

Load Rating Concrete Arch Bridges with Graphic Statics



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The References

OhioLINK:

**Keyword “Graphic Statics” produces
72 individual books.**



The Disclaimer

It is hoped that the practising engineer, who has, as a rule, little time to study mathematical demonstrations or to search through several pages of transformations for a desired formula, will appreciate the collection in simple form (Chapter II) of all of the necessary formulas likely to be needed in practice, and also the ease and celerity with which they can be applied, with the aid of the tables, to the case in hand. A fair trial of the summation formulas given in this chapter will, it is believed, lead to the adoption of them.

These summation formulas are readily applied in the designing of masonry arches.

Nearly all of the formulas given have been deduced for this treatise by two radically different methods. Many of these formulas are old, and while it was desired to give full credit in every particular, it was not found either expedient or possible to do so for each form.

The tables were carefully computed, and when possible by the method of differences, each tenth value being checked by direct computation.

The demonstrations are believed to be sufficiently simple to be easily followed by senior students in Technical schools. With the aid of the tables, class problems can be solved which otherwise would be impossible on account of the time required where direct computation of the various terms must be resorted to.

The author will esteem it a favor if any errors that may be found are at once brought to his notice.

***Lessons from
our Engineering
Forefathers.***

The Fredericktown Arch: How?

50-ft. Melan concrete arch

Built 1896

2ND oldest concrete arch in Ohio

Among first 20 built in U.S.



The Fredericktown Arch: How?

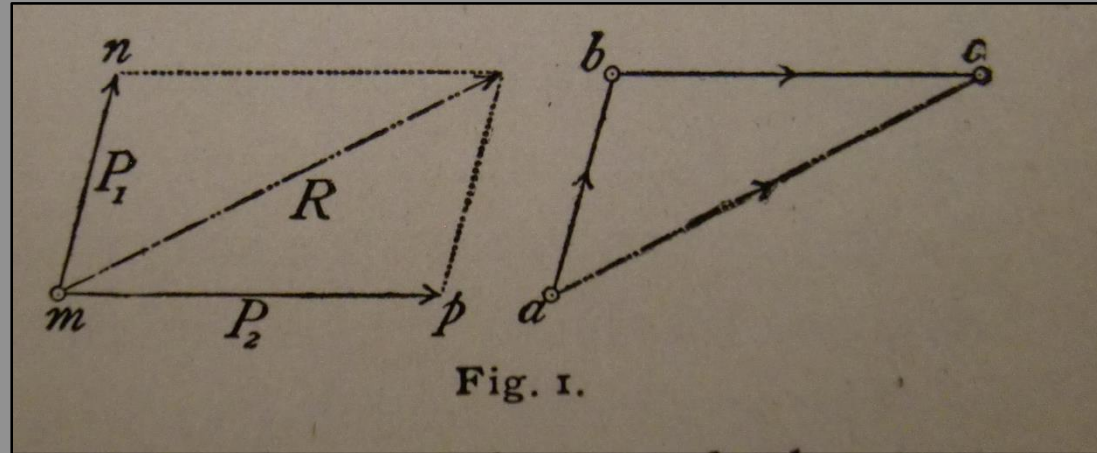


- ***Load rating:
Engineering Judgment.***
- ***3 Ton load posting.***
- ***Local farmer says a fully loaded
fertilizer truck crossed it.***

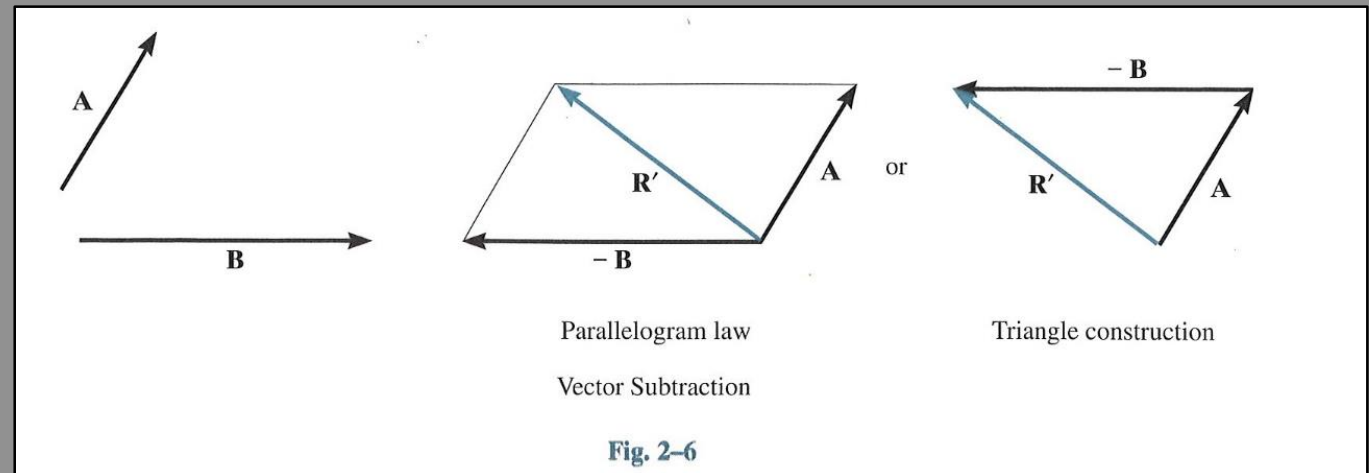
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Graphic Statics

1840 to 1940:



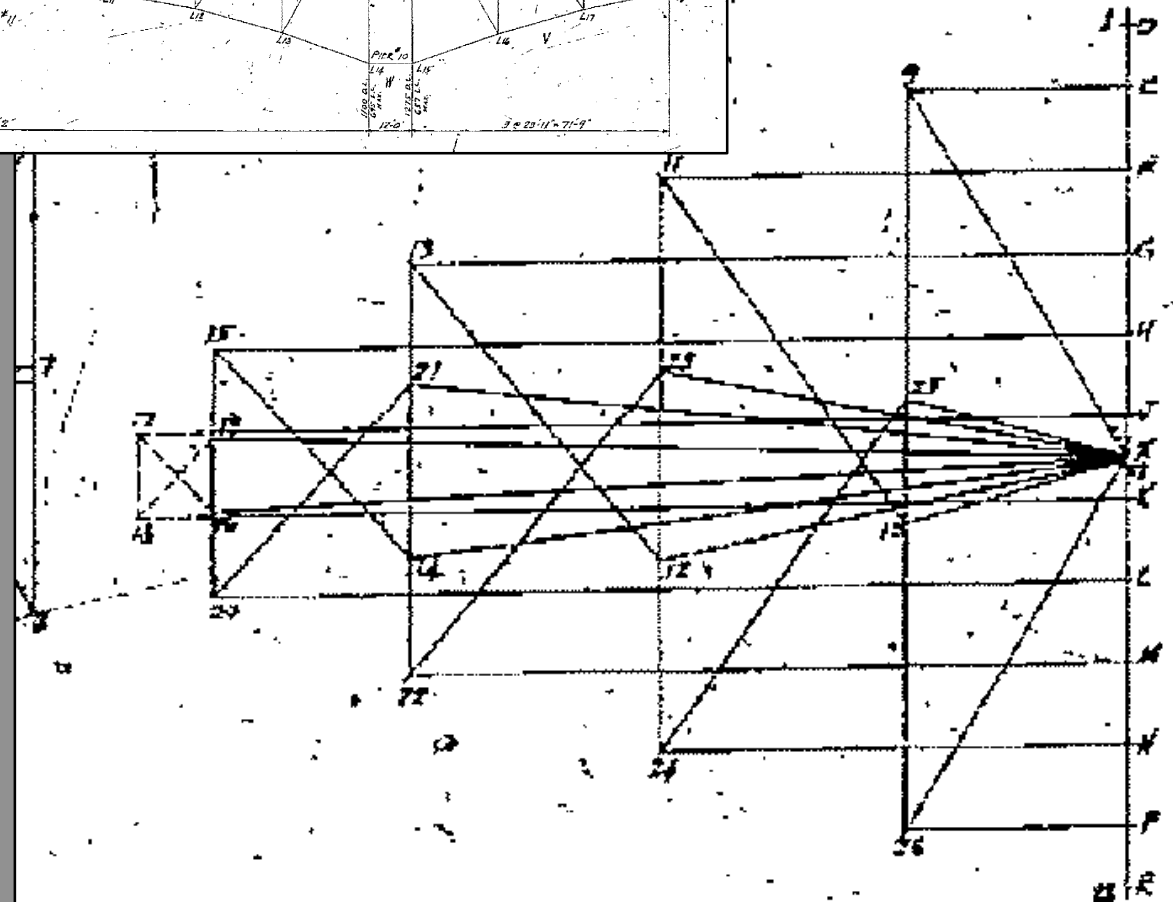
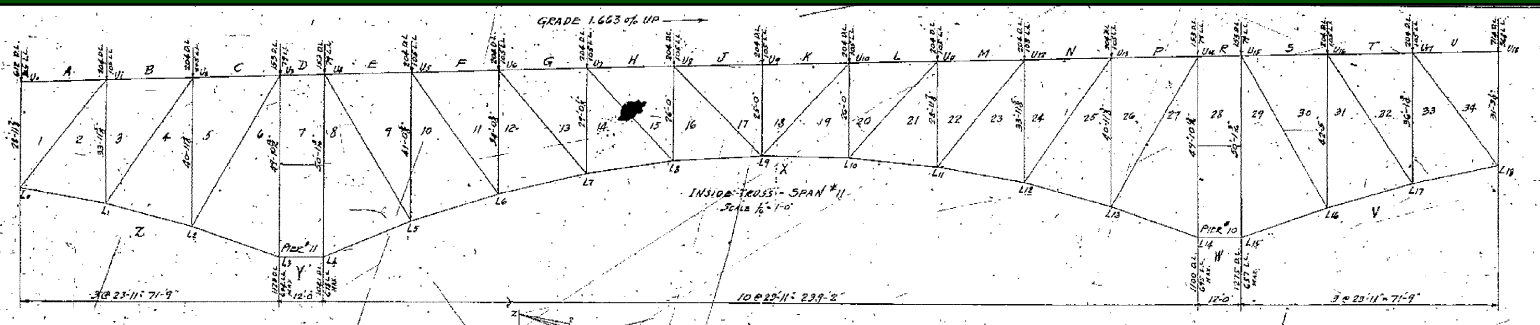
Today:



Graphic Statics

MEMBER	U1U2	U1U3	U1U4	U1U5	U1U6	U1U7	U1U8	U1U9	U1U10	U1U11	U1U12	U1U13	U1U14	U1U15	U1U16	U1U17	U1U18	U1U19	U1U20	U1U21	U1U22	U1U23	U1U24	U1U25	U1U26	U1U27	U1U28	U1U29	U1U30	U1U31	U1U32	U1U33	U1U34	U1U35	U1U36	U1U37	U1U38	U1U39	U1U40	U1U41	U1U42	U1U43	U1U44	U1U45	U1U46	U1U47	U1U48	U1U49	U1U50	U1U51	U1U52	U1U53	U1U54	U1U55	U1U56	U1U57	U1U58	U1U59	U1U60	U1U61	U1U62	U1U63	U1U64	U1U65	U1U66	U1U67	U1U68	U1U69	U1U70	U1U71	U1U72	U1U73	U1U74	U1U75	U1U76	U1U77	U1U78	U1U79	U1U80	U1U81	U1U82	U1U83	U1U84	U1U85	U1U86	U1U87	U1U88	U1U89	U1U90	U1U91	U1U92	U1U93	U1U94	U1U95	U1U96	U1U97	U1U98	U1U99	U1U100	U1U101	U1U102	U1U103	U1U104	U1U105	U1U106	U1U107	U1U108	U1U109	U1U110	U1U111	U1U112	U1U113	U1U114	U1U115	U1U116	U1U117	U1U118	U1U119	U1U120	U1U121	U1U122	U1U123	U1U124	U1U125	U1U126	U1U127	U1U128	U1U129	U1U130	U1U131	U1U132	U1U133	U1U134	U1U135	U1U136	U1U137	U1U138	U1U139	U1U140	U1U141	U1U142	U1U143	U1U144	U1U145	U1U146	U1U147	U1U148	U1U149	U1U150	U1U151	U1U152	U1U153	U1U154	U1U155	U1U156	U1U157	U1U158	U1U159	U1U160	U1U161	U1U162	U1U163	U1U164	U1U165	U1U166	U1U167	U1U168	U1U169	U1U170	U1U171	U1U172	U1U173	U1U174	U1U175	U1U176	U1U177	U1U178	U1U179	U1U180	U1U181	U1U182	U1U183	U1U184	U1U185	U1U186	U1U187	U1U188	U1U189	U1U190	U1U191	U1U192	U1U193	U1U194	U1U195	U1U196	U1U197	U1U198	U1U199	U1U200	U1U201	U1U202	U1U203	U1U204	U1U205	U1U206	U1U207	U1U208	U1U209	U1U210	U1U211	U1U212	U1U213	U1U214	U1U215	U1U216	U1U217	U1U218	U1U219	U1U220	U1U221	U1U222	U1U223	U1U224	U1U225	U1U226	U1U227	U1U228	U1U229	U1U230	U1U231	U1U232	U1U233	U1U234	U1U235	U1U236	U1U237	U1U238	U1U239	U1U240	U1U241	U1U242	U1U243	U1U244	U1U245	U1U246	U1U247	U1U248	U1U249	U1U250	U1U251	U1U252	U1U253	U1U254	U1U255	U1U256	U1U257	U1U258	U1U259	U1U260	U1U261	U1U262	U1U263	U1U264	U1U265	U1U266	U1U267	U1U268	U1U269	U1U270	U1U271	U1U272	U1U273	U1U274	U1U275	U1U276	U1U277	U1U278	U1U279	U1U280	U1U281	U1U282	U1U283	U1U284	U1U285	U1U286	U1U287	U1U288	U1U289	U1U290	U1U291	U1U292	U1U293	U1U294	U1U295	U1U296	U1U297	U1U298	U1U299	U1U300	U1U301	U1U302	U1U303	U1U304	U1U305	U1U306	U1U307	U1U308	U1U309	U1U310	U1U311	U1U312	U1U313	U1U314	U1U315	U1U316	U1U317	U1U318	U1U319	U1U320	U1U321	U1U322	U1U323	U1U324	U1U325	U1U326	U1U327	U1U328	U1U329	U1U330	U1U331	U1U332	U1U333	U1U334	U1U335	U1U336	U1U337	U1U338	U1U339	U1U340	U1U341	U1U342	U1U343	U1U344	U1U345	U1U346	U1U347	U1U348	U1U349	U1U350	U1U351	U1U352	U1U353	U1U354	U1U355	U1U356	U1U357	U1U358	U1U359	U1U360	U1U361	U1U362	U1U363	U1U364	U1U365	U1U366	U1U367	U1U368	U1U369	U1U370	U1U371	U1U372	U1U373	U1U374	U1U375	U1U376	U1U377	U1U378	U1U379	U1U380	U1U381	U1U382	U1U383	U1U384	U1U385	U1U386	U1U387	U1U388	U1U389	U1U390	U1U391	U1U392	U1U393	U1U394	U1U395	U1U396	U1U397	U1U398	U1U399	U1U400	U1U401	U1U402	U1U403	U1U404	U1U405	U1U406	U1U407	U1U408	U1U409	U1U410	U1U411	U1U412	U1U413	U1U414	U1U415	U1U416	U1U417	U1U418	U1U419	U1U420	U1U421	U1U422	U1U423	U1U424	U1U425	U1U426	U1U427	U1U428	U1U429	U1U430	U1U431	U1U432	U1U433	U1U434	U1U435	U1U436	U1U437	U1U438	U1U439	U1U440	U1U441	U1U442	U1U443	U1U444	U1U445	U1U446	U1U447	U1U448	U1U449	U1U450	U1U451	U1U452	U1U453	U1U454	U1U455	U1U456	U1U457	U1U458	U1U459	U1U460	U1U461	U1U462	U1U463	U1U464	U1U465	U1U466	U1U467	U1U468	U1U469	U1U470	U1U471	U1U472	U1U473	U1U474	U1U475	U1U476	U1U477	U1U478	U1U479	U1U480	U1U481	U1U482	U1U483	U1U484	U1U485	U1U486	U1U487	U1U488	U1U489	U1U490	U1U491	U1U492	U1U493	U1U494	U1U495	U1U496	U1U497	U1U498	U1U499	U1U500	U1U501	U1U502	U1U503	U1U504	U1U505	U1U506	U1U507	U1U508	U1U509	U1U510	U1U511	U1U512	U1U513	U1U514	U1U515	U1U516	U1U517	U1U518	U1U519	U1U520	U1U521	U1U522	U1U523	U1U524	U1U525	U1U526	U1U527	U1U528	U1U529	U1U530	U1U531	U1U532	U1U533	U1U534	U1U535	U1U536	U1U537	U1U538	U1U539	U1U540	U1U541	U1U542	U1U543	U1U544	U1U545	U1U546	U1U547	U1U548	U1U549	U1U550	U1U551	U1U552	U1U553	U1U554	U1U555	U1U556	U1U557	U1U558	U1U559	U1U560	U1U561	U1U562	U1U563	U1U564	U1U565	U1U566	U1U567	U1U568	U1U569	U1U570	U1U571	U1U572	U1U573	U1U574	U1U575	U1U576	U1U577	U1U578	U1U579	U1U580	U1U581	U1U582	U1U583	U1U584	U1U585	U1U586	U1U587	U1U588	U1U589	U1U590	U1U591	U1U592	U1U593	U1U594	U1U595	U1U596	U1U597	U1U598	U1U599	U1U600	U1U601	U1U602	U1U603	U1U604	U1U605	U1U606	U1U607	U1U608	U1U609	U1U610	U1U611	U1U612	U1U613	U1U614	U1U615	U1U616	U1U617	U1U618	U1U619	U1U620	U1U621	U1U622	U1U623	U1U624	U1U625	U1U626	U1U627	U1U628	U1U629	U1U630	U1U631	U1U632	U1U633	U1U634	U1U635	U1U636	U1U637	U1U638	U1U639	U1U640	U1U641	U1U642	U1U643	U1U644	U1U645	U1U646	U1U647	U1U648	U1U649	U1U650	U1U651	U1U652	U1U653	U1U654	U1U655	U1U656	U1U657	U1U658	U1U659	U1U660	U1U661	U1U662	U1U663	U1U664	U1U665	U1U666	U1U667	U1U668	U1U669	U1U670	U1U671	U1U672	U1U673	U1U674	U1U675	U1U676	U1U677	U1U678	U1U679	U1U680	U1U681	U1U682	U1U683	U1U684	U1U685	U1U686	U1U687	U1U688	U1U689	U1U690	U1U691	U1U692	U1U693	U1U694	U1U695	U1U696	U1U697	U1U698	U1U699	U1U700	U1U701	U1U702	U1U703	U1U704	U1U705	U1U706	U1U707	U1U708	U1U709	U1U710	U1U711	U1U712	U1U713	U1U714	U1U715	U1U716	U1U717	U1U718	U1U719	U1U720	U1U721	U1U722	U1U723	U1U724	U1U725	U1U726	U1U727	U1U728	U1U729	U1U730	U1U731	U1U732	U1U733	U1U734	U1U735	U1U736	U1U737	U1U738	U1U739	U1U740	U1U741	U1U742	U1U743	U1U744	U1U745	U1U746	U1U747	U1U748	U1U749	U1U750	U1U751	U1U752	U1U753	U1U754	U1U755	U1U756	U1U757	U1U758	U1U759	U1U760	U1U761	U1U762	U1U763	U1U764	U1U765	U1U766	U1U767	U1U768	U1U769	U1U770	U1U771	U1U772	U1U773	U1U774	U1U775	U1U776	U1U777	U1U778	U1U779	U1U780	U1U781	U1U782	U1U783	U1U784	U1U785	U1U786	U1U787	U1U788	U1U789	U1U790	U1U791	U1U792	U1U793	U1U794	U1U795	U1U796	U1U797	U1U798	U1U799	U1U800	U1U801	U1U802	U1U803	U1U804	U1U805	U1U806	U1U807	U1U808	U1U809	U1U810	U1U811	U1U812	U1U813	U1U814	U1U815	U1U816	U1U817	U1U818	U1U819	U1U820	U1U821	U1U822	U1U823	U1U824	U1U825	U1U826	U1U827	U1U828	U1U829	U1U830	U1U831	U1U832	U1U833	U1U834	U1U835	U1U836	U1U837	U1U838	U1U839	U1U840	U1U841	U1U842	U1U843	U1U844	U1U845	U1U846	U1U847	U1U848	U1U849	U1U850	U1U851	U1U852	U1U853	U1U854	U1U855	U1U856	U1U857	U1U858	U1U859	U1U860	U1U861	U1U862	U1U863	U1U864	U1U865	U1U866	U1U867	U1U868	U1U869	U1U870	U1U871	U1U872	U1U873	U1U874	U1U875	U1U876	U1U877	U1U878	U1U879	U1U880	U1U881	U1U882	U1U883	U1U884	U1U885	U1U886	U1U887	U1U888	U1U889	U1U890	U1U891	U1U892	U1U893	U1U894	U1U895	U1U896	U1U897	U1U898	U1U899	U1U900	U1U901	U1U902	U1U903	U1U904	U1U905	U1U906	U1U907	U1U908	U1U909	U1U910	U1U911	U1U912	U1U913	U1U914	U1U915	U1U916	U1U917	U1U918	U1U919	U1U920	U1U921	U1U922	U1U923	U1U924	U1U925	U1U926	U1U927	U1U928	U1U929	U1U930	U1U931	U1U932	U1U933	U1U934	U1U935	U1U936	U1U937	U1U938	U1U939	U1U940	U1U941	U1U942	U1U943	U1U944	U1U945	U1U946	U1U947	U1U948	U1U949	U1U950	U1U951	U1U952	U1U953	U1U954	U1U955	U1U956	U1U957	U1U958	U1U959	U1U960	U1U961	U1U962	U1U963	U1U964	U1U965	U1U966	U1U967	U1U968	U1U969	U1U970	U1U971	U1U972	U1U973	U1U974	U1U975	U1U976	U1U977	U1U978	U1U979	U1U980	U1U981	U1U982	U1U983	U1U984	U1U985	U1U986	U1U987	U1U988	U1U989	U1U990	U1U991	U1U992	U1U993	U1U994	U1U995	U1U996	U1U997	U1U998	U1U999	U1U1000	U1U1001	U1U1002	U1U1003	U1U1004	U1U1005	U1U1006	U1U1007	U1U1008	U1U1009	U1U1010	U1U1011	U1U1012	U1U1013	U1U1014	U1U1015	U1U1016	U1U1017	U1U1018	U1U1019	U1U1020	U1U1021	U1U1022	U1U1023	U1U1024	U1U1025	U1U1026	U1U1027	U1U1028	U1U1029	U1U1030	U1U1031	U1U1032	U1U1033	U1U1034	U1U1035	U1U1036	U1U1037	U1U1038	U1U1039	U1U1040	U1U1041	U1U1042	U1U1043	U1U1044	U1U1045	U1U1046	U1U1047	U1U1048	U1U1049	U1U1050	U1U1051	U1U1052	U1U1053	U1U1054	U1U1055	U1U1056	U1U1057	U1U1058	U1U1059	U1U1060	U1U1061	U1U1062	U1U1063	U1U1064	U1U1065	U1U1066	U1U1067	U1U1068	U1U1069	U1U1070	U1U1071	U1U1072	U1U1073	U1U1074	U1U1075	U1U1076	U1U1077	U1U1078	U1U1079	U1U1080	U1U1081	U1U1082	U1U1083	U1U1084	U1U1085	U1U1086	U1U1087	U1U1088	U1U1089	U1U1090	U1U1091	U1U1092	U1U1093	U1U1094	U1U1095	U1U1096	U1U1097	U1U1098	U1U1099	U1U1100	U1U1101	U1U1102	U1U1103	U1U1104	U1U1105	U1U1106	U1U1107	U1U1108	U1U1109	U1U1110	U1U1111	U1U1112	U1U1113	U1U1114	U1U1115	U1U1116	U1U1117	U1U1118	U
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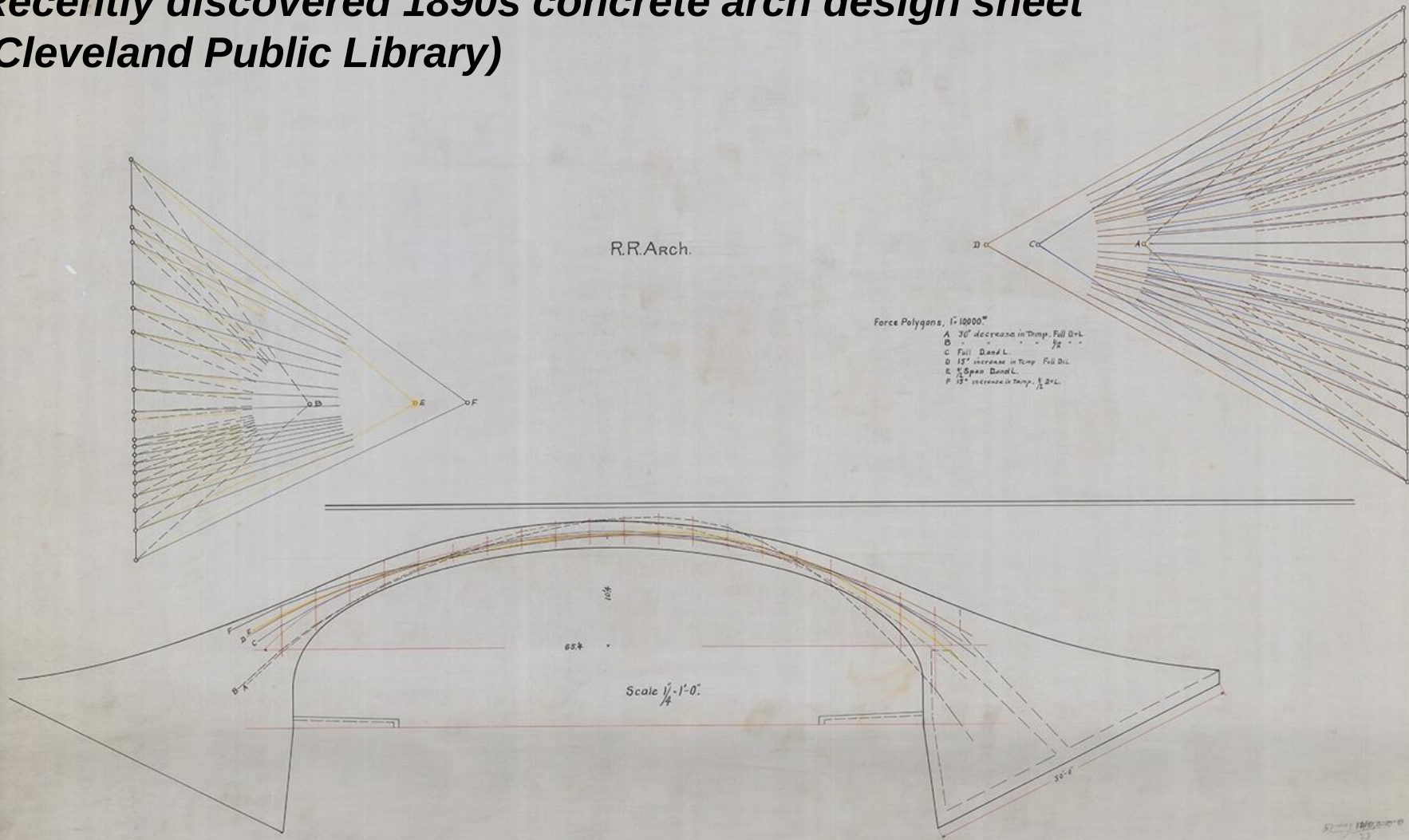
Graphic Statics



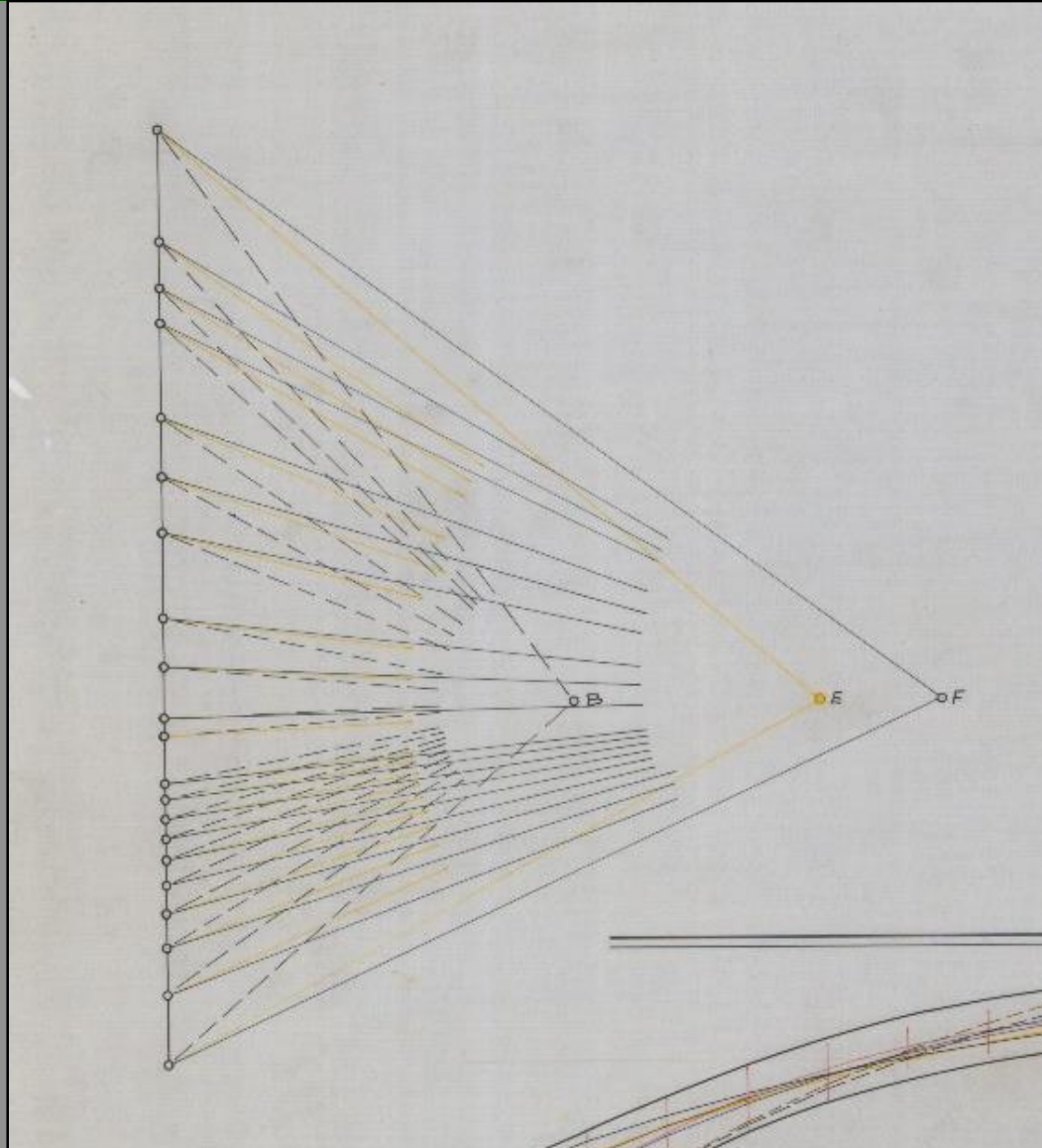
STRESS DIAGRAM FOR LL ON CENTER SPAN.
SCALE 1" = 276,000*

Concrete Arch Design

**Recently discovered 1890s concrete arch design sheet
(Cleveland Public Library)**

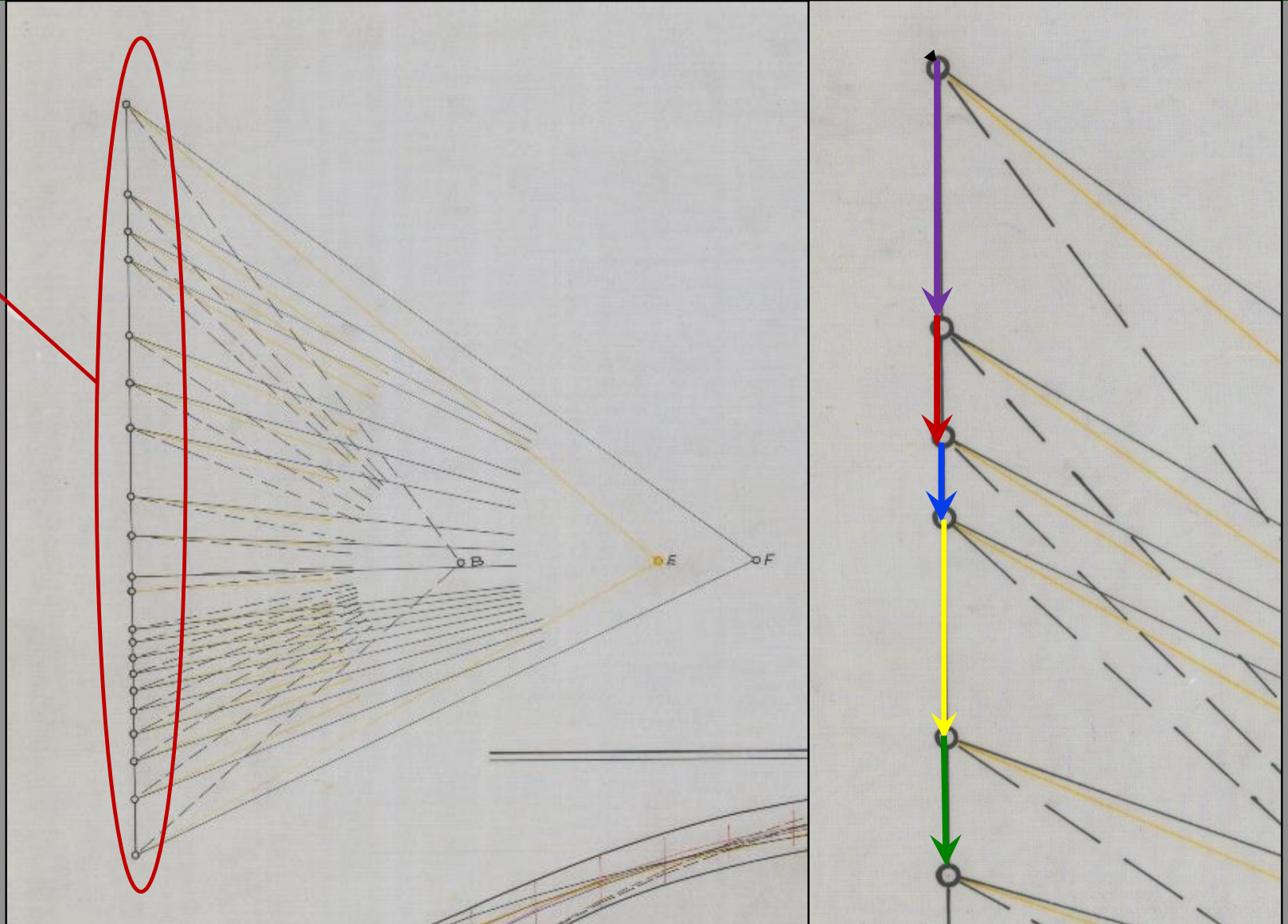


Terminology



Terminology

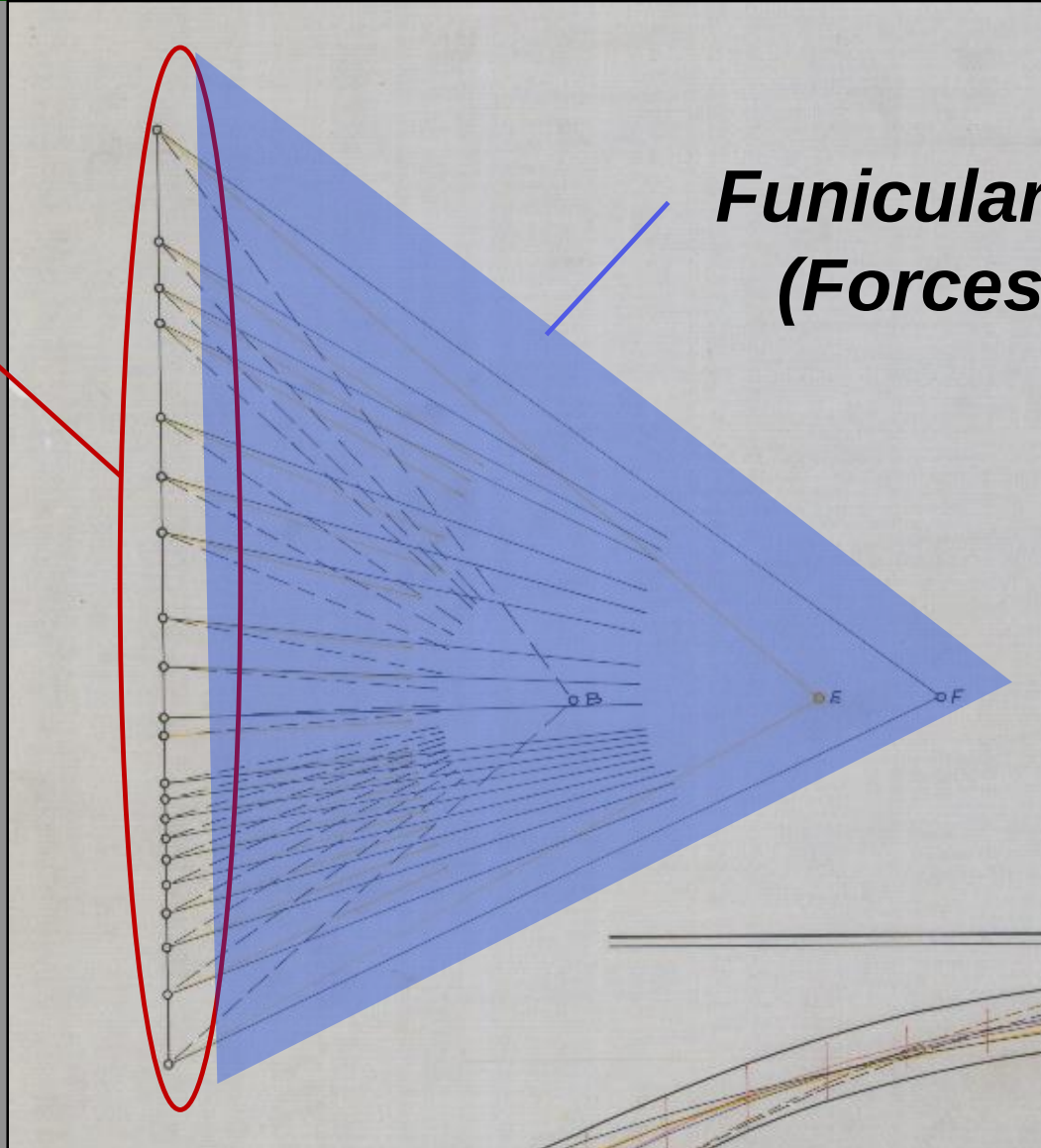
**Force
Polygon**



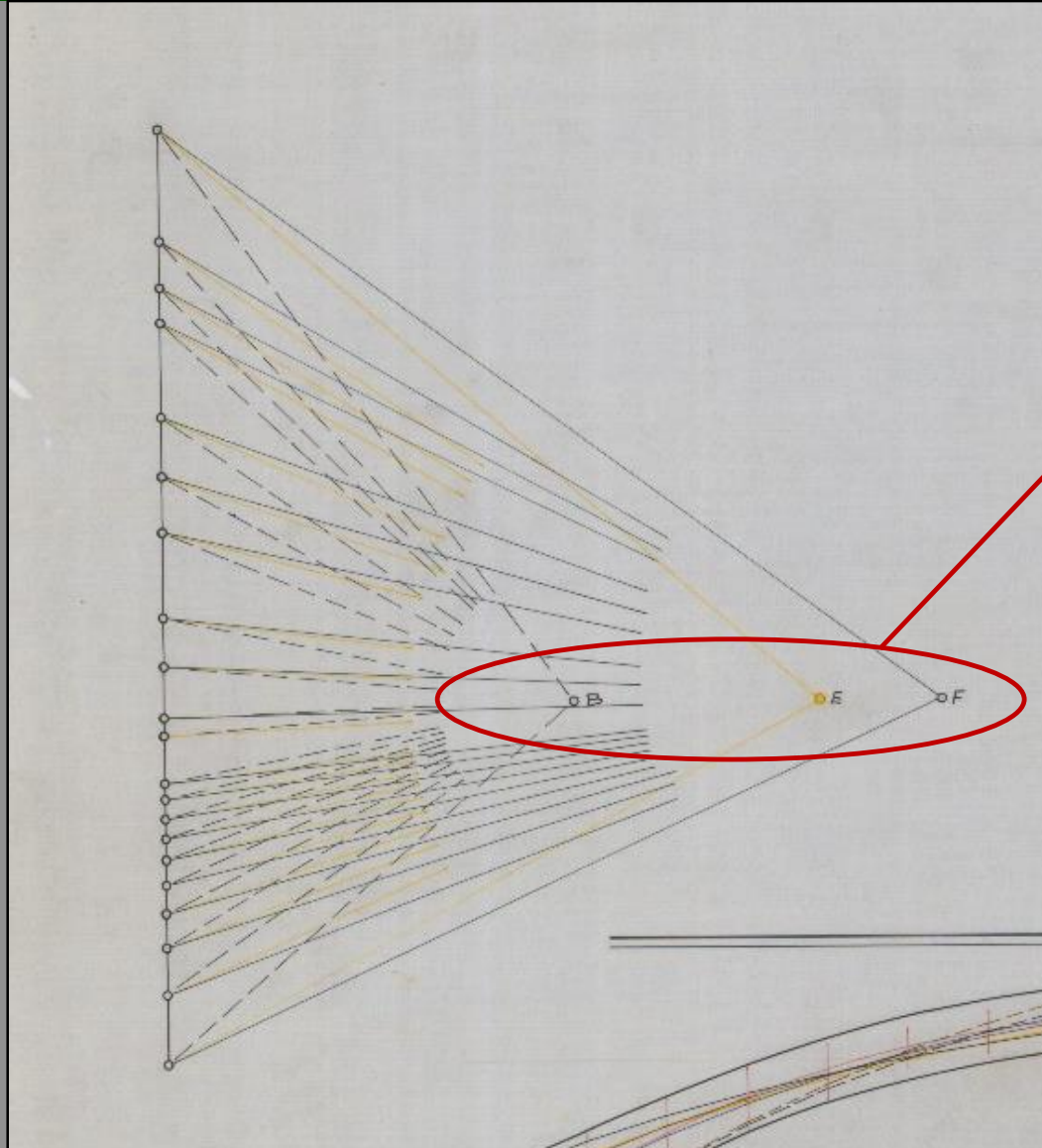
Arch Design

**Force
Polygon**

**Funicular Polygon
(Forces within the arch)**



Terminology



***Poles
(Horizontal
Thrust)***

Scale and Load Cases

Force Polygons, $1'' = 10,000^{\#}$

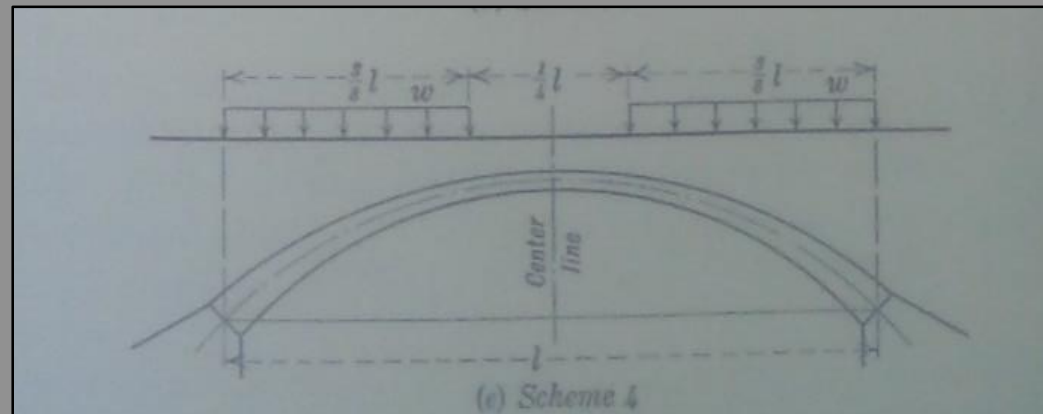
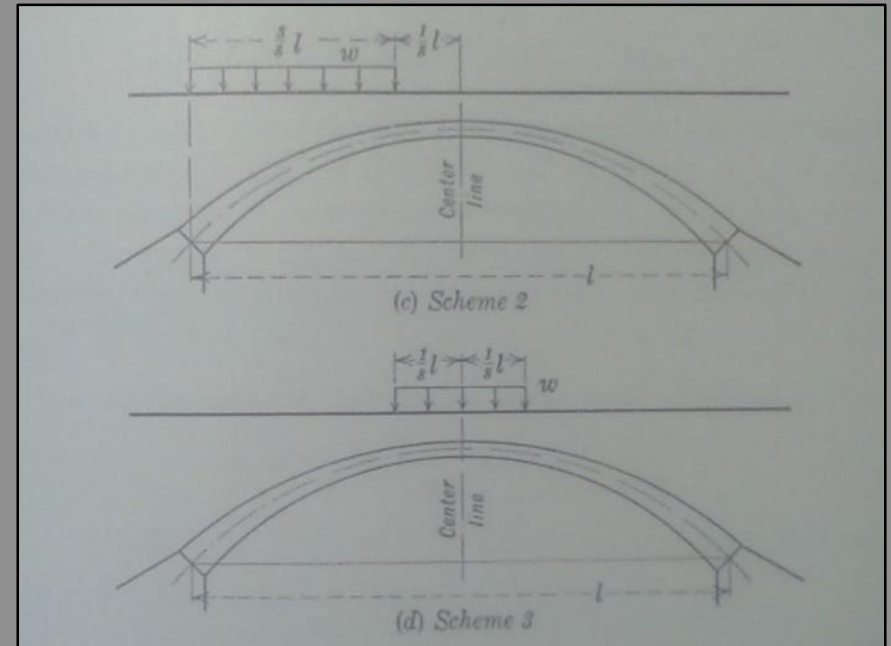
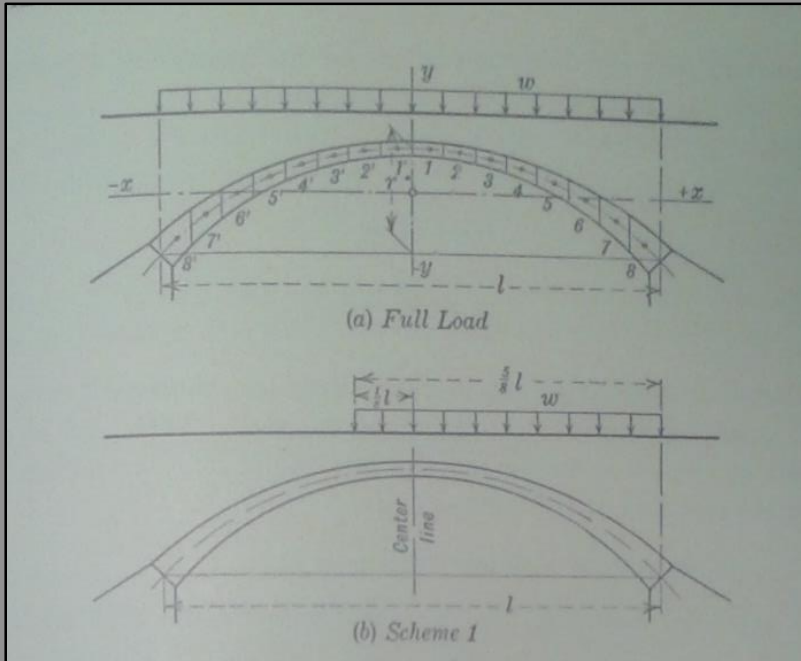
- A 30° decrease in temp. Full D. + L.
- B " " " " $\frac{1}{2}$ " "
- C Full D. and L.
- D 15° increase in temp Full D. + L.
- E $\frac{1}{2}$ Span D. and L.
- F 15° increase in temp. $\frac{1}{2}$ D. + L.

Arch Design Live Loads

Various Loads for Vehicular Bridges

- ***100 PSF common***
- ***Highest found: 312 PSF***
- ***Common Vehicle through 1910s:
11 Ton road grader***

Arch Live Loads Placements



Graphic Statics Analysis

TABLE A.
CALCULATIONS FOR H_0 , V_0 , AND M_0 .

1	2	3	4	5	6	7	8	9
Point.	x	y	x^2	y^2	m_L	m_R	$(m_L + m_R)y$	$(m_R - m_L)x$
1	1.55	.09	2.40	.01	0	0	0	0
2	4.90	.68	24.01	.46	-13,840	-8,640	-15,300	+25,500
3	8.45	2.10	71.40	4.41	-46,800	-29,560	-160,400	+145,700
4	12.85	5.35	165.12	28.62	-116,680	-75,490	-1,028,100	+529,300
Σ		8.22	262.93	33.50	-291,010		-1,203,800	+700,500
Spring- ing.	15.00	8.00			-180,820	-120,640		

Eq. (1) gives $H_0 = \frac{4(-1203800) - (-291010 \times 8.22)}{2[(8.22)^2 - 4 \times 33.50]} = +18,230 \text{ lbs.}$

Eq. (2) gives $V_0 = \frac{700500}{2 \times 262.93} = +1,330 \text{ lbs.}$

Eq. (3) gives $M_0 = -\frac{-291010 + 2 \times 18230 \times 8.22}{2 \times 4} = -1,090 \text{ ft-lbs.}$

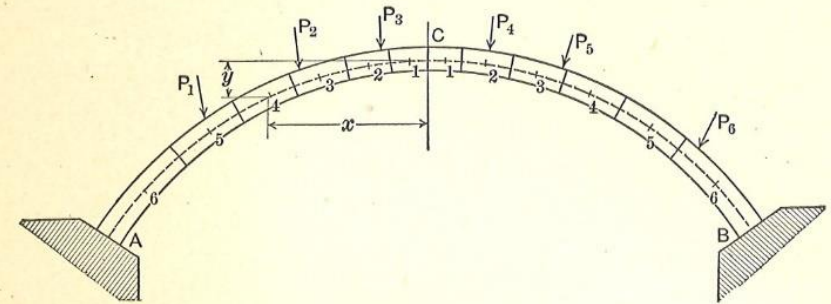
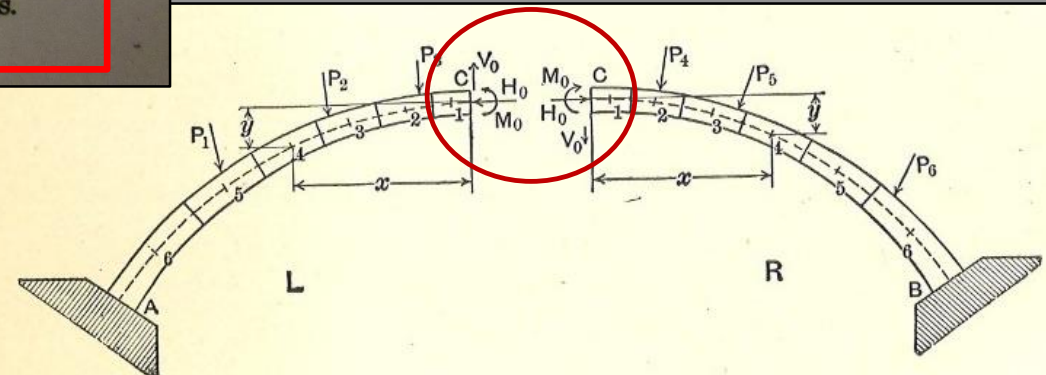
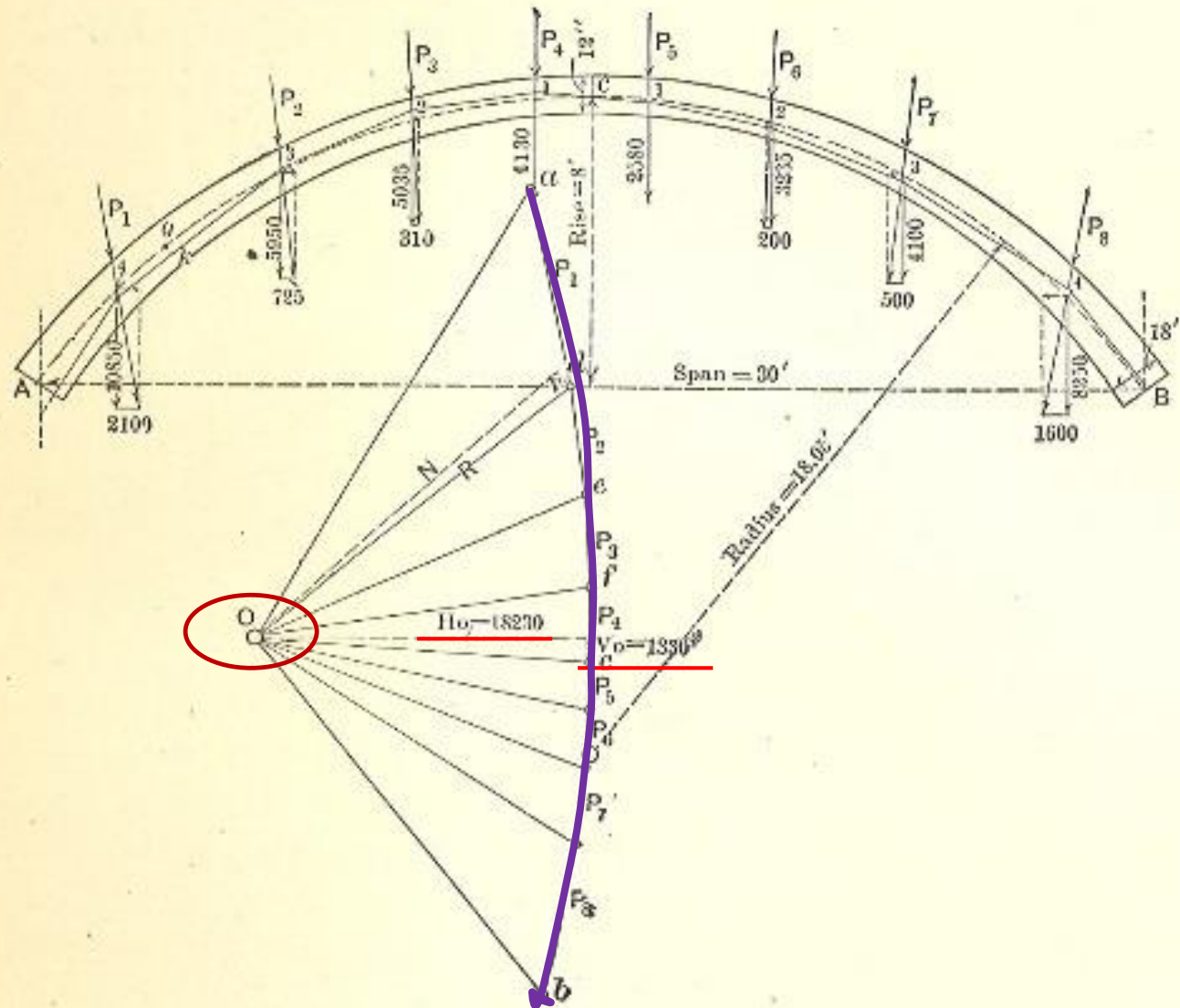


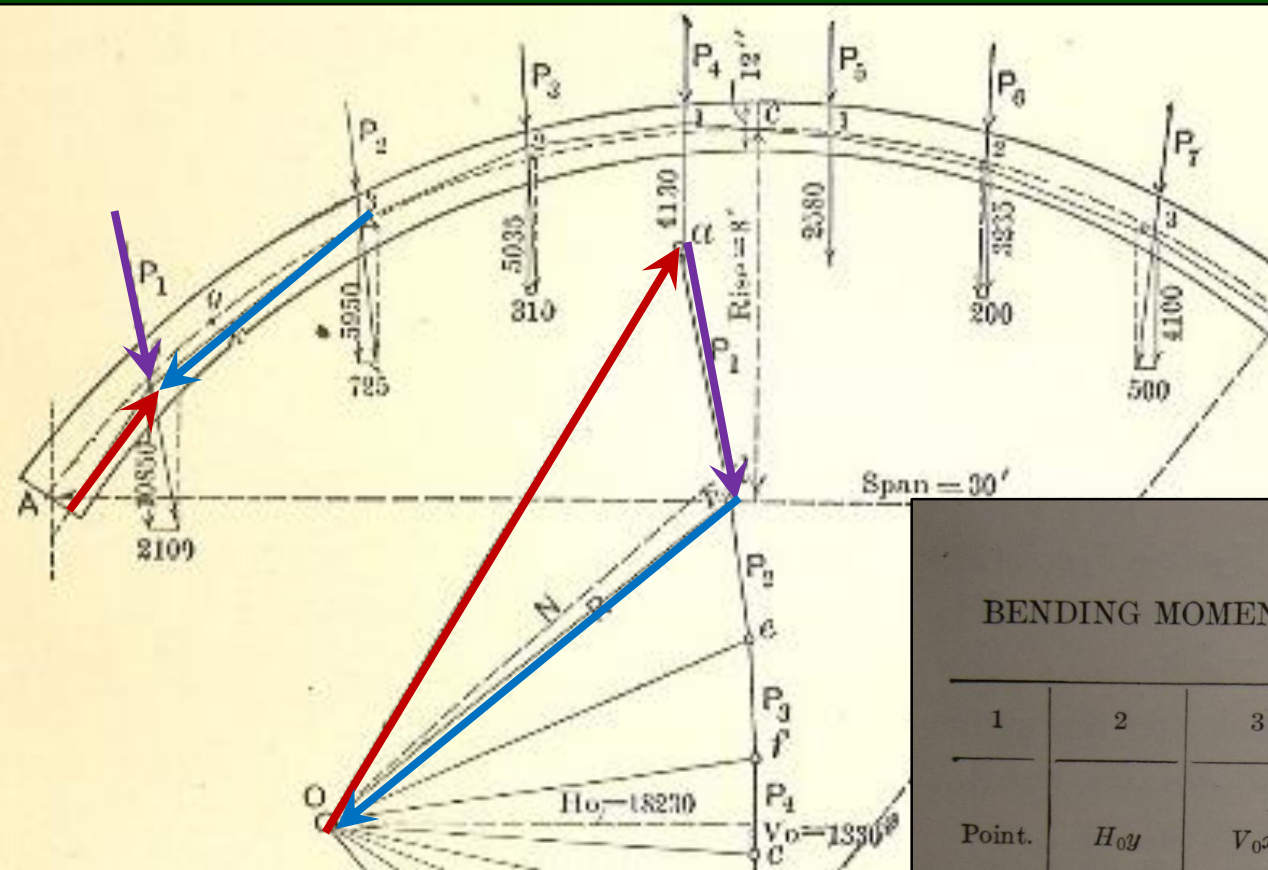
FIG. 99.



Loads



Graphic Statics Analysis



**A Free Body
Diagram**

TABLE B.

BENDING MOMENTS, THRUSTS, AND ECCENTRIC DISTANCES.

1	2	3	4	5	6	7	8	9
Point.	H_0y	V_0x	Bending Moment M		Thrusts.		Eccentric Distances.	
			Left.	Right.	Left.	Right.	Left.	Right.
1	1,640	2,060	+ 2,610	- 1,520	18,450	18,640	+ .14	- .08
2	12,400	6,530	+ 4,000	- 3,860	19,580	19,310	+ .21	- .20
3	38,300	11,260	+ 1,650	- 3,620	22,050	20,770	+ .07	- .17
4	97,500	17,120	- 3,100	+ 3,850	28,800	24,970	- .11	+ .15
Spring- ing.	145,900	20,000	- 16,070	+ 4,140	28,800	24,970	- .56	+ .17

The Decline of Graphic Statics

Graphic Statics

- ***Has inexactness***
- ***Needs drafting tables, papers and pencils***
- ***Determines equilibrium***

Contemporary Statics & FEM

- ***Very precise***
- ***Ease with slide rules, calculators and computers***
- ***Based on material properties***

Graphic Statics Load Rating: The Ground Rules

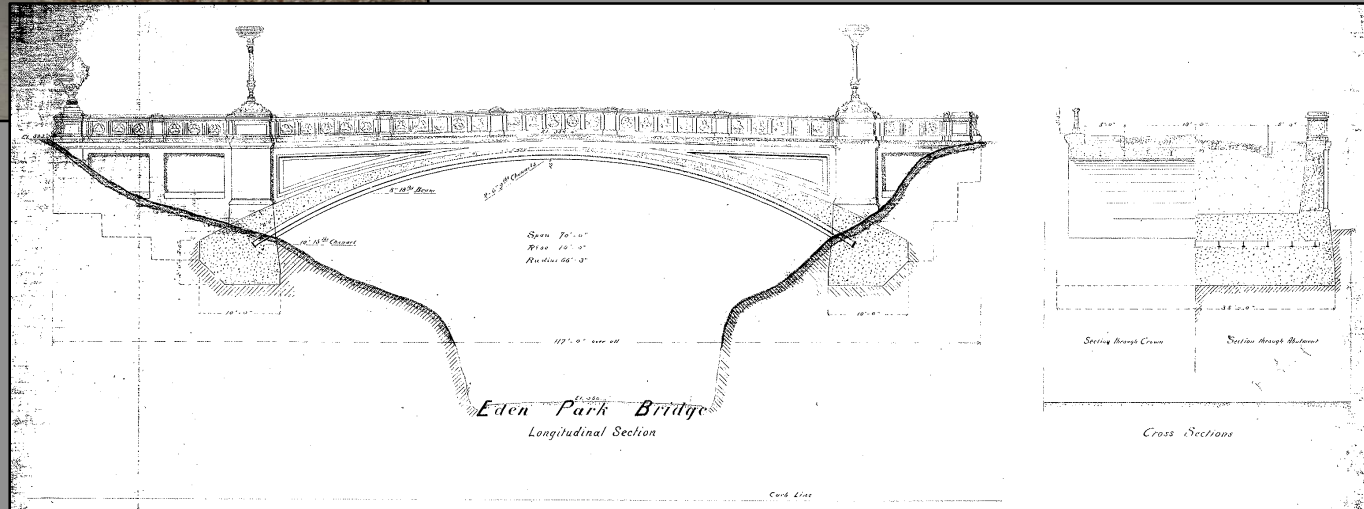
***Compare rating factors with previous
FEM arch load ratings:***

- 1. Use same material strengths***
- 2. Investigate controlling OLL vehicle and placement on arch.***
- 3. Use LFR load rating methods.***

Eden Park Arch



- ***Cincinnati***
- ***Built 1894-95***
- ***70-ft. span***



North Quarry Lane Arch



- ***Cuyahoga County***
- ***150 ft. span***
- ***Built 1938***

North Quarry Lane Arch

Pt.	DL Vert. (k)	DL Hor. (k)	LL (k)	DL + LL Vert. (k)	Pt.
10	5.95	2.92	0.00	5.95	1
9	10.73	4.71	0.00	10.73	2
8	9.14	3.22	0.00	9.14	3
7	7.50	2.14	0.00	7.50	4
6	6.00	1.51	0.00	6.00	5
5	4.69	1.12	0.00	4.69	6
4	3.70	0.77	0.00	3.70	7
3	3.02	0.51	0.00	3.02	8
2	2.53	0.33	0.21	2.74	9
1	2.18	0.20	1.56	3.74	10
0	1.99	0.00	2.25	4.24	11
1	2.10	-0.20	1.81	3.91	12
2	2.39	-0.32	0.25	2.64	13
3	2.84	-0.50	0.00	2.84	14
4	3.47	-0.75	0.00	3.47	15
5	4.41	-1.10	0.00	4.41	16
6	5.66	-1.48	0.00	5.66	17
7	7.16	-2.19	0.00	7.16	18
8	8.94	-3.25	0.00	8.94	19
9	10.66	-4.50	0.00	10.66	20
10	5.93	-2.72	0.00	5.93	21

$\Sigma LL = 6.08 \text{ k}$

$\Sigma DL = 110.99 \text{ k}$

$\Sigma DL \& LL = 117.07 \text{ k}$



Berea Arch

Pt.	DL Vert. (k)	DL Hor. (k)	LL (k)	DL + LL Vert. (k)	Pt.
10	5.95	2.92	0.00	5.95	1
9	10.73	4.71	0.00	10.73	2
8	9.14	3.22	0.00	9.14	3
7	7.50	2.14	0.00	7.50	4
6	6.00	1.51	0.00	6.00	5
5	4.69	1.12	0.00	4.69	6
4	3.70	0.77	0.00	3.70	7
3	3.02	0.51	0.00	3.02	8
2	2.53	0.33	0.21	2.74	9
1	2.18	0.20	1.56	3.74	10
0	1.99	0.00	2.25	4.24	11
1	2.10	-0.20	1.81	3.91	12
2	2.39	-0.32	0.25	2.64	13
3	2.84	-0.50	0.00	2.84	14
4	3.47	-0.75	0.00	3.47	15
5	4.41	-1.10	0.00	4.41	16
6	5.66	-1.48	0.00	5.66	17
7	7.16	-2.19	0.00	7.16	18
8	8.94	-3.25	0.00	8.94	19
9	10.66	-4.50	0.00	10.66	20
10	5.93	-2.72	0.00	5.93	21

$\Sigma LL = 6.08 \text{ k}$

$\Sigma DL = 110.99 \text{ k}$

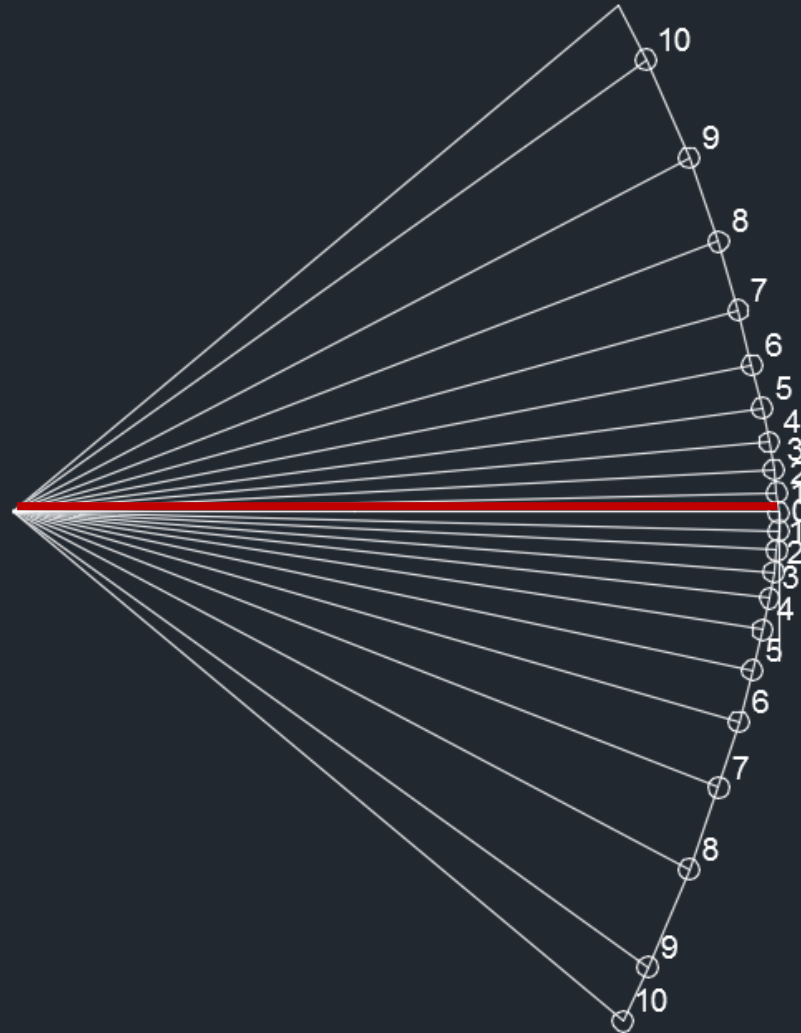
$\Sigma DL \& LL = 117.07 \text{ k}$



DL

DL + LL

Load Rating Variance

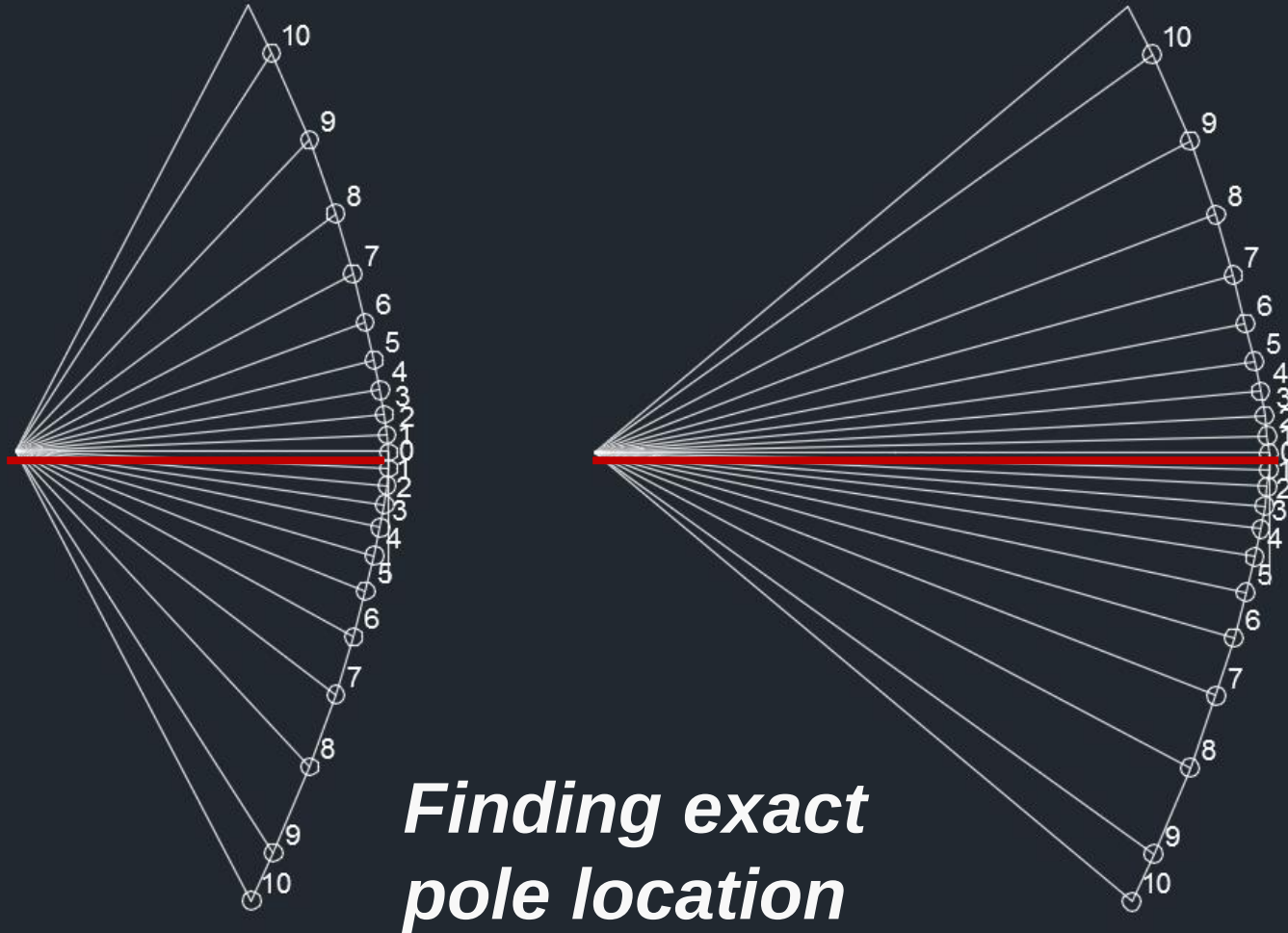


Load Rating Variance

Item	Rating Factors	
	Eden Park	N. Quarry Lane
Controlling Vehicle	4F1	3F1
Location	Crown	Crown
FEM Rating Factor	4.70	2.75
Graphic Statics Methods *	~ 3.0 to 6.0	~ 2.0 to 4.0

**** Graphic Statics still inexact***

Load Rating Variance



The Takeaways

***The Strength of Graphic Statics:
Has a feel like driving a car with
a manual transmission!***

- ***No black box, the engineer can “see” the structure work.***
- ***Easy to follow the process and find issues or errors.***

The Takeaways

- 1. The Past: Can be a great learning tool for engineering students.***

***Taught by Dr. Boothby, Penn State
Architectural Engineering program.***

***Developing workshop for U. of Akron Civil
Engineering, Spring 2018***

The Takeaways

2. The Present: Graphic statics may be easier to use now with CAD and spreadsheets.

Still inexact without refined determination of poles.

The Takeaways

3. The Future: Despite lack of precision, Graphic Statics still is a method useful to bridge engineers and students.

Can develop elaborate spreadsheets to rate greater number of arch locations.

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