# Building research station, Garston, Watford, Herts: research on the strength of bridges: testing of highway bridges

**Building Research Station, Garston, Watford, Herts**

# Research on the Strength of Bridges

*Untersuchungen über die Tragfähigkeit von Brücken*

*Recherches sur la résistance des ponts*

## a) Testing of Highway Bridges

*Messungen an Straßenbrücken*

*Mesures sur ponts-routes*

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### *Early Investigation*

In 1933 the owners of bridges in Great Britain were empowered to restrict the maximum weight of vehicles permitted to cross any given bridge, and did so on the basis of methods of strength assessment then thought appropriate. Experience showed, however, that vehicles very much in excess of the permitted weight could traverse the bridge without apparent ill-effects. It was apparent therefore that the methods used in assessing the load carrying capacity of the bridges were unduly conservative. In 1936 therefore, the Building Research Station commenced an investigation on behalf of the Ministry of Transport into the behaviour under load of various types of highway bridge — more especially those of the masonry arch type and the cast-iron girder type up to about 40 ft. span. Many hundreds of these bridges exist throughout the country. They were built mainly during the periods of canal and railway construction in the late 18th and the first half of the 19th centuries respectively. They carry to-day very much heavier traffic than that for which they were originally intended. The main purpose of the research was to investigate the source of the unsuspected strength of such bridges and hence to lead to more accurate methods of estimating their load carrying capacity. In the years between 1936 and the outbreak of war, when the programme was temporarily discontinued, many loading tests were made on selected bridges. A few

Table 1 Details of Bridges Tested to Destruction

(a) Arches.

| Date of erection | Location | Description | Dimensions: Span | Dimensions: Width | Maximum load applied Tons | Remarks |
|---|---|---|---|---|---|---|
| 1793 | over disused Derby Canal at Breadsall, Derby | Sandstone voussoirs about 14 in. deep. | 12 ft. 2 in. | 17 ft. 9 in. (at crown) | 77,6 | Arch collapsed with 38,8 tons on each of two jacks at crown of arch. |
| 1793 | Over Stratford-on-Avon Canal, Yardley Wood Road, Birmingham | Bonded brick ring; varying thickness 13 in., 14 in., 18 in. | 21 ft. 2 in. | 14 ft. 8 in. (at crown) | 123 | Arch collapsed with 61,5 tons on each of two jacks at crown of arch. |

(b) b Cast iron girder bridges

| Date of erection | Location | Description: Number of girders | Description: Inter-girder construction | Description: Material of fill | Dimensions: Clear-skew span between front edges of bearings | Dimensions: Average square spacing of girders at mid-span | Dimensions: Angle of skew | Dimensions: Square width between centres of webs of outer girders | Dimensions: Maximum overall depth at mid-span | Dimensions: Depth of girder | Dimensions: Section modulus of internal girders at mid-span Inches | Maximum load applied Tons | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1848 | Over disused New-market-Chesterford Railway, Babraham, Cambs. | 7 | Brick jack arches | Mixed | 30 ft. 3 in. | 6 ft. 5 in. | $33^0$ | 21 ft. $3\frac{1}{2}$ in. | 2 ft. 7 in. | 2 ft. 0 in. | 501 | 58 | Bridge failed with 58 tons on a single jack at centre of bridge |
| 1855 (about) | Over River Oues, near Oakley, Beds. | 4 | do. | do. | 35 ft. 6 in. | 4 ft. lin. | $2^0$ | 12 ft. 7 in. | 2 ft. 8 in. | 2 ft. 1 in. | 642 | 115 | Bridge failed with 57 tons on each of two jacks at centre of span |
| 1870 | Over stream at Great Baddow, Essex. | 7 | Cast iron plates | do. | 13 ft. 0 in. | 2 ft. 10 in. | 0 | 16 ft. 3 in. | 1 ft. 7 in. | 1 ft. 0 in. | 83 | 74,6 | Bridge failed with 37.3 tons on each of two jacks at centre of span |

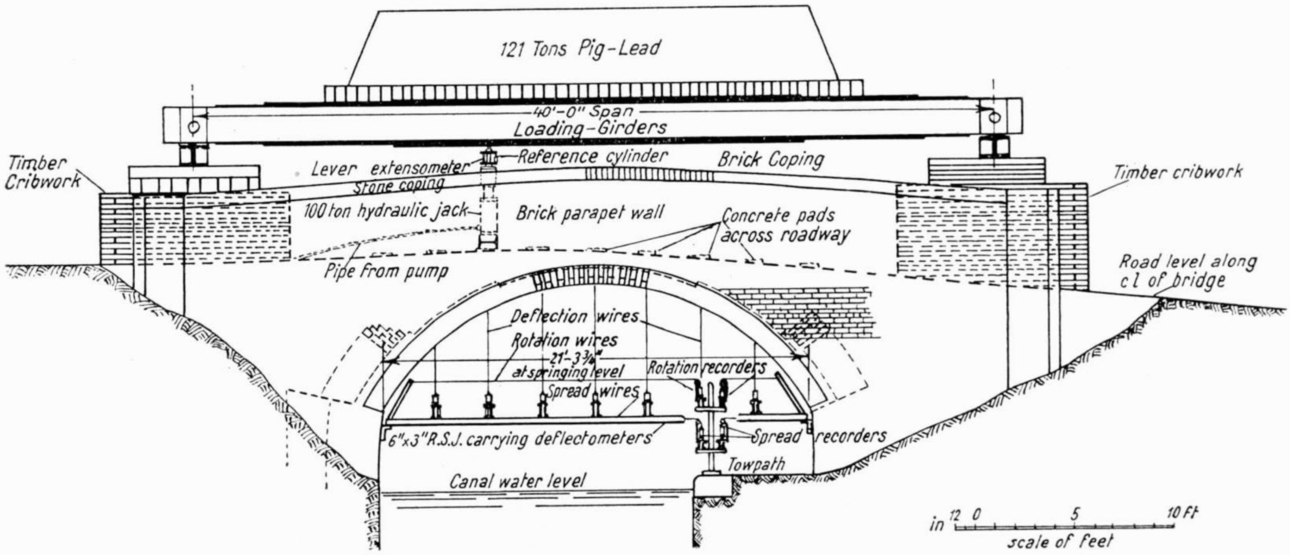


Fig. 1.
General Arrangement for Testing an Arch Bridge to Destruction

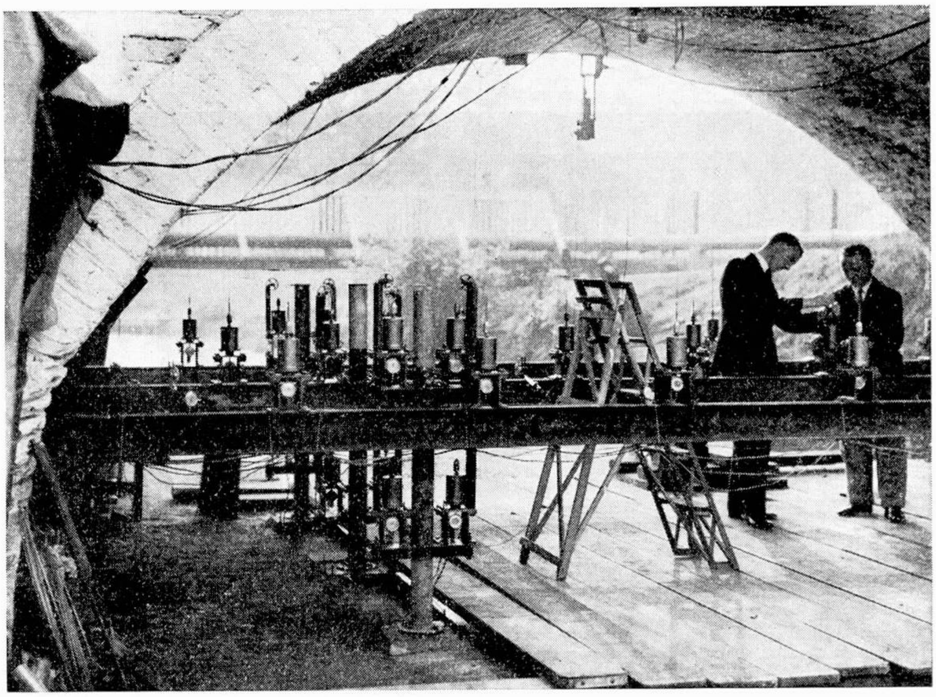

Fig. 2.

bridges, details of which are given in Table 1, were loaded to destruction. Others were tested at various stages during demolition in order to determine the dispersion and distribution of an applied load, and the strengthening effect of parapet walls, spandrel walls, filling, etc.

In the case of the bridges tested to destruction, the load was applied by means of hydraulic jacks. The thrust of the jacks was taken on two 40 ft.

Fig. 3.

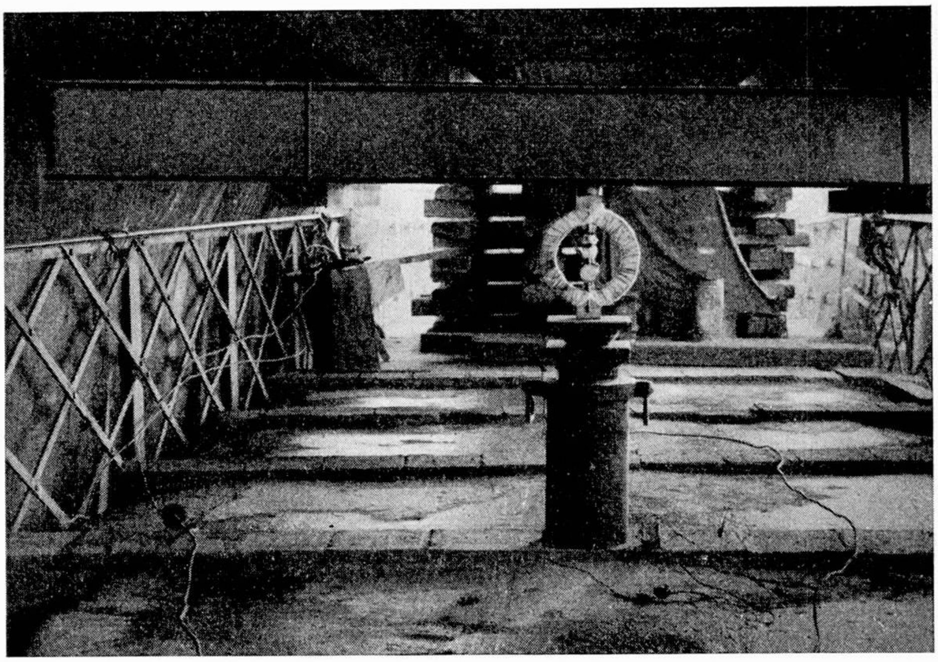

Fig. 4.

steel girders placed about 7 feet apart, parallel to the centre line of the roadway and supported on timber cribs beyond each abutment, as shown in Fig. 1. The girders carried a timber platform upon which was placed pig lead or cast iron. The load transmitted to the bridge was measured by means of proving rings inserted between the jacks and the girders of the loading platform. Before the final loading test, other tests were made to study the distortion of the structures under loads of varying intensity applied at selected positions. In the case of the arches vertical deflections were measured at the eighth points of the span on the centre line of the bridge and also at each side. Transverse spread at the crown, longitudinal spread of the arch, rotation of the abutments and strain readings at various points on the intrados and extrados were observed. A typical test arrangement is shown in Fig. 2. The tests on the cast-iron girder bridges comprised measurements of the deflection of the beams, and the strains in their upper and lower flanges. The typical test arrangement for a bridge of this type is shown in Figs. 3 and 4.

The research on arch bridges had not been completed at the outbreak of war, particularly in respect of tests to destruction, and the more fundamental mathematical investigation. The work that had been completed however, was sufficient to show clearly that such bridges have, in general, a much higher load carrying capacity than would be calculated on the basis of the strength of the arch ring alone and although the strengthening effect of the fill is of considerable scientific interest, little work on the problem has been undertaken recently in view of other more urgent commitments.

In 1942 the problem of the load assessment of bridges had again become an important and urgent matter. The Ministry of Supply wished to classify all bridges as to their military load-carrying capacity and the Station was asked by the Ministry of War Transport to make a series of tests on a selection of typical cast-iron girder and masonry arch bridges to determine the strains and deflections produced by representative military vehicles of various weights. The results of these tests were used as a basis for the assessment of similar types of bridge throughout the country. Some tests were also made on a certain number of other bridges whose assessment, according to the methods in use, was in doubt, and where it was therefore desired to have a check on the actual strains produced. In all cases the method of test was to bring the loading vehicle into position on the bridge and to measure by means of appropriate instruments, the deflection or strain, or both, at certain selected points. As a result of the work much higher military load classifications were given to many bridges, and it was also found possible to suggest an approximate method of classifying cast-iron bridges for emergency use in the field.

### *Cast-Iron Girder Bridges*

The experience and knowledge gained both in the pre-war and war-time tests on the cast-iron girder type of bridge showed that, not only do the fill and jack arches serve to distribute the load quite effectively from a loaded girder to those further from the load, but they also behave as though they formed the compression flange of a T-beam, of which the tension flange is formed by the lower part of the cast-iron girder itself. This T-beam action appears to be due to the consolidation of the fill over a period of years and to the development of a good bond between the fill and jack arches and the girder. The result is that if the strengthening and distributing action of the fill is taken into account, the stresses so calculated are very much lower and very much nearer to the observed values than are those calculated on the basis of previous methods of assessment. Unfortunately, the variability of the materials, and the behaviour of different bridges is such that it has not been possible to obtain exact agreement between the calculated and the observed values, but it has nevertheless been possible to obtain formulae which will indicate the minimum strength of a given cast-iron girder bridge and which have resulted in increased assessments of a very large number of bridges. The most important departure from the earlier methods of calculating live load stresses, agreed to by the Ministry of Transport and the Railway Companies of Great Britain, has been to consider the effective section modulus of the composite beam, that is the girder with those portions of the jack arches, filling material, and road material, which are bounded by the vertical line through the crown of the jack arch on each side of the girder — as equal to that of the bare girder multiplied by a factor $\frac{D}{d}$ where $D$ denotes the overall depth of the bridge and $d$ the depth of the girder at mid-span. In addition, in order to determine the actual load carried by one girder, the appropriate distribution co-efficient is taken as $\frac{S}{72}$ where $S$ is the girder spacing in inches. Where the girder spacing exceeds 72 inches the value of $S$ should be taken as 72.

Thus if $Z$ inches$^3$ is the section modulus of the bare girder at mid-span:
$S$ inches is the girder spacing, measured square to the girders;
and $M$ inch tons is the calculated maximum bending moment produced by the total load on the bridge, including any impact allowance,
then the live load stress $f$ for a tracked or wheeled vehicle of the normal type is given by:

$$f = \frac{M S d}{144 Z D} \text{ tons per square inch.}$$

If the vehicle is of a type which has many wheels per axle distributed across the width of the vehicle and tending to produce a line load on the most heavily laden axle of width $L$ inches, the formula becomes:

$$f = \frac{M S d}{144 Z D} \cdot \frac{2S}{L} \text{ tons per square inch}$$

(The factor $\frac{2S}{L}$ must not exceed a value of 2).

For ease of reference the above method is referred to in Mr. Mitchell's paper as the „$\frac{D}{d}$ method".

A fuller account and discussion of this work was recorded in the Journal of the Institution of Civil Engineers, 1944, 22 (8) 243—307.

*Dynamic Stress Measurements*

Although during earlier tests there had been some observations of the deflection of bridges whilst heavy traffic was traversing them, there had been no opportunity of observing the strains produced by these dynamic loadings. The growing incidence of heavy tracked vehicles, such as tanks, and of exceptionally heavy civil loads caused some concern as to the magnitude of the impact effects produced by such vehicles and at the request of the Ministry of War Transport a programme of work on this problem was begun in 1944. The investigation is still proceeding.

The bridges on which the tests were made were of typical cast-iron girder and brick jack arch construction. A comparison was made between the peak value of the strain produced at mid-span of the lower flange of a girder as a particular vehicle crossed the bridge at uniform speed with the peak value produced at the same point for static loading due to the same vehicle.

In the past the permissible stress in cast-iron girders used in Great Britain for bridges has been 2,5 tons per square inch. Latterly however, it has been felt that a somewhat higher value for this permissible stress could be adopted in cases where the dead load stress forms a big percentage of the total stress in the girders.

Attention has therefore been given to the problem by the Building Research Station and as result of the tests mentioned above and described in greater detail by Mr. Mitchell in the following paper, a formula has been produced connecting the permissible live load stress with the dead load stress. The approach to the problem has been from considerations of impact and fatigue, and the factors of safety to be adopted to cover possible variations in the properties of the materials in the estimation of the dead and live loading. The formula given in Mr. Mitchell's paper has been accepted by the Ministry of Transport and the Railway Companies with the proviso that 3 tons per square inch total stress shall not be exceeded.

It is necessary always to bear in mind that the condition of the cast-iron girders in a bridge is rarely known; that the occurrence of blowholes and slag inclusions is frequent and that even if their presence has been detected it is not possible to determine the consequent reduction in strength of the girder. Moreover, instances of the discovery of unsuspected cracks are on record.

*Investigation of Bridge Deck Specimens*

The investigations on the cast-iron girder type of bridge, to which reference has already been made, showed that there was a very considerable distribution of load, only a fraction of the applied load getting through to the girder immediately beneath it in that system of construction, and it became apparent that possibly similar effects would be observed in the case of bridges with steel girders, particularly those with jack arches. If this was found to be so a very considerable saving in steel would result, as in present methods of design it was usual to assume no distribution of load.

A fundamental investigation has therefore been started in connection with the Ministry of Transport to determine the behaviour of composite bridge deck systems.

An account of the work carried out to date at the Building Research Station is given in the paper by Dr. F. G. Thomas, and it is clear that the much improved understanding of the stress distribution which is resulting from the work will lead ultimately to considerable economy in design.

*Acknowledgements*

The work on bridges described in the three papers has been carried out as part of the research programme of the Building Research Board of the Department of Scientific and Industrial Research, and the papers are submitted by the permission of the Director of Building Research.

**Summary**

[For over ten years the Station has conducted investigations into the strength of various types of bridges. Before the last war, many tests were made on cast-iron girder bridges and masonry arch bridges, with a view to more accurate assessment of the strength of a very large number of bridges which were supposedly weak in relation to the weight of modern traffic. The work on cast-iron bridges has to some extent been published, safe working rules for calculating the strength of such bridges having been evolved and justified.

The work on arch bridges had not been completed at the outbreak of the war, particularly in respect of tests to destruction and mathematical analysis. The investigation had shown clearly, however, that such bridges have a very much higher load-carrying capacity than would be calculated on the basis of the strength of the arch ring alone and although the streng-

thening effect of the fill is of considerable scientific interest, little work on this problem has been justifiable in recent years in view of other urgent commitments.

During the war, many bridges were tested by a field team from the Building Research Station, with a view to establishing a basis for the assessment of the strength of various types of bridges to carry military traffic, or to check the strength of a particular bridge when its loading assessment was in doubt.

Since the war, fundamental research work on the strength of bridges has been recommenced, with particular regard to the possibility of evolving a design procedure which would lead to greater economy of material as a result of more accurate knowledge of the behaviour of bridges under load (see Paper by Dr. F. G. Thomas).

Dynamic loading tests have also been made on cast-iron girder bridges (see Paper by Mr. G. R. Mitchell).

## Zusammenfassung

Die von der Building Research Station durchgeführten Festigkeitsuntersuchungen an verschiedenen Brückentypen erstreckten sich über mehr als zehn Jahre. Vor dem letzten Krieg wurden zahlreiche Messungen an Balkenbrücken aus Gußeisen und Natursteinbrücken durchgeführt, mit der Absicht, die Tragkraft einer großen Anzahl Brücken, die für die Belastungen des modernen Verkehrs als zu schwach betrachtet wurden, genauer zu bestimmen. Die Ergebnisse der Untersuchungen an Gußeisenbrücken sind teilweise bereits publiziert, zuverlässige Dimensionierungsregeln wurden entwickelt und durch die Messungen überprüft.

Die Arbeiten über Bogenbrücken waren bei Kriegsausbruch noch nicht abgeschlossen, vor allem fehlten noch Zerstörungsprüfungen und genauere analytische Untersuchungen. Aber die vorliegenden Ergebnisse zeigten bereits klar, daß diese Brücken eine weit größere Tragkraft besitzen, als die Berechnung mit Berücksichtigung des Bogens allein ergibt. Trotzdem der versteifende Einfluß des Überbaus von beträchtlichem wissenschaftlichem Interesse ist, konnten in den letzten Jahren nur wenige Untersuchungen, die dieses Problem behandeln, wegen anderer dringender Verpflichtungen, überprüft werden.

Während des Krieges wurden viele Brücken durch eine mobile Abteilung der Building Research Station geprüft, um die Tragkraft verschiedener Typen im Hinblick auf den Militärverkehr zu ermitteln oder auch um die Tragfähigkeit einer speziellen Brücke zu bestimmen, wenn darüber Zweifel bestanden.

Nach Beendigung des Krieges wurden die grundlegenden Forschungsarbeiten über die Tragkraft von Brücken wieder aufgenommen, um ein Be-

rechnungsverfahren zu entwickeln, das auf Grund der genaueren Erfassung des Kräftespiels zu Einsparungen im Materialverbrauch führt. (Vergleiche Bericht von Dr. F. G. Thomas.)

Es wurden auch Messungen an Balkenbrücken aus Gußeisen unter dynamischen Belastungen durchgeführt. (Vergl. Beitrag von G. R. Mitchell.)

## Résumé

Les essais de résistance effectués par la Building Research Station sur différents types de ponts se sont étendus sur plus de dix ans. Avant la dernière guerre, de nombreuses mesures ont été faites sur des ponts à poutres pleines en fonte et sur des ponts en pierre naturelle, en vue de contrôler d'une manière précise la capacité de charge d'ouvrages considérés comme trop faibles pour le trafic moderne. Les résultats des investigations effectuées sur des ponts en fonte ont déja été publiés en partie. Des règles sûres ont été mises au point pour le calcul et ont fait l'objet de vérifications par mesures effectives.

Les recherches portant sur les ponts arqués n'étaient pas encore terminées au début de la guerre; en particulier, des contrôles de destruction et des investigations d'ordre analytique plus précises manquaient encore. Les résultats acquis montraient toutefois déjà nettement que ces ponts possédaient une capacité de charge beaucoup plus grande que celle qu'indiquait le calcul basé sur la seule prise en compte de l'arc. Bien que l'influence du renforcement exercé par la superstructure présente un intéret considérable du point de vue scientifique, des tâches plus urgentes n'ont pas permis d'étudier cette question d'une manière très approfondie au cours de ces dernières années sur la base des travaux déjà publiés à ce sujet.

Pendant la guerre, de nombreux ponts ont fait l'objet de vérifications par une équipe mobile de la Building Research Station; il s'agissait de contrôler la capacité de charge de différents types d'ouvrages du point de vue du trafic militaire, voire même de vérifier la résistance de tel ou tel pont particulier en cas de doute.

Après la guerre, les investigations d'importance primordiale sur la capacité de charge des ponts ont été reprises en vue de la mise au point d'une méthode de calcul permettant de réaliser des économies de matériaux, grâce à une connaissance plus précise de la répartition des efforts (voir le rapport du Dr. F. G. Thomas).

Il a été également procédé à des mesures sur ponts — poutres en fonte soumis à des charges dynamiques (voir le rapport de G. R. Mitchell).