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“The Failure of the Embabeh Bridge, Cairo.”

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THE Embabeh bridge over the Nile connects the railway system which centres in Cairo with that of Upper Egypt. It is a single-line through bridge of eight continuous spans and a swing-span; the ordinary spans are 243 feet, the end spans 203 feet 4 inches long, and each arm of the swing-span is 94 feet 3 inches long between centres. There is a corbelled-out passage 14 feet wide for cart traffic on each side. The bridge was built by contract under open competition, the general conditions only being specified; the designs and the tenders were examined by a committee of engineers in the service of the Egyptian Government, on which the railway was represented, and the work was allotted to a well-known French firm. An ordinary span and the swing-span are illustrated in Figs. 1 and 2, Plate 3, respectively. The lateral bracing at the top and bottom was of adequate design.

The unit stresses in all members required by the specification were:—

	Tons per Square Inch.
Wrought iron in compression	3·82
„ „ „ tension	4·45
Steel in compression	5·1
„ „ tension	7·0

The process by which the steel was to be made was not mentioned, nor were chemical restrictions imposed in regard to its composition. Hot punching and bending tests were specified, and the minimum tensile strength prescribed was 28·6 tons, with an elongation of 20 per cent. in 200 millimetres, subsequently revised to 26–29 tons, and an extension 26 per cent. to 22 per cent. It was prescribed that for pieces less than 10 millimetres thick the punched hole must be 3 millimetres less than the finished hole, the rest being drilled out, and for pieces thicker than 10 millimetres, 4 millimetres less; and that in the case of the metal not behaving well under the punch the contractor might be required to drill the holes entirely.

The contractors were afterwards permitted to punch the holes of the full size. The bridge was to be tested by a full train of the heaviest locomotives, with carts on the roadways, and it was further provided that the contractor was to be liable for a year after the bridge had been put into service to make good any defects that might be discovered. The girders were erected by launching over rollers on a rigid bed, and the bridge was opened in May, 1892. It may be noted that after the designs were accepted by the committee, the detailed calculations were checked by a French engineer.

The bridge worked satisfactorily until the morning of the 4th December, 1896, when the west downstream arm of the swing-span was found torn in two, as shown in Figs. 3, 4 and 5. Traffic was suspended, and the pieces that had failed were cut out and were replaced by stronger sections, and before being put into service the bridge was again tested by a full train of locomotives. An examination of the member revealed an old crack which reduced the effective section of the chord by one-third, and from the circumstances that paint was found in the crack it was known to be at least 2 years old, but probably it had opened wider at the time of the failure. A committee was appointed to study the bridge, but before any conclusion was arrived at, the upstream west arm split across on the morning of 26th January, 1897, similarly to the other arm, as shown in Fig. 5. The split pieces were again replaced by stronger sections, but the bridge was not tested by a string of locomotives before being put again into use.

The committee reported that they found a considerable number of cracks in the edges of the chord plates, especially of the spans that had passed over most rollers in the process of launching, and that as the tests of the metal made at the time of building the bridge showed it to be soft steel, while the broken pieces appeared to be hard, it was probable that vibration had caused a molecular change. The committee also drew attention to the fact that the passage of a single donkey on the roadway produced more vibration than the passage of a train, and recommended that the width of the roadways should be reduced. They further recommended that measures should be taken to strengthen the bridge up to the limiting stresses now in use, that until the work was completed only the lightest type of engines should be allowed to cross the bridge, and that when the work was finished the bridge should again be "tested" with live and dead loads as if it were a new bridge.

No action had been taken on this report when the Author joined

the Egyptian railways as President of the Board at the end of March, 1897. He considered the continuous spans, to which no attention had hitherto been given, more dangerous than the swing-span, on account of their want of lateral stability. He therefore stopped the road traffic entirely, and confined the rail traffic to that taken by a small engine weighing 18 tons. The employment of basic Bessemer steel and punched holes appeared sufficient to account for the fractures. It was observed that in places where the cracks crossed a rivet-hole they ran out of their course on meeting the ring of metal hardened by punching; a crack could thus have been traced to its point of origin.

Tests of the metal during the construction of the bridge are given in Appendix I, and the results of chemical and mechanical tests of pieces cut from the split plates are given in Tables I-III. Pieces bearing the same numbers are either identical, as in the case of analysis of a piece after pulling it, or adjacent, as where one strip is pulled and the other is bent.

TABLE I.—CHEMICAL TESTS.

—	No. 1 Up- stream.	No. 5 Up- stream.	Angle No. 6 Up- stream.	Angle No. 9 Down- stream.	No. 13 Down- stream.	No. 16 Down- stream.
Carbon	0·063	0·057	0·105	0·068	0·057	0·064
Silicon	0·006	0·007	0·006	0·006	0·004	0·007
Sulphur	0·034	0·039	0·030	0·037	0·034	0·023
Phosphorus	0·070	0·092	0·094	0·094	0·097	0·074
Manganese	0·396	0·353	0·626	0·634	0·500	0·522

The general length of the tensile test-pieces was 1·18 inch, and width of the strips for bending 1 inch to $1\frac{1}{2}$ inch.

Some of the plates were also examined microscopically both parallel and perpendicular to the surface of the plate, with the result that nothing abnormal was discovered. The effect of rolling appeared evident in the structure of those samples which had a higher tensile strength than would be inferred from their composition.

It was finally decided to replace the swing-span by another of adequate design and more trustworthy metal. As for the continuous spans, seeing that the span was much greater than the economical limit, on account of the impossibly light girders assumed, and greater than the regimen of the river required, the obvious course was to erect additional piers and to strengthen the

TABLE II.—TENSILE TESTS.

Plates.		Direction of Cut.	Elastic Limit.	Maximum Stress.	Elongation.	Contraction of Area.
No.			Tons per Sq. Inch.	Tons per Sq. Inch.	Per cent.	Per cent.
1	upstream . .	Transverse .	13·81	27·28	23·5	48·3
2	" . .	Longitudinal	21·10	27·80	26·0	53·2
3	" . .	"	21·65	27·32	26·5	52·5
4	" . .	Transverse .	23·86	29·45	24·0	46·5
5	" . .	Longitudinal	21·53	28·23	28·5	51·9
6	" . .	"	20·57	29·23	31·0	55·3
7	" . .	"	17·66	26·10	31·8	59·1
8	" . .	"	18·30	26·86	33·2	60·8
9	" . .	"	20·55	29·19	30·0	58·2
10	downstream .	Transverse .	19·77	23·17	4·5	7·3
11	" . .	Longitudinal	17·15	18·40	4·0	24·5
12	" . .	"	20·81	27·23	20·5	57·7
13	" . .	Transverse .	23·18	29·87	21·0	41·4
14	" . .	Longitudinal	19·52	32·00	27·67	61·1
15	" . .	Transverse .	18·86	20·00	5·5	29·5
16 ¹	" . .	Longitudinal	22·81	28·59	26·8	57·9
17 ¹	" . .	Transverse .	23·31	29·94	22·5	43·4

TABLE III.—BENDING TESTS.

The test pieces were bent round a 1-inch rod till the ends met.

Plates.	—	Direction of Cut.	Remarks.
No. 1 upstream .	Untempered	Transverse .	No cracks.
" 3 " .	Tempered .	"	Skin cracks.
" 3 " .	Untempered	"	"
" 6 " .	"	Longitudinal	No cracks.
" 7 " .	"	"	Cracked through opposite rivet-hole; ends bent within 1 inch.
" 8 downstream	"	"	No cracks.
" 9 " .	"	"	"
" 10 " .	"	Transverse .	Skin cracks.
" 10 " .	Tempered .	"	Cracked at flaw in plate.
" 11 " .	Untempered	Longitudinal	No cracks.
" 11 " .	Tempered .	"	Cracked at flaw.
" 12 " .	Untempered	"	No cracks.
" 13 " .	"	Transverse .	"
" 14 " .	"	Longitudinal	Skin cracks.
" 15 " .	"	Transverse .	No cracks.

¹ Test-pieces cut as far from the flaw as possible. The remainder of the pieces were cut as near the crack as possible.

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braces by riveting deep angle-bars to their backs, adding also a stiff girder to carry the outer ends of the footway brackets. This will reduce the stresses to about a quarter of those originally contemplated and will vastly increase the stiffness of the bridge. The repairs will probably enable it to last a good many years, and, even should the girders eventually fail, the new piers will serve.

The use of basic Bessemer steel and punched holes, aggravated by ill-treatment in rolling out over rigid rollers, are enough to account for cracks; but why the first failure did not take place through the old crack, which was the weakest place in the member, or why a month afterwards the symmetrically opposite member should have failed in a similar way, has not been explained. The stresses at that place do not account for it, and the only plausible theory is that that arm of the swing-span must have sustained some injury during erection.

It seems almost incredible that two angle-bars 3·1 inches by 0·3 inch, and 34 feet long, should be considered to form an adequate strut, even though crossed by three similar pieces. The error was obvious; the braces were calculated as columns fixed at their intersections. Not only are they no more fixed in a mechanical sense by the other flimsy members that cross them than are the threads of a net, but they are not even fixed at the ends, being attached to a single plate 18 inches wide and 0·3 inch thick, which, in every bridge of this type within the Author's experience, has become or has always been buckled.

A word of protest must be added against the idea of "testing" a bridge, which still survives. In the present case the bridge failed twice in spite of—and in one case immediately after—the "tests," on the strength of which it was pronounced satisfactory. They in reality hastened the catastrophe, yet a committee of engineers recommend that when the bridge has been strengthened the "tests" should be repeated.

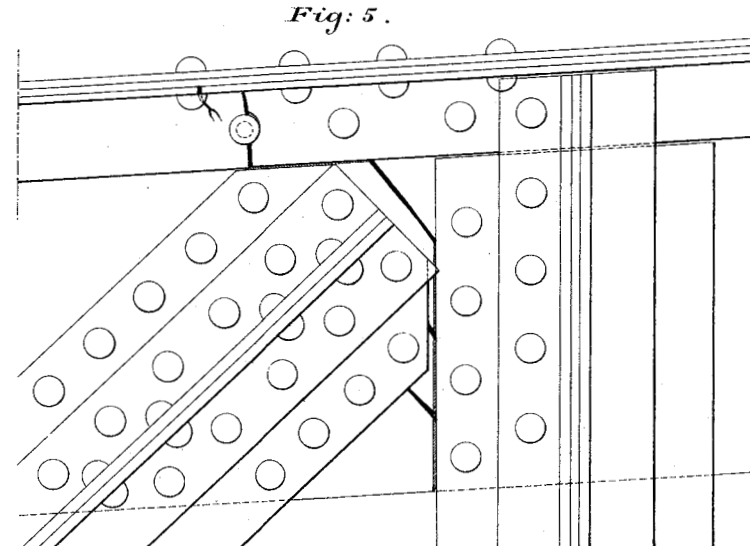
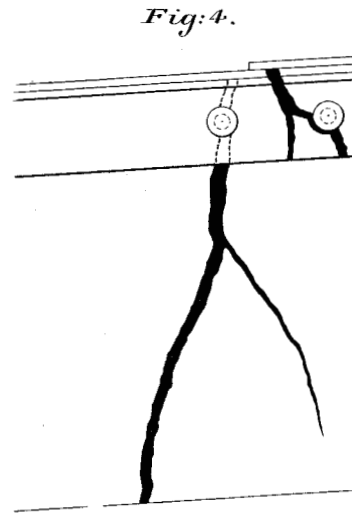
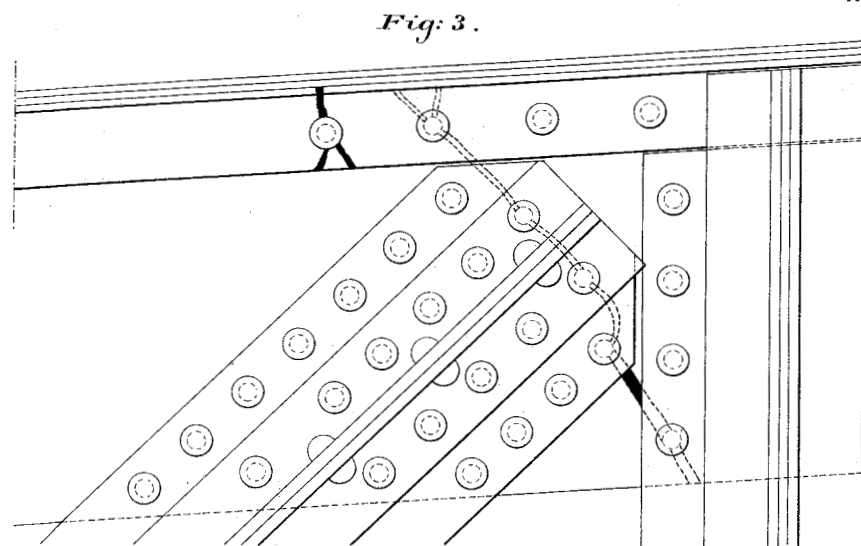
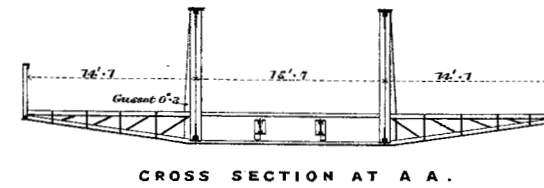
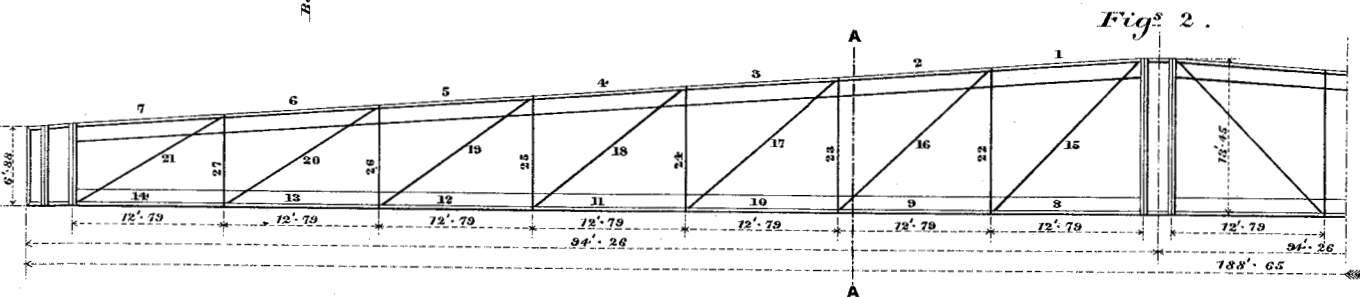
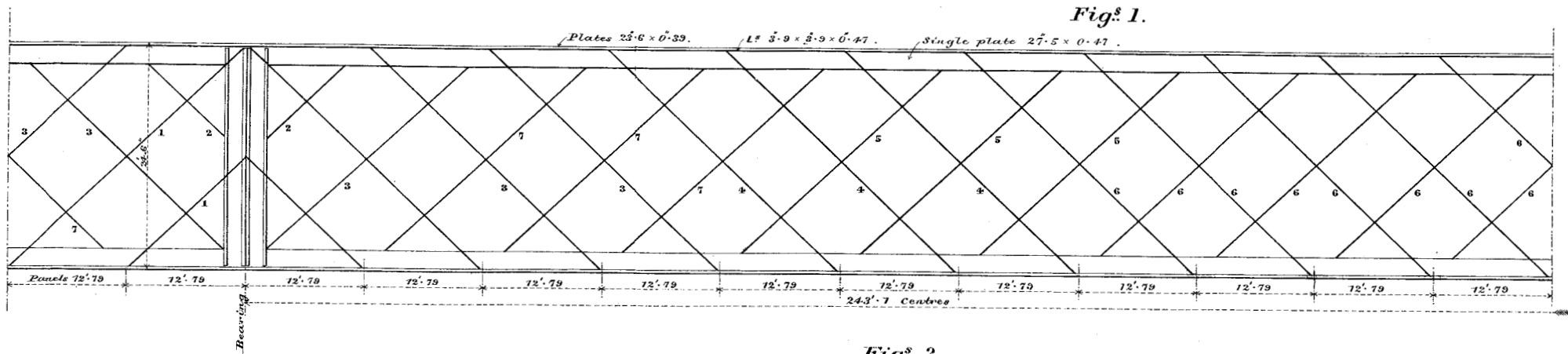
The Paper is accompanied by six drawings and a photograph, from which Plate 3 has been prepared.

APPENDIX.

TESTS OF METAL FOR EMBABEH BRIDGE.

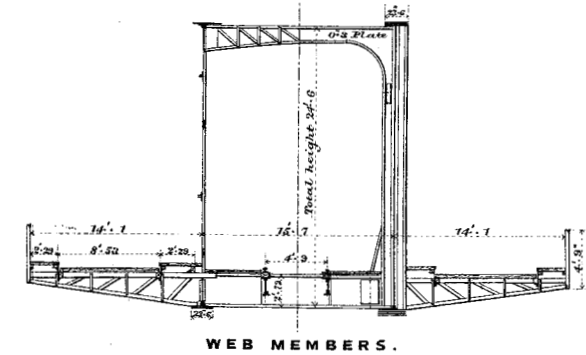
No. of Tests made.		Elastic Limit, Tons per Square Inch.			Tensile Strength, Tons per Sq. Inch.			Elongation per cent. on 8 inches.			Contraction of Area, per cent.		
		Minimum.	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.	Maximum.
Plates lengthways.	2	17.2	17.5	17.8	26.6	26.6	26.6	25.0	26.5	28.0	47.0	54.0	60.9
	10	14.6	17.4	19.1	24.9	26.8	28.6	27.0	29.7	32.0	54.1	60.0	63.0
	10	16.5	17.1	18.4	26.0	26.5	28.0	23.0	27.3	32.0	50.0	55.4	64.7
	3	17.0	17.8	18.3	26.2	26.7	27.5	26.0	26.8	28.0	52.6	54.5	56.0
	9	17.3	18.0	19.1	26.7	27.7	29.0	24.5	27.5	30.0	50.0	58.2	67.5
	5	17.8	18.2	19.1	26.7	27.0	28.2	26.0	26.7	27.5	54.8	60.6	68.0
Plates crossways.	2	17.2	17.2	17.2	26.2	26.3	26.4	26.0	28.0	30.0	57.3	61.2	65.1
	10	16.5	19.5	22.2	27.0	28.0	29.9	20.0	23.4	30.0	44.3	50.4	56.8
	10	16.5	17.4	18.4	26.0	27.7	28.5	22.0	26.4	32.0	39.3	48.2	55.1
	3	17.8	18.0	18.2	26.4	26.6	26.7	26.0	27.0	28.0	55.2	57.7	60.6
	9	16.8	17.5	18.5	26.3	27.5	28.8	24.5	25.6	28.0	46.0	56.3	60.8
	5	16.5	17.3	18.4	26.8	27.5	28.5	26.0	26.5	27.0	57.6	59.2	61.9
Angles.	16	15.2	17.5	17.8	26.4	27.4	28.5	25.0	30.4	35.0	56.3	60.8	66.2
	4	16.5	17.8	18.7	26.9	27.6	28.4	32.0	33.0	35.0	61.2	61.8	62.7
	16	16.5	17.4	17.8	26.0	27.3	28.1	24.0	35.1	34.0	52.0	60.0	67.2
	12	16.8	17.7	18.7	26.4	27.3	28.0	26.0	28.3	31.0	58.0	62.3	66.2
	9	16.5	17.0	17.8	26.6	27.5	28.4	25.0	27.8	29.0	51.0	62.1	69.3
	8	16.7	17.5	18.1	26.0	27.1	28.3	26.0	30.0	32.0	50.0	57.8	70.0
Plats.	7	14.6	15.6	17.1	26.1	27.6	29.0	25.0	29.3	33.0	58.3	62.1	68.3
	2	16.5	17.1	17.7	26.0	26.4	26.6	28.0	29.0	30.0	62.2	62.6	63.1
	2	16.5	16.8	17.1	26.3	27.0	27.7	24.0	26.0	28.0	53.7	56.5	59.4
	10	16.7	17.4	18.0	26.0	27.1	28.0	23.5	27.5	32.0	49.2	60.8	70.0

Many shop tests for splitting, bending, &c., were also satisfactorily performed.



SCALES.


Fig. 1 and 2, 1 Inch = 16 Feet.
3 to 5, 1/2 Inch = 1 Foot.



WEB MEMBERS.	
TIES.	STRUTS.
1, L 3.9 x 3.9 x 0.47 (2) + 1 Plate 6.29 x 0.39	2, L 3.9 x 3.9 x 0.51 (2) + 1 Plate 7 x 0.47
3, L 3.9 x 3.9 x 0.53 (2)	5, L 3.1 x 3.1 x 0.35 (2) + 1 Plate 5.1 x 0.35
4, L 3.5 x 3.5 x 0.45 (2)	6, L 3.1 x 3.1 x 0.3 (2)
6, L 3.1 x 3.1 x 0.3 (2)	7, L 3.5 x 3.5 x 0.47 (2) + 1 Plate 5.9 x 0.47


CHORDS.

UPPER.


1, 2 L 3.54 x 3.54 x 0.39 + 1 Plate 5.6 x 0.31 + 1 Plate 2.6 x 0.31 + 1 Web 17.7 x 0.31 


2, 3, 4, 2 L 3.5 x 3.5 x 0.39 + 1 Plate 5.6 x 0.31 + 1 Web 17.7 x 0.31 -----

5, 2 L 3.54 x 3.54 x 0.39 + 2 Plates 5.6 x 0.31 + 1 Web 17.7 x 0.31

6, 8, 1, 2 L 3.54 x 3.54 x 0.39 + 1 Plate 5.6 x 0.31 + 1 Web 17.7 x 0.31 

LOWER.

8, 2 L 3.54 x 3.54 x 0.39 + 1 Plate 2.6 x 0.31 + 1 Plate 2.6 x 0.31 + 1 Web 17.7 x 0.31 

9 to 11, 2 L 3.54 x 3.54 x 0.39 + 1 Plate 2.6 x 0.31 + 1 Plate 17.7 x 0.31 

BRACES.		POSTS.	
TIES.	15, 4 L 3 ⁵ / ₈ x 3 ⁵ / ₈ x 0 ⁵ / ₃₂ + 1 Plate 12 ⁵ / ₈ x 0 ⁵ / ₃₂	+	22, 4 L 3 ¹ / ₂ x 3 ¹ / ₂ x 0 ⁴ / ₇ + 1 Plate 11 ⁵ / ₈ x 0 ³ / ₃₁
	16, 4 L 3 ¹ / ₂ x 3 ¹ / ₂ x 0 ⁴ / ₇ + 1 Plate 11 ⁵ / ₈ x 0 ³ / ₃₁		23, 4 L 2 ⁷ / ₁₆ x 2 ⁷ / ₁₆ x 0 ³ / ₃₂ + 1 Plate 11 ⁵ / ₈ x 0 ³ / ₃₁
	17, 4 L 2 ⁷ / ₁₆ x 2 ⁷ / ₁₆ x 0 ⁴ / ₃₂ + 1 Plate 11 ⁵ / ₈ x 0 ³ / ₃₁		24, 4 L 3 ¹ / ₂ x 3 ¹ / ₂ x 0 ³ / ₃₁
	18, 4 L 2 ⁷ / ₁₆ x 2 ⁷ / ₁₆ x 0 ⁴ / ₃₂		25, 4 L 2 ⁷ / ₁₆ x 2 ⁷ / ₁₆ x 0 ² / ₂₇
STRUTS.	19, 4 L 2 ⁷ / ₁₆ x 2 ⁷ / ₁₆ x 0 ⁴ / ₃₂	+	
	20, 4 L 3 ¹ / ₂ x 3 ¹ / ₂ x 0 ⁴ / ₇		
	21, 4 L 3 ⁹ / ₈ x 3 ⁹ / ₈ x 0 ⁵ / ₃₂		