

STEEL-CONCRETE BRIDGE CONSTRUCTION.

By J. M. S. WOORE, B.E., Assoc. M. INST. C.E.

(This paper was taken as read during the Session of 1902, and is published in the Journal of the Sydney University Eng. Soc., Vol. VII., 1902.—Ed.)

DISCUSSION.

Mr. J. W. ROBERTS said that the paper was a creditable attack upon a difficult problem. The difficulty was two-fold.

1.—To establish a relation between the co-existent stresses of the two materials, *i.e.*, to evaluate ‘ μ .’

2.—To determine the manner in which the stresses were distributed over the cross-section, *i.e.* to fix position of the neutral axis and evaluate ‘I’.

The co-efficient ‘ μ ,’ or the ratio between the elastic moduli, was a function of the loading. Also, it was different for tension and compression. The author’s formula ignored this important fact and was to that extent unreliable. A formula had been proposed some years back by Mr. Gummow, C.E., of this city, which did take cognisance of the fact, but here again an entirely false assumption had vitiated the result. The position of the neutral axis, and, therefore, the moment of inertia depended on the relation between the elastic moduli in tension and compression.

The factor of safety was best introduced by multiplying the working loads thereby, so as to bring about a condition of rupture, at which point ‘ μ ’ become constant; otherwise ‘ μ ’ became a function of the factor and complicated the case.

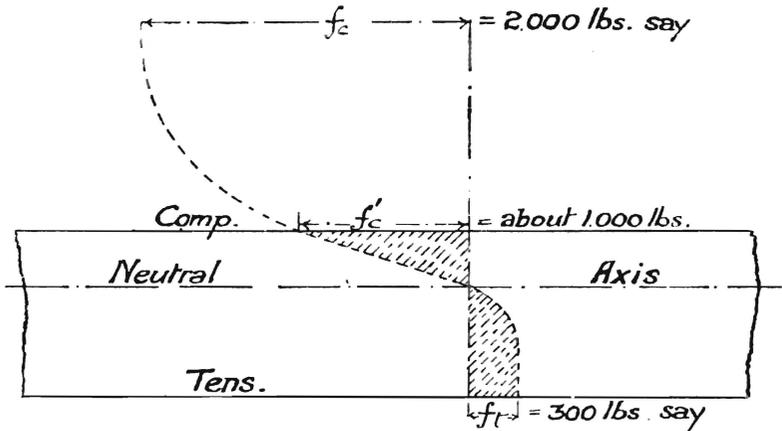
If the author’s formula were correct, it would go to shew that the Monier beam was not an efficient structure, for the iron or steel was never stressed to its working limits under ordinary conditions. The unit stress in the metal could only equal ‘ μ ’ times the unit stress in the adjacent concrete. The safer the load the smaller the value of ‘ μ .’

In his opinion the only rational formula that could be applied to concrete beams was that applied by Professor Johnson to cast-iron and timber, and adapted from Saint Venant, the French engineer. This was based on the stress-strain diagram as ascertained by a testing-machine, both in tension and compression — (Framed Structures, page 126.)

$$M = \frac{fb d^2}{6} \left\{ \frac{m \left[\frac{3(m+3)}{m+2} + 4 \sqrt{\frac{2}{m+1}} \right]}{m+3+2\sqrt{2(m+1)}} \right\}$$

(where 'm' is a co-efficient, depending on, and deducible from stress-strain diagram). For concrete 'm' would probably vary from 5 to 7. The neutral axis would be situated about $1/3$ d from the compression side. The moment of resistance arising from the formula would be about double the mt. r. as ordinarily calculated. Hence the whole mystery about fibre stresses in rupture being twice the tensile limit would vanish and normal conditions prevail.

The diagram shewed the distribution of stress.



Condition for neutral axis :—Shaded areas equal.

The foregoing remarks applied to a plain concrete beam. The formula would require modification to be applied to Monier construction, but the method still remained sound. Further investigations still seemed necessary before one could hope to develop a thoroughly rational formula.

Mr. H. H. DARE observed that Mr. Woore's paper embodied the result of what had evidently been a careful study of a very interesting subject. Concrete-steel construction had of late years come very much to the fore, not only in bridge work, but also in connection with the walls and flooring of warehouses and other large buildings, service reservoirs, etc., built in situ, and quite recently in minor portions of construction such as buckled plates, bridge cylinders, and concrete-steel piles, which were manufactured and brought to the work when they were to be used.

Concrete-steel construction had originated in Europe, and the majority of the experiments had been made by European engineers. The discussions upon the subject by such authorities as Bauschinger, Spitzer, Melan, and others, had filled many pages in European publications, but were not available to the student here. Mr. Woore's paper dealt rather with American than European practice, but it was to be remembered that Europe and not America was the home of concrete-steel. The first notice of importance upon the subject in American literature had been, he believed, Von Emperger's paper read before the

American Society of C.E. in 1894. Since then quite a number of concrete-steel bridges had been built in the United States, some of which were described in Appendix III. of Mr. Woore's paper.

With regard to that portion of the paper dealing with concrete-steel beams, he did not propose to submit any discussion, except to say that the mathematical investigation appeared to cover the ground with regard to the area to be provided to meet the bending moments in a concrete-steel girder. No reference however, was made to the methods proposed for coping with the shearing stresses, such as the use of stirrups or inclined bars and other devices, upon the efficacy of which there seemed to be some doubt. However, while we had such excellent timber for constructural purposes as existed in Australia, concrete-steel girders were not likely to have much vogue here, unless it were for inside floor construction in large warehouses, etc., and possibly in important wharves.

Professor Warren's experiments on reinforced beams were of interest in this connection, and showed the great increase in the modulus of rupture when the beams were reinforced with iron bars.

It was with reference to the use of concrete-steel in arched bridges that he had been, and was, chiefly concerned. At the present time, he was preparing the design of a large low level bridge to take the place of the existing timber bridge on the road from Richmond to the Kurrajong. This would consist of thirteen arched spans of 50 feet in the clear, each 4 ft. 2 ins. rise, to carry a roadway 21 feet wide, with provision for a tramway of standard gauge. The estimated cost was slightly over £20,000, and tenders would shortly be invited. Before deciding upon the system to be followed, several studies had been made by Mr. Bradfield and himself of different forms of construction, two of which were on the Melan, and one on the Wunsch system. His first feeling had been in favour of a Melan arch with braced ribs about 3 feet apart, as this would have allowed of the use of the Hawkesbury shingle for concrete, and also because it might have been possible with this form of construction to use a centreing hung from the ribs, and so obviate risk to the staging from floods, which though not very common in the Hawkesbury just then, were severe when they did occur. However, after going into the matter, they had ruled out first the Wunsch system, which appeared extravagant in the matter of the concrete, then the Melan and Thacher systems, which did not give the same facilities for cross bonding the whole structure as the Monier system, an adaptation of which had been adopted. He said "an adaptation," because in all the Monier works of which he had any cognisance, the material used had been a compo. or mortar consisting of 1 cement to 3 sand, while in the Richmond bridge, they were only using about 2 inches of this compo to encase the top and bottom grills (formed of $\frac{1}{2}$ in. and $\frac{3}{8}$ in. bars, 3 in. mesh), while the body of the arch in between these grills would be formed by fine concrete, $3\frac{1}{2} : 1\frac{1}{2} : 1$ made of the excellent shingle which could be procured near at hand. The difficulty in using the $3\frac{1}{2} : 1\frac{1}{2} : 1$ material right through would have been in ramming the stone among the grills, so as to give a proper adhesion to the bars.

Having decided upon the system to be followed, it had remained to determine what ratio of the modulus of elasticity between the iron and concrete should be adopted, and also what should be the maximum tension and compression allowed in the concrete of the arch ring. It was here that reference had been made to Mr. Woore's paper, which gave an excellent summary of the information available upon those subjects.

First as to the modulus ratio (*See Journal S. U. E. S., Vol. VII., Page 40*), Mr. Woore quoted:—

AUTHORITY.	MOD. E. STEEL.	MOD. E. COMPO. OR CONCRETE.	RATIO.
Beer.	35,000,000	2,800,000 (Compo or Fine Concrete)	12 to 1
Thacher.	28,000,000	1,400,000 (Concrete)	20 to 1
Prof. Johnson.	28,000,000	1,000,000 (Concrete)	28 to 1
Bradfield.	30,000,000	750,000 (Compo)	40 to 1

Judging from Considère and A. L. Johnson's tests on beams with a single grill, Mr. Woore thought that, in that case, the ratio might be as high as 100 to 1.

The ratio of 40 to 1, quoted by Mr. Bradfield in his paper read before the Society* had been adopted in two small arch bridges built with 1 : 3 compo. by the Public Works Department, and was that which had been deduced by, he thought, Spitzer, from the 1892 Austrian experiments on large arch spans. It had been found that in this case the ratio in the first stage of the test was 15 to 1, and when the first hair crack appeared, 65 to 1. 40 to 1 was the mean ratio. This was for a 1 : 3 compo. The higher the ratio, the less iron, which was the expensive material required. He should be very chary about allowing the 100 to 1 ratio in any construction. The ratio adopted for the Richmond Bridge had been 20 to 1, *viz.*, 28,000,000 Mod. E. of Steel, 1,400,000 Mod. E. of Concrete and Compo. This 1,400,000 agreed fairly well with the recent experiments made by Professor Warren and incorporated in his paper read before the Royal Society last year.† It was there stated that for mortar briquettes 1 : 3, age 3 months, the tensile strength was 219 lbs. per square inch, while the Mod. E. varied from 1,718,759 lbs. per square inch, at the beginning of the test, to 1,393,750 (or practically 1,400,000) at the end. The first figure would more nearly represent the condition

* "Some Notes on Monier Construction"—J. J. C. Bradfield, M.E., Assoc. M. Inst. C. E., Journal Sydney University Eng. Soc., Vol. V., 1900.

† See Journal, Royal Society N.S.W., Vol. XXXVI., 1902.

of the arch under the maximum load, but making allowance for workmanship the 1,400,000 seemed a very fair assumption.

In Professor Warren's experiments for 1 : 3 mortar at 6 months and 12 months old, the tensile strength was 281 lbs. per square inch in each case. Mr. Woore gives for 4 : 2 : 1 concrete, age 1 month, tensile strength 300 to 350 lbs per square inch, for 1 : 3 mortar 200 to 250 lbs. This latter agrees fairly well with Professor Warren's results, though it is somewhat higher considering the age of specimens. In the Richmond Bridge they had decided not to allow more than 50 lbs. per square inch tension on the concrete, but sufficient iron had been provided to prevent even this limit being reached, the maximum calculated tension not exceeding 40 lbs at any point.

From Professor Warren's tests for 1 : 3 mortar at 3 months, the breaking load (average) in compression was 2,783 lbs. per square inch, or say 12 times the tensile strength. Mr. Woore gave 2,500 lbs. per square inch for 4 : 2 : 1 concrete, and 2,000 lbs. per square inch for 1 : 3 mortar, age 1 month. Allowing the 2,500 lbs. per square inch as a fair average for 3 months old compositum and concrete they had in the Richmond Bridge, a factor of safety of nearly 7 in compression, the maximum calculated compression in that case being 385 lbs. per square inch.

Many examples had been brought forward of the imperviousness of concrete and mortar enclosing iron. Some time ago he had occasion to have a Monier pipe removed, which had been embedded in ground saturated with brackish water for some years, and upon knocking out some of the compositum. this was found quite dry inside and the wires un tarnished. As to the adhesion, this was ample, especially with cross bonding as on the Monier system, but it still seemed doubtful whether the adhesion would not be destroyed to some extent by vibration due to a constant railway or tramway service. At Richmond there would probably never be a sufficiently frequent tram service to do much damage, but to stiffen the arch they were allowing for spandrel walls stretching over the piers from quarter point to quarter point, and reinforced with iron bars, which would be united to the bars of the upper grill at the junctions.

Later on, perhaps, the Society might have a paper upon the complete design of the work referred to, shewing the methods proposed for the construction, including the foundations which were of interest. In that case he hoped that Mr. Woore would join in the discussion.

Mr. WOORE, writing in reply, remarked that it had given him much pleasure to read the interesting criticisms of his paper on "Steel Concrete Bridge Construction," and he had to thank Messrs. J. W. Roberts, B.E., and H. H. Dare, M.E., Assoc. M. Inst., C.E., for the moderate tone they had adopted in the discussion of a subject which was admittedly difficult and complicated.

Firstly, considering the remarks of Mr. Roberts, who stated that the co-efficient of elasticity of concrete was different for tension and compression, and that "the Author's formula ignores this important fact, and is to that extent unreliable," he might draw attention to the

fact that his treatment of the theory of steel-concrete was founded on the analysis of W. Beer and J. B. Johnson, his formulæ (1) and (2) for position of neutral axis and moment of inertia of a beam containing one layer of metal being identical with those of Mr. Beer, except that $(\mu - 1)$ takes the place of μ .

He considered that it was justifiable to ignore the difference between the value of the tensile and compressive moduli of elasticity for the following reasons :—

(1) Disagreement between recorded tests—even as to whether modulus of elasticity was greater in tension or compression [compare Hartig's experiments as quoted by Mr. Beer (P.I.C.E., Vol. CXXXIII., p. 389) with Henby's tests (Journal of the Association of Engineering Societies, September, 1900, p. 156)].

(2) Great modification in the value of the tensile modulus of elasticity of concrete beams caused by the presence of iron or steel bars, as proved by the experiments of M. Considère, A. L. Johnson, and W. K. Hatt.

As to the position of the neutral axis and the value of the moment of inertia depending on the relation between the elastic moduli in tension and compression, it appeared to him that these quantities depended more on the amount and distribution of the metal bars in the section.

It seemed to be Mr. Roberts' opinion that a formula for the strength of steel-concrete, was not correct which inferred that the iron or steel was not stressed to its working limits under ordinary conditions. It had been proved, however, by the well-known Puckersdorf experiments, that the stress each material took was in direct proportion to its modulus of elasticity. This being the case, the stress in the iron or steel could never reach its ordinary working value for a corresponding safe working stress in the concrete. Evidence in support of this might be deduced from Professor Hatt's tests. The load producing total failure being that at which the elastic limit of the steel was reached, the average stress in the steel for the load at which the concrete cracked would be about thirteen tons per square inch.

Mr. Roberts' application of the formula of Saint Venant to concrete beams was most interesting. In this connection, he (Mr. Woore) might draw attention to Professor Hatt's formulæ for steel-concrete which were founded on the stress—strain diagrams, and appeared to fit the experimental results with some degree of accuracy (see Eng. News, February 27th and July 17th, 1902).

Bearing in mind the many complications and unknown quantities that enter into the calculation of steel-concrete structures, such as stresses due to shrinkage, variations in strength of concrete due to method of mixing, and proportions and qualities of ingredients used, he would suggest that for the present it might be sufficiently accurate to use a partly empirical formula such as

$$f = \frac{My}{FI}$$

F being the ratio between the modulus of rupture and tensile strength of concrete, and I and y being determined as already indicated. The figures in Table 1 of his paper, under the heading of "Value of F at first crack," supported this suggestion.

Turning to Mr. Dare's comments on the subject under discussion, he noted that Mr. Dare considered that he had scarcely laid sufficient emphasis on the European origin of steel-concrete construction. Being called upon to prepare plans for steel-concrete work for roofing a number of railway subways, he had found it necessary to make a complete study of the matter, but was, unfortunately, unable to obtain first hand reference to the more important European literature of the subject. He had, however, referred, in his paper, to the work of J. Melan, W. Beer, M. Considère, and others, and to the experiments of the Austrian Society of Civil Engineers and Architects, as well as to the work of American engineers, and it must be admitted that these latter had done much to advance the science of steel-concrete construction.

With regard to the railway subways just mentioned, steel rail bearers, independent of the concrete, had been designed to carry the rails. The work had not been carried out, principally, he believed, because it was feared that the constant vibration due to passing trains would interfere with the concrete setting.

Mr. Dare drew attention to the doubtful advantage of stirrups in steel-concrete beams. As these beams, when tested, almost invariably commenced to fail by developing tension cracks at, or near, the centre; it seemed that stirrups did not materially add to the strength up to the point at which the concrete fails in tension.

With reference to the infrequent use of steel-concrete girders, it must be noticed that the formulæ for moment of resistance, would be just as applicable to arches when subjected to bending moments, as to beams.

Mr. Dare's description of his work on the Richmond-Kurrajong road bridge was interesting and instructive, especially as regards the use of 3 to 1 mortar in conjunction with concrete as a means of overcoming the principal objection to the Monier system. He considered, however, that it would be necessary to take some precaution in order to avoid a joint parallel with the arch ring, and to ensure a good bond between the two materials.

Mr. Dare considered that there was some risk attached to the use of a modulus ratio as high as one hundred. This appeared, however, to be about the value deduced from tests of actual steel-concrete beams, in which the presence of the metal seemed to greatly increase the modulus of elasticity of the concrete, and he would again draw attention to the experiments of M. Considère, A. L. Johnson, and W. K. Hatt.

He was gratified to think that his notes on steel-concrete should have called forth such interesting discussions, and he was looking forward to reading the paper which Mr. Dare had promised.