which for a length of 800 feet, "is equal to £75 per lineal foot, giving an excess of £18 per foot over the tubes, of which we "have 7,000 feet in length. By this data, we show an excess of nearly 10 per cent. in the "Suspension, as compared with the Tubular principle for the particular locality with which "we have to deal, besides having a structure perishable in itself, on account of the nature of "the materials; and to construct them entirely of iron would involve an increase in the "cost which no circumstance connected with our Local, or any other consideration at "Montreal, would justify. We attain our ends by a much more economical structure; and, "what is of still greater consequence, a more permanent one. And as Mr. Roebling says, 'No "'suspension bridge is safe without the appliances of stays from below.' No stays of the "kind referred to could be used in the Victoria Bridge, both on account of the navigation "and the ice; either of which coming in contact with them would instantly destroy them. "No security would be left against the storms and hurricanes so frequently occurring in "this part of the world.

"No one, however capable of forming a judgment upon the subject, will doubt for one "moment the propriety of adopting the suspended mode of structure for the particular place "and object it is designed to serve at Niagara. A gorge, 800 feet in width, and 240 feet "in depth, with a foaming cataract, racing at a speed of 20 to 30 miles an hour, underneath, "points out at once that the design is most eligible; and Mr. Roebling has succeeded in "perfecting a work capable of passing over 10 or 12 trains an hour, if it should be required "to do so. The end is attained by means the most applicable to the circumstances. These "means, however, are only applicable where they can be used with economy, as in this "instance."

68. My own sentiments are so fully conveyed in the above extract from Mr. Ross's letter, that I can add no further remark upon the subject, except perhaps that there appears to be a discrepancy in that part which relates to *cost*.

69. In dividing the £80,000 into items, Mr. Ross has deducted £20,000 for masonry, and left the residue or £60,000 for the 800 feet of roadway. Now it appears evident that this amount should include the "land chains;" and assuming their value at about £15,000, there would be only £45,000 left for the 800 feet of roadway, thus reducing the cost per lineal foot to about that of the tube. But in the application of a suspension bridge for the St. Lawrence, the item £15,000 for "land chains" would of course have to be added to the cost of the 7,000 feet of roadway, which would swell the amount per foot to a little over that of the tubes.

70. In all that has been said respecting the comparative merits of the different systems of roadway, you will perceive that a *complete or wooden structure* has not been alluded to: because, in the first place, when the design for the Victoria Bridge was at first being considered, *wood* was not deemed sufficiently permanent; in the second place the structures alluded to in the Report as being inferior to that now in progress are proposed to be constructed of stone and iron work; and as a third reason, the construction of the tubular roadway is already so far advanced that any alteration to the extent of abandoning *iron* and adopting *wood* must involve monetary questions of so serious a nature as to render the subject beyond discussion, or even being thought of in this Report.

71. In conclusion, therefore, I have to state to you (my deliberate opinion) that the present design now being carried out for the Victoria Bridge is the most suitable that can be adopted, taking all the circumstances into consideration to which the question relates. In making this statement, I must ask you to bear in mind that I am not addressing you as an advocate for a tubular bridge. I am very desirous of calling your attention to this fact, for really much error prevails upon this point through the impression that in every case I must appear as an advocate; no one is more aware than I am that such inflexible advocacy would amount to an absurdity.

72. I entirely concur in what Mr. Ross says respecting the propriety of applying the

REPLY.

As regards Mr. Roebling's bridge, as I stated in my first report to you, "though there is no suspension principle to the passage across the Niagara gorge: no other system of bridge building yet devised could cope with the large span of 800 feet, which was there absolutely called for, irrespective of the other difficulties alluded to.

73. Where such spans are demanded, no design of "beam" with which I am acquainted would be at all feasible. The tube, trellis, and triangular systems are all impracticable in a commercial sense, and even as a practical engineering question the difficulties involved are all but insurmountable.

74. Over the St. Lawrence we are fortunately not compelled to adopt very large spans, none so large, in fact, as have been already accomplished by the simple girder system. It is under these circumstances that the suspension principle fails, in my opinion, to possess any decided advantage in point of expense, whilst it is certainly much inferior as regards stability for railway purposes. The flexure of the Niagara Bridge, though really small, is sufficiently indicative of such a movement amongst the parts of the platforms, as cannot fail to augment where wood is employed before a long time elapses.

"incompatibility of a suspension bridge with "all the requirements of a railway bridge as "to strength and rigidity; yet in this case as "large spans are totally unnecessary for any "reason of excessive cost of foundations, or "height of piers, or in reference to the naviga-"tion, I think it unnecessary to discuss it." I think so still, though not sharing in Mr. Stephenson's admiration of the Niagara suspension bridge which has not by any means the strength or rigidity which I believe to be obtainable with the same amount of material better disposed. Mr. Roebling's real merit is in having overcome the prejudice existing against the application of suspension bridges to railway purposes, and so far he has done great service.

But I have, probably long ago, exhausted your patience, though far from having exhausted the examination of Mr. Stephenson's report, which, however, I trust I have satisfactorily proved, neither justifies the cost of the Victoria Bridge, estimated at £1,400,000, nor reasonably impugns any of the suggestions made by me "for constructing a permanent and sub-"stantial railway-bridge" on the same site for less than £400,000, thereby saving a million of money.

I am, Sir,
Your most obedient Servant,
CHARLES LIDDELL.

75. I beg that this observation may not be considered as being made in a tone of disparagement; on the contrary, no one appreciates more than I do the skill and science displayed by Mr. Roebling in overcoming the striking engineering difficulties by which he was surrounded. I only refer to the question of flexure on the platform as an unavoidable defect in the suspension principle, from which the comparatively small spans that are available in the Victoria Bridge may be entirely removed out of consideration.

I am, Gentlemen,
Your obedient Servant,
(Signed) ROBT. STEPHENSON.

24, Great George-street, Westminster,
November 3rd, 1855.

P.S. In my last communication I stated that in order to bring more clearly before you the comparative merits of different kinds of girders now in use for railway purposes, I had designed some experiments, and intended that the results should be contained in this Report. They are in progress; but as they cannot be completed previous to my leaving this country for two months, I have been compelled to close my Report without them.

R. S.

GRAND TRUNK RAILWAY OF CANADA.

VICTORIA BRIDGE, MONTREAL.

MR. BRUNEL'S REPORT

AND MR. LIDDELL'S REPLY.

To the Directors of the Grand Trunk Railway of Canada.

VICTORIA BRIDGE.

18, *Duke Street, Westminster, November* 30*th*, 1855.

GENTLEMEN,

1. In compliance with the request of Mr. Robert Stephenson, a copy of whose letter conveying that request I beg to enclose, I have carefully examined the Plans of the Victoria Bridge, and have made myself acquainted, so far as the shortness of the time that was allowed me would admit, with all the circumstances of the case.

2. I should observe, that I would not have ventured to have offered any opinion upon so difficult and serious a subject after the consideration of only a few weeks, if I had not previously been acquainted, in some degree, with the peculiar natural difficulties to be overcome, and the reasons for adopting the particular plans which have been matured and ultimately determined upon by Mr. Stephenson.

3. Without some such general knowledge of this particular case—though even this must be imperfect—I should not have felt justified in even offering suggestions.

4. Engineers who have frequently had the heavy responsibility of conducting such large works can alone properly appreciate the amount of thought and of labour that is necessary in seeking out and weighing all the various circumstances that ought to influence a man's judgment before determining on his plans; circumstances and considera-

To R. McCalmont, Esq., one of the Directors of the Grand Trunk Railway of Canada.

VICTORIA BRIDGE.

SIR,

The following are the remarks I have to offer upon Mr. Brunel's Report in defence of the Plans of the Victoria Bridge, made at the request of Mr. R. Stephenson.

Mr. Brunel appears to have contented himself with accepting "the reasons for adopting "the particular plans" of Mr. Stephenson, and the sum of £1,400,000 "as the gross amount "*always assumed* as the cost of the bridge," and though he afterwards says that the plans advocated by me are "*well known* as *possible alternatives*," and may be discussed on their own merits, he nowhere does discuss them, so as to exhibit the real points in difference, viz. the cost at which a permanent and substantial bridge can be erected over the St. Lawrence at Montreal, and the method of construction of such a bridge requiring the least time.

I think that the "various circumstances" here so much insisted upon, ought to have been stated by Mr. Brunel. No other than engineering circumstances, so far as I can see, could enter into consideration. The work is a very straightforward one in this point of view, and any design having reference to all the natural difficulties, must, in the want of personal

MR. BRUNEL'S REPORT.

tions which are not even apparent to superficial or hasty observers, and which are often lost sight of even by the Engineer himself, after his decision has been finally made; and those who have had much experience in such labours know how impossible it is for any man to form a sound opinion without having been under the necessity of investigating in detail all the circumstances, and weighing them maturely and repeatedly, and at intervals of time, and with that anxiety which the sense of responsibility as to the result can alone induce.

REPLY.

knowledge, be based on the data contained in the Reports and Papers of the American engineers who have written on the subject, and on those obtained from the Reports of Mr. Stephenson and Mr. Ross. *The mode of execution so as to save time, and the price at which the work may be executed*, are the matters in which the estimates put before Mr. Brunel differ so enormously. If there are "various circumstances" requiring masonry at an average cost of 10*s*. per cubic foot, and the iron in the superstructure at £56 per ton, and a period of eight years for the completion of the work, they should be stated. There are certainly no "such circumstances" discoverable from any of the Reports now before me, with whatever thought and labour they may have been investigated in detail, and whatever may have been the "anxiety which the sense of responsibility as to the result can alone induce:"—nor indeed can I find any "circumstance" affecting the structure when built, of the effect of which there can be any difference of opinion, excepting the ice movements,—nor any "circumstances" affecting the building of the structure, on which there is any room for doubt, excepting as to the nature of the bottom, and that is described in the Specification to be "formed of flat bedded limestone of generally uniform surface, so that a secure foundation is readily obtained."

MR. BRUNEL'S REPORT.

5. I feel it necessary in my own justification to make these observations, because the very circumstance that this branch of Engineering is one to which I have particularly turned my attention, leads me to know with what diffidence a prudent man ought to approach such a subject, and how impossible it is for him to make himself acquainted with all the circumstances which may have been known to, and may have influenced the original and responsible designer; and if I offer any suggestions involving modifications of any part of the plans hitherto determined upon, I do so with great hesitation, and real doubts as to my ability, or that of any other man, to form a safe opinion in competition with that of the Engineer (provided he is a competent man) who has been long engaged on the work.

6. Guarding myself, therefore, against the imputation of presumption, to which I should be most justly obnoxious if I deliberately set up my opinion in such a case against that of Mr. Stephenson, I shall proceed to lay before the Directors as unreservedly as I have done, or should do to Mr. Stephenson himself, the impressions, and it would not correctly express the state of my own mind if I used a stronger term, that I

What causes may have influenced Mr. Brunel to assume so much diffidence in offering an opinion on a bridge which was *designed*, *specified*, and *contracted for*, before the Engineer ever saw the site, I shall not attempt to guess,—the nature of the site of which was *minutely described* by men eminently qualified to do so, before the bridge was even thought of in England, and concerning which two American engineers had furnished detailed plans and estimates, and clear logical reports in support of those plans and estimates, previous to the formation of the Grand Trunk Railway Company of Canada.

Can it be that Mr. Brunel has not had put before him, or gathered for himself, the full information on the "case," that is so easily obtainable, and therefore guards himself "against the imputation of presumption" in offering an opinion on an engineering work, which, for reasons stated by Mr. Stephenson, "offers none of the formidable difficulties which "surrounded the erection of the Britannia "bridge," and which difficulties, we may therefore conclude, are completely known? From a passage in the last paragraph of Mr. Brunel's Report, in which he says "he can know nothing at all about it," (the site,) it is not an unfair inference that such is the cause of his diffidence.

MR. BRUNEL'S REPORT.

have derived after discussion with Mr. Stephenson before he left England, and from subsequent consideration of the matter.

REPLY.

The undertaking of the Victoria bridge, from whatever point of view the case is considered, is not in any way an extraordinary one, except in respect to its *extent*. The necessity for erecting the bridge was determined. The site of the bridge was fixed after due consideration of local circumstances and influences. The water-way is a question more easily settled than in most cases of the kind, for it may vary within wide limits without affecting the stream.

The foundations are known. The height of the bridge is fixed by the local authorities. The ice phenomena are known, and the appliances necessary to meet them are known. The proportions of the spans are taken as fixed, and, at proper prices for the work, they are about the most economical that could be adopted. With none of all the questions that might arise on these points had Mr. Brunel to deal in answering my Report. Adopting, in great measure, the foregone conclusions, I naturally considered only how the work might be ***efficiently and substantially*** executed: and I think it would have been mere squeamishness on my part, to have shrunk from reporting my opinions on the question put to me as requested by the Directors of the Grand Trunk Railway through you. As a case for special pleading it may be very well to argue thus:—It having been resolved to spend one and a half million of money on the bridge, the consideration given to the work by Mr. Stephenson affords presumptive evidence that the bridge, as designed, is the best under all "circumstances of the case." But this is to argue from false premises, and the inference drawn rests only upon the authority of a name. It is well, therefore, that you should bear clearly in mind, that the true questions at issue are, 1st, whether a bridge built as designed should cost the sum of £1,400,000; and if so, 2nd, whether a cheaper bridge, sufficient for the purpose, cannot be devised? Throughout his Report Mr. Brunel never touches these points, and hence I have thought it right to direct your attention to them.

MR. BRUNEL'S REPORT.

7. I should state, that I have also received and read a copy of a letter addressed by Mr. Liddell to Mr. McCalmont. As the Plans advocated in this letter are such as are generally known and would naturally suggest themselves, amongst many others, as possible alternatives, and therefore can be discussed upon their own merits, I should prefer doing so without any further reference to that letter, or to the particular statements and estimates advanced by the writer, as I think this course is best fitted to insure that calm, deliberate, and unprejudiced discussion of the comparative merits of the several plans, as applied to this case, which so serious an inquiry demands.

8. The question may be stated very simply, although the considerations involved may be numerous and far from simple; it is, I apprehend, this: whether, under all the existing circumstances, any plan or mode of proceeding either wholly or partly differing from that now in course of execution can be wisely and safely adopted, which shall effect any material saving in the cost of this Bridge?

Considering the enormous difference between my estimate and Mr. Stephenson's, it would surely have been but fair and reasonable in Mr. Brunel to have replied specially and in detail to any one of my particular statements and estimates, in order to inform the Directors where the difference lies. There is, however, no such reply. Mr. Brunel avoids it to insure to himself "calm, deliberate, and unprejudiced "discussion," and, dealing in generalities and diffuse arguments, leaves at last his clients to hang upon his "*ipse dixit*."

I shall not treat Mr. Brunel's Report in the same way, for the question is one of practical engineering science, which admits of its being cleared of all such generalities; and instead of being made a question of professional authority, is one of common sense and judgment applied to well-ascertained facts and experience.

MR. BRUNEL'S REPORT.

9. The work which has to be constructed may be considered as consisting mainly of two parts, which, although closely connected by their relative bearing upon each other, may be advantageously considered separately in many respects and up to a certain point. These parts are the substructure or piers, including the abutments, and the superstructure or roadway.

10. The Engineering difficulty of the work is unquestionably the resisting of the action of the packed ice against the piers and abutments. I shall therefore first refer to the division of the work in which this difficulty has to be met,—and particularly to the ice-breakers or fenders.

11. Engineering difficulties are very generally regarded as mere questions of expense; and, assuming that a difficulty must be overcome, and that judicious means are devised for the purpose, the execution or application of these means may, generally speaking, be treated merely as a question of cost, and, if the requisite cost is incurred, the difficulty is assumed to be overcome; but this is not strictly true in practice.

12. Very few of the great difficulties in engineering, resulting from the operation of natural causes, can be entirely overcome, or the result rendered positively certain by any amount of skill or at any cost. The success is at best a question of degree, and what is called certainty, a mere calculation of probabilities; and a certain amount of risk, more or less, still remains; and while this is a strong argument against incurring excessive cost in the execution of a work, which after all can never insure certainty—it is also necessary to bear it in mind when considering plans which, speaking in general terms, have been found hitherto to succeed; it is necessary to examine into the degree of that success, and to consider what value has been attached to the amount of risk still remaining in the examples serving as precedents, and what amount of risk it is wise or profitable to run in the particular case under consideration.

13. This mode of viewing the subject is particularly necessary in the present case.

14. Engineers in the North of the American Continent have had much experience

REPLY.

I think that the sequel of my reply will show that "the resisting of the action of the packed ice against the piers" is only an *apparent engineering difficulty*, and that Mr. Brunel has mistaken the case. See answer to Paragraphs 18, 22, 23, and 24.

Mr. Brunel here enters on a somewhat abstruse part of the philosophy of engineering, to which I do not pretend to have given much attention; yet, with all due deference, I venture to examine the reasoning in these paragraphs, as Mr. Brunel applies the "*principles*" they contain to determine "the form "and mode of construction of the individual "piers."

He states that engineering difficulties are very generally regarded as mere questions of expense, and, assuming that a difficulty *must* be overcome, if judicious means are devised for the purpose, the execution or application of these means may be treated merely as a question of cost; but, because the result cannot be rendered positively certain, or the safety of the structure cannot be insured by *any* amount of skill or at any cost,—"the success is at best a question of "degree, *and what is called certainty, a mere* "*calculation of probabilities*." So that Mr. Brunel deems it a mere calculation of probabilities as to when the Eddystone and Bell Rock and Skerryvore light-towers are to be overwhelmed, owing to incompleteness in the engineering design to resist the operation of natural causes tending to destroy them,—when the Thames Tunnel, from the same cause, is to be burst up,—when the railway over Chat Moss is to sink to its bottom,—when the Menai Suspension Bridge, (a far nobler and *cheaper* structure, by the way, than the Niagara Suspension Bridge,) is to be irreparably destroyed,—when, from the same cause, the Britannia Bridge, the Suspension Bridge at Pesth, the aqueduct of Roquefavour, the viaduct over the Goeltzschthal, and other triumphs of engineering skill, are to be swept away.

in the construction of ice-fenders; and have, I believe, constructed many in various ways with great ingenuity and skill, of various degrees of strength, according to the necessities of the case, and the materials at hand, and no doubt some of the best have succeeded admirably, or at least are said to have done so; but at best these have been but rough expedients, intended to add to the security of some existing works cleverly adapted to the peculiar position in which they were placed, or intended to meet any very probable contingency, and capable of being strengthened or repaired if they should prove weak, or become partially damaged by any unusually severe winter; but in taking these as precedents, the questions arise, what has been the degree of that success, and what was the amount of risk still incurred, and can we rely upon them as safe precedents? Have we, for instance, from any past experience, the means of judging whether if any considerable number, say 50, of the best of these were all exposed to the action of the most powerful ice-packed river in America for a length of time, one or two would not on the average be carried away every ten years? I apprehend that no such degree of success could be proved by any past experience, yet what would be the result of even such an average in the present case, where there are 24 piers? The probability would be that one or two bridge piers, at the least, would be actually carried away or interrupted on the average two or three times in 20 years; or that, most likely, expenses of repairs to an enormous amount would have to be incurred to remedy partial damages, or to meet threatening dangers, and the chances are not very great against this occurring once or twice soon after the opening. The consequences of such results would be too serious to contemplate, if they can possibly be avoided. On the other hand, the same average would give a probability of perhaps a hundred years' duration in the case of a single ice-breaker, where the powers in action were less violent, and at the same time the consequences probably would be far less important, and the means of speedy repairs much more ready.

15. These calculations of comparative probabilities are not given as strictly correct, or capable of being so accurately determined,

This is a view of these works which few will share.

Certainty being, in mathematical language, measured by unity, *probability* is measured by fractions; and, according to all experience of judiciously and honestly executed works, for overcoming engineering difficulties, the fraction representing the probability of their failure is so extremely small that the risk becomes quite inappreciable, and with those provisions for maintenance necessary for all works, has *no money value*, which is the only test of *risk.*

Mr. Brunel, however, considers risk a strong argument against incurring an "*excessive cost*" in the execution of the work. The assumption is that the *difficulty* was to be "judiciously" overcome, which precludes the idea of *excessive cost*, so that this argument is "*ad captandum.*" He says further, it is necessary to bear this uncertainty of the success of all works in mind, in considering plans which *have been found hitherto to succeed.* "It is necessary," he says, "to "*examine into the degree of that success*, and "to consider what value has been attached to "the amount of risk *still remaining* in the "examples serving as precedents, and what "amount of risk it is wise or profitable to run "in the particular case under consideration."

My view is, that it would be unwise and unprofitable knowingly to *run any risk* whatever: and I consider Mr. Brunel's views as at once destitute of practical meaning and most derogatory to the science of Engineering. The question really turns on what are the most judicious means of providing against risks.

After much inquiry I do not hear of any instances of an American railway bridge out of the many that have been built, some of them comparable in extent to the one under consideration, on stone piers, having been carried away by ice, though there are one or two cases on record of earlier-built bridges having been so carried away. But there are bridges on the Ohio, the Susquehanna, the Potomac, the Schuylkill, and the Niagara, built long before the railway bridges, which have resisted the force of the ice in these rivers for fifty years at least. There is, therefore, no calculable probability of bridges, as ordinarily constructed in America, failing from such cause, no appreciable *risk* run, in adopting what has been uniformly successful, since experience has been acquired and has become available.

Ice-breakers are chiefly used in America to protect the *wooden piers* of bridges. In streams with a gentle current, a simple in-but merely as sufficiently approximate to correctness to show how necessary it is to investigate what is called success, and to weigh well the relative value of different degrees of security according to the degree of risk, and the cost of failure, in the particular work under consideration.

16. Applying these principles in the present case, it must be evident that it would be worth incurring considerable expense to insure a greater amount of security to the work, and that ordinary examples cannot safely be taken as precedents on which any body of prudent men would rely in such a case as the present.

clined beam, covered with thick sheet iron, and supported by uprights and diagonal pieces, is all that is found necessary for an ice-breaker. But in rapid currents a *crib-work*, having the form of a triangular pyramid, the up-stream edge of which is covered with sheet iron, is required to offer sufficient resistance to shocks. The crib-work is *sometimes filled in with loose blocks of stone.*

When the piers of bridges are of stone, as in most of the railway bridges over the great rivers, the cut-water is almost invariably the *ice-breaker*, and though differently formed and constructed on different rivers, they are almost always cased either with wooden *baulks edged with iron, or with cast or malleable iron bars laid on crossbearers of wood.*

There is a bridge not far from Montreal, erected by a private individual, across a branch of the St. Lawrence, as wide as the Thames at London, where the current is very rapid, and the ice very heavy. The piers of this bridge are constructed on wooden crib-work filled with loose stones, resting on the bed of the river, and have stood for twenty years, although the superstructure was blown away from two of the spans by a hurricane in July of last year; and this is not the only instance on record of the hurricane having prevailed where the ice was harmless.

After expatiating in a tissue of assumptions, guesses, and doubts, upon the expedients adopted by American engineers in the construction of ice-fenders and their success, Mr. Brunel asks, "Have we, from any past experience, the means of judging whether if any "considerable number, say 50, of the best of these-ice fenders were all exposed to the action "of the most powerful ice-packed river in America for a length of time, one or two would "not, on the average. be carried away every ten years?"

Mr. Brunel has applied a new term—ice-fender—to what has hitherto been called in this discussion an *ice-breaker*. It may be assumed he means the same thing. He seems to admit that American engineers *may* adapt the piers of their bridges, and the ice-breakers attached to them, to the work they have to do in each particular case; that an ice-breaker on bridge piers on the Schuylkill would be different in strength from one on the Susquehanna, and one on the Delaware different from that over the Potomac or the Ohio. In point of fact, there are, over each of these rivers, bridges of ten, twenty, and thirty spans of 100 to 220 feet each, the piers of which are protected by ice-breakers of various constructions, which have hitherto proved perfectly efficient for that purpose, and there can be no reasonable doubt that the same *principles of protection* to bridge piers from ice are applicable at Montreal, as at Cercle Ville or Troy; and that the final result in the St. Lawrence would be the same as on the American and other Canadian rivers over which there are bridges, viz. "*an average*" of *no material damage at all in the ordinary course of events.*

But Mr. Brunel jumps from the opinion that one or two "*ice-fenders*" out of fifty would be carried away in every ten years, to the "calculation of a probability, that one or two of "the 24 PIERS of the *Victoria Bridge would be actually carried away on the average of* "TWO OR THREE *times in twenty years.*"

Now if 50 gave one or two "*ice-fenders carried away*" once in ten years, 24 should give one or two "*ice-fenders*" (not *piers*) carried away once (not two or three times), in twenty years, which is a very different thing from Mr. Brunel's deduction, and yet a conclusion equally arbitrary with the original *guess* on which it is based.

The statement that "most likely *expenses for repairs to an enormous amount would* "*have to be incurred to remedy partial damages or to meet threatening dangers*," is, like that of the assertion of "the chances not being great against one or two of the piers being "carried away *once or twice* soon after the opening."

The logic of the next sentence is incomprehensible to me,—"The consequences of such

REPLY.

"results would be too serious to contemplate, if they can possibly be avoided." I shall leave it to the contemplation of its readers. Not only are these "calculations of comparative probabilities," as Mr. Brunel s pleased to call them, not "strictly correct," as he admits, but they are not even "sufficiently approximate to correctness," as he would have it believed, to show anything at all. They do, however, show how the principles upon which authority influences us in matters of opinion can be abused, and how the name of a great and important branch of exact science may be perverted.

But out of his calculatious of probabilities, Mr. Brunel would have it supposed that he has deduced principles, which, applied to the present case, render it "evident that it would "be worth incurring considerable expense to insure a greater amount of security." A greater amount of security than what; than that which has not been known to fail? or what security is it that the "body of prudent men are to rely upon in such a case as the present"? on the security of a kind of work which has never been adopted, without special protection by wood or iron, or on that which is the "*ordinary*" means of success? And what is the meaning here of "*considerable expense?*" As compared with what, is it considerable? Mr. Brunel makes no mention of prices or amounts, either absolute or comparative; yet upon such vague expressions as these, he would fain dispose of a difference in estimates amounting to a million sterling. In short, Mr. Brunel's *ipse dixit*, as to the necessity for spending the money named in the contract, would, I am convinced, have carried much more authority with those who are able to form a judgment on such matters, than the *quasi* arguments he has put forth to *lead* others to that conclusion, but which I have shown to be merely unsupported and untenable assertions.

MR. BRUNEL'S REPORT.

17. The forces in action in this case are probably greater than in any other example—the height to which the ice is known to pack against any obstacle renders it certain that this ice must rest solidly on the bed of the river at many places although the water may pass freely through it, and the effects of the grinding and crushing of such packed ice must be frequently very great, even to the bottom of the river.

18. There are of course several modes, more or less effective and more or less permanent, of forming a body which, either by its mere mass or by its form, will offer resistance to or break up bodies of packed ice; amongst others are piers—or, more properly, islands—formed of heavy materials, held together and protected to a certain degree by timber bonds and piles; or a mass may be formed of concrete, or other such materials, cased with iron, or with a framed and planked surface of wood; but all these plans partake of the character of temporary expedients, requiring continued attention and more or less frequent repairs, and the economy of which arises only from the circumstance that they are capable of being constructed of materials which are at hand, and that the extent

To the term "mass" Mr. Brunel appears to attach no other meaning than *size*. Mass mechanically defined means weight. Mr. Brunel, then, is wrong in saying that the piers should not "*depend at all upon their mass*," equally as upon their form. Do they not, in fact, depend absolutely for power of resistance to the forces acting against them on the two combined? Can Mr. Brunel raise an argument upon the idea that any engineer has suggested mere size without relation to density and form for a construction to oppose the force of floating ice? Upon "mass" or "*weight*" depends the *inertia* of the piers to resist these forces. Without mass form is merely ideal; without form mass is comparatively useless; and the hypothesis of size without specified weight and form is absurd. In the sense he gives the word, he is at direct issue with Mr.

of works, or other circumstances, would not repay the establishment on the spot of all those appliances which are required for more perfect workmanship. As regards their permanency—piles filled in with loose materials are easily deranged, individually, in their position by the action of external violence; they are liable to be disturbed also by the mere action of water freezing within them, and the aggregate strength does not come into operation in resisting the action of these destructive agencies on the separate parts.—Cast-iron framing or plating and concrete are each particularly liable to be injuriously affected by intense cold. There is no greater delusion than that which leads to the assumption that concrete forms a homogeneous compact mass. I refer to what it really is in practice; what it is intended to be is quite a different material.

19. It is very rarely indeed that concrete made under any difficulties is ever afterwards capable of being examined "in situ."

20. In the few cases which have come under my observation it has proved anything but satisfactory.

21. I can mention a case where it had been formed honestly and carefully, and where, nevertheless, it was found to be so honeycombed that rats could run between the interstices from the mere want of a sufficient proportion of sand and small materials in the first mixture, or the want of the more perfect intermixture of all the proportions in the mass, or from the partial setting of the cement before any pressure rendered it compact: my experience would lead me to expect nothing more from even good concrete, when used in large quantities and under any difficulties, than a substitute for a compact bed of gravel, with this disadvantage—that Nature, by the aid of time, never fails to make such a bed compact, whilst human agency, without the assistance of long periods of time, cannot insure this.

22. There appears also to me, in this particular case, to be a serious objection to any mode of construction which depends at all upon its mass for its power of resistance; these piers have to be placed, with comparatively small intervals between them, directly across the river, the force and destructive action of the ice will be increased materially by any increase of size of the obstacle, and by

Stephenson, who says "the forces brought into "action are of a formidable nature, and can only "be counteracted by a structure of a most solid "and *massive* kind."

At the end of Paragraph 22, indeed, Mr. Brunel makes the strange assertion that by "increasing the *strength* of the piers you do "not increase their power to resist the pressure "of the ice." This, however, on further scrutiny appears to be a mere confusion of language, "*strength*" being used for "*width*" or "*size*." But even with this correction the sentence only proves that Mr. Brunel, in forming his opinion, has not availed himself of the information on the ice phenomena of the Saint Lawrence so beautifully detailed by Mr. Logan, in the Transactions of the Geological Society of London, 1842. I shall content myself with merely pointing attention to this part of the subject here, for I shall have to enter upon it at length immediately, (Paragraph 23.)

There are strong objections to discussing a question of the nature of the one before us on vague generalities, in the style chosen by Mr. Brunel, however much they may tend to the "*calmness, deliberation, and* "*freedom from prejudice*" so much prized by that gentleman. Mr. Brunel is in fact answering my Report; and he very unfairly, as it appears to me, instead of meeting it point by point raises general questions, stating his own case, in his own way, on the point which he is about to plead against, and leaving it to be inferred that the untenable hypotheses so set up on purpose to be overturned by specious arguments, have been advanced by me. This is too transparent in the present instance to deceive any one, and I only regret that I should be obliged to occupy so much of your time and patience in deliberately exposing it.

As regards "*islands*," for foundations of the piers, I have spoken of them in my reply to Mr. Stephenson's Report, Paragraph 22, where the subject is more definitely entered into, and therefore will not say more here.

With regrad, however, to the assertion that "*cast-iron framing or plating, and concrete* "*are each particularly liable to be injuriously* "*affected by intense cold*," I shall only say that the extensive use of cast iron in construction in Northern Russia, Germany, and Sweden, as well as in North America, where the cold is as intense as in Canada, proves that the objection in reference to it is invalid; whilst as regards concrete, which once properly formed becomes as solid as rock, and which never can

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any diminution of the intervening space; even with the narrow piers proposed, the proportion of the width of the obstacle to the space left for the passage of the ice is considerable, and from this circumstance the attempt to resist the pressure by mere strength of pier would be futile.	be deposited in water at a temperature lower than 32°, and against the freezing of which, until set, there can be no difficulty in providing with ordinary prudence, the assertion must evidently have been made without any consideration. In the recent practice of American engineers, cast-iron plates have been used with effect for the very purpose of the *outer covering* of the ice-breakers of bridge piers.

To the opinion of Mr. Brunel, which he acknowledges to be based on the use of *bad* concrete, I can only say, that my own experience has taught me an exceedingly different lesson, viz. that judiciously and honestly made concrete or bêton is as good, and as substantial, as a breccia or pudding-stone of Nature.

In England we have no examples, that I am cognisant of, of the exposure of concrete to the wear of rivers or tides, and hence my reason for proposing that the foundations of the Victoria bridge should be encased in iron. But this system of foundations under the name of *Bêton*, or *Maçonnerie en Bêton*, has been so largely and successfully practised in France and Germany for more than a century, with temporary encasements of slight planking, that there really is no longer any question either of its efficiency or economy.

If the question were only of the general application of concrete in foundations as a substitute for piling or other means of consolidation and security against settlement, I should not stay to answer what the practice and experience of our greatest architects and engineers for the last 50 years so completely prove to be a delusion on Mr. Brunel's part. But as the application of concrete, or bêton, as a substitute for ashlar or other masonry put in by coffer-dam in deep water has seldom been made in this country, it appears necessary to say a few words here in justification of that part of my Report, if it were only to show how utterly groundless are Mr. Brunel's objections to the use of "*rough stone concrete in cement*."

The ingredients of bêton are, hydraulic mortar or cement and small broken rubble-stones or rough gravel. The quality of the hydraulic mortar it is essential should be uniformly excellent; i. e. that it should set hard under water in a short time. The size of the stone has varied in practice, according to the application, from river gravel to stones of half a cubic foot in size, and this is not an absolute limit. With these materials combined, and used according to the *dictates of experience*, the foundations of jetties in four fathoms water in the sea to the height of low-water mark—of locks in navigable rivers up to summer water level—of vast and deep water cisterns on compressible ground in the centre of great cities—of railway and other bridges over great rivers, subject to ice and floods carrying huge trees, in France and Germany, have been successfully placed by distinguished engineers responsible for their success. The way of using bêton directly, that is without previous piling, or setting a platform at the bottom, or the construction of coffer-dams admitting of laying the foundation dry, and without permanent casing, *on its own independent* merits, in short, was first practised in modern times in 1748, at Toulon. Since the discoveries of Vicat on the nature of hydraulic lime, and the general adoption of the system of setting up a temporary establishment for the manufacture of artificial cements, or *puzzolanas*, on any work of sufficient extent to warrant it, this use of bêton has obtained prodigious extension in France and Algiers, and with the progress of experience, is becoming the general practice. Mr. Vignoles established a manufactory of artificial puzzolanas at Kieff, for the works of the noble bridge he erected over the Dnieper, on foundations of concrete.

Having taken pains to inform myself of the practice of French engineers in reference to the largest and most recent applications; for instance, at the Pont de Langon over the Dordogne, where the bottom is gravel, the summer water is 18 feet deep, and floods rise in a few hours sometimes as much as 28 *feet* above summer level: having received details from the engineer himself who superintended and had all the responsibility of the work, respecting the facility, certainty, and cheapness with which this great work (in imitation of many others) had been carried out, I venture to set aside Mr. Brunel's opinion of concrete, and to advise him to gather his experience on this subject elsewhere than from his own works, if the example quoted in his Report, on which he relies, be taken from them. In the cases which have come under my observation, of concrete made of the right materials and used according to proper directions, the results have been perfectly satisfactory. There is no doubt that concrete, put in "with honesty of intention and great care," yet from want of knowledge of the materials required and of the method of using them, might turn out very bad. But I am of opinion, that no one who has ever seen properly-made concrete—"good concrete"—could reasonably compare it "to a compact bed of gravel, with this disadvan-"tage, that Nature by the aid of time never fails to make such a bed compact, "whilst human agency, without the assistance of long periods of time, cannot insure this." For, *the fact is*, that the *most compact bed of gravel* will yield easily to shovel and pick or running stream, while "good concrete" can only be removed by blasting, and has been successfully exposed to the severests tests of endurance in a hundred instances.

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23. These ice-breakers, placed as they are in a line across the river, cannot be treated as fenders covering some works in the rear or depending for safety upon their diverting a stream of ice, and thus getting rid of, rather than resisting and destroying, the force acting against them; they would thereby only increase the strain upon their neighbours, or the effect would be counteracted by the similar effect produced by the adjoining piers; they must each, individually, be constructed so as to meet, resist, and destroy their own share of the action of the ice, without causing this to react upon the adjoining piers.

"These ice-breakers"! What ice-breakers? nothing has been described; allusion in general terms has been made to "modes more or less "effective of forming a body which will break "up bodies of packed ice, amongst other piers, "or more properly *islands* formed of heavy "materials, held together by timber bonds and "piles, or a mass of concrete cased with iron," but in no more specific way does Mr. Brunel describe these ice-breakers.

This paragraph has no meaning that I can discover. If "*these ice-breakers*," whatever they may be that Mr. Brunel has imagined, "get rid of the force," they assuredly must most effectually "resist and destroy it." If they "resist and destroy it," they assuredly must most effectually "get rid" of it. How, in the name of reason, can they increase the strain on their neighbours, or how can "the effect be counteracted" (what effect? I might ask) by a similar effect produced by the adjoining piers if "the force is got rid of?"

I come now to treat of the ice phenomena, and of the provisions to be made to counteract the effect of the ice. I go into a consideration of this subject, because Mr. Brunel has evidently not done so himself; and it is desirable, in order to come to a just conclusion, that this part of the subject should be well understood, for Mr. Brunel has enunciated the opinion that "the engineering difficulty of the work is un-"questionably the resisting of the action of the ice against the piers and abutments." [Paragraph 10.]

As soon as frost sets in, a margin of ice forms along the shores of the river and around the islands and projecting rocks, and wherever there is still water it is immediately cased over. The wind and freshets acting on this glacial fringe break off portions, and these proceeding down the stream constitute a moving border on the outside of the stationary one, which, as the intensity of the cold increases, is continually augmented by the adherence of ice sheets which have been coasting along it. And as the stationary border thus robs the moving one, this still further outflanks the other, until, some part of the margins from the opposite shores nearly meeting, the floating ice becomes jammed up between them, and a night of severe frost forms a bridge across the river.

As soon as this winter barrier or ice bridge is thrown across, at any point, the accumulation of ice rapidly increases, the progress of the downward floating ice, which has by this time assumed a character of considerable grandeur, being stopped.

REPLY.

Wherever this floating ice meets with an obstacle in its course, the momentum of the mass breaks up the striking part of it into huge fragments, that pile over one another; or if the obstacle be stationary ice, the fragments are driven under it and over it and there closely *packed.*

When the barrier gains any position where the current is stronger than usual, the augmented force with which the masses then move, pushes and packs so much below, that the space left for the river to flow in is greatly diminished, and the consequence is a perceptible rise in the waters above, which, indeed, from the very first taking of the "ice bridge," gradually increases for a considerable way up. As the contraction, by packing, of the channel St. Mary's below Montreal, proceeds, the river dammed up by the barrier, which in many places reaches to the bottom, attains in the harbour, opposite Montreal, a height usually 20 and sometimes 25 feet above its summer level, *and the water ebbs and flows according* to the amount of impediment it meets with from the packed ice barrier or bridge.

It is *at this period* that the grandest movements of the ice occur. A sudden rise of the water, occasioned in the way above mentioned, lifting up a wide expanse of the whole covering of the river so high as *to free* and *start it* from the many points of rest, and resistance offered by the bottom, where it had been packed deep enough to touch it, the vast mass is set in motion by the flow of the river more or less rapidly as the barrier is more or less diminished. Proceeding onward with truly terrific majesty, it *piles up over* every obstacle it encounters; and when forced into a narrow part of the channel, the lateral pressure it there exerts drives the bordage up the banks, where it sometimes accumulates to the height of forty or fifty feet.

In the front of the town of Montreal, there was built in 1840, a mignificent revetment wall of cut limestone, to the height of twenty-three feet above the summer level of the river. This wall is now a great protection against the effects of the ice: broken by it, the ice piles on the street or terrace above and there stops; but before the wall was built the sloping bank guided the moving mass up to the gardens and houses in a very dangerous manner, and many accidents used to occur. It has been known to pile up against the side of a house distant more than two hundred feet from the margin of the river, and there break in at the *windows of the second floor.*

A few years before the erection of the revetment wall, a merchant was tempted by the commercial advantages of the position to build a large cut-stone warehouse by the river side. The ground floor was not more than eight feet above the summer level of the river. When the ice barrier or bridge was formed, the usual rise of the water inundated the lower story, and the whole building becoming surrounded by a frozen sheet, a general expectation was entertained that it would be prostrated by the first movement. *But the proprietor had taken a very simple and effectual* precaution against this. Just before the rise of the waters, he securely fixed against the sides of the building, at an angle of less than 45°, a number of stout oak logs a few feet asunder. *When the movement came, the sheet of ice was broken and pushed up the incline thus formed, at the top of which meeting the wall of the building it was reflected into a vertical position, and the pieces falling back on each other, such an enormous rampart of ice was in a few minutes placed in front of the warehouse as completely shielded it from all possible danger.* In some years the ice has piled up nearly as high as the roof of this building.

This picture of the movement of the ice and of its force and effects is condensed from Mr. Logan's paper. Here is Mr. W. Tierney Clark's description of the ice movements in the Danube at Pesth, observed during the erection of the Pesth bridge:—"The ice con-
" tinued firm until the 17th of January, when about three p. m. it began to move in
" one unbroken sheet from the Dolphin, where it had parted, to the Buda shore. A few
" minutes afterwards it began to move from side to side with tremendous violence. A stage
" on which were three pile engines, for driving the piles on the upper part of the dam, was
" carried away instantaneously by the enormous force of the ice, which came crashing on till
" it touched the outer row of the piles of the dam, when after a squeeze which threatened to
" smash every timber, *the ice broke up into pieces which kept rising up as if forced on by the*
" *pressure behind and formed an embankment against the side of the dam.* The whole

" lasted about ten minutes, and the first squeeze was the worst the dam had to contend with, " and not the *slightest damage*, if we except that to the *small stage above mentioned*, was " sustained.

" After the ice had got fairly in motion, and attained the velocity of the current, the " noise and uproar of the immense masses, cracking and crashing against one another, and " against the dolphin and dam was tremendous, and altogether formed a scene it would be " difficult to describe. Sometimes a stoppage would take place, owing to the accumulation " of ice between the dolphin and the dam, which kept that above back until a mass of ice " more resembling an island than anything else it can be compared to, would force the whole " mass before it, breaking up the large blocks accumulated at the dam into a thousand " pieces.

" Considerable excitement prevailed at Buda, Pesth, and even at Vienna, owing to the " different opinions as to whether the dolphin was sufficiently powerful to resist the pressure " it was subjected to, and heavy bets were laid on the issue. The result, however, was most " satisfactory, for with the exception of the fender piles, which were somewhat worn and " damaged by the ice, not the slightest harm was done either to the dolphin or the dam."

From this description it is again evident that the force of the ice is greater in *appearance than in reality*.

The simple contrivance described by Mr. Logan shows how easy it is to *elude* the effects of the ice, and the description of Mr. W. Tierney Clark shows that it is *not very difficult* to construct ice-breakers capable of resisting the force of ice, even during its most violent movements.

But the violent effects of the ice, at Montreal, are incidental to the rising of the river and the sudden "slipping" of some of the ice-dams, and it is therefore very important to consider where and how these are formed, and whether the ebb and flow of the water they give rise to can be ameliorated or even prevented :—

" The length of river which sends down the ice for the formation of these dams is about " fifty miles, extending from Montreal to Lake St. Francis. This lake being comparatively " deep becomes frozen over early, and arrests the ice which descends from Prescott and the " intermediate islands—another stretch of about fifty miles of river—Cornwall therefore pre- " sents phenomena similar to Montreal. The great distance, numerous islands, the strong " currents and rapids between Prescott and Cornwall, send down inordinate quantities of ice, " which being arrested by the solid crust over the Lake St. Francis, 'flashes' the river " opposite Cornwall. In like manner, the current, the rapids of the Coteau, Cedars, " Cascades, and the Sault St. Louis, and Normand, bring down the 'manufacture' of fifty " miles of river to be arrested principally between Montreal and Longue Point. The shallow " expanses of Lake St. Louis and the Laprairie basin are of no value in arresting the ice, on " account of their strong currents. If Lake St. Louis were frozen over at the same time " with Lake St. Francis, the winter inundations at Montreal would be diminished about 50 " per cent.; but as it does not present a barrier to the ice descending from the rapids above " it, until the same time that the river is closed opposite Montreal, it affords no protection. " It is worthy of remark, however, that the causes which produce the closing of Lake St. " Louis and the river opposite Montreal, at about the same time, have no connection with " each other. The river 'takes' here because, by the rise of water, the current is slackened, " and the floating ice from above is arrested against the 'ice bridge' below, without current " enough to force it under—like logs in a boom—whereas the level of Lake St. Louis is not " altered, but a certain time and degree of cold are necessary to enable the opposite bordages " to encroach upon its strong current. If the early part of the winter be mild or changeable " or accompanied by much wind, these bordages may be broken off repeatedly by the swell " before they are closed; but if the winter sets in, as in December, 1851, with uninterrupted " severity, this lake is closed sooner, less ice descends, and a diminished rise of water " is the result at Montreal. This explains the apparent anomaly of greater inundations in " 'open winters,' and less in severe ones, *i.e.* from the damming back of the waters by ice.

" The Laprairie basin is so very shallow, that it is not frozen over until its depth is " increased about ten feet by the action of the ice dams below.

REPLY.

" While this lake-like expanse is of no more value than Lake St. Louis in arresting the " early ice, its extensive shoals and margins furnish proportionally the largest in quantity, " and the most formidable in character, of the material of which the ice-dams are composed. " The ice which descends from points above the Lachine Rapids, is composed of ' fragments " ' of the glacial fringe broken off by the wind, and enlarged in their descent by the cold ;' " but in the Laprairie basin the strong clear ice which forms round the islands, rocks, and " upon the shore and shoals with the first frosts, is forced up and broken off from its attach- " ment to the sides and bottom, by the lift of subsequent rises of water, and—from the " peculiar bend of the coast between Longue Point and the Lachine Rapids—there exist no " projecting ' jetties' of land to retain this formidable bordage in the place of its formation. " With the rise of water the current ' in shore' increases, and sets the whole field, some- " times half a mile in width and two or three miles in length, in motion. These form the " ' league after league' mentioned by Mr. Logan, and by their momentum these masses break " up the resisting barrier and force under with such violence the blocks which form the dam. " This process may be repeated, a new bordage being broken off by a second rise of the " water, and sent down to aid in a still further elevation of the river. When a sufficient " quantity has been sent down to raise the level of the Laprairie basin about ten feet, the " current therein is so diminished that it becomes frozen over, and then all further supply is " cut off.

" The natural inference from the foregoing is, *that if the bordage ice can be retained " ' in situ ' and the ' taking over ' of Laprairie basin thereby be expedited, a very great " portion of the supply furnished for the ice-dams would be cut off, and the intensity of " these be correspondingly diminished.* This hypothesis is confirmed by the fact that in " severe winters, when the ice takes rapidly, there is a lighter inundation than in milder ones. " In the former case the time required to close the river (and therefore the quantity of ice " which can pass down in a given time) is a minimum ; while in the latter the stopping " and starting, the freezing and ' slipping' extend over a longer period of time, and a " greater quantity of ice passing down, a greater dam is formed and a greater inundation " takes place.

" A most important effect of a protracted closing over of the open water is the greatly " increased quantity of snow, which falling in this water is converted into ' frasil' or ' anchor " ice,' and, having about the same specific gravity as water, is carried under the sheet ice " and ' banks' upon the shoals, reducing the water-way of the stream.

" For the foregoing reasons, it seems pretty evident that the intensity of the ice pheno- " mena at Montreal is due to the great area of open water which exists until January above " the city—to the absence of natural features above the town for arresting or detaining the " ice formed within the area of the Laprairie basin—and to the existence of such arresting " features immediately below and opposite to the city.

" Inasmuch as the natural bridges of ice, wherever formed, have the effect of arresting its " further descent, which descent is the sole cause of the *grand* movements of the ice " described, and of the winter inundations, it appears to me that an artificial bridge, in as " far as it will aid in arresting descending ice, retain ' in situ' the bordages, elevate the " level of the water—thereby diminishing the current—and expedite the closing over of the " river above us, will unquestionably tend to diminish, rather than increase, the intensity of " the ice phenomena at Montreal."

With a few verbal alterations I have taken the above from Mr. Keefer's Report on a survey for the Railway bridge over the St. Lawrence at Montreal, made in 1851, and published in 1853.

No one can read these observations without feeling their truth. Resting upon Mr. Logan's and Mr. W. Tierney Clark's descriptions and Mr. Keefer's inferences, I think it is abundantly evident, 1st, that though the forces in action during the movement of the ice may be greater in the St. Lawrence than in any other river, yet they are easily to be coped with by simple well-known and well-tried expedients. That as the manner in which ice is known to pack against any obstacle renders it certain that this ice must rest solidly on the bed of the river at many places, the ice itself forms a protection to the obstacle, and the effects of grinding and crushing are comparatively harmless to that obstacle.

REPLY.

2nd. That Nature provides a ***huge mass*** of ice to protect obstacles exposed to the momentum of fields of it in motion; and thus Nature herself contradicts Mr. Brunel's notion that the power of resistance to ice must not depend upon masses.

3rd. That the function of ice-breakers, even placed quite apart from the main obstacle (such as the dolphin of the dam of the Pesth bridge), is exactly that of diverting the stream of ice, breaking it up, and thus of independently "resisting and "destroying their own share of the action of the ice without causing this to react on the "adjoining piers."

4th. That in the particular case in question, the size of the piers, as well as the spans, in reference to the water-way, is to be settled by general considerations of navigation, &c., but that as a special question, having reference to the ice phenomena only, the force and destructive action of the ice will be materially *de*creased (not increased, as Mr. Brunel has it) by any increase of size of the obstacle and by any diminution of the intervening spaces. And, indeed, the inference of Mr. Keefer—that if the bordage-ice can be retained *in situ*, and the taking over of Laprairie basin thereby be expedited, a very great portion of the supply furnished for the ice-dams would be cut off, and the intensity of them correspondingly diminished—suggests a consideration well worth the serious attention of the municipal government of the city of Montreal, as well as of the Shareholders of the Grand Trunk Railway, whether by artificial dams the movements of the ice may not in a great measure be prevented, the inundations reduced, and the size of the bridge diminished.

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24. The form of the ice-breaker must be such as to lift up the ice and break it in two, leaving the parts to fall off sideways and pass through the openings, and for this purpose an oblique sharp cut-water of a hard material, extending from the bed of the river to the greatest height reached by the packed ice, must form the front of each ice breaker or pier.

25. Upon this there can be no difference of opinion.

26. Any such cut-water will form a considerable portion of a whole pier, and I know of no other material than ashlar of which it can be constructed at a moderate cost with any prospect of durability.

27. By the report of the American Engineers themselves, it is evident that they treat the ice-fenders generally as provisional works thrown up to protect others, and calculated by themselves to require renewal or repair. This mode of treating them does not, for the reasons I have given, seem to me fitted for the present case.

28. The character of the bed of the river will also influence much the nature of the construction, even where permanency may not be an essential condition. Piles may be used where the bottom is gravelly or admits of pile-driving; but with a rocky bottom at a moderate depth, and with no sufficient thickness of loose materials above,

REPLY.

Instead of "to the greatest height reached "by the packed ice," it would have been more correct to have said *to the greatest height reached by the water while ice is still floating*: for, once the ice packs against the pier, the ice-*breaker* can be of no use "to break it in "two, leaving the parts to face off side-ways." Thus Mr. Brunel does not state the facts so as to put the case beyond difference of opinion. It is only to that height at which floating ice may impinge against the cutwater and quoins that *ice-breakers*, properly so called, are needed.

The character of the bed of the river is specified in the contract as being "formed "of flat-bedded limestone of generally uni-"form surface, so that a secure foundation is "readily obtained." One who had read these words would not have spoken of the "*prudence*" of resorting to piles. It is an impossibility.

no such expedient could be prudently resorted to.

29. I believe that no construction of ice-breaker in such a case can be so certainly effectual as a simple cut-water, combined with the pier that carries the bridge, so as to bring into operation the united strength of the two, and the whole made of the strongest materials, so as to admit of the smallest dimensions; and that stone, in the shape of ashlar, if it can be procured, is under all circumstances the best material in every respect, both as regards strength, durability, and facility, and cost of repair; but, moreover, I am convinced that it would practically even be the least costly in the first construction. The form and size of a simple ashlar pier, capable (so far as we have the means of judging) of resisting the forces known to be in operation, can be determined with some degree of certainty, so as to insure what may be practically termed safety,—but the form, the size, the dimensions of the parts, and every detail of any combination of piles and stone, or cast-iron plates and concrete, or of any other such expedients, are none of them susceptible of being determined by any calculations from precedent. Any opinion can be little better than guess-work, and will depend mainly upon the character of the man and the influences which may operate upon him at the time—all very unsafe guides in so serious a matter: and after the first effects of a great anxiety for economy have softened down, other anxieties and doubts as to the result would arise, and in practice would lead to such additions to one part, and alterations in another, to give increased strength and security, that I feel convinced the result would be a much more costly work than a simple ashlar pier, particularly as there would, in my opinion, be no great difference in the first cost, even if no such additions were made to the first design of a reasonably-strong ice-breaker of other materials than ashlar. Such being my very decided opinion, not only I cannot suggest any modification of the principle of construction recommended by Mr. Stephenson for the piers, but I consider it to be the best and cheapest, and to be the only one I am acquainted with that is at all fitted to the particular case.

In discussing the question of the Piers two points must be kept distinct—the cost of the piers themselves and of the foundation-work. Now as to the piers themselves I do not dissent from the conclusion, that ashlar piers of the form designed by Mr. Stephenson will be efficient. At 2*s.* 6*d.* a foot (the price of the work given by Mr. Ross), the piers would amount to about £200,000; and though, in my opinion, it is perfectly needless expenditure to introduce ashlar work at 2*s.* 6*d.* per foot when good range-work can be obtained at half the price, and would be equally efficient and safe, it is a small part of the question at issue, and hardly worth discussion here, as to which of the two should be used.

But as to the foundation-work, which is to cost the prodigious sum of £600,000—*i. e.* the difference between £800,000 (the whole cost of masonry and foundations as stated in Mr. Stephenson's report) and the £200,000 above given for the masonry of the piers alone—is nothing to be said to that? Is this question to be disposed of by a mere *dictum*, that piers of the form and material designed by Mr. Stephenson are the "*best and cheapest*," without any reference to the cost of the preparations for building these piers, which are not in themselves expensive pieces of masonry? Is this question, I say, to be answered by a mere *ipse dixit*, that "the form, the size, "the dimensions of the parts, and every detail "of any combination of piles and stone, or "cast-iron plates and concrete, or of any "other such expedients, are none of them "susceptible of being determined by any "calculation from *precedent?*—Any opinion "can be little better than *guess-work*, and will "depend upon the character of the man and "the influences which may operate upon him "at the time."

This is not even special pleading—it is a mistake. For as to the form and dimensions, and every detail of suitable combinations of piles and plates and concrete in foundations, we have several successful economical precedents in England; and there is now going on at Westminster a grander example of bridge-founding than any that has been undertaken since London bridge, consisting chiefly of iron piles, plates, and concrete, executed under the direction of an engineer *responsible* for its success.

Now as to the adaptation of analogous construction to the foundations in question. Weight and form, (the elements of inertia and friction, which are the forces to be calculated in reference to the momentum or pressure of the ice,) are as determinable for the encased concrete as for the ashlar, and by the same kind of precedents. Mr. Brunel's assertions therefore are evidently made at random. I may ask, indeed, was there ever an ashlar cut-water put in to resist the shocks of ice in America? Certainly not, for "the *great aim of American Engi-*" *neers is to secure the greatest returns on the investments*, and not to spend a farthing in " construction that can be saved. The fact that the means of the Americans are dispropor-" tioned to works of which there is felt to be an imperative necessity, compels them to practise " economy, and to supply *as far as possible, by expedients, the lack of capital*;" and thus the greatest cost ever hitherto incurred for bridge piers has been for *a rubble cut-water on a foundation of crib-work filled with loose stones*, the rubble *being faced with iron fenders to smash up the ice*.

But let us see what is the value of this very decided opinion, that the piers proposed by Mr. Stephenson are the "best and cheapest;" or, in other words, what will be the cost of acting on this opinion of Mr. Brunel?

We have, as I have before stated, the cost of the ashlar masonry given us by Mr. Ross at 2*s*. 6*d*. a foot. The whole quantity above water, being about 1,250,000 cube feet, will cost £156,250: the whole quantity below summer-water level being 350,000 cube feet, at the same rate would cost £47,750. But the cost of the whole work, above water and below, is given at £800,000. Therefore the cost of putting in the foundations up to summer-water level amounts to no less a sum than £800,000—£156,250, or £643,750, which is just equal to 36*s*. 6*d*. PER CUBE FOOT. If then we can substitute anything for the ashlar work *under water* at a less cost than 36*s*. 6*d*. per cube foot, it of course will be so much saved.

For the purpose of putting the matter in the most intelligible form, I will lay before you a short calculation with all its data.

The under-water dimensions of the largest pier, reduced as proposed by Mr. Ross, are not more than 90 feet long by 23 feet wide by 12 feet deep. The superficial area of the sides and end of it would therefore be 2700 super feet, and the cubic contents about 960 cubic yards. The construction I have to suggest (for the purposes of this calculation), in place of ashlar work as proposed, is as follows:—it, no doubt, will be held by Mr. Brunel to be "one of those expedients not susceptible of being determined by any calculation "from precedent," but for the present I will assume that it will fulfil its purpose as an alternative, though needlessly expensive, and therefore an exaggeration of cost.

Suppose a caisson of wrought iron fitted *in situ*, and then filled with bêton in the usual manner of doing such work; I will take the outer casing at 3000 superficial feet, to make full allowance for the construction I propose, and the cubic contents of the encased foundation at 1200 cubic yards.

The iron, made on the average 1 inch thick, at £36 a ton, would cost £1944, say £2000. The bêton, made of the best cement and the limestone of the district, would cost about £2 a yard *in situ*, or £2400. The total cost would therefore not exceed £4400. Now, the average depth of piers, as *specified*, is under two-thirds the depth of the deepest, say two-thirds. The average cost of such foundations for the piers, at the same rates, would therefore be, say £3000, and 24 piers multiplied by 3000 is but £72,000. If it is said that this is not strong enough, I answer:—double the thickness of iron; sheath the cut-water in 4 inch forged bars; tie it all down with Lowmoor iron rods 3 inches thick:—let 4 feet into the rock at every 10 feet all around;—*and when you have multiplied all appliances to a needless superfluity of strength, you shall still not reach one-fifth of the cost of the contract price of the Foundations of these Piers.* I give this illustration to show how little an opinion put forward in the manner of Mr. Brunel ought to be regarded.

I have elsewhere spoken at length on the use of concrete; and so certain am I of the reliance that may be placed on it, if applied with knowledge of its nature, and with ordinary care, that I broadly assert, a man who can deny the efficiency of concrete, must either be ignorant on the subject, or must wilfully shut his eyes to facts. I rely upon proofs from the practice of Engineers and Architects in England, France, and Germany; and I defy Mr. Brunel to show any case of failure that cannot be perfectly accounted for by want of proper information, by want of proper attention, or by want of will to carry the work properly out.

REPLY.

There is nothing more certain than that such a construction as I have suggested would stand as well as the foundations recommended by others, nothing more certain than that they would stand better. Their specific gravity would be greater; their strength would be greater; their form to break the ice could be made the best possible, though indeed it is questionable whether any better form or greater strength can be required than those usually employed in America; and the material exposed is harder and less destructible by abrasion than stone. Wrought iron, in such a position, of the least thickness proposed, would last for a century, and might then easily be renewed in such parts as were required for a defence against the ice, *i. e.* in the cut-waters; and as for concrete, Nature would have come in to assist the Engineer by rendering it as hard and unchangeable as the rock upon which it was founded.

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30. The form and mode of construction of the individual piers having been thus determined upon, their height and the number required must be decided by considerations of the superstructure. As regards the span, if no circumstance existed to influence the dimensions of the openings but the mere question of the cost of first construction, the most economical span would be a mere matter of calculation; but while on the one hand some practical difficulties place a limit to the span which it would be convenient to erect, on the other hand, as the construction of these piers is the only part of the work attended with much difficulty or involving much risk of any heavy contingencies, and as the chances of any future difficulty or expense will be diminished exactly in the ratio of any diminution of the number of these piers, and as the destructive action of the ice would to a certain extent be diminished by increasing the openings, the best dimensions of span would probably exceed those which would give exactly the minimum cost. It will be seen that this influences the suggestions I may hereafter make; but I shall not now advert to it further than to say that these practical considerations would fix the *minimum* span at about that which has been proposed, and would of course give the advantage to any plan that admitted of any larger spans being adopted.

31. All the circumstances of the case also, and which need not be detailed, evidently require that the superstructure should be wholly or mainly constructed of iron.

32. Under these conditions of dimensions and of material, there are three known means of carrying a railway across such spans.

By Suspension Chains.

By Arches.

Mr. Brunel here says, shortly stated—

1st. That abstractedly the size of the spans depends on the relative cost of superstructure and piers.

2nd. That there are "practical difficulties" which place limits to the span, thus fixed by abstract considerations.

3rd. That there are heavy risks to the stability of the piers which indicate that any extension in size of the spans is desirable, beyond what would be fixed on abstract considerations only.

4th. That 242 feet spans, the size chosen, is about the size fixed by "these practical considerations."

Now, 1st. abstractedly as to cost. The proportion of span to pier is only correctly adjusted when the cost of the two is the same.

2nd. The practical reasons for limiting the span are nothing more or less than money-value for the work done. Mr. Brunel, though limiting the span to 242 feet for "practical considerations" in this part of his Report, afterwards recommends spans of 320 feet as forming a cheaper bridge by £60,000.

3rd. The "great risk of heavy contingencies during the work, and the chances of future difficulty and expense after completion" to the piers, should increase the spans, by Mr. Brunel's argument, even beyond 320 feet.

4th. "These practical considerations," therefore, do not fix the span at 242 feet, but at something above 320 feet.

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And by Beams or Girders.

33. As regards the first, if it is required that the roadway should be capable of carrying ordinary railway trains at moderate speeds, even of the weights and at the speeds now considered ordinary and moderate, and all past experience leads to the belief that the requirements in these respects will increase rather than diminish, I do not see that the Suspension principle promises any advantages, and indeed I do not consider that it is at all applicable to the present case.

34. The peculiarity of the Suspension Bridge is merely this—it is a beam in which all the parts which would be in a state of compression are omitted, and their want supplied by attaching the extremities of the parts in a state of tension to some fixed points—the weight of the beam or bridge is thus reduced to less than half: this is all that is gained, and if there were no countervailing objection, this would be a very great gain, and would admit of very extended spans, but the deficiencies and disadvantages are very numerous.

35. All rigidity is lost; and as soon as you begin to add materials to introduce stiffness, you are simply restoring portions of the beam and approximating to its original construction. Again, the fixed points must be obtained, and unless high rocky cliffs exist on each side, the chain must be carried back to a considerable distance—nearly doubling again the quantity of material required—still, as this additional weight does not affect the suspended portion, the principle admits of the use of much greater spans, provided rigidity is dispensed with and the load limited.

36. With these limitations the suspension principle is particularly fitted for cases of large single spans, where good fastenings can be obtained at either extremity, or it may be conveniently applied to three openings, of which the sides are little more than half the span of the centre; but if a succession of openings are spanned by suspension, and the variable load bears any large proportion to the weight of the bridge, the chains must be secured to the tops of the separate piers, or the load passing over one opening would overhaul the slack of all the chains of the other openings and destroy the bridge. If the chains are secured to the tops of the piers, these piers must each be strong enough to resist the strain, and there is no necessity for going into any calculations to see that to make such a structure secure in the present case, in which the height of the roadway or the base of the additional piers is already upwards of 60 feet above the foundation, would require enormous piers and an immense amount of stiffening to the floor, involving a much greater cost than any system of girders or beams with more numerous but much less costly piers. It is unnecessary here to refer to the bold and excellently-contrived Suspension Bridge recently executed at Niagara, beyond expressing my admiration of it. Every one of the circumstances and the reasons which rendered the application of the suspension principle not only wise and judicious but the only means of meeting the difficulty in that case, do not in my opinion render it applicable in the present case.

37. Arches I consider also inapplicable, the height at which they must be placed so as to be beyond the possibility of damage by the ice, would render it impossible, or at least very costly and very inconvenient by reason of the increased obstruction they would cause to the ice, to build the piers sufficiently strong to stand the thrust of such arches, aggravated as it would be by the effects of expansion and contraction; and such a work could not be considered safe if an accident to one arch would necessarily endanger the whole or a considerable portion of the rest, which would be the case unless the piers were each capable of supporting the thrust of the arch.

38. There are, moreover, many other difficulties and disadvantages. The spans must be of the largest ever yet made, and the expansion and contraction would give rise to difficulties which have not yet been contended with; and as the springing must be kept above the reach of the ice at the point where it would probably pack highest, namely, next the piers, the soffit of the arch,

REPLY.

As regards Suspension Bridges, as I stated in my first Report to you "though there is *no incompatibility of a Suspension Bridge with all the requirements of a Railway Bridge as to strength and rigidity;* yet in this case, as large spans are totally unnecessary for any reason of excessive cost of Foundations or height of Piers, or in reference to the navigation, it is unnecessary to discuss it. But as this may be read by Engineers as well as by you, I beg to record my dissent from Mr. Brunel's doctrines on the subject of Suspension Bridges as set forth in Paragraphs 34, 35 and 36 of his Report, and on the subject of iron arches as set forth in Paragraphs 37 and 38—though it would be irrelevant here to give my *reasons for dissent.*

and consequently the roadway, must be raised some 30 feet or upwards higher than it need be by the present plan.

39. Girders or beams offer in my opinion the only easy, safe, and economical mode of construction: and if such is the case, the question is indeed reduced to very narrow dimensions; for although, as on many points where the real differences are small, the extent to which the advocacy of different views is carried is very great, it is really comparatively unimportant as a mere question of cost, in spans of ordinary dimensions, what form of girder is adopted.

REPLY.

From Paragraphs 39 to 51 inclusively, Mr. Brunel treats of the superstructure of the bridge by Beams; and upon this branch of the subject he appears to deem his authority of weight, as he himself states, by way of preface to his remarks, that it is one "to which he has particu-"larly directed his attention." I cannot however bow to Mr. Brunel's authority. There are manifest fallacies in the fundamental principles for the employment of iron in construction which he has embraced; and all his arguments and *statements* (I cannot call them deductions, for I can find no logical inference throughout his pleading) are based upon these fallacies. The same fallacies pervade the Reports of Mr. Stephenson and Mr. Clark; and for the sake of convenience I have replied to them all together, and at present I will confine myself to pointing out those passages of Mr. Brunel's Report with which I differ; and for my answer I must refer to the general exposition of the principles which I have myself followed in the construction of Girder-bridges given in reply to Mr. Stephenson, pp. 10 to 18.

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40. A beam or girder, whatever may be the pattern, if reasonably well constructed, and of dimensions within the limits which do not involve any practical difficulties in the particular mode of construction adopted, will vary in weight and strength according to its length and depth, and if no very peculiar circumstances exist connected with facility of access to the spot or means of erection, the cost is not materially influenced by the pattern selected. Of the three or four different modes of construction hitherto adopted, whether simple beams of boiler plate, or diagonally-framed beams (the most scientific form of which is that known as Warren's girder, and *on the top of* which the roadway is placed), or pairs of beams constructed on either of these two methods, combined and formed into a tube, *through* which the roadway passes, as in the Britannia Bridge, or the Newark Bridge, which are examples of each, or whether large and simple trussed frames, such as the Chepstow Bridge, and that now constructing at Saltash, on the Bow and String form, of which many have been made by different Engineers—and amongst the large ones that at Windsor—are all mere varieties of beams which, with moderate spans, and so long as they are applied to those spans, and under those circumstances for which each

The statement in Paragraph 40, that "the "cost is not *materially* influenced by the "pattern" is a mistake.

To state that simple beams (*i. e.* of course, beams calculated as separate girders—forming the sides of a bridge), when placed in pairs, *form a tube*, is also a mistake.

To say that the quantity of material required and the cost per foot run, of all patterns of girders, vary "*about directly as the spans re-" quired, and inversely as the depth that can be "allowed*, and not to any material extent by "the adoption of one pattern in preference to "another," is not only a repitition of the mistake above indicated, but is actually a misstatement of the formula for determining the strength of girders, for the spans required and the depth "which can be allowed"—an inconceivable oversight in the enunciation of a formula of calculation by one "who has turned his atten-"tion particularly to this branch of engineer-"ing."

happens to be fitted, the quantity of material and the cost per foot run vary about directly as the span required, and inversely as the depth which can be allowed, and not to any material extent by reason of the adoption of any one pattern in preference to another.

41. It is impossible to meet statements and assertions made to the contrary by a negative proof when such statements are unsupported by explanation or by existing facts. It can only be repeated that in a beam of a given depth and length there is a limit or a minimum amount of material which will produce the required amount of strength, if the material is disposed in the most perfect manner, and without any waste; that in practice this minimum or perfection cannot be attained, but that by every one of the variations in the modes of construction referred to, if properly carried out, and if within the limits of dimension before referred to as fitted to each, this minimum can be approached so nearly equally by the different modes, that the selection between them must be governed by practical considerations of the circumstances of the case, and not by any abstract calculation of the quantities theoretically required.

42. The trellis bridge system consists merely of a substitution of numerous diagonal bars for the simple plates in the sides of a tube, or in the vertical web of a beam. In the present case the amount of material saved would be very small, even assuming that such diagonals are equally efficient with plates, which is by no means certain, if due allowance is made for imperfection of workmanship, while the difficulties of erection and the amount of skilled work required on the spot would decidedly be increased; and whatever may be the merits of trellis work in smaller spans and under different circumstances, I cannot see any advantages to be derived in its application in the present case; at all events none that are not equally attainable by Warren's girders, while the latter has the merit of disposing of the material "theoretically" in the most economical manner, and of being of a portable construction.

43. Warren's girder is, I think, admirably

A glimmering of the true point at issue seems here to have dawned on Mr. Brunel. The principle I contend for could scarcely be better enunciated than in these words: "In a beam of "given depth and length there is a minimum "amount of material which will produce the "required amount of strength, *if the material* "*is disposed in the most perfect manner and* "*without any waste.*" But the application of this fundamental principle is altogether ignored by Mr. Brunel in the end of the paragraph. He there reverts to the vague statement without "attempt at proof, that this minimum is equal "in all, and that practical considerations of the "*circumstances of the case* and not abstract cal-"culations," must govern the selection between them. What are "these practical considera-"tions?" What are "these circumstances of "the case,"—so often referred to, never pointed out? Mr. Brunel says he can give no negative proof to meet statements and assertions which are contrary to his dicta. It would be well if he would give something positive in the shape of proof on a scientific question capable of demonstration.

This statement concerning the trellis bridge is either the result of misinformation as to its nature, or is a consequence of Mr. Brunel's being incurably imbued with the fallacy above put forth, that it is immaterial to what pattern the top and bottom are shaped.

Mr. Brunel admits the eligibility of Warren's adapted for many circumstances; it consists of separate parts, which, although they require some nicety of workmanship, may be finished at the manufacturer's, taken to pieces, and sent to countries or localities where workshops could not be erected or artisans obtained capable of working metals, or even of doing boiler-work, which is the simplest possible metal-working, but where skilful labourers may be found who can put together even complicated pieces; but it is not so well fitted for spans exceeding 200 feet, as the parts become too large.

girders up to 200 feet span. Mr. Clark will not sanction more than 150, with his *direct approbation*, but he admits 250 by implication, and hesitatingly, even 330.

44. Trusses are very good for the larger spans where great depth of beam can be applied, and where large pieces can be manufactured on the spot and can be lifted entire into their place. The tubular bridge is especially applicable where the spans are upwards of 200 feet, and when a large quantity of work is in question, and where the carriage of materials to the spot is tolerably easy, and where no difficulty exists in obtaining and employing on the spot a large number of boiler-makers, and where the tubes can be lifted into their place in single pieces as at the Britannia, or built on a stage "in situ," as can be done at the Victoria Bridge. I think all the circumstances of the Victoria Bridge happen to be those for which the simple plate tube is particularly fitted: owing to the headway required the beams of whatever forms must be placed above the roadway and the railway pass between them; owing to the great length of the bridge, it would not be easy to carry to the successive openings the large pieces required in a truss bridge, which, in spans of these dimensions, by reason of the depth that can be given, admits perhaps of the greatest economy of material, but a Warren girder tube or a plain boiler plate tube could be erected on a stage.

45. In a span of 250 feet to 300 feet, however, the parts of a Warren girder become inconveniently large, and, assuming that even a good design could be made for so large a span, which I doubt, there would not, I believe, be any appreciable difference in the total amount of material.

The whole of this statement is made, it is charitable to suppose, by one who has not taken the trouble to calculate the weights of the parts. The greatest weight of the single parts of a Warren bridge are as follows:—

	242 feet	330 feet
Struts	1 ton	2 tons
Ties	18 cwt.	35 cwt.
Compression bars	2½ tons	4½ tons
Tension bars (single piece). .	1 „	1 „

and certainly these are not weights difficult to handle, more especially as they can be lifted from barges direct on to every scaffold or staging.

46. There is a serious disadvantage in the Warren girder, which equally applies to the trellis system, in the form in which they are usually designed. When applied in large spans, and in cases which require them to be placed above, and therefore on each side of the roadway, as usually constructed, the upper web must be stiffened laterally by cross-bracings, and the rails must be carried by

In answer to this assertion I shall here merely state, that in the tubular bridge the material of the top and bottom is so ill-disposed for the purpose of bearing the strains to which it is subject, that the quantity required for those parts very far exceeds the quantity required in the top and bottom flanges of a girder, with the addition of the cross bracing. For further elucidation on this point, I must refer to the general exposition already alluded to.

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cross-girders, the materials in neither of which add to the strength of the girder, while in the boiler plate tube the material requisite for the strength of the top and bottom web form a perfect top bracing far superior to any that can be applied by diagonal rods, and form a complete floor for the railway.

47. It may be said that the top and bottom web of the Warren or trellis might be carried across and made exactly similar to that of the tubular bridge, and I think that this would be an improvement on any that have been constructed; but by the time this and a few other practical difficulties are remedied in a more complicated system, they begin to resemble the tube so closely that one is disposed to ask what the discussion is about, and what advantage there can be in substituting in one, and that a small part of the whole, a rather complicated system requiring a different class of work for the simplest of all possible work, and instead of keeping up a perfect uniformity of workmanship in the whole.

48. There is also a disadvantage more particularly in the Warren's girder, though to some extent felt also in the trellis girder, when applied above the roadway, which must be met, and by some considerable expenditure. There is a class of accidents on railways not so rare but that they must be calculated upon as very likely to occur at some period upon a portion of railway of nearly a mile and a quarter in length. When one or two heavily-laden trucks in a train get off the line by the breaking of an axle or other cause, they are dragged along at a high velocity, with a force that might carry away the diagonal bracing of such a girder, and the fracture of any one brace of a Warren's girder would destroy the bridge.

REPLY.

This paragraph is a repetition, with circumstances, of the fallacies contained in Paragraphs 40 and 42.

This seems inconsistent with Mr. Brunel's view of the great size of the parts of a Warren girder, referred to in Paragraph 45; and the assertion that "the fracture of any one brace "of a Warren girder would destroy the bridge," shows that Mr. Brunel has not well considered the principles of its construction. For unless the fatal blow predicted were to fracture not only one diagonal bracing, but the pair, and also the horizontal tie or lower flange of the bridge, the injury would be limited to the one diagonal brace struck, which could be repaired without difficulty. But the fact is, that in a superstructure of such spans the separate members of the bridge are of such strength and dimensions that a waggon dragged along off the line, as suggested by Mr. Brunel, would be smashed to shivers against any *unprotected* brace with which it came in contact, with little or no damage to the brace itself. I say *unprotected*, for this is a necessary assumption to render Mr. Brunel's supposed fracture possible. But, as I have said in answering Mr. Clark, *perfect protection* can be given, and this so easily that it seems needless to do more than state the facts.

As bearing on this point, *i. e.* as to the strength of wrought-iron bars to resist fracture by a blow, an interesting fact may be quoted from Mr. Tierney Clark's account of the Suspension Bridge at Pesth. "On examining the state of the bridge," [after the bombardment of Pesth, from Buda, by the imperial general, and the storming of Buda by the insurgents, in 1848,] "it appeared that although many shot had struck the bridge, "there was but *one* that had done damage of any consequence. This shot, a 24-pounder, "and fired apparently from the Blocksberg, had unfortunately taken effect on one of the "long forked links which connected with the curved link of the upper chain, on the Buda "side of No. 3 pier; the ball struck the outer bar about 12 inches from the head, and "forced it close up to the second bar, which however was unhurt; there were in the "damaged bar several cracks or rents from the upper edge downwards, one of which "cracks extended to the depth of 3 inches. It was almost impossible to replace the "damaged link, owing to its being one of a set of ten, thereby rendering it necessary to "remove the outer links from each of the adjoining sets before the faulty link could be "got at; and one of the sets, as before stated, was the curved bars in the tower itself. The "bar struck was reduced, as was supposed, about one half in strength," and was afterwards thoroughly repaired.

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49. Such an accident has occurred on a tubular bridge, but owing to the simplicity of construction, and the continuity of all the parts, no serious consequences resulted.

It is a pity Mr. Brunel has not detailed the effects of this accident, so as to give some idea of the force exerted in striking the projecting angle irons, as even this might afford some criterion by which to judge of the effects on the large tie bars and struts of a Warren girder.

50. There is also another disadvantage which is a practical difficulty, which has prevented the uniting the girders of the several spans so as to admit of any increased strength being obtained from the principle of the continuous beam, which can be so easily and advantageously applied with the boiler-plate girders.

51. The increased strength obtained, or, what is the same thing, the diminution of material required to obtain the same strength by these means, is considerably greater than the small reduction of weight obtained by the substitution of lattice or triangular work for plates in the sides; and thus a continuous beam or tube of boiler plates makes a lighter and cheaper bridge with spans of 180 feet and upwards than a succession of independent Warren girders of the same span. And, on the whole, I am convinced, and know from practical experience, that even assuming a Warren's girder could be well constructed for a span of 250 to 300 feet, if erected under the circumstances of the Victoria bridge, of the same strength and stability, and equally well protected against contingencies as a tubular bridge, that the cost would be considerable greater, and, being free from any prejudice in favour of the one form or the other, unless I might be supposed to have a partiality for the truss, which I have preferred in the large spans I have built, I am decidedly of opinion, that, for facility of execution, economy, and durability, the tubular bridge is the best adapted for this particular case.

The "practical difficulty" of applying the principle of continuity to bridges formed of a series of Warren girders, has only to be named to bring to the mind of an engineer desirous of employing these girders, the means of overcoming the difficulty completely and satisfactorily, and a little closer examination of this point proves that the theory of these beams is applicable with *peculiar neatness to diagonally-braced girders.*

Mr. Barton found no difficulty in applying the principle to the trellis girders of the Boyne Viaduct, and Mr. T. W. Kennard *has* applied the principle in Warren girders. With a very slight modification of details in the Warren girders, the principle of continuity may be applied with precisely the same economical results as the plate-sided or trellis-sided girders.

The argument here founded, on the very proper suggestion that the principle of continuous beams should have been adopted, falls to the ground, because the source of the economy obtainable is the same in each kind of girder. But, Mr. Brunel further says, that "a *continuous beam or tube* of boiler "plates makes a lighter and cheaper bridge "than a succession of *independent* Warren "girders of the same span." Upon this point I beg to observe, in the first place, that according to the best of my judgment in the matter, founded on precedents, the weight of a tubular bridge girder must be about double that of a Warren girder for the same span, within the limits of spans now under consideration. If this be true, Mr. Brunel exaggerates the economy to be derived from the principle of continuity applied in sets of four spans, for this cannot practically exceed 40 per cent. saving on independent beams covering the same spans.

And, in the second place, does not this statement of Mr. Brunel, that a *continuous* beam of tubes is *lighter* than a series of *independent* Warren girders, imply that independent tubes are heavier than independent Warren girders for spans of 180 feet and upwards? And yet, in this very paragraph, Mr. Brunel writes that Warren girders of 250 feet span, *erected under the circumstances* of the *independent* girders of the Victoria Bridge, of the same strength and stability, would cost *considerably more.* And again, only a few paragraphs back in the Report, we find him saying that "the Warren girder "is admirably adapted for *many circumstances;* it consists of separate parts, which, "although they require some nicety of workmanship, may be finished at the manufacturers, "taken to pieces and sent to countries or localities where workshops could not be erected "or artizans obtained capable of working metals, or *even of doing boiler-work*, which is "the simplest possible metal-work, but where skilful labourers may be found who can put "together even complicated pieces."

If, for once, I have been able to correlate aright Mr. Brunel's "circumstances," then his conclusion as to tubes being "best adapted for this particular case" is a most marvellous *non sequitur.*

As regards Mr. Brunel's *knowledge from practical experience, that a Warren girder bridge of equal efficiency with a tubular bridge would cost considerably more,* I challenge him to cite his experience and to prove his knowledge. It surely cannot be the knowledge derived from the experience quoted by Mr. Stephenson and Mr. E. Clark in their Reports, if so, I must refer you to my replies to these Reports as my answer to the assertion.

Mr. Brunel confesses to "having preferred a truss in the large spans he has built," and it is well known that he has never applied a tube for any of his bridges of large span. Why then should he prefer it in the large spans to be built by Mr. Stephenson? Is there anything in the situation to warrant such a change of views? If wages are higher in Canada than in England, it surely is a reason for *preferring* that design where the most part of the work has to be done in England and the least part in Canada. But if not, still what possible reason can be assigned for preferring a truss for himself and a tube for Mr. Stephenson?

MR. BRUNEL'S REPORT.

52. Having thus very fully stated my reasons for concurring entirely with Mr. Stephenson in the general principles of construction adopted by him, I shall proceed to give, as I promised at the commencement of this Report, the impressions which a careful consideration of the subject has produced upon my mind, as to the means of introducing some economy in various parts of the works, and as the utmost which can be effected, even if all my suggestions prove capable of being adopted, and should all prove as successful as I could wish, will be to make a reduction of some £200,000 or £250,000. I cannot refrain from calling your attention to a few facts connected with the cost of this work, which show how groundless may be the expectation raised by brilliant promises of extraordinary economy to be effected in such works by the introduction of mechanical contrivances, however ingenious.

Having now examined, at some length, Mr. Brunel's "*reasons,*"—having in some degree exposed their looseness, inaccuracy, and fallacious character, having shown how utterly untrustworthy is his authoritative assertion, that for "*facility of execution, economy, and* "*durability, the tubular bridge is the best* "*adapted for this particular case,*" and differing from him, as I do, on almost every opinion, it is unnecessary to follow him very closely into "*the impressions* which a careful "consideration of the subject has produced "upon his mind, as to the means of introducing "some economy in various parts of the work," or into the reductions, and which are estimated by him as at the utmost £250,000.

My suggestions were offered to you on the simple consideration of the cost at which "*a substantial and efficient bridge over the* "*Saint Lawrence could be built,*" and of the best form for the purpose. They were not based upon a fixed estimate of £1,400,000, nor

MR. BRUNEL'S REPORT.

53. In the comparisons which are frequently made between the cost of different schemes, in which the ascertained cost of one with all contingencies, and contracted for under good security, is compared with a theoretical result obtained probably from an over-sanguine, if not a prejudiced, view of the advantages of some other plan, provision for contingencies common to both are very apt to be omitted, different dimensions to be assumed, and as the calculations if made at all in detail are made by totally different processes, the most contradictory results may be obtained. The only safe way of making a comparison is to select those portions of the work in which the change proposed would effect any difference of cost, and to ascertain separately the amounts of these differences, assuming the other parts to remain the same, as they must do practically.

54. In the present case the gross amount which appears to have been always assumed as the cost of the bridge, namely, £1,400,000, includes approaches, contingencies, plant, scaffolding—a very costly item in such a case, permanent way—even painting, by no means a small item, and numerous other items of cost which cannot be effected by any modification of the details of the superstructure, and the aggregate of which cannot amount to less than from £250,000 to £300,000. Of the remainder only about £400,000 is absorbed by the tubing or superstructure, and of this only about £120,000 is the cost of that part to diminish which (not to eliminate it, for that is impossible) so much ingenuity has been expended in the construction of Trellis girders, Warren's girders, and others, and assuming that theoretical perfection in the construction of a girder would reduce this to half, which I doubt, it is to a saving of some portion of £60,000 that the pretensions of the Inventors must be limited in this case; and for the reasons I have given I do not consider that the means by which any such saving would be attempted are even applicable in the present case.

55. It is not then by the introduction of any new mechanical contrivances or any change in the principle of construction that I can suggest any prospect of saving, but as a practical man rather than an engineer, considering the circumstances under which this difficult work was originally designed, I have looked to the probability of there having been some superfluity of strength of materials

REPLY.

upon a design assumed without proof to be the best for the purpose; and therefore they were not confined to the small parings that could be made by lessening the dimensions of the piers or abutments, or by widening the spans of the superstructure, but they went to the root of the matter, and raised the question whether the design was the best, and whether the estimate was reasonable.

Mr. Brunel not choosing to travel out of his instructions, has adopted the contract designs, and the contract amounts, as fixed irrevocably for those designs, and therefore must be limited to small sums in any saving he can show. But even on this view he is singularly unfortunate in his suggestions; for on the two principal items of saving suggested, Mr. Ross considers any saving impracticable, and on the third Mr. Brunel appears to be at variance with Mr. Stephenson, and overrates the economy obtainable by adopting the principle on which the suggestion is founded.

Mr. Brunel does not admit that there is any less material for the same strength in the top or bottom flanges of the Warren girder, than in the top and bottom of the tube; he supposes that there *may be theoretically* a saving of £60,000 in the sides, though he "*doubts*" this.—(He ought to be able to say it is so or it is not.)—But this amount is equal to all the saving that he proposes to effect by a change to continuous bearings, a saving only to be effected by thinning down the iron of the tubes, as designed by Mr. Stephenson, to a degree which would go far "*to eliminate their strength.*"

MR. BRUNEL'S REPORT.

and of dimensions adopted, and some expenses submitted to, to remove doubts or to meet fears and prejudices, and which might now safely be omitted.

56. First, as to the dimensions of the masonry of the piers, and particularly of the abutments. Mr. Stephenson has already I know recommended that the depth or length in the direction of the river of the piers should be reduced at the base by about 6 feet or 7 feet, and at the top by about 13 feet. I believe this will effect a very considerable saving, not less than £60,000 or £70,000, and I fully concur in the opinion of the safety and feasibility of the reduction. I would carry out the same principle of reduction in the abutments, and I would suggest the consideration of the necessity of any continuous wind wall or slopes of ashlar masonry. It would seem to me that a pier not much exceeding in thickness those in the middle of the river, tied on to the embankment, brought close up to it by wings merely sufficient to unite the embankment to the pier, would be sufficient, or that a length of 50 or 60 feet at the utmost of ashlar facing to the slope would be sufficient, and I would suggest the entire omission of the stone superstructure except a mere entrance to the tube. If all of these reductions can be effected in the abutments, I think that notwithstanding the progress already made on the south side a saving of £60,000 or £70,000 might possibly be made.

57. In the spans adopted my impression is that some modification may probably be introduced by bringing into operation one of the principal advantages of the simple tubular system. I quite agree with Mr. Stephenson in opinion that the whole bridge could not be constructed as one continuous beam, but I think an intermediate course might be adopted. If the tubes were formed in sets of four, each fixed to the piers at the centre and rolling upon the others, I should not apprehend any difficulties from the expansion and contraction; it would not be greater, or very little so, than at the Britannia Bridge, and the effects of the inclined plane would be obviated by making the rolling surfaces horizontal.

58. If the tubes are made continuous to this extent, a very slight addition to the quantity of iron, with a slight modification of the

REPLY.

In Paragraph 56, Mr. Brunel supports the proposal to diminish the piers and so to save £60,000 or £70,000. Mr. Ross protests against any such course. Mr. Brunel must arrive at the £70,000 by calculating the masonry to be saved at 6s. 6d. a foot, *i. e.* at two thirds of the actual cost of the work, including all expenses. Mr. Ross says you cannot take off more than 2s. 6d. a-foot, as all but the cost of stone, mortar, and labour would be incurred, whether the piers be reduced or not. If this be so, Mr. Brunel's £70,000 is reduced to £27,000.

Mr. Brunel also proposes to reduce the abutments, and to save another £60,000 or £70,000; but this also Mr. Ross rejects as impracticable; and no doubt if we had his estimates we should find equally good reasons urged for reducing this saving of £70,000 to £27,000, as those given for doing so in reducing the stone-work of the piers.

Again, in the superstructure, Mr. Brunel proposes continuous bearings, and suggests by that means, in combination with increased size of spans and diminished number of piers, a saving of some £60,000 more. But alas! Mr. Ross disagrees with him here also. He cannot allow more than £25,000 as the saving for each pier dispensed with, and makes out the increased cost of a superstructure of tubes caused by widening the spans to be more than the saving effected by reducing the number of piers. Nor does Mr. Stephenson seem to confirm his suggestions of saving iron by continuous bearings.

Last of all (Paragraph 59) he suggests a saving on a mere chance,—*on a calculation of probabilities*, perhaps,—for he says he can "*know nothing at all about it*," yet he offers the suggestion "*thinking it likely that Mr. Stephenson and Mr. Ross, from the anxious considerations of the difficulty of the case,* relative thickness of plates at different parts, the spans will allow of being increased from 242° to 295°, and I should not hesitate to recommend extending them to 320°: by the first, three piers might be dispensed with, by the second, four, and a saving effected of from £50,000 to £60,000; and in a bridge of such length the change of dimensions from the spans between the six piers now in progress and the remainder would not be observable.

59. Lastly, I would suggest the reconsideration of the total amount of water-way allowed.

60. Upon the question of the sufficiency or insufficiency of the extent of the 6000 feet and upwards, determined upon by Mr. Stephenson, I have not, of course, attempted to form any opinion. I never examined the site, and I can know nothing at all about it, but I think it likely that the first results of a very anxious consideration of the difficulties of the case, and a sense of the serious responsibility that rested upon them, may have led Mr. Stephenson and Mr. Ross to have given an excess of water-way rather than a deficiency, and that they might not feel justified, merely because they had grown more confident in the probable stability of these piers, in recommending an alteration of those plans which had gone before the public and been sanctioned (if any sanction was required) by the proper authorities; if upon reconsideration it should be found that so large a water-way was not absolutely required, it must be borne in mind then that for each opening that could now be dispensed with on the North shore and replaced by embankment, a saving of more than £35,000 would probably be effected.

I am,
Gentlemen,
Your obedient servant,
(Signed) I. K. BRUNEL.

To the Directors of the
Grand Trunk Railway of Canada.

"*and a sense of the serious responsibility that* "*rested upon them, may have given an* "*excess of water-way,*" but "*that they might* "*not feel justified in recommending an altera-* "*tion of those plans which had gone before the* "*public;*" and this suggestion at haphazard —for he "*knows nothing at all about it,*"— seems worthy of some attention, if, indeed, any diminution of work is allowed to make any difference at all in cost to the Company. The suggestion relates to a reduction of the water-way beyond that last adopted, which is already a reduction from the amount specified.

The number of spans contracted for, as stated in the Specification, were 32 of 220 feet, and one of 330, but it is now reduced to 24 of 242 feet, and one of 330; that is, the whole length of the bridge is reduced from 7978 to 6576. And yet no corresponding diminution of cost appears to have been made, or is spoken of, in any of the Reports under discussion. Yet this slice of work taken out, valued as per contract, is worth £218,000. Now Mr. Brunel has either, without being aware of this, made a calculation that £1,400,000 is probably a fair estimate; or if aware of it, has very strangely omitted to allude to it. He suggests, however, that the water-way may be still further reduced. It has already been reduced by 1332 feet, that is, by more than one-sixth of the water-way originally designed. It is easy to carry the imagination a span further, with the temptation held out of £35,000 gained for each span saved. But, judging from Mr. Ross's opinion respecting other savings, I can hardly suppose that he would admit that such an amount of saving as £35,000 on each span would be at all practicable. Indeed, if it were proposed to do away with the whole bridge, I doubt whether, by Mr. Ross's method of reasoning, even half the cost could be saved.

Upon Mr. Ross's showing, however, it is useless now to talk of saving spans, for the foundations of both abutments are put in, and built above summer level. For the same reason, also, vanishes the hope of saving anything on diminished abutments, so that the only saving suggested by Mr. Brunel possible to be carried out, is first, that by reducing the dimensions of the piers, and equivalent to a sum estimated by him at £70,000, but by Mr. Ross at £27,000; and, secondly, by reducing the number of piers, by means of the introduction of the principle of continuity, of £50,000 or £60,000 more, *i. e.* a saving of £130,000 at the utmost.

I have now followed this Report through its whole length. It is a document difficult to characterise without offence. Where argument is attempted, the arguments are illogical, if not sophistical; but, in general, arguments are superseded by strong assertions, founded neither upon independent proof, nor upon the authority of any known precedent whatsoever.

REPLY.

The Report commenced with the avowed intention of answering my Report, but under a pretended desire to insure "calmness, deliberation, and freedom from prejudice," anything in the shape of direct reply is avoided; and not a *tittle* of proof is given in justification of the design and estimates of the bridge as contracted for, whether as regards special fitness for its purpose or due economy of construction, unless it be that the *dictum* of Mr. Brunel is "to be supposed to have that extent of authority which determines "belief without a comprehension of the proof. Let it, however, be borne in mind that "whatever deference is due to great names and competent judges, they are not to be "regarded as infallible—as oracles of a scientific religion, or as courts of philosophy with-"out appeal." *

I am, Sir,

Yours, &c. &c.

CHARLES LIDDELL.

* Sir G. C. Lewis "On the Influence of Authority in Matters of Opinion, Chap. xiii. on the Abuses of the Principle of Authority."

GRAND TRUNK RAILWAY OF CANADA.

VICTORIA BRIDGE, MONTREAL.

REPORT OF MR. EDWIN CLARK,

AND MR. LIDDELL'S REPLY.

To the Chairman and Directors of the Grand Trunk Railway of Canada.

VICTORIA BRIDGE.

GENTLEMEN,

1. I have been requested by Mr. Robert Stephenson to state my views on a Report made by Mr. Liddell, in which the adoption of Warren's girders is recommended as the most economical principle of construction for the Victoria Bridge, and in which the cost of such girders is compared with that of other forms of girder, and other modifications are suggested in respect to that structure.

2. With respect to the construction of the piers and approaches I shall offer no suggestion, as it is impossible to form any opinion on this part of the structure, without a thorough acquaintance with the local circumstances, on which the construction of foundations of course entirely depends.

3. It is evident however that the cost and dimensions of the piers and abutments will be independent of the form of girder that may be adopted, and it does not appear from the plans I have seen, that any unusual expenditure in this respect has been necessary on account of the form of superstructure, while the construction of the "ice-breakers" appears to me to have been judiciously effected by the use made of the weight of the piers themselves in their formation. Any independent construction for such a purpose on a bed of rock must necessarily have in-

To R. McCalmont, Esq., one of the Directors of the Grand Trunk Railway of Canada.

VICTORIA BRIDGE.

SIR,

Having read Mr. Clark's "Statement of his views" on my Report addressed to you on the 22nd of September, 1855, I beg to hand you the following reply :—

As Mr. Clark says it is impossible to form any opinion on the construction of the piers and approaches, it is almost needless for me to reply to the general remarks made by him in the third paragraph of his Report, not only because they appear to be made without a correct conception of the meaning of my Report, but more especially as the parts of the bridge to which these remarks refer are fully discussed in my replies to the other Reports.

It is important, however, to observe that Mr. Clark, in confining his observations to the Superstructure, treats of that part of the bridge which, by Mr. Stephenson's Report (Paragraph 67), is estimated to cost only £400,000, out of £1,400,000. Moreover, be it observed, this £400,000 is for the Superstructure *fixed complete, including scaffolding and all other preparations ;* and, as the weight of the Superstructure as designed appears (by Mr. Clark's Report) to be about 7,200 tons

MR. CLARK'S REPORT.

volved the use of a considerable weight of stone for its security. I must here remark, that from the experience I have had of the effect of ice on a bridge I have lately constructed over the Rhine near Arnheim, that I attach much more importance to its action than Mr. Liddell appears to do,—the packed ice (in spite of numerous ice-breakers) having broken the very heavy cast-iron plates of which the cylinders of that bridge are formed.

REPLY.

only, *the cost per ton of Superstructure is nearly* £56, including scaffolding, &c. Now it is quite certain that the cost of the iron tubes erected in Canada, exclusive of the scaffolding and preparations necessary for fitting them up, if let by public tender, would be under £28 per ton, *i.e.* under one-half of the whole cost as estimated by Mr. Stephenson. Therefore the Report of Mr. Clark is in reality confined to the comparison of work, the actual cost of which must be within £200,000. For the whole cost of the tubular girders cannot exceed that sum.

Now admitting, for a moment, Mr. Clark's assumption,—that "whatever be the form "of girder, the top and bottom flanges must be of precisely the same area in all girders "of the same strength and depth"—I will engage to produce a Contractor to undertake the Superstructure of Warren's girders, constructed with the top and bottom flanges of equal weight to those of the proposed tubular girders, as given by Mr. Stephenson, for the sum of £200,000, *fixed complete, including scaffolding and all other preparations*, *i.e.*, at one-half of his estimate for erecting the tubular girders. But I shall show in the sequel that Mr. Clark's assumption as to the equality of weight of all girders is a *fundamental error.*

One word with regard to Mr. Clark's experience of the effects of ice:—What are the facts in reference to the "Bridge over the Rhine, near Arnheim?"

Mr. Locke is the English Engineer of the Prussian Extension of the Dutch Rhenish Railway, in which line the bridge in question occurs; Mr. Brassey was the Contractor; Mr. Stephen Ballard his resident Manager. The bridge is over the *Yssel*, at Westerfort, not over the *Rhine*, near Arnheim. The working drawings of the bridge were made in Mr. Clark's office. Mr. Clark, as I am informed, was never on the spot before or during the execution of the work. Some of the plates of one of the cylinders were broken by the ice, but this was during the progress of the works, and in consequence of the cylinder not being filled with brickwork or concrete. The frost came on suddenly and stopped the filling after one course of plates were put on, ready to be filled. It was feared that damage would be done, and timber struts were placed across the cylinder, but this proved insufficient. Some of the plates were *torn* clean off, and others were broken. The other cylinders that were filled with brickwork and concrete stood without damage. The cylinder plates were broken by the ice pressing out sideways, and as the cylinder was not filled, a very slight force was enough to break them.

MR. CLARK'S REPORT.

4. With respect to the proposed superstructure, and its comparison with other forms of girder, I have had sufficient experience to enable me with some confidence to express an opinion on the conclusions arrived at by Mr. Liddell, and I will endeavour to do so without bias, although being interested in the patent which had been obtained for the girders which are recommended by that gentleman, I might be considered as biassed in favour of their adoption. *As regards the advantage in respect of cost of any particular form of girder, the question is brought into a very narrow compass, from the fact that whatever be the form of girder,*

Without remark on Mr. Clark's fitness to express an opinion, biassed or unbiassed by his feelings as a patentee, we now come to the pith of the subject of his Report. In the few lines of this paragraph, which I have had printed in italics, is contained the enunciation of a principle, on the truth of which I am at direct issue with him.

Mr. Clark states, that "*whether the sides "consist of trellis work, triangles, or plates, or "form portions of a tube, the top and bottom "flanges must be of precisely the same area, in "girders of the same strength and depth.*" In this view of the case the sides of course are omitted as an element of strength in all.

I must here repeat much that appears in my

MR. CLARK'S REPORT.	REPLY.
whether the sides consist of trellis work, triangles, or plates, or form portions of a tube, the top and bottom flanges must be of precisely the same area in girders of the same strength and depth; the only economy that can exist in respect to different forms must be therefore confined to the sides, or to a small part of the whole weight of the girders.	reply to Mr. Stephenson's Report, to which I beg to refer you for a more complete statement of my conception of the principles on which girders should be proportioned. My view of the question is this. In girders of the same depth, in which the connecting web is not an element of strength, the horizontal strain of compression and extension on the top and bottom flanges respectively is the same, for the same weight of girder and the same load upon the girder.

The area required in the top and bottom flanges to resist this strain, depends essentially on the form in which the metal in them is exposed to strain, and upon the description of iron used, and therefore is not necessarily "*the same in girders of the same strength* "*and depth whatever be the form.*"

The strength of the girder, if the area of the flanges be the same, depends not only on the quantity of the material used, but essentially on the form of the flanges, that is, on the disposition of the metal in them, if by "*strength*" we understand the absolute resistance to destruction of the flanges, whether by buckling, crushing, or tearing asunder. These are elementary propositions or axioms.

Mr. Clark, however, seems to attach another meaning to the word "strength." It appears from his reasoning (confirmed also by Mr. Stephenson's Report, Paragraphs 27—60), that he means by "strength" a certain assumed power of resistance per square inch of section of the iron in the top and bottom flanges of all malleable iron beams, whatever be their form and quality. But this is literally begging the question. For, while in Warren's girders (above 100 feet span) and in other good forms if trussed girders, the iron applicable to them is of a scantling, and is exposed to strain in a form in which it is adapted to bear the greatest load of which wrought iron is capable—*i. e.* about 25 tons per square inch of iron, either in extension or compression—the iron in tubular-bridge girders is exposed to strain in almost the worst form it can be put, and is, in itself, of a comparatively weak kind.

Mr. Clark, in his book on the Britannia Bridge, has fixed the absolute resistance of the iron in tubular girders at 14·8 tons per square inch of compression, and 18·6 tons for tension, (by a process of calculation which omits the effect of the sides,) as a basis for obtaining the constants in the empirical formulas which he has adopted.

With these data, the areas of the top and bottom flanges, for the same strength, in Warren girders and in tubular-bridge girders would have to be:—

For the top as 14·8 in the Warren to 22 in the tube,—that is, as 1 in the Warren to 1·48 in the tube.

For the bottom as 18·6 in the Warren to 25 in the tube,—that is, as 1 in the Warren to 1·34 in the tube.

Without going further into the consideration of other causes of increased weight in tubular over trussed girder bridges, I have said perhaps sufficient to demonstrate the fallacy of Mr. Clark's fundamental principle. But I may here mention, that the view I take of the error of his method of proportioning the parts of a bridge was pointed out to Mr. Clark at a very early period in his career, in a letter from the Astronomer Royal which Mr. Clark quotes at page 514 of his book, where he justifies Mr. Stephenson for not adopting the rule pointed out by that eminent philosopher, by the peculiar nature of the case.

"The true process," as Mr. Airey wrote, "is to find the whole actual strain on the "bridge, and to multiply it by the *factor of safety*,* and then compare the product with the "actual strength."

By Mr. Clark's practice the factor of safety varies with every form of girder that he may design, even in equal spans. In the best form of tubular-bridge girder, that of the Britannia, it is fixed very low, viz. under three times the strain from the weight of the bridge

* By "factor of safety" is meant the number representing the proportion between the working load (including the weight of the girder itself) and the load which would break the girder.

itself together with that of the test load [when the bridge is considered as a continuous beam], for the reasons given by Mr. Clark, viz. "that, as the weight of the structure "formed a very important part of the whole strain, Mr. Stephenson was justified in "reducing the factor of safety."

In bridges of equal span the same factor of safety should evidently be applied in instituting any comparison, and it is quite unfair to argue from the case of the Britannia Bridge, and that the same strain shall be taken for all bridges, without regard to the factor of safety. As a matter of fact, strains of 6 and 7 tons per square inch may be applied on Warren girders, keeping the same factor of safety as when 4 and 5 tons respectively are applied on *any* tubular-bridge girder.

It is a matter of opinion whether the factor of safety, even for a bridge of such great weight as the Britannia, should be taken so low as has been done, and it can only be justified for the reasons put forth by Mr. Clark as stated above. The case is exceptional. For the spans are 460 feet; and the weight of a tube—1553 tons—is therefore in immense excess of the moving load,—300 to 350 tons. But if, as I contend, the same factor of safety should be used for equal spans, however great they may be, then of course it leaves the question open as to the best form of girder; whereas, if a stated strain per square inch of iron is made the datum for starting from, and its relation to the factor of safety be altogether neglected, it matters not what form of girder is put up,—the top and bottom flanges must be precisely the same area for the same arbitrarily adopted strain, when the girders are of the same depth, and the sides are omitted as an element of strength,—a conclusion which is evidently too absurd to be adopted on the mere *dictum* of any one.

MR. CLARK'S REPORT.

5. The great differences asserted by Mr. Liddell to exist between the weight of the three forms tabulated in his Report, are therefore on this simple consideration evidently founded on some misapprehension, even if we admit the tubular girders to be by far the least economical of the three.

6. With respect to the Warren girder, which he compares with apparent advantage over the others, I will add, that when the span is small and the depth considerable, the strain on the sides of a *plain* (tubular?) wrought-iron girder requires plates of such extreme thinness, that, as a question of durability, altogether apart from strength, it is necessary and usual to use a much thicker plate than theory would require, and a waste of material to that extent undoubtedly takes place.

7. It is here that I consider the Warren girder possesses the advantage;—as the material being thrown into bars, instead of thin plates, no such increase of strength is required; nor are bars of iron of such dimensions so liable to suffer from oxidisation as thin plates with so large a surface of exposure.

8. There is again another advantage possessed by the Warren girders, viz.: that if they are required to be erected in countries

The inference drawn by Mr. Clark in the paragraph No. 5, of "misapprehension" on my part, at once falls to the ground, resting as it does on a "simple consideration" which I have shown to be fallacious, and inconsistent with sound engineering practice. Mr. Clark again alludes, in the after-part of his Report, more in detail to my supposed "misapprehen-"sions," and it will be more convenient to reply to him there.

In paragraphs 6, 7, 8, and 9, Mr. Clark admits all the advantages in Warren's girders of 150 feet span that I contend for, but condemns them if above that size, although there is as yet no single instance of any bridge above 150 feet span having been built, excepting that of the Newark Dyke, which was one of the first erected, and to which I shall allude, in answer to Paragraph No. 10.

It is curious in reading these paragraphs to observe how the patentee warms to his subject. He not only finds the Warren girders superior to others up to 150 feet span, by reason of their less weight and greater durability, "*but also for the facility with which* "*they can be put together without tools, in* "*countries where skilled labour is unattain-* "*able:*" and Mr. Brunel, in his Report, (Paragraph 40,) applies the same terms of commendation to the girders for spans of 200 feet; although, he says, "it is not so well fitted for "spans exceeding 200 feet, as the parts become "too large."

MR. CLARK'S REPORT.

where skilled labour is unattainable, the facility with which they may be put together without tools is sometimes of great advantage, and on these grounds I have frequently recommended their adoption, and some very fine bridges have been most successfully completed.

9. The bridge at the "Kremlin," [Crumlin] where the spans are 150 feet, which, under the superintendence of Mr. Charles Wild, was designed and erected by Mr. T. W. Kennard, is certainly the finest example of this description of girder that can be referred to.

10. I must, however, in candour confess that the advantages I have enumerated are peculiar to girders of moderate span. Not only when the span is large, as at the Victoria Bridge, does *the practical difficulty of uniting such long and ponderous columns and chains present serious difficulties, and the amount of superabundant material which then becomes requisite for ensuring lateral strength in such a jointed system, gives to the plain [tubular] girder adopted by Mr. Stephenson an important advantage, whilst the requisite strength of the sides in a tubular girder of such dimensions no longer renders necessary any waste of materials.* Another important advantage in the use of plain sides (especially on *so long* a viaduct, and where the girders are all above the platform) arises from their security in the case of a train running off the line; a contingency which has already more than once occurred on such bridges without detriment, whereas a structure such as that proposed must infallibly be destroyed by such an accident.

REPLY.

Mr. Clark, (paragraph 9,) in his admiration of Warren girders, goes out of his way to make a statement respecting the Crumlin viaduct, entirely without foundation. Mr. Wild's formula for calculating the strains on the parts of the Warren girders of the Crumlin viaduct was adopted, and the calculations were checked by him. But certainly the design for the bridge was not made under his superintendence, nor, to the best of my belief, has he ever been on the ground before or since the work was commenced. Mr. Wild's scientific acquirements and experience in building with cast and wrought iron are too well known to make it necessary for me to do more than allude to them. Mr. Wild is part owner of the patent for the Warren girder, and for his suggestions as to many of the details of the work, I freely acknowledge my obligations to him. But for the design of the bridge, and the adoption of the Warren girder, I as Engineer am alone responsible.

Mr. Clark, in paragraph No. 10, recovering from his admiration as a patentee of the Warren girder, and disclaiming all superiority for them beyond 150 feet spans, gives preference to the tubular construction for the reasons adduced in the sentence opposite, which I have had printed in Italics.

Now compare this sentence with the following, paragraph, 13, below:—

"No other girders of the same depth, "strength, and rigidity, can be substituted with "any important saving in weight, while *boiler* "*plate work* is invariably less costly than the "*forged work* requisite for other forms of "girders, and although by placing the Warren "girder beneath the roadway, I have no doubt "an efficient Warren girder bridge might be "constructed for the spans of 250 feet; yet it "would be neither economical nor practical to apply that principle of construction to "the large span of 330 feet *without entirely modifying the details of construction at present* "*in use.*"

From this it appears that Mr. Clark has a suspicion that, by a modification of details, even a 330 feet span may be constructed both "practically and economically." It is true that he mixes up the question with that of danger from a roadway laid between Warren's girders—with which the question of cost and weight has nothing whatever to do—and so shirks the difficulty which is evidently disturbing his mind. But I will take him on his own ground at present, leaving the question of the danger from the position of the roadway to the sequel. Mr. Clark justly says that the large span would require a modification of details. Why Mr. Clark knows (who so well as he, the part owner of the patent?) that the details of construction of nearly every different span of Warren girders yet put up have been different; and if he can admit that an efficient Warren bridge of 250 feet might be constructed with some "*saving of weight,*" however "*unimportant,*" it seems strange that he should be at a loss to design one of 330 feet.

It is almost evident, indeed, from this sentence, that except for the difficulty of the roadway at the bottom, Mr. Clark concedes the superiority of Warren's girders over tubular girders of 250 feet span, even in spite of the "*ponderous columns and chains, and the* "*superabundant material which then*," according to Mr. Clark, "*becomes requisite for* "*ensuring lateral strength in such a jointed system.*"

Now what are the facts of the case respecting these "ponderous columns and chains," and the bugbear of "danger?"

For Warren girders of spans of - - - - - - - - - -	242 feet,	330 feet,
the heaviest length of the compression flange between the points of support would weigh about - - - - - - - - - -	$2\frac{1}{2}$ tons.	$4\frac{1}{2}$ tons.
Ditto ditto tension bars (single piece) - - - - - - - - -	1 „	1 „
The heaviest struts, about - - - - - - - - - - - -	1 „	2 „
„ ties „ - - - - - - - - - - - - -	18 cwt.	35 cwt.

and in the whole girder, of which I have had designs made, as in all other girders of a similar kind, the *forged work required* is not 2 per cent. of the whole. The bars are all of a much thicker, and cheaper, and stronger form of iron than the plate required for a tubular bridge, and the "superabundant" material required to "ensure lateral strength" is not only not more in proportion to the whole weight than in smaller girders, *but the proportion actually diminishes as the size of the girders increases.*

As regards danger in passing between girders of Warren's or any other kind of diagonal bracing, I need hardly, I think, say one word. It is unquestionably a thing so easy to be provided against that the merest tyro should be ashamed to make the objection. There are many bowstring bridges erected in this country in which the road passes between the girders, and a notable example of the adoption of this system is the large bridge now being put up by Mr. Brunel at Plymouth; and why such objection should be taken in the case of the Victoria Bridge, and not in the case of bridges in England, is a curious question. But as I have before said, perfect protection can be given without difficulty, perfect protection should be given, and perfect protection was provided for in the design made for my first Report to you.

Mr. Clark claims perfect security to the tubular girders in the case of trains running off, and this I do not dispute; but his conclusion of "infallible destruction" to a Warren girder by a train running off the line, is, to say the least of it, a vague assertion, supported neither by evidence nor argument, or rather it is not true, as any one who has formed a correct conception of the principle of Warren's girder will inform him.

But if it be said that the danger from a train running off the line, to a Warren girder bridge, and a bowstring girder bridge, is different in degree, I reply that I never put forward a Warren girder as the one thing essential. On the contrary, if you will refer to my Report, you will see that I state "that from the experience obtained, in the "erection of the Crumlin viaduct, I am able to speak precisely as to the *cost* at which "Warren girders can be erected, and satisfied as I am of their being good and substantial, "I have no hesitation in recommending them, *though there are other forms of trussed girders* "*that are equally good in all respects.*"

If a Warren girder cannot be shown to be easily protected, then adopt the bowstring. I do, however, say that—whatever be the form—whether as regards weight or economy, for the same strength, trussed girders are to be preferred to tubular bridges; that tubes are decidedly objectionable for the further reason, that they form dark and noisy tunnels, shutting out light and air and prospect, for no reason that I can find. On this last-mentioned score plain girders are equally objectionable, for to protect them from snow they would require a covering, and so far become noisy and disagreeable tunnels like the tubes; but I cannot subscribe to the assertion of Mr. Stephenson, Mr. Clark, and Mr. Brunel, that this top, required to protect the roadway, converts a pair of plain girders into the same thing as a tubular girder.

MR. CLARK'S REPORT.

11. Without being aware of the data on which the table given by Mr. Liddell is computed, we have practical evidence of the relative weights of plain and Warren girders, in

In support of his opinion Mr. Clark adduces what he calls "practical evidence of the relative "weight of *plain* (tubular) and Warren girders in "two existing bridges of somewhat similar span."

MR. CLARK'S REPORT.

two existing bridges of somewhat similar span to that of these tubes, viz., the tubular bridge erected by Mr. Stephenson over the River Aire, span 225 feet, total weight, including roadway and bearings for a single line, 235 tons; and secondly, the Warren girder at the Newark Dyke, designed by Mr. Charles Wild, span 240 feet, total weight for single line 292 tons, including bearings; while the spans for the Victoria Bridge are 242 feet, and total weight of single line including bearings, 275 tons.

REPLY.

Let us examine what Mr. Clark calls "practical evidence."

In these bridges the clear width

Of Newark Dyke is - - - -	13 feet
Of the Aire is - - - - -	11 "
The depth of Newark Dyke is	16 feet
" " Aire "	20 ft. 9 in.
The span of Newark Dyke is	240 ft. 6 in.
" Aire "	225 "

The Newark Dyke Bridge was the first Warren girder of great span ever erected. The working drawings were made by Mr. Wild. All the parts subject exclusively to compression were formed of cast iron, "not only on account of its power of ultimate "resistance being greater than that of wrought iron, but also on account of its cheap-"ness, and the facility with which it can be cast into the best shapes for resisting "compression." Since the erection of this bridge, however, the arrangement of the parts of the Warren girders has been so altered that wrought iron is advantageously substituted for cast iron throughout; *i. e.* in the forms now adopted the full value of wrought iron to resist compression is obtained, without any increase of cost and with considerable diminution of weight, while the facilities of erection are greater than when cast iron is used. We are indebted for this modification to Mr. T. W. Kennard.

In the Newark Dyke Bridge the material used is

		Tons.	Cwt.
In the girders	cast iron - - -	138	5
Ditto	bar iron - - -	106	5
In the platform,	*chiefly cast iron* - -	50	0
		294	10

In the Aire Bridge the whole of the girders is of boiler-plate and angle iron - 235 tons.

The Aire Bridge was built originally only 11 ft. 10 in. wide at the bottom, and 9 ft. 3 in. at the top, and was afterwards widened by 21 inches at top, making it 11 feet clear inside. In order to make it equal in width to that of the Newark Dyke Bridge we must add about 20 tons to the weight of it, making 255 tons. Then, if we allow an increased weight of the top and bottom flanges in the inverse ratio of the depths of the girders, viz. as 20 ft. 9 in. to 16 feet, and deduct the difference due to the diminished depth of the side, we obtain a further weight, making the whole 261 tons. This again has to be increased for the difference of spans, in the ratio of the squares of 225 to 240; *i. e.* the total weight of the tube for the Aire Bridge reduced to the same depth and span as the Newark Dyke Bridge would be about 287 tons in the former, against 294 tons in the latter; and in the Newark Dyke Bridge is included a platform of 50 tons weight, which is about double the weight necessary; so that the *true comparison* shows that the weights of the two bridges are nearly equal for equal spans.

So far Mr. Clark's comparison will stand as "practical evidence" of two bridges, one tubular, the other of Warren girders of equal spans, being of equal weight. But there is another point to be considered, and a very important element it is, in making any such comparisons, viz.—What is the relative strength of the two bridges?

With equal loads (the usual test loads for such bridges) the strain from compression on the Aire Bridge is upwards of 4 tons per square inch, on a form of iron on which there is little experience of what it will bear without buckling: but the actual crushing weight of the best form of tubular bridges was fixed, from the last experiments on the model made for Mr. Stephenson in reference to the Britannia Bridge, at 14·8 tons per square inch, and taking that figure, although it is far above the strain at which buckling is stated to have commenced (see Mr. Clark's book p. 180), and is deduced from an experiment which

Mr. E. Hodgkinson *rejected* because he "conceived that there must be some error in it" (see Report of Royal Commission on Iron Structures, p. 159), the factor of safety for the bridge, in reference to the top, is still only 3¾.

In the bottom the strain is about 7 tons per square inch, and taking the figure fixed from the same experiment for the greatest power to resist tension at 18·6, although it is also in excess of the point at which failure is stated to have commenced, the factor of safety is only 2¾.

Now, in the Newark Dyke Bridge I find, from a paper written by Mr. Charles Wild, that the factor of safety is in reality about 9 for compression, and at least 5 for tension, *i. e.* the quantity of material in the upper beam is 2¼ times that of the Aire Bridge, to give the same strength, and in the lower beam nearly twice. So that the Newark Dyke Bridge is nearly twice as strong as the Aire Bridge. But let us look at this result in reference to the Victoria Bridge.

The bridge over the Newark dyke being, as I have said, the first of any considerable span erected, is of a complicated and of expensive construction, considering the material used. Yet, "including *staging for fixing and putting together, and expense of testing*," the cost per ton was under £20, whereas that of the Victoria Bridge is estimated at £56; and further, the total cost of this bridge, nearly double the strength of the Victoria Bridge, was only £5501. 10*s.* for a single line, whereas an equal span of the Victoria Bridge is estimated at £15,400. So that *the true deduction* from the "practical evidence" adduced by Mr. Clark is, that a tubular bridge is *more than five times the* COST *of Warren's girder for equal spans of equal strength.*

MR. CLARK'S REPORT.

12. Mr. Liddell makes a distinction between the weight of plain girders and tubes, which no doubt arises from a misapprehension hereafter explained. A tube is nothing but two plain girders placed side by side, which though it increases their lateral strength, cannot in any way increase their weight; and the tube at the Aire Bridge during the process of widening that bridge after its completion by order of the Board of Trade, did in fact exist for a time, as regards the top, as two independent girders, which were subsequently united. There is moreover this advantage in a tube, where the span warrants such a construction, that it not only forms, but shelters its own roadway, which, with independent girders, would cause a great addition to the weight of the bridge without any increase of strength.

The statement in Paragraph 12 is the natural consequence of the double fallacy involved in Mr. Clark's fundamental principle of determining the proportions of beams, and is of course untrue.

I have already shown, by such proof as ordinary language will admit of, that the *strength* of the top flange depends essentially on the disposition of the iron in it; and the subject is further elucidated in reference to Paragraphs 27 to 60 of Mr. Stephenson's Report. But Mr. Clark, in making his calculution, not only omits the element of strength in the sides, which in some measure justifies, by a rough compensation, the high value at which he estimates the resistance to compression and tension, but he ignores the principle on which the strength of the sides may be made to add to the strength of beams. This principle comes into play when plain girders are used, having a strength of middle web proportioned to its work, and when the top and bottom flanges are so adjusted as to give the best result from the materials employed. I employ the well-established formulas of Napier, Moseley and other writers on the subject of the strength of materials for calculating the proportions of such beams, with constants derived from the experience of the French Engineers, who have adopted this form of girders, to the extent of 5000 tons, on the *Chemin de Fer du Midi* and the *Chemin de Fer de l' Ouest*, and others, for bridges with spans from 100 to 264 feet.

The tubular girder, instead of being "nothing but two plain girders placed side by "side," is *two plain girders, with all their elements of strength so deteriorated by bad disposition of the material, that for the same efficiency they must be little short of double the weight of plain girders for spans of* 240 *feet.*

The experience on which the construction of plain girders depends is very sound and extensive; that upon which such thin-topped tubes are constructed is very circumscribed, —there is but *one example extant*,—and to my mind it is unsatisfactory.

To cover, in a perfectly efficient manner, a pair of Warren girders or a pair of plain girders, would, *including the top cross bracing*, require only 1½ cwt. of iron per foot run.

MR. CLARK'S REPORT.

13. I am confident therefore, that no other girders of the same depth, strength, and rigidity can be substituted with any important saving of weight, while *boiler-plate* work is invariably less costly than the forged work requisite for other forms of girders, and although by placing the Warren girder beneath the roadway, which would be here very objectionable, on account of the decreased headway, I have no doubt an efficient Warren bridge might be constructed for the span of 250 feet, yet it would neither be economical nor practical to apply that principle of construction to the large span of 330 feet, without entirely modifying the details of construction at present in use.

My observations on Paragraph 13 are put with those to No. 10.

14. Taking however Mr. Liddell's figures, no advantage, as regards cost, is shown by that gentleman, if we correct an oversight that he has evidently fallen into in his tabular statement of comparative weights, where he has taken *two* tubes as requisite for a single line, and consequently estimated the tube as double its actual weight.

15. That gentleman estimates the weight of two plain girders for a span of 220 feet to be about 150 tons, this, I believe, to be under the requisite weight, but it is evident that if these two plain girders are simply placed side by side, they then form the tube, while Mr. Liddell estimates the weight of the tube at 254 tons. This is evidently a serious mistake, and doubtless arises as follows.

16. In the remarks preceding his table, that gentleman states, that in practice it is found necessary to make tubular girders even 70 per cent. heavier than his estimated weight. Now the only existing independent tube of this span is the Aire Bridge, which must therefore be the girder he is referring to in this remark; while this is also evident from the fact that 250 tons, the 70 per cent. which he states is added in practice gives 431 tons, which is the weight estimated by Mr. Liddell, but is in reality twice the weight of that structure reduced to a span of 220 feet. The error has doubtless, therefore, inadvertently arisen from taking two tubes for comparison with two girders, whereas a single tube forms the complete line.

When Mr. Clark undertakes to correct, what he is pleased to term "an oversight," it would become him to be careful in his assumptions and arguments.

In comparing, as I have done, for a single way of 220 feet span, plain girders of 150 tons with a tube of 254 tons, I have allowed for the tube rather greater weight, in proportion to the span, than that stated to be the weight of a tube of the Victoria Bridge of 242 feet span. The weight of a single tube of the Victoria Bridge reduced for a 220 feet span, would be 228 tons supposing the depths to be the same. Now, on Mr. Clark's hypothesis of an "over-"sight," and in order to "correct" the error, the weight of the plain girders must be doubled [making 300 tons to compare with 228]; *i.e.* the two plain girders would be heavier than the tube by one-third of its weight, a conclusion which is evidently absurd.

In Paragraph 16, Mr. Clark is pleased, moreover, to put forward an ingenious calculation to account for my "oversight," which is as devoid of foundation as the assertion of the oversight itself. He says that I estimate a single span of the Aire Bridge at 431 tons weight, "*which is in reality twice the weight* "*of that structure reduced to a span of 220 feet.*" i. e. that the single way of the Aire bridge reduced to a span of 220 feet is only 215½ tons. But Mr. Clark states the weight of the Aire Bridge to be 235 tons for a span of 225 feet, (see Paragraph 11) and this reduced to a span of 220 feet would give 224½ tons [instead of 215½] for a single line, or 449 tons for a double line, and it requires an addition of 77 per cent.

to my figures (254 tons) to make 449; so that the array of figures, by which the 70 per cent. is made to fit for the purpose of bearing out the assertion of an oversight on my part, is a mere juggle. But giving him the benefit of the supposition that the weight stated (431 tons) is "twice the weight of the Aire Bridge reduced to a span of 220 feet," how does it really affect the case? why, only so, that the comparison will be of 150 tons of plain girders against 215½ of a tube instead of 254. In fact, however, the actual weight of single way of the Aire Bridge, reduced to a span of 220 feet and *increased to the width of* 16 feet, which are the dimensions on which my table is based, is 257 tons, almost exactly the weight stated in the table and arrived at by totally independent calculation.

Mr. Clark certainly does say that "he believes 150 tons to be under the requisite "weight for plain girders," but he nowhere ventures to state what his estimate for them would be, and I think it hardly possible that any one reading this cautiously-expressed sentence would imagine that he meant by these words to express so wide a margin as lies between even 150 and 215½, much less that between 150 and 254, or rather 257.

It is not, however, a difference of calculation of weights, to the amount of 10 or 20 or even 40 tons in a span, that affects the question now before us, but one of far greater importance—*the difference between bridges calculated to cost a million and a half, and half a million respectively.* And surely it is only diverting attention from this main point, to embarrass the subject with the examination of unimportant discrepancies, where absolute accuracy of comparison was not only not pretended to, but from want of exact information was impossible.

Although the tubes I have calculated are so nearly the same weight as that of the Aire Bridge which I have shown (Paragraph 12) to be of dimensions giving a very low factor of safety; yet, by a disposition of the iron to obtain the greatest strength, I have designed a tube of only 254 tons for comparison, *on equal terms as regards the factor of safety*, with plain girders of 150 tons and Warren girders of 142 tons.

But, as I stated in my first Report, "such tubes cannot be recommended in practice." Five thousand pounds are said to have been expended on experiments to ascertain the best form of tubes for the Britannia and Conway Bridges; and what I have called the "Britannia type" was adopted by Mr. Stephenson in preference to that used in the Aire Bridge. And imagining that so monumental a structure as the Victoria Bridge,—a structure which was to cost so vast a sum of money, would be in the strongest possible form; relying also upon Mr. Stephenson's Report "To the Directors of the Grand Trunk Rail-"way of Canada" of May 2nd, 1854, in which he "unhesitatingly recommended the adop-"tion of a tubular bridge *similar in all essential particulars* to that of the Britannia over "the Menai Straits," I made the calculation of what *additional weight* was required to carry out the principle of the tubes of that bridge and the Conway Bridge, and ascertained it to be 70 per cent. more than I had estimated from my design for a 220 feet span.

I have again examined my calculations, based on the formulæ and data in pages193—748, 761, also pages 585, 586 of Mr. Clark's book, and adopting the principle laid down in page 573, where it is stated that in the Britannia small tubes no plates were less than half an inch thick, "*for it was not considered prudent to expose a thinner plate to the action "of time and weather*," I find that these calculations are correct. Indeed, my statement of its appearing necessary to add 70 per cent. to the weights in the table is merely an affirmation of what I had ascertained to have been carried out in practice in the bridges referred to by Mr. Stephenson, the details of construction of which are very fully reported by Mr. Clark. No other engineer has erected a tube, and these are the only examples of that kind of tube.

MR. CLARK'S REPORT.

17. It will moreover be seen that the total length given by Mr. Liddell is considerably understated, the actual length of the bridge being 6576 feet, instead of 6042 feet as taken in estimate.

I have not given in my Report, or taken in my Estimate, a length of 6042 feet. I took the measurement of the bridge from a published drawing, in which it is stated that "the total length of tube" is "6138 feet;"

and finding this length to agree nearly with the length produced by multiplying the number of spans to which the bridge has been reduced, (as I had been informed,) by the dimensions of the spans and piers given in the specification, I concluded that I was right. It is not wonderful, where the dimensions are varied to the extent they have been since the contract was let, that I should not be absolutely correct.

In the contract the specification is for 32 spans of 220 feet, 1 span of 330 feet, and 32 piers, being a total length between the abutments of 7978 feet, which is now reduced to 6576, a reduction of 1402 feet in length, or more than one-sixth of the whole, *without any reduction of the estimate.*

If the difference in length is corrected, however, it will add about £11,000 to my estimate of the superstructure, making the total amount £134,000 instead of £123,000.

MR. CLARK'S REPORT.

18. But a much more inexplicable error occurs in that gentleman's estimate of the weight of the tube for the span of 330 feet, for, even assuming his erroneous estimate for a tube of 220 feet span to be correct, the weight of the 330 feet span derived from these figures would only be 570 tons, whereas Mr. Liddell has taken it at 923 tons, to which he states 70 per cent. is to be added, making 1569 tons! or nearly four times the weight actually necessary.

I nowhere state that 70 per cent. is to be added to the weight of a tube of 330 feet span,—the width of the middle opening of the Victoria Bridge. The whole course of my argument is counter to such a statement. I neither made it nor is it to be inferred from my Report that I intended it. In fact, I distinctly limited my statement to tubes of 220 feet span. In tubes of spans of 330 feet, the distribution of the iron is such that the quantity of ineffective iron in the sides is not great compared to the quantity ineffective in smaller tubes, and the distribution of the iron in the top and bottom flanges has the same relative advantages.

As regards Mr. Clark's calculation, that the weight of the tube of 254 tons would be increased only to 570 tons by an increase of span to 330 feet, it would be correct *if* the depth of the girder were kept in the same proportion to the span in both; but it appears from the specification that the depth of the small-span girders is 20 feet, and of the centre-span 25 feet.

Now the proportional weights of two girders of 220 and 330 feet span and 20 and 25 feet depth respectively, the former being 254 tons, would be

220 feet span = 254 tons;
330 ,, ,, = 684 ,, ;—

If Mr. Clark's statement was correct, the depth of the centre span would be 30 feet.

On the principle here adopted, *i.e.* of constant ratios of depths to spans, the weight of a span of 330 feet, as compared with the small spans of the Victoria Bridge (242 feet weighing 275 tons) would be 539 tons, without any extra allowance for the necessary larger bearing on the piers and the cast-iron bed plates, &c., necessary for the supports.

As compared with the Aire Bridge reduced to corresponding dimensions with the tube of 254 tons (as shown in answer to Paragraph 16) the weight would be 578 tons, so that in no example adduced by Mr. Clark can he make the weight, on his own principle of calculation, *so little as one-third* of 1569 tons instead of "nearly one-fourth" as he states.

For my table of comparisons, however, I took the girders as the same depth throughout. For the purpose of *comparison* it is quite immaterial whether they are taken so or on varied proportions if all are treated alike, and on this principle of calculation the weight of a tube for a span of 330 feet would be 895 tons. The difference between 895 tons and 923 is for the quantity of iron in bed plates, &c., beyond what is required in the smaller spans.

MR. CLARK'S REPORT.

19. I am therefore confidently of opinion that as regards efficiency, or cost, and inde-

As regards "efficiency," there has been no question raised. As regards "cost" Mr. Clark pendent of the other weighty considerations I have mentioned, no advantage of any importance can be obtained by any change in the form of girder adopted by Mr. Robert Stephenson.

20. I have arrived at these conclusions, apart entirely from the consideration that contracts, involving great loss if they are broken through, have been already entered into for these girders, and some progress made in their construction.

I remain,

Gentlemen,

Your obedient Servant,

(Signed) EDWIN CLARK.

Dec. 12*th*, 1855.

has evaded the question. As regards "other "weighty considerations," the only tangible objections to be found throughout Mr. Clark's Report are—the alleged difficulty of guarding against danger to a Warren girder by a train running off the line, and the want of shelter to the roadway. If these are "weighty consider- "ations" in such a case, I know not what consideration ought to be called puerile. Answers have been given to these objections opposite Paragraphs 10 and 12.

I will add nothing further to what is already tedious.

I am, Sir, &c. &c.

CHARLES LIDDELL.

March 1856.

GRAND TRUNK RAILWAY OF CANADA

VICTORIA BRIDGE, MONTREAL.

MR. ROSS'S REPORT

AND MR. LIDDELL'S REPLY.

To R. Stephenson, Esq., M.P., &c. &c. &c.

VICTORIA BRIDGE.

Montreal,
30th Nov., 1855.

MY DEAR SIR,

1. Your favour of 2nd inst. in reference to the Victoria Bridge I have received, and in reply, I have to observe that the question of economy in the masonry is one which in every point of view had received from me the most mature consideration that my acquaintance with the subject and the peculiarities incident to this locality pointed out as necessary, and I shall endeavour to make clear to you, as shortly as I can, how far my opinions upon this subject are verified by the experience we have already had, both as regards the form and character of the design for efficiently answering its purposes, as well as the disposition of its leading features (*stone and iron*) with the view to the utmost practicable economy.

2. The various points referred to in your letter I shall take up in the order in which they occur.

3. First,—The abutments. These it appears are considered unnecessarily large, and more costly than the tubes, and it is suggested that they may be reduced by making openings in, or by shortening them. These abutments are not in reality what upon paper they appear to be—a solid mass

To R. McCalmont, Esq., one of the Directors of the Grand Trunk Railway of Canada.

VICTORIA BRIDGE.

SIR,

Having already entered very fully into almost every point of the objections made to my suggestions, respecting the construction of this work, in my replies to the Reports of Mr. Stephenson, Mr. Brunel, and Mr. Clark, and finding that Mr. Ross's letter appears to be a reply to the savings suggested by Mr. Brunel, rather than to anything put forward by me, I shall be able to confine my remarks on it to very narrow limits; and I must refer you to the replies mentioned for any point of detail on which explanation may seem wanting.

Mr. Ross's Report has been of use to me, by giving me a clue to the *prices* and *quantities* I have used in my examination of the estimated cost of masonry and under-water work, in my replies to Mr. Stephenson's and Mr. Brunel's views on this most important point. The prices and quantities derived from Mr. Ross's statements I do not pretend to put forward as quite correct, but they are sufficiently accurate for the uses I have made of them.

The dimensions here given are not very exactly defined, but sufficiently so to give an approximation to the quantity of masonry proposed to be put in the abutments. I reckon the whole amount to be about 450,000 cubic feet, and have taken it at this in calculations made elsewhere in my replies.

MR. ROSS'S REPORT.

of masonry. *They are hollow*, each having eight openings or cells 48 feet in length and 24 feet in width, separated by cross walls 5 feet in thickness. The flank wall on the down-stream side rising nearly perpendicular is 7 feet in thickness, and that on the up-stream side is sloping from its foundation upwards to an angle of 45°; its thickness is 12 feet, and presents a smooth surface to facilitate the operations of the ice, on which account its form had thus been determined; and to insure greater resistance to the pressure of the ice the cells are filled up with earth, stone, and, gravel, so that one solid mass is thus obtained at a moderate cost. The subjoined plan and section of this work will better explain its form and proportions.

REPLY.

This mass of masonry does, however, appear to me to be excessive in quantity; and if it be intended to make it ashlar throughout, at 2*s*. 6*d*. per cube foot, very *extravagant* in point of expense.

4. The idea of introducing any other description into the abutments than those described is altogether inadmissible; passages through it, where ice could accumulate, would ensure its inevitable destruction upon the first hydraulic pressure it had to encounter.

5. I have observed in this immediate neighbourhood the effects of swift currents created by obstructions in the river on a recently-formed causeway ; constructed of timber, connecting a small island below the bridge with the shore, having openings about 12 feet in width at intervals of about 30 feet.

6. In the autumn of last year these openings were partly covered by heavy timber and planking, strongly secured by iron work, and the consequence has been that during last winter, the first crush of the ice in forcing its passage through destroyed every timber, plank, and bolt that opposed it; having got under, it was immediately blocked up, and the pressure of water still forcing its way, the jam became at length so tight that it burst with an explosion.

I have no idea what proposal this refers to. It does not appear to bear upon any suggestion advanced in my Report. It seems to me to prove that though the superstructure of the intervals in the causeway were burst up by their own flotation and that of the ice jammed under them, as might have been expected, yet the lengths of causeway were in no way affected by the crush of the ice; thus presenting an instance in which a timber causeway resisted heavy ice in "swift currents." And it certainly does not "prove" anything as to any other description of work; it can prove nothing more than that "heavy timber planking" over the openings in a causeway is "altogether inadmissible" for the abutments.

7. It is stated that the length of the abutments is unnecessary and greatly in excess; upon paper this may seem so, and a recollection of the idea conveyed to my own mind subsequent to the earlier considerations of this subject which led me to the conclusion of adopting their dimensions, prevents my attaching so much importance

As the embankments in question are only in from 1 to 3½ feet water during summer, and the rising of the waters is caused by its being dammed back by the formation of an ice barrier below; and as the ice is said to "ground" over all this expanse of shoal, I cannot understand how "the current over-charged with ice, sweeping its way along the front of the embankto such a view as I otherwise might do. You will recollect that the bridge is approached from the north shore by an embankment 1200 feet, and from the south shore 800 feet in length, the river being thereby narrowed to this extent; the waters thus far embayed, have now to find their way through the bridge, and the current overcharged with ice sweeping its way along the front of the embankment into the nearest passage, attains ere reaching it a velocity which nothing but the most substantial masonry could resist.

8. This, it will be seen bears on the question of the length to which such masonry should extend, and I am *more than ever convinced* that I have not exceeded the limits which prudence dictates, *thus confirming* my original view in reference to this particular and very important point. I think you will readily admit that I have given ample reasons in justification of the extent of the abutments, bearing in mind that the form of *construction* contributes more to their apparent magnitude than a cursory glance at their appearance upon paper would justify one in supposing; and as to their cost, it is not to be supposed that the large and costly preparations made in machinery and other appliances for carrying on these works, could in fairness be allowed to remain altogether unaccounted for until redeemed by the slow progress of each succeeding pier. You will remember the consideration given to this subject at the time the contract details were under discussion, and I believe the most equitable adjustment was then arrived at for the mutual protection of both parties to the contract.

9. The two abutments have been proceeded with, and both have had their foundations (the most expensive parts) completed. The northern abutment commenced last year is finished to the level of 8 feet above summer-water level, and its extreme end for about 60 feet in length is raised to the height of 20 feet above that level, forming a slope to the embanked approach, which is (through its extreme length of 1200 feet) brought up to nearly the same level, and secured, I hope, for all time.

10. The south abutment is also finished to the height of 3 feet above summer-water level, and secured for the winter. This

"ment," can attain "a velocity which nothing "but the most substantial masonry could "resist."

Upon this subject, Mr. Keefer says, p. 37 of his Report,—"The real difficulty with the "St. Lawrence, opposite Point St. Charles "[the site of the bridge]—the point where a "jam is most feared—*seems to be a superabundance of room.* The great breadth of the "river, and the diminished current, when the "water is high, permit the ice to ground on "these shoals; whereas, if the channel were "confined somewhat as it is in summer, the "water would maintain its passage, as it does "*at the head of every rapid* in the St. Lawrence "and Ottowa."

The substantial masonry, it would then appear, might be *confined* to the face of the abutment and to a short wing wall; and thus the process by which Mr. Ross confirms "his "original view in reference to this particular "and very important point," is, to my mind, anything but an "ample reason in justification "of the extent of abutments."

Moreover, as the embankment and abutments are at right angles to the stream, and formed so as to allow the ice to slide up them, it is quite evident that it is only where the ice gets into the current passing through the bridge, that it can have had any such action as Mr. Ross speculates upon, and so it appears to me that an exaggerated notion of *probable* effects has led to great extravagance in works to provide against them.

But then "as to their cost." Mr. Ross seems conscious that the estimated sum of £200,000 for the work of such dimensions, even executed in the most costly way, is startling. He therefore debits the *piers* with part of it, on account "of the large and costly preparations made in "machinery, and other appliances for carrying "on these works." It will, however, presently be shown, that the piers have enough to answer for without this sop from the abutments; and so, for the present, the £200,000 must be considered as paid for the abutments and embankments until we see reasons for placing it to some other account.

MR. ROSS'S REPORT.	REPLY.
abutment would have been nearly completed this summer but for the unexpected depth of deposit, gravel, sand, and large boulders we had to clean out before reaching the rock, amounting to 8 feet in depth, more than we anticipated or had any reason to expect from our previous examination and soundings. Next summer, I hope, will enable us to finish this part of the structure; all the stone for which is prepared and now upon the adjoining land, covering several acres to the extent of 3 and 4 blocks in depth.	
11. Next as to the piers, it is alleged that their depth is far greater than necessary; this, it appears, is on the assumption that they are 39 feet deep in the shaft; a reference to the accompanying diagram of Pier No. 5 disproves this statement, the depth you will perceive is only 33 feet. The tube requires a bearing surface of 21 feet, we have therefore only 6 feet on either side; the idea of any reduction, therefore, at once falls to the ground, and even if such were admissible, your estimate of the value of such reduction is erroneous; this you will at once see, when you consider that placing the first foundation stone in any one of these piers, requires an outlay of from 55 to 60 per cent. of the total cost of each pier; there is therefore only about two shillings and sixpence a cubic foot left for the remainder, and if any reduction had to be made, this rate would determine its just value.	This appears to be in answer to a suggestion of Mr. Brunel (Paragraph 54 of his Report) or one adopted by him: but the saving by this proposed reduction of the piers seems to be almost eliminated by the statement of Mr. Ross. At all events, the whole amount to be saved cannot exceed £27,000 or thereabouts, at Mr. Ross's price of 2*s.* 6*d.* per cube foot.
12. It is true, that in the arrangement for payments on account, a uniform distribution of the cost of each completed pier has reference to the masonry alone, a reasonable distribution being made between the above and below water level, the latter being paid for at a rate allowing of some remuneration for the previous outlay; at the same time, reserving for that above such level, a sufficiently ample allowance to ensure its completion.	
13. The two large centre piers being alluded to, I would merely remark in reference to these, that they were designed as distinctive objects, marking the navigable channel, that no reasonable grounds for complaint on this account could be alleged, their ample	In Paragraph 13 there is proposed a saving of £12,000 by reducing the breadth of the large centre piers by one-fourth. But is this saving to accrue to the Shareholders? No; the depth of foundation is found greatly to exceed expectation, and Mr. Ross proposes "to treat this

dimensions also serve as a necessary protection against accidents incident to every navigation where it is possible to run against any obstruction existing within reach of reckless and unguarded steering; although these reasons cannot be altogether overlooked, it has long since occurred, however, to me, that in breadth they might be diminished about 25 per cent., and such diminution I had in contemplation, provided any further observation in reference to the ice did not deter me from such a course: in regard to this, I have further to observe, that these piers are in deep water where the ice does not ground, and where the pressure, in consequence, requires greater power of resistance; any diminution in these piers which I might, according to my own views of the case, be induced to adopt, I should treat as *some compensation* (*as far as it went*) for the increased depth of the foundations generally, which are found greatly to exceed our expectations. Although every pains had been taken to ascertain what these would be, we find in the progress of the works that the bed of the river, in most parts, is formed of large boulders, heaped together in large masses, the interstices being filled up with gravel, sand, and mud, in many instances forming a hard, concreted mass, and in others the reverse, beds of quicksand and mud being as frequent as any other. Three thousand tons of such material we had to clean out of the foundation of No. 5 Pier, as you will see indicated on the diagram already referred to, below the level at which our previous examination would lead us to expect the foundation we sought; one of the boulders taken out by admeasurement would weigh about eleven tons; mastes of three and four tons are strewed as thickly as pebbles on the seashore. The shallows in the river are evidently formed by these deposits, and I have no doubt, in every instance where these shallows appear, we shall have to encounter similar difficulties. In Pier No. 3, we found a depth of 4 feet at one end, and 9 feet at the other to clear out, ere we reached the rock. These unlooked-for *contingents* have materially retarded our season's operations, otherwise we should by this time have Nos. 3, 5, and 6 nearly completed, as it turns we require another season to accomplish this; and here I think it would be well to observe that, up to No. 6 inclusive, the expensive outlays have already been incurred, the dams have been completed, and in all, except No. 4, the water has been pumped out, and the machinery erected for setting the stones, but No. 5 is the only one where we have been able to complete any masonry, owing to the unlooked-for causes I have already described.

" diminutionin the piers as some compensation " (as far as it goes)" for the increased depth of foundations. It is thus clearly intimated that compensation is to be made to the Contractors for the depth of foundations in excess of what they were specified to be. I point this out as the reason for my having assumed, throughout my calculations of the masonry in the piers, that the foundations are as specified in the Contract for the sum of £1,400,000. If the piers are to go deeper, it is to be inferred from the Contract, as well as from this avowal of Mr. Ross, that compensation will have to be made for the extra cost of these "*contingents*," to the amount, if necessary, of £100,000; and I consider myself justified therefore in dealing with the case as I have done, in calculations relating to this point.

14. These contingents rendered it impossible to complete one pier in less than two seasons, though, as in the case of No. 1 Pier, where no such unlooked-for difficulty arose, the whole was begun and completely finished in one season; thus saving the removal and re-erection of all the machinery and appliances necessary, besides the reparation of such damages as the winter operations may produce.

The fact stated in Paragraph 14 is important as bearing on the question of the *time required* to complete the work. This, to my mind, is a point of vast importance; and therefore I proposed a system of concrete foundations peculiarly applicable to the situation of the Victoria Bridge, and which, besides its economy, has incomparable advantages as regards rapidity of execution.

15. With regard to the ice-breakers, which is the next question referred to, the comparative cost between the detached, or ordinary ice-breakers, and those attached to the piers, as in the present design, this question is easily disposed of. You will remember three years

Paragraph 16 gives a general description of the " large shoes of crib-work surrounding the " base of each pier," proposed by Mr. Keefer; but Mr. Ross omits to mention " that the appli- " cation of this crib-work to the *sides* of the " piers was made [in Mr. Keefer's bridge] with

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ago, when considering the mode of construction to be adopted, that in every point of view the plan of detached ice-breakers was found to be so far deficient in merit, both as to cost and efficiency, as to lead at once to its total abandonment; I shall endeavour, in as few words as I can, to recall to your recollection the reasons which led to this conclusion.

16. I was fully informed at the time of the mode described in the Report you refer to, which contemplated the planting of very large cribs, covering an area of one quarter of an acre each, and leaving a clear passage between them of 240 feet; these islands (as they are called) of timber and stone were designed to have a rectangular well, left open in their middle, out of which would rise the solid masonry towers, supporting the weight of the superstructure; this inclosure of solid crib-work was intended to surround the masonry, yet detached from it, and receive the shock and grinding of the ice, yielding to a certain extent by its elasticity, without communicating the shock to the masonry; and if damaged, could be replaced with facility: they were designed also to reach the height of 30 feet above summer water-level, this being necessary on account of the great height which the ice generally attains; the up-stream face was intended to be sloped, one of the primary requisites essential to the effectual performance of its duties. This mode of construction, you will readily perceive, comprehends very formidable dimensions, and it is only partially true, as stated, that it could be made available as serving as a coffer dam for getting in the foundations of the masonry.

REPLY.

" particular reference to *preventing the ice* " *from reaching the spring of the arches*, which " would be the lowest and most exposed part " of the superstructure:" and that, as " in the " Victoria Bridge the roadway *is far above* " *that to which the ice ever reaches.*" Mr. Keefer would probably have omitted the crib-work at the sides of the piers, and thus have reduced the quarter-acre to proportions not much in excess of the solid ashlar work now proposed.

I have spoken at some length on this point in my reply to Mr. Stephenson's Report, and it is needless to go further into the question here.

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17. The usual precautionary measures of clay puddle would still be necessary to block out the water; and having already given you a description of the nature of the foundations we have to deal with, I need not now recount the difficulties which under such circumstances would present themselves.

18. You will also perceive that these quarter-acre islands would occupy 25 *per cent.* of the water breadth of the river, one of the most prominent reasons for their abandonment when first considered.

19. The space occupied by the piers, as being *executed*, is only *seven per cent.*; this

REPLY.

Mr. Keefer proposed that the "shoes" should serve during the construction of the bridge as *coffer-dams* "*composed of the cheapest mate-* "*rials.*" Mr. Ross, in Paragraph 17, reminds us that from "the description he has given of " the nature of the foundations to be dealt with, " he need not recount the difficulties which, " under such circumstances, would present " themselves" to making use of the crib-work shoes as coffer-dams.

In Paragraph 19, Mr. Ross says, "*our* " *present dams* are generally about 5 to 6 " feet above summer-water level, and *cover* " *an area corresponding nearly with that des-* " *cribed; latterly we have constructed them* " *similar to these, filling the external barrier*

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is a most important feature in the relative merits of the two modes of construction. Our present dams are generally about 5 to 6 ft. above summer water level, and cover an area corresponding nearly with that described; latterly we have constructed them similar to these, filling the external barrier with stone and the inner with clay, necessary to render them water tight: the force of the current is necessarily increased, and the natural consequence, owing to the fragile nature of the deposits forming the bed of the river, is to undermine rapidly the part exposed to the action of the waters, thus rendering them more insecure every day, and requiring an immense amount of expensive labour for their protection. I mention these facts, which our experience has brought to light, as an additional reason why we should not resort to such an objectionable mode of construction as to their cost. Assuming the existing dams to serve the purpose, as far as they go, we should have to raise them to the height of 25 ft. above their present level, and to add as much to their length up stream as the necessary slope at that end would require.

20. These ponderous erections would measure about 350 ft. in circumference, and from their foundations to the top would measure 40 feet—25 feet above the present dams: the walls thus formed of timber and stone would be about 20 feet in thickness: the cubic contents of this mass above the level of the present dams would be 200,000 feet, and the masonry saved thereby would be exactly 20,000 feet, which is all that is required to form the stone cut-water or ice-breaker attached to the piers. I believe no man capable of instituting a comparison, and with *these facts before him*, will for one moment hesitate in giving the preference to the attached ice-breakers as now being executed. Their more permanent efficiency, founded in every instance upon the solid rock, placed beyond the reach of any influence exerted by the currents, and their incomparable pre-eminence in relation to the space they occupy, together with their immunity from accidents (not requiring

REPLY.

" [of wood cribs] *with stone and the inner with " clay, necessary to render them water-tight.*"

And thus it appears that in the course of writing the short Paragraph 18, the difficulties which " the large boulders heaped together, " forming the bed of the river in most parts, " the interstices filled with gravel, sand, and " mud " presented, and which he thought it needless to " recount," have vanished, and his present dams are similar to Mr. Keefer's shoes, and have been rendered water-tight by the usual simple means of clay-puddle filled into the inner cribs.

The assertion in Paragraph 18 that " these " quarter-acre islands would occupy 25 *per " cent.* of the water breadth of the river"—must not, for Mr. Keefer's sake, be passed unnoticed. Mr. Keefer proposed 22 clear spans of 240 feet, with one of 400 feet.

The Victoria Bridge is to consist of 24 spans of 242 feet clear, and one of 330 feet. The difference in *water-way* then of the two designs is only 458 feet; or, the water-way between the " islands" was 7 per cent. less than between the proposed piers.

Now, considering that since the contract for the Victoria Bridge was made, a reduction in the water-way has been made to the extent of 1332 feet, or three times the difference between the waterway proposed by Mr. Keefer, and that now adopted, this allusion to the proportion occupied by the " islands" does not bear examination.

There are two points in this paragraph calling for remark.

The quantity of " 20,000 cubic feet exactly," in the part of the piers forming the ice-breakers, gave me a means of confirming the dimensions on which my calculations for the estimates given elsewhere are founded.

The sentence—" and lastly, though not least, " their evident economy in the first cost, places " them immeasurably in the scale of merit " beyond the temporary mode suggested as the " substitute, on grounds which I think I have " made clear, are altogether untenable."

If I permitted myself to indulge in mere verbal criticism, I might rely on Mr. Ross's having placed the ashlar ice-breakers immeasurably, in the scale of merit, beyond the mode suggested, *on grounds which he has made clear, are altogether untenable.* But the "*economy in "first cost*" being mentioned, it is most important to remark, that " to place a stone of the pro- " posed ashlar ice-breakers in any one of the " piers, requires an outlay of 55 to 60 per " cent. of the total cost of each." And that

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repairs of any kind)—a light in which the other mode can never be regarded—and lastly, although not least, their evident economy in the first cost, places them immeasurably in the scale of merit beyond the temporary mode suggested as the substitute, on ground which I think I have made clear, are altogether untenable.

21. I believe I have now gone through the various points referred to in your letter, to which you called my particular attention, and hope my explanations of the existing state of our operations will satisfy you that we have pursued the right course in the designing and prosecution of this work.

REPLY.

thus about £480,000 has to be spent in preparation for putting in the proposed ice-breakers. Whereas, Mr. Keefer's estimate for the whole bridge, 30 feet higher than the Victoria Bridge and as long, is only £320,000, of which the superstructure was to cost £115,000, leaving £205,000 as the total estimated *first cost* of Mr. Keefer's *embankments*, *abutments*, "*shoes*" *and piers*—one-third of which, perhaps, may be taken for the cost of the shoes, or about £70,000 to compare with £530,000, the money involved in putting in the "permanent "ice-breakers now in progress."

22. The only observation I would desire to add, would be in reference to the reasons which led to the adoption of 242 feet as the span best suited in point of economy to fill up the space we had to deal with, although the masonry bears a larger proportion to the entire cost than a due regard to economy would appear to warrant, we find that to diminish the number of piers by one only, one each side of the centre span, would in this item save 9 per cent., or about £50,000; whereas the spans would be thereby increased exactly 10 per cent., which would add 20 per cent. to the cost of the superstructure, as the proportion due to the sectional area of the tubes by this increase, which would amount to about £80,000.

Mr. Ross's calculation of the size of the spans in relation to the piers is really amusing.

As positively as we can demonstrate, that to divide a given line into two parts, such that their products may be a maximum, the two parts must be equal, so positively can it be shown that, until the cost of the superstructure equals the cost of the piers, the most economical proportion has not been arrived at. Mr. Ross, however, proves to his own satisfaction, that although the piers are estimated to cost £800,000, and the superstructure only £400,000, we cannot increase the spans and diminish the number of piers without a loss!

Mr. Brunel has given a juster estimate of this, as it is no doubt founded on the relative amounts of superstructure and piers given him.

There is no doubt, however, that if the piers were at anything like reasonable rates, and supposing the foundations to be as specified, the size of the span fixed is nearly of proper proportion. If, however, the cost of the piers is to be increased, as Mr. Ross leads me to suppose they may be, by what he says in Paragraph 13, and if the cost of the piers has to be added to, by charging to them a part of the sum said to be charged to abutments to cover the costly preparations necessary for erecting the piers, then the proportions are still further wrong than they appear to be, when the relative cost of superstructure and piers is as £400,000 to £800,000, *i. e.* one to two.

To give an air of proof to his opinion, Mr. Ross calculates the increased cost of the superstructure on the assumption that *the depth* of the girders would be the same whatever the span. By merely proportioning the depth to the span in the ratio adopted for the centre span of 330 feet, viz. 25 feet depth for this span, Mr. Ross's proof of his having the most economical span would have gone clean *against* him. Mr. Clark, to suit *his* purpose, assumed the depth to bear a constant proportion to the span, making the depth of the 330 feet span 30 feet.

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23. The centre span is of course an exception, the reasons which determined this were local, both as to height and width, and could not be departed from.

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24. You will bear in mind, that a clear height of 60 feet is required at the navigable channel, a descent of 1 in 132 brings us to 36 feet above such level at the abutments; the ice in December last year rose to within 8 feet of this point, as you will see indicated on the diagram of No. 5 pier, and some hours before it reached this point it made a clean sweep of all our dams and temporary works surrounding the pier and abutments, although filled with stone and protected in all possible ways by sloped fronts on the up-stream side. In many statements which have been put forward, great stress has been laid upon the fact of some one or two experimental crib ice-breakers, fixed some short distance above the site of the bridge, withstanding the shock of several winter operations; I have seen these, and I have observed the cause of their standing the test to be entirely owing to the fact of their being only some two or three feet above low-water level and in shallow water, so that as soon as the waters rise they are covered over, and so completely loaded with the accumulating masses of ice, that they are *firmly held in their places*; their insignificance alone saving them from destruction; time, *however, has swept even these* away. and they are nowhere to be found.

REPLY.

The facts here stated by Mr. Ross as to "some one or two experimental crib ice-" breakers are" curious.

Mr. Ross has "*seen these.*" He "has ob-" served the *cause of their standing the test.*" It is therefore to be inferred that they do stand the test; it is true it is only "by reason of their insignificance," but still *they do stand* and are held firmly in their places *by the ice.* But then, he says, *time, however, has swept even these away, and they are nowhere to be found;* therefore they have not stood the test well. Mr. Ross may know what he means; I am sure I do not, and so I will not speculate further upon this strange account.

I am,
Yours, &c.
CHARLES LIDDELL.

25. In conclusion, I feel it my duty to state, that if after having duly considered the subject, you still think a saving can be effected in any part of the masonry, beyond what I have pointed out as possible in the centre piers, I shall make it my aim to carry it out to the fullest extent practicable.

And I am, dear Sir,
Yours sincerely,
(Signed) ALEX. M. ROSS.

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