A P P E N D I X

to the

"STRENGTH OF MASONRY ARCHES".

TEST OF ARCH NO. 3.

By

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DATA & DIMENSIONS OF ARCH NO. 3.

Built,	-	March 1912.
Tested,	-	May 1912.
Type of arch,	-	Segmental Hingeless Brick Arch.
Span,	-	10 feet.
Rise,	-	11.50 inches.
Radius,	-	13 feet.
Width,	-	3 feet 1½ inches.
Angle subtended,	-	42 degrees.
Thickness,	-	9½ inches (one brick two rings).
Material,	-	Common wire cut red bricks.
Joints,	-	3-1 Portland Cement mortar; no joint less than ½" thick.
Bond,	-	All stretchers, no inter-annular bond.
Built,	-	18th. 19th. 20th. & 25th. March.
Centres dropped,		2nd. April.
Minimum interval,		8 days.
Tested,	-	10th. May.
Interval,	-	46 days.
Method of loading,		Hydraulic pressure.
Distribution of load,		Uniform - by sand fill.
Method of measuring,- Deflections,		"Deflectograph" and "Deflectometer" for crown.

Method of measuring

Horizontal thrust, - Extensometer as before.

The arch was tested in the following manner.

(1) Load taken up to 15.8 tons (35400 lbs.) at intervals of about 2000 lbs. from 3 tons, (redisual load).

(2) Procedure repeated.

(3) Load taken straight up from 3 tons to 9½ tons 21,100 lbs.) and from thence by intervals of about 6000 lbs. to the breaking load 42.25 tons (94700 lb s.)

Readings were taken at each addition of load.

IMPROVEMENTS IN APPARATUS.

The author mentioned at the end of Chapter 4. the substitution of a zinc plate for the tracing cloth and carbon paper in the Deflectograph. This has been adopted with superior results. The attachment of the spring on the Deflectograph has been altered, so that the decrease in effective leverage owing to the

obliquity of the "roller" arm, is balanced by the increased compression of the spring. Thus the roller is pressed more uniformly against the intrados of the arch. The proposed "Deflectometer" has also been added. This is a very simple apparatus and gives excellent results. It consists of a needle pointer embedded in the arch, and moving along a steel scale graduated in hundredths of an inch. The scale is supported from a length of angle iron which rests on and is fastened to the skewbacks.

Owing to the unavoidable absence of the author it was found impossible to provide an additional extensometer as desired.

RESULTS OF TEST NO. 3.

The numerical results will be found tabulated in table 4. and plotted in Plates 17, 18, and 19.

Photographs of the fracture appear in Plates 15 & 16.

DISCUSSION OF TEST NO. 3.

This test was successfully carried out and good results have been obtained.

The vexed question of the horizontal thrusts has not been completely solved. The values agree fairly well with theory this time as will be seen from the curves, but the divergence of the results in Test No. 2 are still unexplained. All the measurements were taken by the author, and the extensometer was exactly the same in both cases. It will be seen from Column 15 where the radius of the line of stress (according to Navier's principle) is tabulated, that with the increase of load the radius at the crown in general diminishes. This is quite in accordance with the Catenary Theory which says that as the load potential increases the curvature of the line of stress at the crown becomes

sharper, and the line of stress moves higher up in the arch ring.

The deflections were too small to measure on the "Deflectograph", but were accurately recorded by the "Deflectometer". They agreed very well with Test 2. A comparatively large permanent set occurred after the first loading, but this was only very slightly increased at the end of the second. The arch seemed to have periods of "stiffness" after increases in deflections, akin to metals after the yield point has been passed. The curves of Deflection against Horizontal Thrust seem to follow a fairly straight line, particularly in the second and third series. During the test the arch appeared to bend to quite a considerable extent in a horizontal plane, (that is, in the direction of its width), - a most peculiar occurrence. It was

best noticed when the load was taken off. The arch moved back "sideways" quite visibly.

The first cracks occurred at the springings ~~with~~ at a load of 65500lbs. ~~in the~~ similar to the second test. A slight superficial crack in one of the bricks was noticed at a much lower load, but it was due to the superior strength of the neat cement pointing shearing the edge of the bricks. At a load of 79900 lbs. the cracking became serious, and the bricks began to spall off badly at the springings, thus showing that they were crushing. When the load reached 87,700 lbs. it was clear that the arch was failing. As the load was further increased a curious thing happened. The arch began to crush and buckle just to the right of the crown. From the second to the seventh brick from the centre the arch ring crushed. Longitudinal cracks from the springing upwards to that point formed, the two rings separated.

a reverse curve set in, the joints opened, and the arch FAILED and came down on the centres, after having supported a total load of 94,700 lbs. (42.25 tons). But the end was not yet reached when the arch came down on the centres. The pressure was released. The arch ROSE two inches, although it was apparently totally crushed, and was actually sagging at the point where failure occurred. The centres were then lowered about couple of inches and the load was re-applied. It reached almost its former amount, and the arch again descended on the centres. For the second time the pressure was released and the arch AGAIN rose, but to a less extent. The centres having been lowered another few inches the pressure was again applied. The arch fell on the centres for the third and final time, and when the load was removed it was evident that complete failure had at last occurred.

It was most remarkable how an arch in such a deplorable condition could still support a heavy load.

The photographs show the nature of the fracture quite clearly.

The joints only began to open when the bricks crushed, thus bearing out the author's statement to that effect in Chapter 2.

Until the arch began to fail the two brick rings each took their fair share of the thrust, for no apparent shearing or separation took place between them.

It was noticed that the skewbacks were considerably deformed at the end of the test. The bolts were sheared and the webs of the I Beams were buckled. It is doubtful, however, whether this had much effect on the failure as the skew back plates were hardly damaged at all.

New skewbacks, tie rods and bearing plates

will be needed for the next arch.

The cause of failure of both Arch No. 2 and Arch No. 3 was undoubtedly the crushing of the bricks.

TABLE IV.

SYNOPSIS OF RESULTS.

Average Compressive Strength of one brick,	-	107,000 lbs.
do. do. per sq. ft.	-	380,000 lbs.
do. do. of mortar joint.	-	38,920 lbs.
do. do. per sq. ft.	-	138,000 lbs.

(From test 2 as owing to misunderstanding no joints were tested in compression for test 3.)

Average Compressive Strength 3" cube of Cement Mortar-		2,890 lbs.
do. do. per sq. ft.	-	46,900 lbs.
Average cohesive strength of 1 joint,	-	180 lbs.
do. do. per sq. ft.	-	640 lbs.
Total load on Arch at 1st. crack,	-	65,500 lbs.
do. per sq. ft.	-	2,783 lbs.
Total Horizontal Stress,	-	75,000 lbs.
do. do. per sq. ft.-		30,000 lbs.
Deflection at Crown,	-	0.44 inches.
Total load on Arch at failure,	-	94,700 lbs.
do. per sq. ft. do.	-	3,156 lbs.
do. Horizontal Stress, do.	-	117,500 lbs.
do. do. per sq. ft.	_	48,000 lbs.
Previous Deflection, per sq. ft.		1.42 inches.
Percentage of Strength of one joint,	- $\frac{48,000}{1,380}$	- 34.8%

	Load. lbs.	Load per sq. ft. lbs.	Extensions. Top. Front. inches.	Bottom. Front. inches.	Top. Back. inches.	Bottom. Back. inches.	Mean. inches.	Actual. inches.	Total stress. lbs.	ft. lbs.	lin. ft. lbs.	l. f. Elas. Theory.	Actual Theor.	Ratio thrus load.
*	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0	0	0	0	-	
*	3060	102	-	-	-	-	-	0.004	5340	2175	1780	1275	1.390	17.45
*	6300	210	-	-	-	-	-	0.008	10680	4350	3560	2625	1.350	17.45
*	6300	210	-	-	-	-	0.000	0.008	10680	4350	3560	2625	1.350	16.91
	8300	276	0.0005	0.0005	0.002	0.002	0.001	0.0092	12250	4900	4083	3450	1.180	16.91
	10660	355	0.001	0.002	0.004	-	0.002	0.0105	13400	5700	4466	4437	1.006	14.79
	12720	424	0.002	0.005	0.004	-	0.004	0.012	16000	6400	5333	5300	1.004	12.95
	14880	496	0.003	0.007	0.005	-	0.005	0.013	17300	6900	5766	6200	.930	12.60
	17320	577	0.004	0.009	0.006	-	0.006	0.0145	19400	7750	6466	7212	.895	11.60
	19580	653	0.005	0.010	0.007	-	0.007	0.0155	20600	8250	6866	8162	.840	11.20
	22040	735	0.006	0.012	0.011	-	0.010	0.018	24000	9600	8000	9200	.869	10.50
	24480	816	0.008	0.014	0.014	-	0.012	0.020	26600	10600	8866	10200	.869	10.89
	26640	886	0.010	0.016	0.017	-	0.014	0.022	29400	11800	9800	11075	.885	10.88
	28800	960	0.011	0.018	0.020	-	0.016	0.024	32000	12800	10666	12000	.889	11.01
	31000	1030	0.013	0.020	0.021	-	0.018	0.026	34600	13800	11533	12960	.891	11.10
	33200	1106	0.014	0.021	0.022	-	0.019	0.027	36000	14400	12000	13900	.865	11.15
	35400	1180	0.015	0.023	0.023	-	0.020	0.028	37400	15000	12466	14800	.843	10.84
*	6300	210	-	-	-	-	-	0.008	10680	4350	3560	2625	1.350	10.54
	8300	276	0.001	0.002	0.004	0.002	0.002	0.010	13300	5400	4433	3450	1.283	16.91
	10660	355	0.004	0.006	0.006	0.004	0.005	0.013	17300	6900	5766	4437	1.300	16.04
	12720	434	0.007	0.009	0.005	0.009	0.008	0.016	21400	8600	7133	5300	1.340	16.70
	14880	496	0.010	0.012	0.013	0.011	0.011	0.019	25400	10800	8466	6200	1.365	16.80
	17320	577	0.013	0.015	0.015	0.013	0.014	0.022	29400	11800	9800	7212	1.355	17.00
	19580	653	0.014	0.017	0.017	0.015	0.016	0.024	32000	12800	10666	8162	1.310	16.99
	22040	735	0.016	0.020	(0.023)	0.017	0.018	0.026	34600	13800	11533	9200	1.249	16.30
	24480	816	0.017	0.020	0.025	0.018	0.020	0.028	37400	15000	12466	10200	1.221	15.68
	26640	866	0.020	0.021	0.028	-	0.023	0.031	41300	16500	13766	11075	1.239	15.30
	28800	960	0.020	0.024	0.031	-	0.024	0.032	42600	17000	14200	12000	1.180	15.80
	31000	1030	0.021	0.025	0.032	-	0.025	0.033	44000	17600	14666	12960	1.135	14.79
	33200	1106	0.022	0.027	0.034	-	0.028	0.036	48000	19200	16000	13900	1.149	14.20
	35400	1180	0.025	0.028	0.035	-	0.029	0.037	49000	19600	16333	14800	1.100	14.40
*	6300	210	-	-	-	-	-	0.008	10680	4350	3560	2625	1.350	13.79
	6300	210	-	-	-	-	-	0.008	10680	4350	3560	2625	1.350	16.91
	21100	703	0.025	0.024	(0.030)	-	0.025	0.033	44000	17600	14666	8800	1.438	16.91
	25900	863	0.027	0.027	(0.035)	-	0.027	0.035	46600	18700	15533	10800	1.438	20.95
	33100	1106	0.031	0.032	(0.042)	-	0.032	0.040	53300	21500	17766	13800	1.285	17.99
	41900	1396	0.036	0.033	(0.045)	-	0.035	0.043	57400	23000	19133	17400	1.100	16.00
	46300	1543	0.036	0.035	(0.045)	-	0.035	0.043	57400	23000	19133	19400	.984	13.71
	52560	1752	0.040	0.041	(0.057)	-	0.041	0.049	65000	26000	21666	22000	.989	12.39
	58700	1956	0.042	0.043	(0.057)	-	0.044	0.052	69200	27750	23066	24400	.950	12,36
*	65500	2183	0.048	0.047	(0.063)	-	0.048	0.056	75000	30000	25000	27300	.918	11.81
	72300	2410	0.054	0.050	(0.069)	-	0.054	0.062	83000	33100	27660	30100	.918	11.42
*	79900	2663	0.061	0.054	0.076	-	0.061	0.069	92000	36800	30666	33400	.918	11.42
*	87700	2923	0.068	0.058	0.080	-	0.067	0.075	100000	40000	33333	36600	.908	11.38
	94700	3156	0.081	0.063	-	-	0.080	0.088	117500	48000	39166	39500	.991	12.39
	2	3	4	5	6	7	8	9	10	11	12	13	14	15

EXPLANATION OF TABLE.

Column.

1. No. of reading.
2. Total load on Arch.
3. Load per sq. ft. - Total load/Area.
4,5,6,7, Differences from extensometer readings.
8. Mean elongation on 100 inches.
9. Total elongation (Mean - Residual).
10. Total Horizontal thrust.
11. Mean compressive stress per sq. ft. on cross section of arch ring.
12. Stress per lineal foot of Arch ring.
13. Theoretical stress per lineal foot.
14. Ratio - Actual/Theoretical.
15. Radius of line of stress.
16 & 18. Not taken this test.
17. Rise of Arch of Crown from "Deflectometer".
19. Total deflection from unloaded profile.
20. Deflection from No. 3 (6,300 lbs.)
21. Deflection beyond first permanent set.
22. No. of reading.

REFERENCE

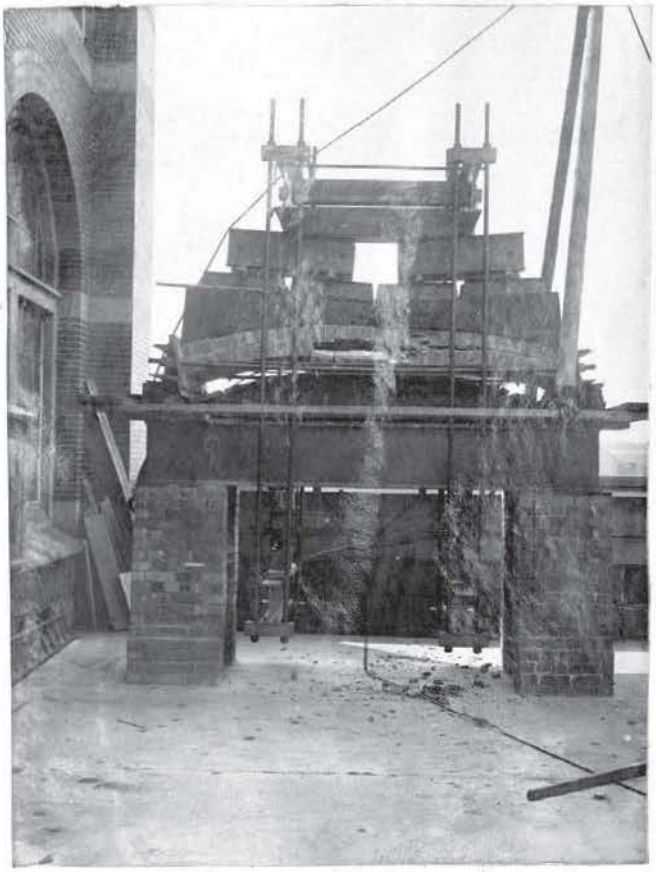
Line No.

1. * No load.
2. * 3060 lbs. of sand on Arch.
3. * All apparatus on top of Arch. Total load 6,300 lbs.
4. * Commencement of test. Permanent or residual load 6,300 lbs.
18. /// 1st. series completed. Load back to 6,300 lbs. 2nd. series begun.
32. /// 2nd. series completed. Load back to 6,300 lbs, Final series begun.
41. /// First appearance of cracks of any importance (at springings).
43. /// Bricks spalling off at springings.
44. Arch beginning to fail.
45. Crushing and Buckling near Crown.

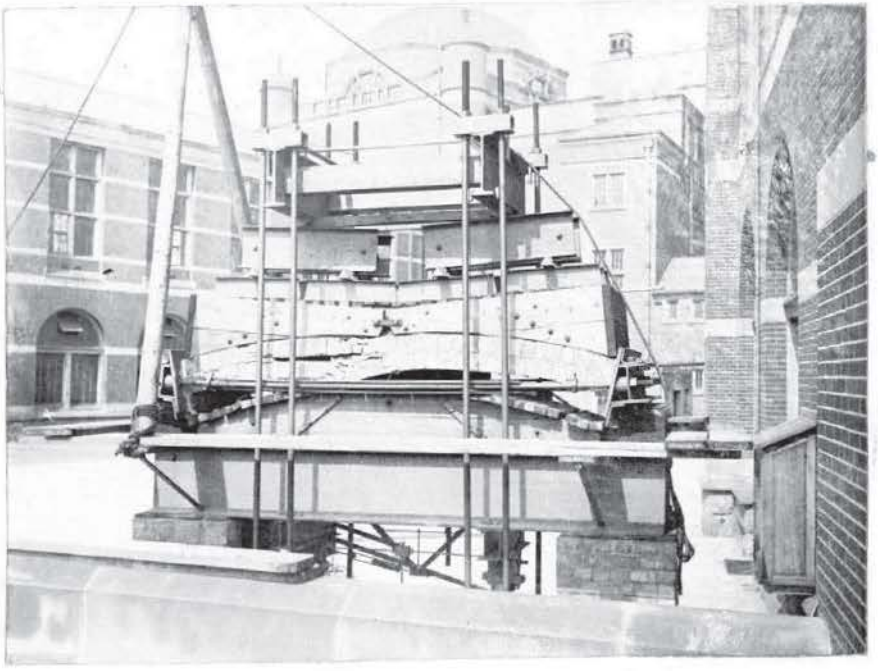
FAILURE.

Rise Crown inches.	DEFLECTION AT CROWN, Total, inches	Unit Defl.n inches,	permset. inches,	No.
11.50	0.00	0.00	-	1.
11.495	0.005	0.00	-	2.
11.49	0.01	0.00	-	3.
11.49	0.01	0.00	-	4.
11.49	0.01	0.00	-	5.
11.49	0.01	0.00	-	6.
11.48	0.02	0.01	-	7.
11.47	0.03	0.02	-	8.
11.45	0.05	0.04	-	9.
11.44	0.06	0.05	-	10.
11.43	0.07	0.06	-	11.
11.42	0.08	0.07	-	12.
11.39	0.11	0.10	-	13.
11.38	0.12	0.11	-	14.
11.37	0.13	0.12	-	15.
11.36	0.14	0.13	-	16.
11.35	0.15	0.14	-	17.
11.45	0.05	0.04	0.00	18.
11.45	0.05	0.04	0.00	19.
11.44	0.06	0.05	0.01	20.
11.43	0.07	0.06	0.02	21.
11.42	0.08	0.07	0.03	22.
11.41	0.09	0.08	0.04	23.
11.39	0.11	0.10	0.06	24.
11.38	0.12	0.11	0.07	25.
11.38	0.12	0.11	0.07	26.
11.37	0.13	0.12	0.08	27.
11.36	0.14	0.13	0.09	28.
11.34	0.16	0.15	0.11	29.
11.33	0.17	0.16	0.12	30.
11.33	0.17	0.16	0.12	31.
11.44	0.06	0.05	0.01	32.
11.44	0.06	0.05	0.01	33.
11.28	0.22	0.21	0.17	34.
11.25	0.25	0.24	0.20	35.
11.20	0.30	0.29	0.25	36.
11.17	0.33	0.32	0.28	37.
11.16	0.34	0.32	0.28	38.
11.14	0.36	0.35	0.31	39.
11.10	0.40	0.39	0.35	40.
11.06	0.44	0.43	0.39	41.
11.01	0.49	0.48	0.44	42.
10.95	0.55	0.54	0.50	43.
10.83	0.67	0.66	0.62	44.
10.08	I.42	1.41	1.37	45.

Plate 15



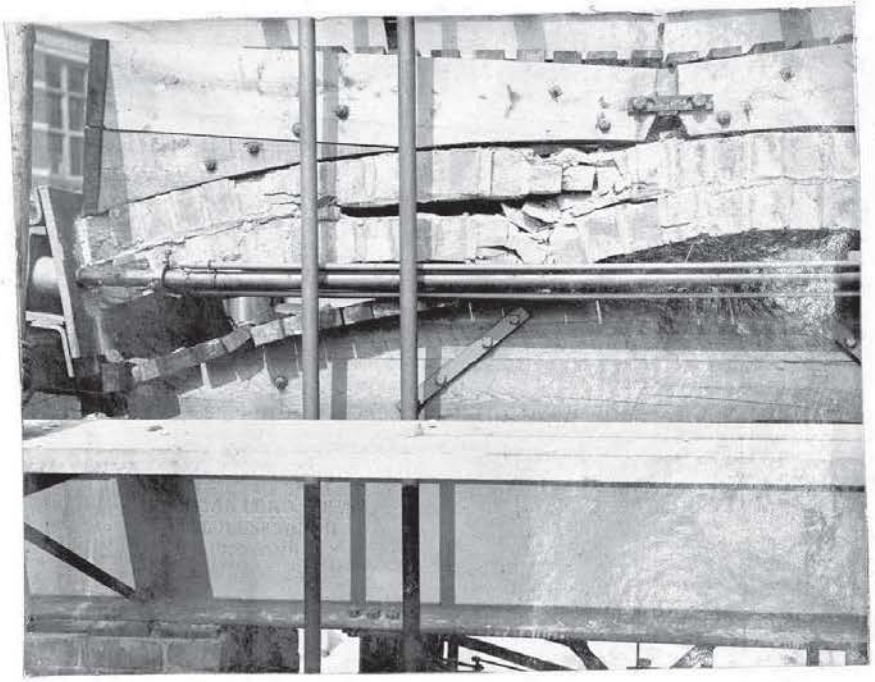
Arch No.3. Final Stage



Arch No.3. Final Stage (Back View)

VCA
1912

Plate 16



Arch No.3. Near View of Fracture

WJA.
1912

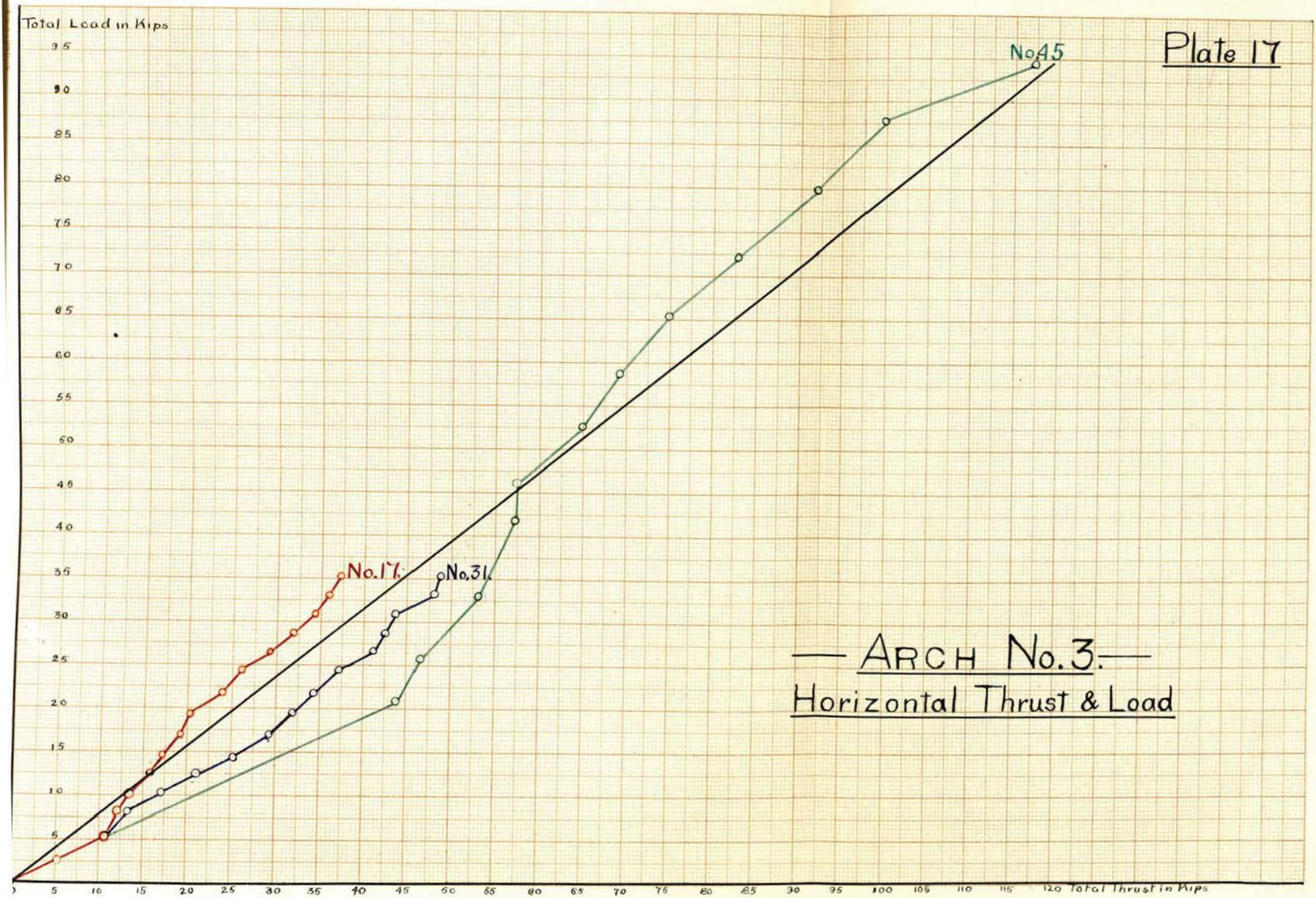
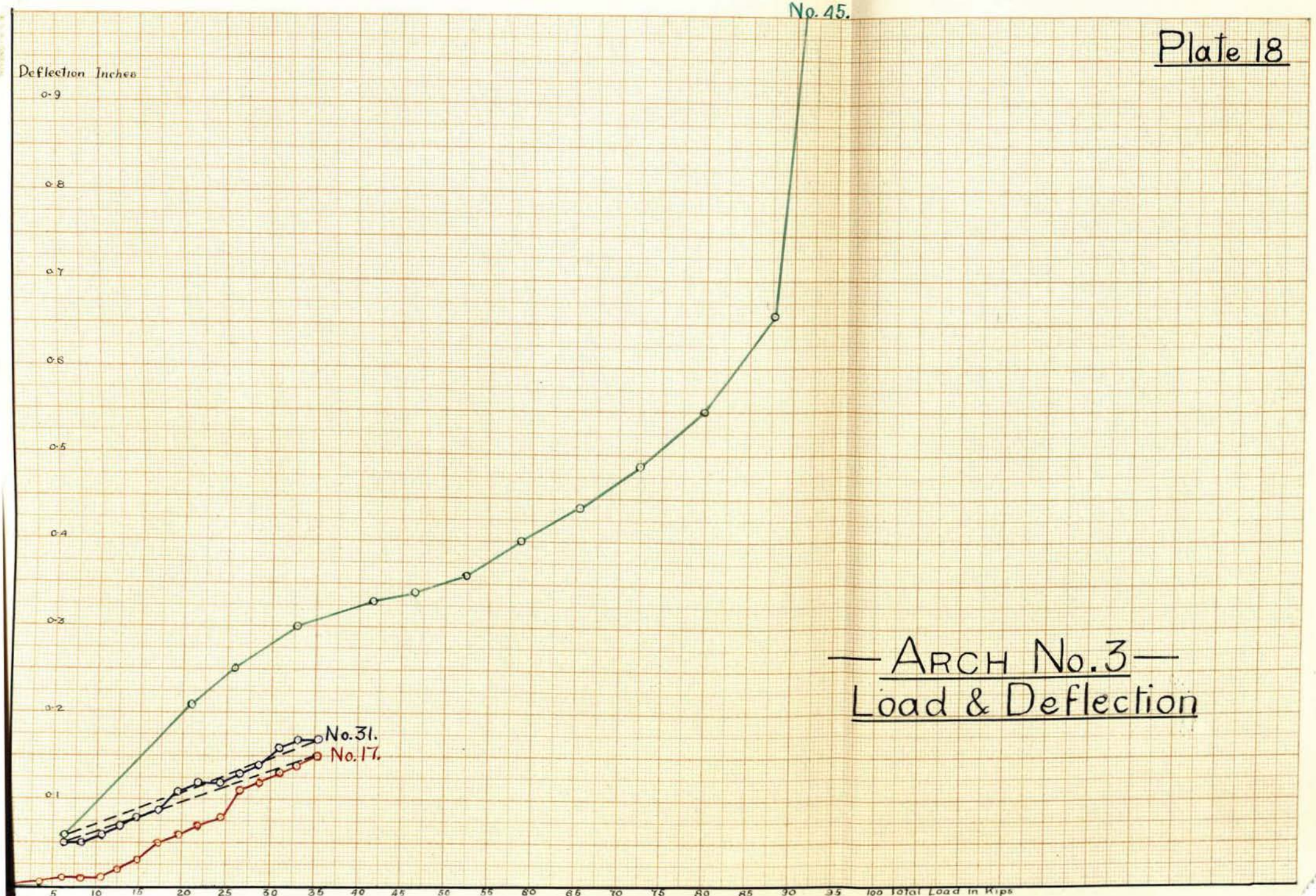


Plate 17

— Arch No. 3. —

Horizontal Thrust & Load

Plate 18



— Arch No. 3 —
Load & Deflection

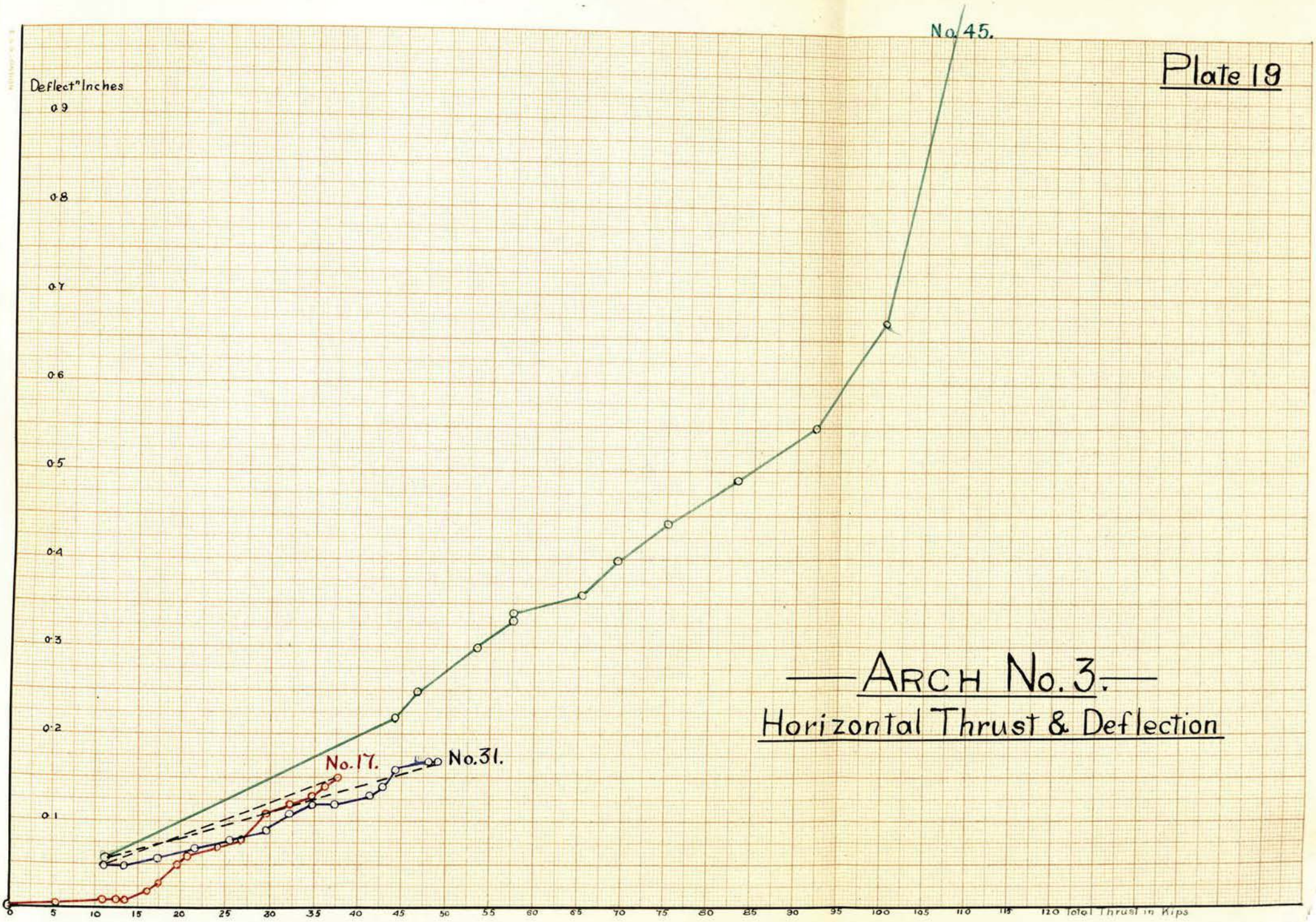


Plate 19
Deflect" Inches
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120 Total Thrust in Kips
No. 45.
No. 17.
No. 31.
ARCH No. 3.
Horizontal Thrust & Deflection