VIII. *Experiments to determine the effect of Impact, Vibratory Action, and long-continued Changes of Load on Wrought-Iron Girders.*

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A question of great importance to science and the security of life and property has been left in abeyance for a number of years,—namely, to determine by direct experiment to what extent vibratory action, accompanied by alternate severe strains, affects the cohesive force of bodies. It is immaterial whether the body be crystalline, homogeneous, or elongated into fibre, such as cast or wrought iron; the question to be solved is, how long will a body of this description sustain a series of strains produced by impact (or the repeated application of a given force) before it breaks? In the case of bridges and girders, this is a subject on which no reliable information has yet been given which may be considered as a safe measure of strength for the guidance of the architect and engineer. It is true that regulations have been established by the Lords Commissioners for Trade; but they appear to have had their origin on limited data, and in cases where the material and workmanship are good they may be relied upon as sufficient for the public safety. What, however, is wanted is experimental data to enable the engineer to comply satisfactorily with the conditions of the Board of Trade, and cordially to unite with the Government in affording ample security to constructions in cases where the lives of the public are at stake.

To remove all doubts on this question, I have been enabled, through the liberality and at the request of the Board of Trade, to undertake a series of experiments to determine, or to endeavour to ascertain, whether a continuous change of load, and the strains produced by those changes, have any effect (and to what extent) upon the ultimate strength of the structure,—or, in other words, to ascertain the rate of endurance the material is able to sustain under these trials.

To comply with this request, a wrought-iron beam was constructed, representing the girders of a bridge of questionable strength, to be employed to determine, experimentally, the strength and durability of such a structure. This beam was made of the ordinary construction, of moderately good, but not the best quality of iron, and subjected to vibration and a perpetual change of load until the cohesive powers of the material were destroyed.

Of the resisting-powers of material under the severe treatment of a continuous change of strain, such as that which the axles of carriages and locomotive engines undergo when rolling over iron-jointed rails and rough roads, we are very imperfectly informed.

Few facts are known, and very few experiments have been made bearing directly on the solution of this question. It has been assumed, probably not without reason, that wrought iron of the best and toughest quality assumes a crystalline structure when subjected to long and continuous vibration—that its cohesive powers are much deteriorated, and it becomes brittle, and liable to break with a force considerably less than that to which it had been previously subjected. This is not improbable; but we are apparently yet ignorant of the causes of this change, and the precise conditions under which it occurs.

In the year 1837 I instituted a long series of experiments to determine an important quality in the strength of materials, viz. the powers of crystalline bodies to sustain pressure for an indefinite period of time, and to ascertain whether cast iron, when subjected by a given weight to long-continued transverse strain, would or would not be subject to fracture.

It appears that former writers on the transverse strength of materials had come to the conclusion that the bearing-powers of cast iron were confined within the limits of that force which would produce a permanent set, and that it would be unsafe to load this material with more than one-third of the weight necessary to break it. This assumption is incorrect, as in the experiments to which we refer some of the bars, six in number, were loaded within one-tenth of the weight that would break them.

From these experiments it was ascertained that cast iron, when sound, is more to be depended upon, and exhibits greater tenacity in resisting long-continued heavy strains, than is generally admitted, and its bearing-powers have deserved a much higher reputation than has at any former period been given to them. This is even more apparent with wrought iron, as it is safer, being more tenacious and ductile, and less liable to flaws and imperfections, which, too, should they exist, are much more easily detected than in cast iron.

The experiments, as respects the effects of time, on loaded cast-iron bars 1 inch square and 4 feet 6 inches between the supports, were exceedingly curious and interesting. They embraced a period of seven years, from 1837 to 1844, when they were discontinued,—the heaviest-loaded bars continuing to sustain their load without any apparent increase in the deflection. The deflections were taken monthly and carefully recorded, and the following Table exhibits the changes that took place in both the hot- and cold-blast iron bars from June 1838 to June 1842. It is satisfactory to observe that during the whole time of the experiments the bars, whether loaded with the lighter or heavier weights, exhibited little or no change beyond what may be traced to the variations of temperature. One of the bars was, however, found broken, but whether from accident or the effects of continued strain I am unable to determine. I am inclined to believe that the former was the case, as the corresponding bars retained their position, indicating changes so exceedingly small as to be scarcely perceptible, even when examined by the microscope and our best instruments.

Deflections produced with permanent weights on hot- and cold-blast cast-iron bars 4 feet 6 inches between the supports.

Cold-blast, Weight in lbs.	Deflection, in inches.	Date of observation.	Temperature, Fahr.	Hot-blast, Weight in lbs.	Deflection, in inches.
336	1·316	June 23rd, 1838.	78°	336	1·538
336	1·308	April 19th, 1842.	58°	336	1·620
392	1·824	June 23rd, 1838.	78°	392	1·803
392	1·828	April 19th, 1842.	58°	392	1·812
448	1·457	June 23rd, 1838.	78°	448	
448	1·449	April 19th, 1842.	58°	448	

From the above it will be seen that there is no increase in the deflection of the cold-blast bar with the 336 lb. load, but a slight increase of ·082 of an inch in the hot-blast. With the 392 lbs. there is a slight and progressive increase in both bars, and in those with a load of 448 lbs. there is no change but what is due to the difference of 20° of temperature between the month of June and that of April. As respects the load of 448 lbs., it is proper here to observe that the hot-blast bars broke at once with that weight, and one of the cold-blast bars also broke after sustaining the load 37 days, but whether by accident or from vibration is not determined. It is, however, evident from the breaking of the hot-blast bars, and one of the cold-blast, that the load of 448 lbs. approximated very close on the point of fracture, and that the slightest vibration of the floor would break the bar.

Viewing the subject in this light, it would appear from these experiments that time is an element which in a greater or less degree affects the security of materials when subjected to long-continued pressure. It may at first sight appear that the cohesive powers and the resistance may be so nicely balanced as to neutralize each other, and in this state would continue to sustain the load in that condition *ad infinitum*, provided there be no disturbing force to produce derangement of the parts, and thus destroy the equilibrium of the opposing forces. This cannot, however, be expected, and I think we may reasonably, under ordinary conditions of disturbance, conclude that long-continued strain will tend to lessen the cohesive force which unites the particles of matter together, and ultimately destroy that power of resistance so strongly exemplified in the above experiments. (Vide Report, Transactions of the British Association for 1842.)

As the object of this inquiry is to ascertain the limit of safety in structures, such as railway bridges, subjected to vibration and impact from a rolling load, it may be necessary, for the purpose of illustration, to refer to experiments made by the Commission appointed in 1848 to inquire into the application of iron to railway structures. In these inquiries the late Professor HODGKINSON and Professor WILLIS entered elaborately into the experimental as well as the mathematical investigation; but the experiments which bear more directly upon the present inquiry are those of Captain HENRY (now Sir HENRY) JAMES and Captain GALTON, for determining the effects pro-

duced by passing weights over bars with different velocities, and subjecting others to reiterated strain corresponding to loads equal to some fractional part of the breaking-weight. The latter experiments were made with cams, caused to revolve by steam machinery, which depressed the bars and allowed them to resume their natural position for a large number of times. Two cams were used; one communicated a highly vibratory motion to the bar during the deflection, and the other greatly depressed the bar subjected to it, and released it suddenly when the ultimate deflection due to the load had been obtained, the rate of deflections being from four to seven per minute. Three bars, subjected by the first-mentioned cam to a deflection equal to what would have been produced by one-third of the statical breaking-weight obtained from similar bars, received 10,000 successive depressions, and when afterwards broken by statical pressure, bore as much as similar bars subjected to dead weight only. Of two bars subjected to a deflection equal to what would have been caused by half the statical breaking-weight, one broke with 28,602 depressions, the other withstood 30,000, and did not appear weakened to resist statical pressure.

Of the bars subjected to the second cam, three bore 10,000 depressions, each giving it a deflection equal to what would be produced by one-third of the statical breaking-weight, without having their strength to resist statical pressure apparently at all impaired; one broke with 51,538 such depressions, and one bore 100,000 without any apparent diminution of strength; whilst three bars, subjected by the same cam to a deflection equal to what would be produced by half the statical breaking-weight, broke with 490, 617 and 900 depressions respectively. It must therefore be concluded that iron bars will scarcely bear the reiterated application of one-third their breaking-weight without injury.

A bar of wrought iron 2 inches square in section and 9 feet long between the supports, was subjected to 100,000 depressions, by means of the first-mentioned or rough cam, each depression producing a strain corresponding to about $\frac{5}{9}$ths of the strain that permanently injured a similar bar. These depressions only produced a permanent set of ·015 inch.

Three wrought-iron bars were subjected to 10,000 depressions each from the step-cam, depressing them through $\frac{1}{3}$ inch, $\frac{2}{3}$ inch, and $\frac{5}{6}$ inch respectively, without producing any perceptible permanent set. A bar depressed through 1 inch obtained a set of ·06 inch, and one depressed 300 times through 2 inches acquired a set of 1·08 inch. The largest deflection which did not produce any permanent set appears, by an experiment on a similar bar, to be that due to rather more than half the statical weight which permanently injured it.

A small box girder of boiler-plate riveted, 6 in. by 6 in. in section and 9 ft. long, was also subjected to depressions by means of the rough cam, principally with the view of ascertaining whether any effect would be produced on the rivets by the repeated strain; but a strain corresponding to 3752 lbs. repeated 43,370 times did not produce any appreciable effect.

From the experiments made by the Commissioners it may be inferred—

1st. That cast-iron bars or girders are not safe when subjected to a series of deflections due to one-half the load that would break them.

2nd. That they are perfectly secure in sustaining a dead weight not exceeding one-third of the weight that would break them; and

3rd. That these reiterated deflections appear to have no injurious effect upon the metal from which the bars were cast.

As respects wrought iron, it appeared from the experiments that a progressive increase in the deflections and permanent set was observable during every depression produced by the same cam as that employed on the cast-iron bars, exhibiting great deficiency in its elastic powers. Where the bar retained its power of restoration up to 30,000 deflections, with 10,000 more changes it took a set of ·06 inch, and from that number, with 810 additional depressions, the set increased to 1·84 inch, evidently showing that it would have continued still further to increase until the bar was rendered useless.

Comparing these experiments with those obtained from the riveted wrought-iron beam in the following experiments, it will be found that a load equivalent to one-fourth the breaking-weight produced no visible change nor any permanent set after being subjected to 1,000,000 depressions of ·17 and ·22 inch. By increasing the load from one-fourth to two-fifths, it sustained 5175 additional deflections of ·22 inch, when it broke. The difference between the experiments on the wrought-iron bar and the wrought-iron manufactured girder consists in the greater rigidity of the latter, and in its increased power of resistance to vibration and the force of impact, the weight on the girder descending upon it by the force of gravity.

The institution of experiments for the purpose of ascertaining the value of wrought-iron riveted plates, in the form of tubes, through which a railway train should pass, was a conception which led to a new era in the history of bridges, and ultimately effected the passage of the estuary of the Conway and the Menai Straits. These experiments not only gave the form and strengths required for the construction of these colossal structures, but they developed an entirely novel system of constructive art, and established the principle on which wrought-iron bridges should in future be made. Since then some thousands of bridges, many of them of great span, have been constructed, composed entirely of wrought iron, and are now in existence supporting railways and common roads to an extent hitherto unknown in the history of bridge-building, and such as could not have been accomplished by any other description of material than malleable iron or steel.

The construction of the Britannia and Conway bridges in the tubular form led to other constructions, such as the tubular girder, the plate and lattice girder, and other forms, all founded on the principle developed in the construction of the large tubes as they now span the Conway and the Menai Straits. In the tubular bridges, it was first designed that their ultimate strength should be six times the heaviest load that could ever be laid upon them, after deducting half the weight of the tube. This was considered a

fair margin of strength; but subsequent considerations, such as generally attend a new principle of construction with an untried material, induced an increase of strength, and, instead of the ultimate strength being six times, it was increased to eight times the weight of the greatest load.

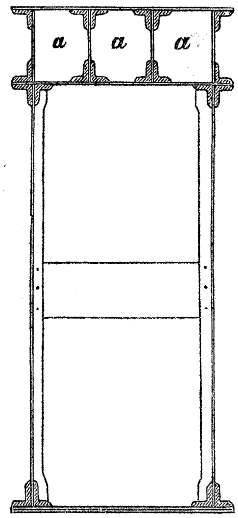
The stability and great success of these bridges gave increased confidence to the engineer and the public, and for several years the resistance of six times the heaviest load was considered an amply sufficient margin of strength.

Owing to the success of these undertakings, there was a general demand for wrought-iron bridges in every direction, and numbers were made without any regard to first principles, or to the law of proportion necessary to be observed in the sectional areas of the top and bottom flanges, so clearly and satisfactorily shown in the early experiments. The result of this was a number of weak bridges, many of them so disproportioned in the distribution of the material as to be almost at the point of rupture with little more than double the permanent load. These discrepancies, and the erroneous system of contractors tendering by weight, led not only to defects in the principle of construction, but the introduction of bad iron and, in many cases, equally bad workmanship. Now there is no construction which requires greater care and more minute attention to sound principles than *wrought-iron girders*, whether employed for bridges of large or small span or for buildings. The lives of the public entirely depend upon the knowledge and skill of the engineer, and the selection of the material which he employs.

The defects and break-downs which followed the first successful application of wrought iron to bridge-building led to doubts and fears on the part of engineers; and many of them contended for eight, and even ten times the heaviest load as the safe margin of strength. Others, and amongst them the late Mr. BRUNEL, fixed a lower standard; and I believe that gentleman was prepared in practice to work up to one-third or two-fifths of the ultimate strength of the weight that would break the bridge. Ultimately it was decided by the authorities of the Board of Trade, but from what data I am not informed, that no wrought-iron bridge should with the heaviest load exceed a strain of 5 tons per square inch. Now on what principle this standard was established does not appear; and on application to the Board of Trade the answer is, that "The Lords Commissioners of Trade require that all future bridges for railway traffic shall not exceed a strain of 5 tons per square inch."

The requirement of 5 tons per square inch on the part of the Board of Trade is not sufficiently definite to secure in all cases the best form of construction. It is well known that the powers of resistance to strain are widely different with wrought iron, according as we apply a force of tension or compression; it is even possible so to disproportion the top and bottom areas of a wrought-iron girder calculated to support six times the rolling load, as to cause it to yield with little more than half the ultimate strain or 10 tons on the square inch. For example, in wrought-iron girders with solid tops it requires the sectional area in the top to be nearly double that of the bottom, to

equalize the two forces of tension and compression; and unless these proportions are strictly adhered to in the construction, the 5-ton strain per square inch is an error which may lead to dangerous results. Again, it was ascertained from direct experiment that double the quantity of material in the top of a wrought-iron girder was not the most effective form for resisting compression. On the contrary, it was found that little more than half the sectional area was required, and, when converted into rectangular cells similar to *a*, *a*, *a*, was in its powers of resistance equivalent to double the area when formed of a solid plate. This discovery was of great value in the construction of tubes and girders of wide span, as the weight of the structure itself (which increases as the cubes, and the strength only as the squares) forms an important part of the load to which it is subjected. On this question it is evident that the requirement of the Board of Trade cannot be applied in both cases, and is therefore ambiguous as regards its application to different forms of structure. In the 5-ton per square inch strain there is not a word said about the dead weight of the bridge; and we are not informed whether the breaking-weight was to be so many times the applied weight plus the multiple of the load, or, in other words, whether it included or deducted the weight of the bridge itself.



These data are wanting in the railway instructions; and until some fixed principle of construction is determined upon, accompanied by a standard measure of strength, it is in vain to look for any satisfactory result in the erection of road and railway bridges composed entirely of wrought iron.

I have been led to inquire into this subject with more than ordinary care, not only on account of the imperfect state of our knowledge, but from the want of definite instructions from the authorities whose duty it is to secure the safety of bridges and to protect the public from malconstructions. To accomplish this, I have in the following experimental researches endeavoured to arrive at the extent to which a bridge or girder of wrought iron may be strained without injury to its ultimate powers of resistance. I have endeavoured to ascertain the exact amount of load to which a bridge may be subjected without endangering its safety, or, in other words, to determine the fractional strain of its estimated powers of resistance.

To arrive at correct results and to imitate as nearly as possible the strain to which bridges are subjected by the passage of heavy railway trains, the apparatus specially adapted for that purpose was designed to lower the load quickly upon the beam in the first instance, and subsequently to produce a considerable amount of vibration, as the large lever with its load and shackle was left suspended upon it in the second. The apparatus was sufficiently elastic for that purpose, as may be seen on reference to the drawings.

The beam A, Plates VI. & VII., is composed of an iron plate riveted with angle-irons 22 feet long, $\frac{1}{8}$ of an inch thick, and 16 inches deep.

It was supported on two brick piers 20 feet apart. Beneath the bottom flange is fixed the lever B, which, by means of the link and shackle C, grasps the lower web of the beam close to the fulcrum D. This fulcrum, on which the lever oscillates, is formed of a vertical bar E, which acts as a standard, and has screw-nuts to regulate the height from the cast-iron plate F to the fulcrum D. The machinery for lifting the lever and scale at H consists of the shaft and pulley I, driven by a water-wheel; and from this shaft the apparatus for lifting the load is worked by a strap from the pulley on the pinion-shaft K, which drives the shaft and spur-wheel L, giving motion to the connecting rod M. This rod has an oblong slot at its lower end, in which the pin at the end of the lever works. From this description it will be seen that, in turning the spur-wheel L, the weight is not raised until the bottom of the slot comes in contact with the pin of the lever, when the load is taken entirely off the beam. That being accomplished, the connecting rod descends, when the load is again laid upon the beam and left suspended with a vibratory motion for some seconds, until the remainder of the stroke is completed, when the connecting rod again rises for the succeeding lift. In this way the weights are lifted off and replaced alternately upon the beam at the rate of seven to eight strokes per minute. The apparatus is worked night and day by a water-wheel, and the number of changes are registered by the counter attached to the vertical post at G.

The girder subjected to vibration in these experiments is a wrought-iron plate beam of 20 feet clear span, and of the following dimensions:—

	inches.	
Area of top, 1 plate 4 inches $\times \frac{1}{2}$ inch	2·00	
„ 2 angle-irons $2 \times 2 \times \frac{5}{16}$	2·30	
	——	4·30
Area of bottom, 1 plate 4 inches $\times \frac{1}{4}$ inch	1·00	
„ 2 angle-irons $2 \times 2 \times \frac{3}{16}$ inch	1·40	
	——	2·40
Web, 1 plate $15\frac{1}{4} \times \frac{1}{8}$		1·90
Total sectional area		8·60
Depth	16 inches.	
Weight	7 cwt. 3 qrs.	
Breaking-weight (calculated)	12 tons.	

The beam having been loaded with 6643 lbs., equivalent to one-fourth of the ultimate breaking-weight, the experiment commenced as follows:—

TABLE I.—Experiment on wrought-iron beam with a changing load equivalent to one-fourth of the breaking-weight.

Date, 1860.	Number of changes of load.	Deflection produced by load.	Remarks.
March 21.	0	0·17	
„ 22.	10,540	0·18	
„ 23.	15,610	0·16	
„ 24.	27,840	....	Strap loose, and failed to lift the weight.
„ 26.	46,100	0·16	
„ 27.	57,790	0·17	
„ 28.	72,440	0·17	
„ 29.	85,960	0·17	
„ 30.	97,420	0·17	
„ 31.	112,810	0·17	
April 2.	144,350	0·16	
„ 4.	165,710	0·18	
„ 7.	202,890	0·17	
„ 10.	235,811	0·17	
„ 13.	268,328	0·17	
„ 14.	281,210	0·17	
„ 17.	321,015	0·17	
„ 20.	343,880	0·17	The strap broke.
„ 25.	390,430	0·17	
„ 27.	408,264	0·16	
„ 28.	417,940	0·16	
May 1.	449,280	0·16	
„ 3.	468,600	0·16	
„ 6.	489,769	0·16	
„ 7.	512,181	0·16	
„ 9.	536,355	0·16	
„ 11.	560,529	0·16	
„ 14.	596,790	0·16	

The beam having undergone above half a million changes of load, by working continuously for two months, night and day, at the rate of about eight changes per minute, without producing any visible alteration, the load was increased from one-fourth to two-sevenths of the statical breaking-weight, and the experiment proceeded with till the number of changes of load reached a million.

TABLE II.—Experiment on the same beam with a load equivalent to two-sevenths of the breaking-weight, or nearly $3\frac{1}{2}$ tons.

Date, 1860.	Number of changes of load.	Deflection, in inches.	Remarks.
May 14.	0	0·22	In this Table the number of changes of load is counted from 0, although the beam had already undergone 596,790 changes, as shown in the preceding Table.
15.	12,623	0·22	
17.	36,417	0·22	
19.	53,770	0·21	
22.	85,820	0·22	
26.	128,300	0·22	
29.	161,500	0·22	
31.	177,000	0·22	
June 4.	194,500	0·21	
7.	217,300	0·21	
9.	236,460	0·21	
12.	264,220	0·21	
16.	292,600	0·22	
26.	403,210	0·23	At this point the operations were suspended, the beam having suffered a million changes of load.

The beam had now sustained one million changes of load without any apparent injury; it was then considered necessary to increase the load to 10,486 lbs., or two-fifths of the breaking-weight, when the machinery was again put in motion. With this additional weight the deflections were increased, with a permanent set of ·05 inch, from ·23 to ·35, and after sustaining 5175 changes, the beam broke by tension a short distance from the middle. It is satisfactory here to observe that during the whole of the 1,005,175 changes none of the rivets were loosened or broke.

TABLE III.—Beam repaired.

The beam fractured in the preceding experiment was repaired by replacing the broken angle-irons on each side, and putting a patch over the broken plate equal in area to the plate itself. Thus repaired, a weight of three tons was placed on the beam, equivalent to one-fourth of the breaking-weight, when the experiments were again continued as before.

Date.	Number of changes of load.	Deflection, in inches.	Permanent set, in inches.	Remarks.
1860. August 9.	158	....	....	The load during these changes was equivalent to 10,500 lbs., or 4·6875 tons at the centre. With this weight the beam took a large but unmeasured set.
Aug. 11.	12,950	....	....	During these changes the load on the beam was 8025 lbs., or 3·58 tons.
„ 12.	25,742	0·22	?	
Aug. 13.	25,900	0·18	0	Load reduced to 2·96 tons, or $\frac{1}{4}$th of the breaking-weight.
„ 16.	46,326	0·18	0	
„ 20.	71,000	0·18	0	
„ 24.	101,760	0·18	0	
„ 25.	107,000	0·18	0	
„ 31.	135,260	0·18	0·01	
Sept. 1.	140,500	0·18	0·01	
„ 8.	189,500	0·18	0·01	
„ 15.	242,860	0·18	0·01	
„ 22.	277,000	0·18	0·01	
„ 30.	320,000	0·18	0·01	
Oct. 6.	375,000	0·18	0·01	
„ 13.	429,000	0·18	0·01	
„ 20.	484,000	0·18	0·01	
„ 27.	538,000	0·18	0·01	
Nov. 3.	577,800	0·18	0·01	
„ 10.	617,800	0·18	0·01	
„ 17.	657,500	0·18	0·01	
„ 23.	712,300	0·18	0·01	
Dec. 1.	768,100	0·18	0·01	
„ 8.	821,970	0·18	0·01	
„ 15.	875,000	0·18	0·01	
„ 22.	929,470	0·18	0·01	
„ 29.	1,024,500	0·18	0·01	
1861.				
Jan. 9.	1,121,100	0·18	0·01	
„ 19.	1,214,000	0·18	0·01	
„ 26.	1,278,000	0·18	0·01	
Feb. 2.	1,342,800	0·18	0·01	
„ 11.	1,426,000	0·18	0·01	
„ 16.	1,485,000	0·18	0·01	
„ 23.	1,543,000	0·18	0·01	
March 2.	1,602,000	0·18	0·01	
„ 9.	1,661,000	0·18	0·01	
„ 16.	1,720,000	0·17	0·01	
„ 23.	1,779,000	0·17	0·01	
„ 30.	1,829,000	0·17	0·01	
April 6.	1,885,000	0·17	0·01	
„ 13.	1,945,000	0·17	0·01	
„ 20.	2,000,000	0·17	0·01	
„ 27.	2,059,000	0·17	0·01	
May 4.	2,110,000	0·17	0·01	
„ 11.	2,165,000	0·17	0·01	
„ 20.	2,250,000	0·17	0·01	
Sept. 4.	2,727,754	0·17	0·01	
Oct. 16.	3,150,000	0·17	0·01	

At this point, the beam having sustained upwards of three million changes of load without any increase of the permanent set, it was assumed that it might have continued to bear alternate changes to any extent with the same tenacity of purpose as exhibited in the foregoing Table. It was then concluded to increase the load from one-fourth to one-third of the breaking-weight; and having laid on 4 tons, which increased the deflection to ·20 inch, the work was proceeded with in the same order as in the previous experiments.

TABLE IV.

Date.	Changes of load.	Deflection, in inches.	Permanent set, in inches.	Remarks.
1861.				
Oct. 18.	0	0·20		
19.	4000	0·20	0·	
Nov. 18.	126,000	0·20		
Dec. 18.	237,000	0·20		
1862.				
Jan. 9.	313,000	....	....	Broke by tension across the bottom web.

From these experiments it is evident that wrought-iron girders of ordinary construction are not safe when submitted to violent disturbances with a load equivalent to one-third the weight that would break them. They, however, exhibit wonderful tenacity when subjected to the same treatment with one-fourth the load; and assuming that an iron girder bridge will bear with this load 12,000,000 changes without injury, it is clear that it would require 328 years, at the rate of 100 changes per day, before its security was affected. It would, however, be dangerous to risk a load of one-third the breaking-weight upon bridges of this description, as according to the last experiments the beam broke with 313,000 changes; or a period of eight years, at the same rate as before, would be sufficient to break it. It is more than probable that the beam might have been injured by the previous three million changes to which it had been subjected; and assuming this to be true, it would then follow that the beam was progressing to destruction, and must of necessity at some time, however remote, have terminated in fracture.

The experiments throw considerable light on this very intricate and very important subject. They are probably carried sufficiently far to enable us to state with certainty what is the safe measure of strength; and as much depends upon the quality of the material and the skill with which the girders are put together, it becomes necessary for the public safety that a measure of strength should be established without encumbering the structures with unnecessary weight. On this question it must be borne in mind that every additional ton that is not required beyond the limits of safety, is an evil that operates as a constant quantity tending to produce rupture; and hence follows the necessity of a careful distribution of the material, in order that the tube or girder shall be duly proportioned to the strains it has to bear, and that every part of the structure shall have its due proportion of work to perform.

I have assumed, for the sake of illustration, that every description of material, as regards its cohesive properties, follows the same law as that which we have experimented upon, or, in other words, in the ratio of its physical powers of resistance, that is to say, any beam will follow the same law in regard to its ultimate powers of resistance, when operated upon by a corresponding load due to that power. If this be true, we have only to follow the same rule as observed in the experiments, by loading cast-iron or wooden beams in the ratio of their cohesive powers of resistance, and their breaking-weights respectively. This has not been proved experimentally, but I hope at some future time to have an opportunity of extending the experiments, in order to determine to what extent these views are correct.

The Lords Commissioners of Trade, in the exercise of their functions as conservators of the public safety, have adopted the rule that no railway bridge composed of wrought iron shall exceed with its heaviest rolling-load a strain of five tons per square inch of section upon any part of the bridge. The formula for this maximum of strain upon the material has been deduced from my own experiments on the model tube at Millwall.

Assuming the top of the girder to be sufficiently rigid to prevent buckling by compression, the formula for the strength of the bottom section derived from these experiments is

$$W=\frac{adc}{l},$$

where the constant $c=80$.

Applying this formula to the beam experimented upon, we have

a, the area of the bottom $=2\cdot4$ inches,
d, the depth of the beam $=16$ inches,
c, the constant deduced from the model tube $=80$,
l, the span or distance between the supports $=240$ inches.

Hence $$W=\frac{2\cdot4\times16\times80}{240}=12\cdot8 \text{ tons},$$

the ultimate strength of the beam.

In order to determine the strain per square inch in these experiments, we find

$$S=\frac{lw}{4ad},$$

where S represents the strain per square inch upon the section a, produced by the greatest load w, laid upon the middle of the girder.

It is necessary to observe that in a girder properly proportioned, the greatest strain per square inch will take place upon the bottom section; so that if the strain upon the bottom section of such a girder be within the Government Commissioner's condition of safety, the strain upon the top section will necessarily be within that limit also. In a girder having the cellular structure at its top section, the area of the top section should be very nearly once and a quarter that of the bottom section, or the areas of their

sections should be respectively as 5 : 4; and the strain per square inch upon these parts will be respectively inversely as their areas; that is, the strain per square inch upon the top section will be $\frac{4}{5}$ths of the strain per square inch upon the bottom section. In one of the foregoing experiments, we have

l, the length of the girder=240 inches,
w, the weight laid on the middle=2·96 tons,
a, the area of the bottom section=2·4 inches,
d, the depth of the girder=16 inches;

therefore $$S=\frac{240\times 2{\cdot}96}{4\times 2{\cdot}4\times 16}=4{\cdot}62 \text{ tons},$$

the strain per square inch on the bottom section of the girder.

Applying this formula to the whole series of experiments, we obtain the following summary of results:—

Summary of Results.—1st Series of Experiments.

Beam 20 feet between the supports.

No of experiment.	Date.	Weight on middle of the beam, in tons.	Number of changes of load.	Strain per square inch on bottom.	Strain per square inch on top.	Deflection, in inches.	Remarks.
1	From March 21st to May 14th, 1860	2·96	596,790	4·62	2·58	·17	
2	From May 14th to June 26th, 1860	3·50	403,210	5·46	3·05	·23	
3	From July 25th to July 28th, 1860	4·68	5,175	7·31	4·08	·35	Broke by tension at a short distance from the centre of the beam.

The number of 1,005,175 changes was attained before fracture, with varying strains upon the bottom flange of 4·62 tons, 5·46 tons, and 7·31 tons per square inch.

Beam repaired.—2nd Series of Experiments.

4	August 9th, 1860 . .	4·68	158	7·31	4·08	. . .	The apparatus was accidentally set in motion.
5	August 11th and 12th	3·58	25,742	5·59	3·12	·22	
6	From August 13th, 1860 to October 16th, 1861	2·96	3,124,100	4·62	2·58	·18	
7	From October 18th, 1861 to January 9th, 1862	4·00	313,000	6·25	3·48	·20	Broke by tension as before, close to the plate riveted over the previous fracture.

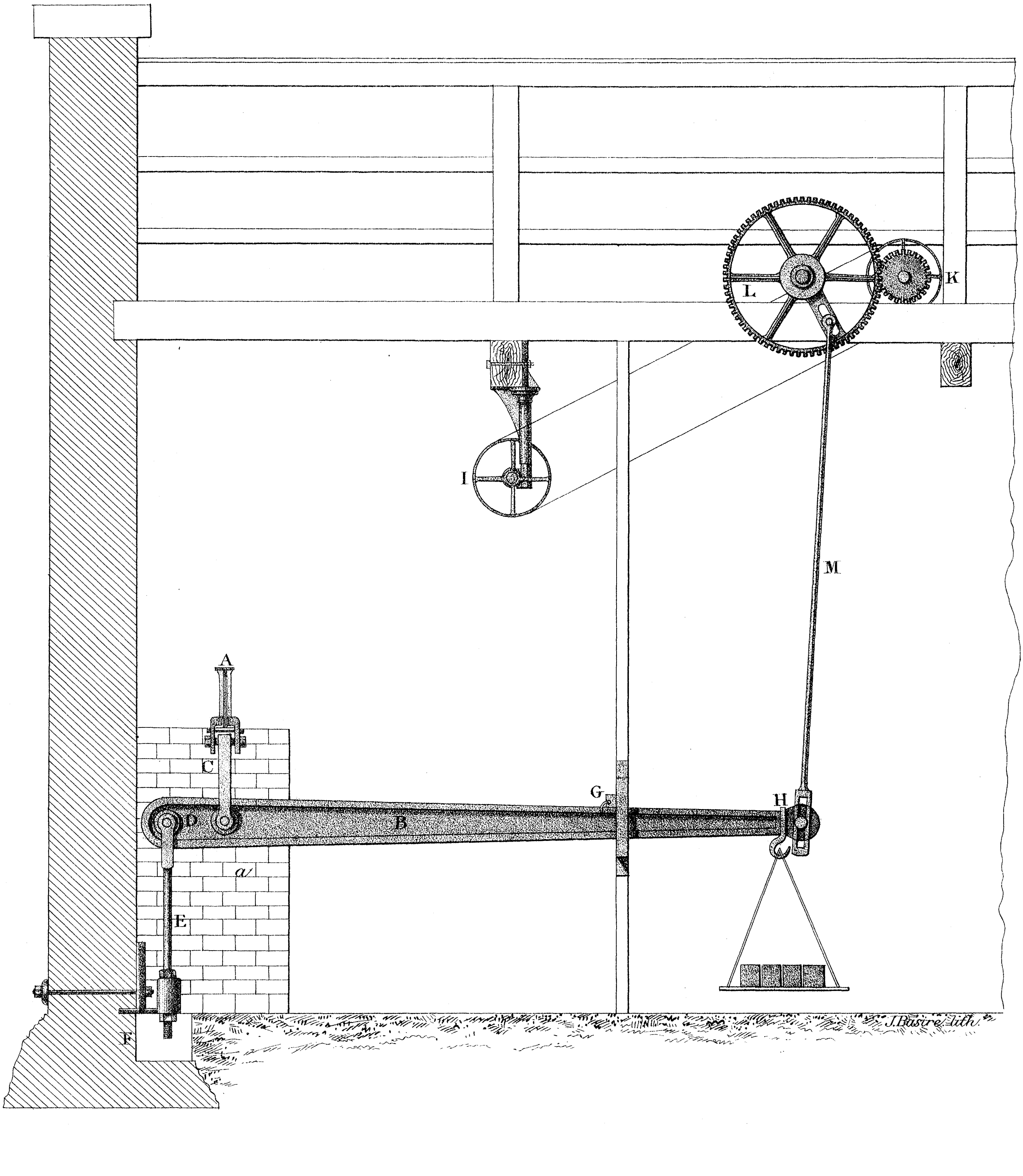
Here the number of 3,463,000 changes was attained when fracture ensued.

From the above it is evident that wrought-iron girders, when loaded to the extent of a tensile strain of seven tons per square inch, are not safe, if that strain is subjected to alternate changes of taking off the load and laying it on again, provided a certain amount of vibration is produced by that process; and what is important to notice is, that from 300,000 to 400,000 changes of this description are sufficient to ensure fracture. It must, however, be borne in mind that the beam from which these conclusions are derived had sustained upwards of 3,000,000 changes with nearly five tons tensile strain on the square inch, and it must be admitted from the experiments thus recorded that five tons per square inch of tensile strain on the bottom of girders, as fixed by the Board of Trade, appears to be an ample standard of strength.

As regards compression, we have only to compare for practical purposes the difference between the resisting-powers of the material to tension and compression, and we shall require in a girder without a cellular top from one-third to three-fourths more material to resist compression than to resist tension; and as the strength of wrought iron in a state of compression is to its strength in a state of tension as about 3 to $4\frac{1}{2}$, the area of the top and bottom will be nearly in that proportion, or, in other words, it will require that much more material in the top than the bottom to equalize the two forces.

In the experimental beam the area of the top was considerably in excess of that of the bottom, it having been constructed on data deduced from the experiments on tubes without cells, which required nearly double the area on the top to resist crushing. In the construction of large girders, where thicker plates are used, this proportion no longer exists, as much greater rigidity is obtained in the thicker plates, which causes a closer approximation to equal areas in the top and bottom of the girder; and from this we deduce that from one-third to three-fourths, and in some cases one-third additional area in the top has been found, according to the size of the girder, sufficient to balance the two forces under strain.

The foregoing experiments, however, were instituted to determine the safe measure of strength as respects tension, and it will be seen that in no case during the whole of the experiments was there any appearance of the top yielding to compression.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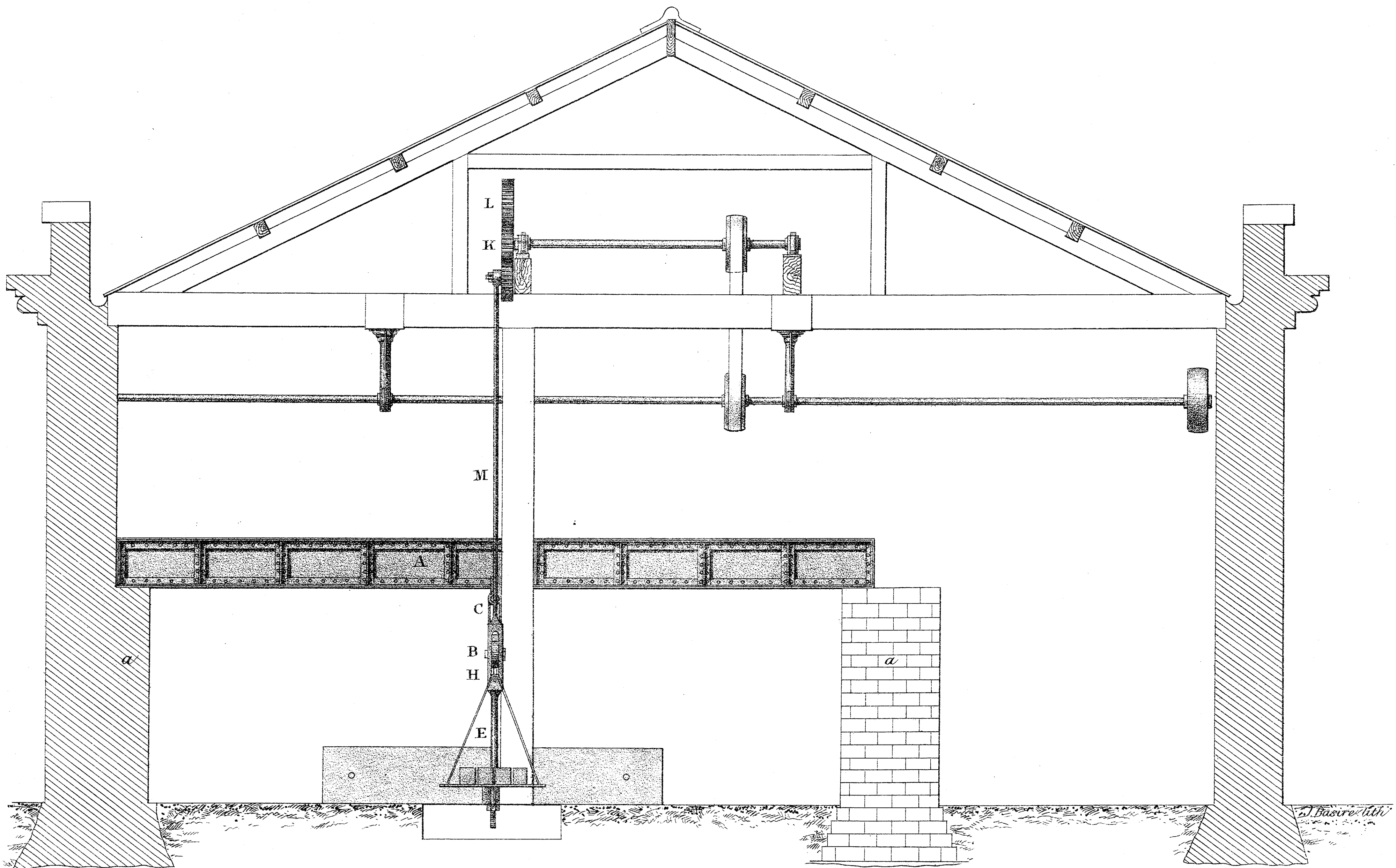
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