(Paper No. 3066.)

“A Simple Method of Bonding the Brickwork of a Square Arch with Oblique Faces.”

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THE method of construction described in this Paper was carried out in developing one of the oblique arches on the Leicester to Rugby section of the Great Central Railway. The arch was constructed under a heavy embankment with very flat slopes, and, the bridge being only 70° askew, it was thought advisable to build

the central portion of the arch square, turning the faces only on the skew, thus making the greater portion of the arch simpler to build, and, at the same time, ensuring greater strength where there was most weight. The junction of the square and skew portions of the arch was effected by a series of curved courses, none of the bricks of which were cut. The additional courses in the skew-faces were run out along the impost, special stone springers being made to receive them. The lettering adopted by the late Mr.

G. W. Buck,¹ M. Inst. C.E., has been followed as far as possible in *Figs. 1, 2 and 3*, the usual preliminary calculations being omitted, as they can be easily deduced from his formulas.

The following are the general particulars of the bridge:—

Radius of arch, r (c D, <i>Fig. 2</i>)	13·45 feet.
Thickness of arch, e (DF, <i>Fig. 2</i>)	1·92 „
Span on square, c (AB, <i>Fig. 1</i>)	26·00 „
Span on skew (AG, <i>Fig. 1</i>)	27·668 „
Arc of segment, a (BL, <i>Fig. 1</i>)	35·276 „
Heading spiral (GL, <i>Fig. 1</i>)	36·523 „
Length along springing to perpendicular from acute) quoins (GB, <i>Fig. 1</i>)	9·463 „
Angle of obliquity, θ (AGB, <i>Fig. 1</i>)	70°
Angle subtended at centre of circle by arc (AOG, <i>Fig. 3</i>)	150° 16' 28"
Angle of heading spiral (BLG, <i>Fig. 1</i>)	15° 1'
<i>Skew-face—</i>	
Span of ellipse (ag, <i>Fig. 3</i>)	28·626 feet.
Thickness of arch (ea, <i>Fig. 3</i>)	2·043 „

It is first necessary to find the angle of the springers on the face (G K, *Fig. 3*), so as to fix the skewback and the height of

Fig. 2.

Fig. 3.

Scale, 1 inch = 20 feet.

springers at the face of the arch. The eccentricity of the face, or focal distance below the axis of the cylinder in the oblique segment (c O, *Fig. 3*), is found from the following formula—

$$c O = \frac{c \cot^2 \theta}{a} (r + e)$$

substituting the values in the above list, C O = 1·501.

The distances G H and H K have now to be found, so as to fix the width and height of the quoin springers on the face. The positions of the points O and G on the line O G K are known, and

¹ "A Practical and Theoretical Essay on Oblique Bridges," by G. W. Buck, 4th Edition, London, 1895.

also the extradosal ellipse $e F J j$. From these the point K (the intersection of the straight line and the ellipse) can be found relatively to the axes ecj and $O c F$. Taking first the points O and G on the line O G K—

$$O - x_i = o \text{ and } y_i = -1.501 \text{ foot, or CO.}$$

$$G - x_{ii} = 13.834 \text{ feet or } \frac{\text{skew-span}}{2} \text{ or } \frac{AG}{2}.$$

$$y_{ii} = 3.45 \text{ feet, or distance of centre of circle below springing line.}$$

Substituting these values in the equation to a straight line when two points are given—

$$\frac{y - y_i}{x - x_i} = \frac{y_{ii} - y_i}{x_{ii} - x_i}$$

$$\frac{y + 1.501}{x - o} = \frac{3.45 \text{ feet} + 1.501 \text{ foot}}{13.834 \text{ feet} - o} = \frac{4.951 \text{ feet}}{13.834 \text{ feet}}$$

and simplifying, it is found that

$$x = 2.794 y + 4.194 \text{ feet} \quad . \quad . \quad . \quad (1)$$

Now, taking the ellipse $e F j$,

$$\frac{1}{2} \text{ major axis} = ea + \frac{ag}{2} = 16.356 \text{ feet} = a$$

$$\frac{1}{2} \text{ minor axis} = r + e = 15.37 \text{ feet} = b;$$

substituting these values for a and b in the equation to the ellipse:—

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$\frac{x^2}{(16.356)^2} + \frac{y^2}{(15.37)^2} = 1$$

and simplifying,

$$x^2 = 267.519 \text{ feet} - 1.133 y^2 \quad . \quad . \quad . \quad (2)$$

Substituting the value of x from equation (1) in equation (2) and solving it for y , the ordinates of the point of intersection K are found to be—

$$x = 15.753 \text{ feet and } y = 4.137 \text{ feet,}$$

and deducting CG from x or CH and Cc from y , then—

$$GH = 1.919 \text{ foot}$$

$$\text{and HK} = 0.687 \text{ ,,}$$

From these dimensions the faces of the quoin springers can be accurately worked.

The next consideration is the main development of the arch and the method of dealing with the courses. It had already been found that four courses of the bricks in use on the work, with joints, made 1 foot $1\frac{1}{4}$ inch, enabling the number of courses required for the square and skew portions of the arch to be determined. First taking the square arch: the length of the segment, B L, *Fig. 1*, is 35.276 feet; by trial it is seen that the nearest number of courses that will go into the length is one hundred and twenty-eight of 0.2755 foot each, or 1 foot $1\frac{1}{4}$ inch bare for four courses. Similarly, for the skew portion, the length of the heading spiral, L G, *Fig. 1*, to be divided is 36.523 feet; this will require one hundred and thirty-two courses of 0.2767 foot each, or 1 foot $1\frac{1}{4}$ inch full for four courses. Thus four courses more are contained in the skew than in the square portion of the arch. These will have to be dealt with along the impost line.

The checks cut in the springers to receive the spiral courses of bricks on the skew arch are calculated in the usual way as follows—

$$\begin{aligned} \text{MN (Fig. 1)} &= \text{two courses of bricks} = 2 / 0.2767 \text{ foot} \\ &= 0.5534 \text{ foot, or } 6\frac{5}{8} \text{ inches full,} \\ \text{the angle MLN} &= \beta = 15^\circ 1' \\ \text{and angle LMN} &\text{ is a right angle.} \end{aligned}$$

Solving the triangle, the length of the check along the springing line—

$$\text{LN} = 2.1355 \text{ feet}$$

and the perpendicular M P, or the distance of the check round the arch on square section (A P, *Fig. 2*) = 0.535 foot. The checks have been taken for two courses, this making stones of convenient size, and four are put in along the springing, thus making the length of skew arch 8.542 feet.

Taking now the acute side of the arch: the skew courses are at an angle of $15^\circ 1'$ (β); with the square courses this necessitates a piece of curved arch to run them in tangentially and avoid any cutting of bricks. By trial it is found that two courses will be a convenient number to use, and from this the radius of the circle describing the upper face of the next springer may be determined. The same calculation also fixes its length.

The angle at the centre, $\beta = 15^\circ 1'$, and the versine RS = two courses on the square = 0.551 foot, hence the radius—

$$\text{QT} = \frac{\text{RS}}{\text{versin } \beta} = \frac{0.551 \text{ foot}}{\text{versin } 15^\circ 1'} = 16.135 \text{ feet,}$$

and the length of the check—

$$\begin{aligned} QR &= QT \sin \beta = 16.135 \times \sin 15^\circ 1' \\ &= 4.179 \text{ feet.} \end{aligned}$$

On the obtuse side the case is reversed. Having taken two of the courses on the straight, on the acute impost to run the skew joints in tangential to the square, it naturally follows that six will now have to be got rid of along the springing line on the obtuse side, namely, the four in excess on the skew portion of arch, together with the two used as explained. If a flatter curve had been necessary on the acute side, and more courses had been taken, the extra number would have had to be worked out along the springing on the acute side. This is governed by the particular case under consideration. WV , in *Fig. 1*, are the six courses that require dealing with, and equal 1.66 foot. The angle at the centre of circle, WUX , is the same as before— $\beta = 15^\circ 1'$.

Accordingly the versine

$$\begin{aligned} XY &= WV \cos \beta = 1.66 \cos 15^\circ 1' \\ &= 1.6033 \text{ foot,} \end{aligned}$$

and the radius of circle VX , running out tangentially to the obtuse impost at the point X , *Fig. 1*; being the line followed by the sixth joint, will be equal to

$$\frac{XY}{\text{versin } \beta} = \frac{1.6033}{\text{versin } 15^\circ 1'} = 46.95 = UV.$$

Concentric circles described from the other joints give the points at which they cut the springing line, and also fix the length of the stones along the impost. It was found most convenient, for the lengths of these stones, to first take a check for one course only (marked No. 5), and then two checks for two each (Nos. 3 and 4). This arrangement leaves an odd course at B ; but, as will be seen from *Fig. 1*, a single check at the obtuse quoin G has been cut below the springing line in order to make the obtuse and acute quoins symmetrical on the face. This leaves an odd course also on the skew portion of the arch, which, being worked in with the other odd one at B , makes the double check marked No. 2, a part of it being straight and the remainder struck to the proper curve for the first joint.

The lengths of these checks were calculated by taking parallel arcs to the circle VX according to the number of courses, 1, 3,

and 5, and calculating the lengths of the chords for the respective versines. Thus for check No. 5—

$$R = \text{radius} = 46.95 \text{ feet} + 0.2767 \text{ foot} = 47.2267 \text{ feet.}$$

$$O = \text{versine} = 0.2767 \text{ foot.}$$

$$\begin{aligned} \text{length of check} &= \text{tangent} = \sqrt{O(2R-O)} \\ &= 5.1048 \text{ feet.} \end{aligned}$$

For check No. 4 the total length of the tangent from the point X is first found, and the length of check No. 5 deducted, and so on for the others.

The radius at the centre of the arch was found in the same manner as at the acute springing. In this case, it will be seen from *Fig. 1* that the joint—four courses to the left on the skew portion of the arch—has to be run into the joint at the centre of the arch on the square portion. This gives a distance along the heading spiral of 1.1067 foot, and, the angle β still being the same, the versine will be found to equal 1.069 foot and the radius 31.297 feet.

The development, *Fig. 1*, shows that the locus of the centres of the circles describing the joints of the courses travels along the heading spiral produced, viz., from T to U. Also the line of contact of the square arch with the curved portion is not square to the axis, but slightly inclined (line RX). This variation from the square is equal to the perpendicular from the point U on the line TR, and is found by adding GB, LQ, and QR together and deducting GW and WX.

Thus—	GB	=	9.463 feet.	
	LQ	=	8.542 "	
	QR	=	4.179 "	
			<hr/>	22.184 feet.
Deduct	GW	=	8.542 feet.	
	WX	=	12.595 "	
			<hr/>	21.137 feet.
Variation from square		=	<hr/> 1.047 feet.	

This can also be found by multiplying the length TU by $\sin \beta$.

The lines were set out on the laggings for the bricklayers as follows: First, the face-lines of the arch were laid down on the centres, and from them the heading spirals at the faces; the heading spirals at the back of the skew-faces were next drawn in. On these lines every fourth course was pricked with dividers, and

marked with small nails. The coursing spirals were now filled in between them by means of a bending lath. The tangential line RX was then laid down at both ends of the square arch, and the courses were marked on it as before. The correct positions of the curved courses were now found by calculating the versine for about every sixteenth joint and lining in the curve thus found with a bending lath, care being taken to make the lines come tangential to those already laid down on the skew square arch; the intermediate joints were then put in, the spaces being measured out with dividers. The impost stones gave the curved lines at the springing. The bricklayers found no more difficulty in laying the bricks to the curved portion of the arch than to the square part. The two inner rings of the arch were built in English bond, and the back rings were bonded wherever two of them came flush.

To find the height of springers at the extrados of the arch as shown on square section, *Fig. 2*. The radius of arch and the thickness—

$$r + e = 15.37 \text{ feet.}$$

The distance round the arch for two courses (the height of check in *Fig. 1*) has already been calculated—

$$AP = 0.535 \text{ foot.}$$

Proportionately the height of check at the back is found to be 0.611 foot. By the table of circular measure the angle at the centre AcP for radius r and arc AP is $2^\circ 16' 44''$.

The angle AcD has already been given—

$$= \frac{150^\circ 16' 28''}{2} = 75^\circ 8' 14''$$

deducting AcD from 90° ,

the remainder, $LAcQ$	$= 14^\circ 51' 46''$
and adding $LAcP$	$= 2^\circ 16' 44''$
the whole angle $p c q$	$= 17^\circ 8' 30''$

Multiplying the sine of this angle by the extradosal radius, the height $p q$ is determined—

$$\begin{aligned} p q &= (r + e) \sin p c q \\ &= 15.37 \text{ feet} \sin 17^\circ 8' 30'' \\ &= 4.53 \text{ feet.} \end{aligned}$$

Deducting the height Cc or Qq , the height of the springer above

the impost line is 1·08 foot ($4\cdot53$ feet $- 3\cdot45$ feet) = 1 foot 1 inch. Adding the depth of stone below springing (also 1 foot 1 inch), and the total depth of springers (viz., 2 feet 2 inches) for the ordinary double checks on skew portion of arch is obtained. The springer No. 5 will not be the same height as the check is for one course only. This height, as well as the exact heights of checks Nos. 3 and 4, were found by laying down the development full size on a platform, from which also the zinc templets for all the checks themselves were made, as well as the bed and joint moulds required for the masons.

The Engineer for the work referred to was Mr. E. Parry, M. Inst. C.E., of Nottingham, the contractors being Messrs. Topham, Jones & Railton.

The Paper is accompanied by three drawings, from which the Figures in the text have been prepared.

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