

063-0605-22L

Computational Structural Design I

Computational Graphic Statics

Dr. Lluís Enrique

Block Research Group (Prof. Dr. Philippe Block)

HS2022



BRG

<http://block.arch.ethz.ch>



@blockresearchgroup



BRG



Lecturer



Dr. Lluís Enrique

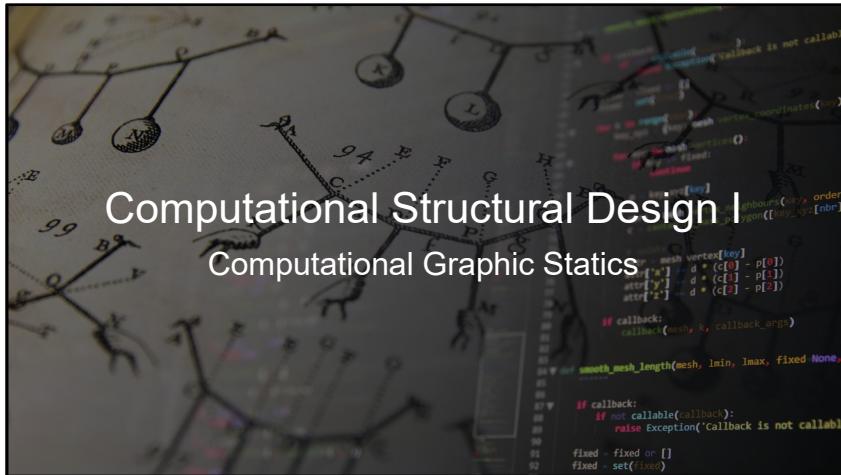
PhD student instructors



Chaoyu Du



Selina Bitting



Computational Structural Design I

Computational Graphic Statics

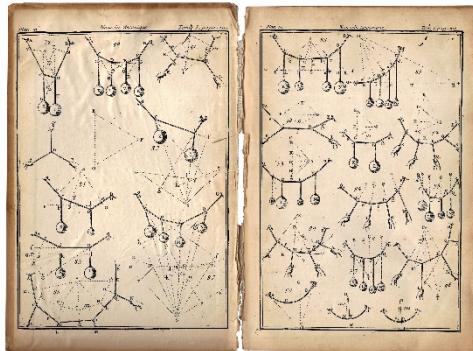
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Computational Structural Design II

Advanced Form Finding & Digital Fabrication

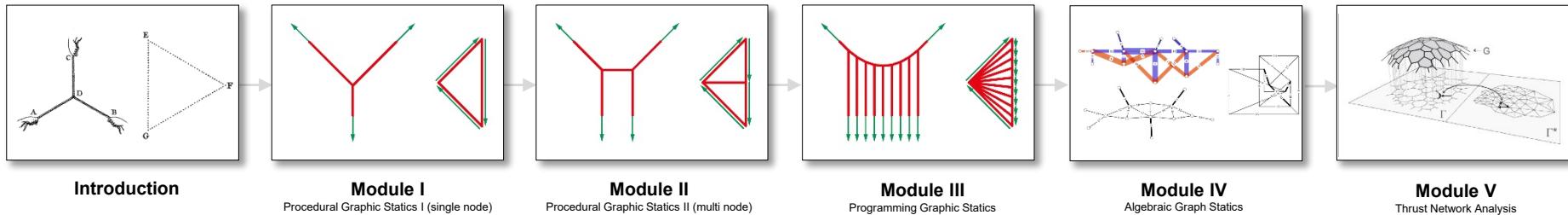
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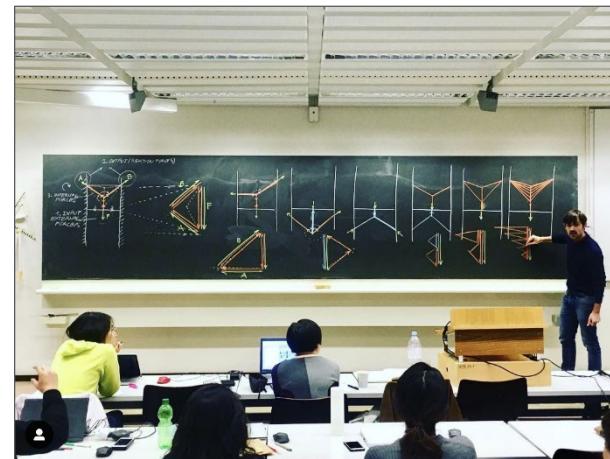
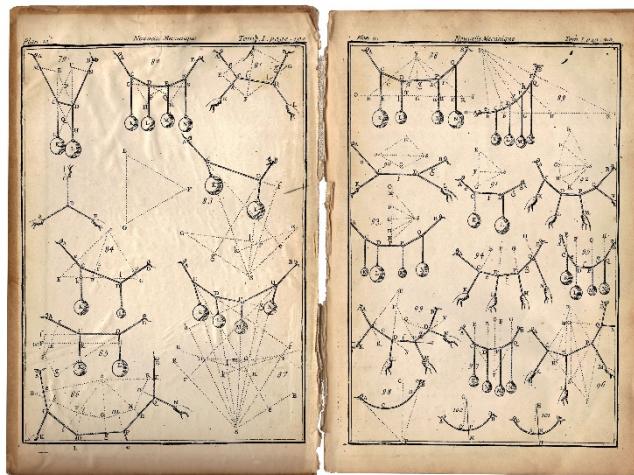
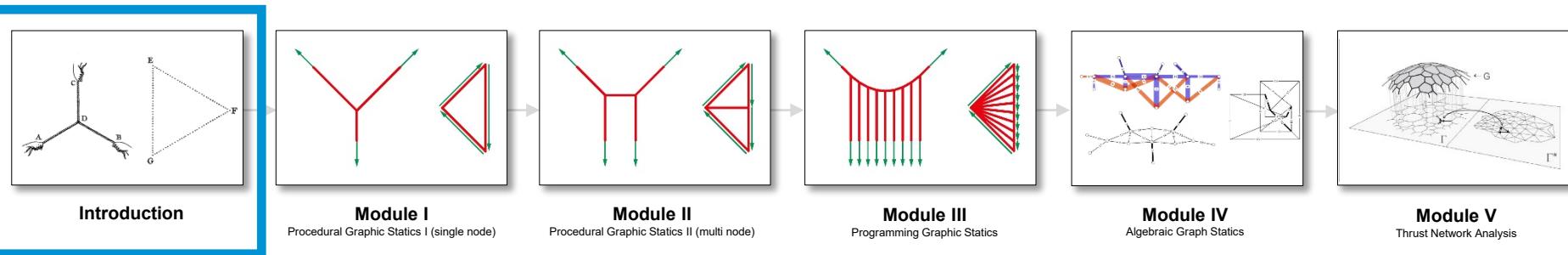


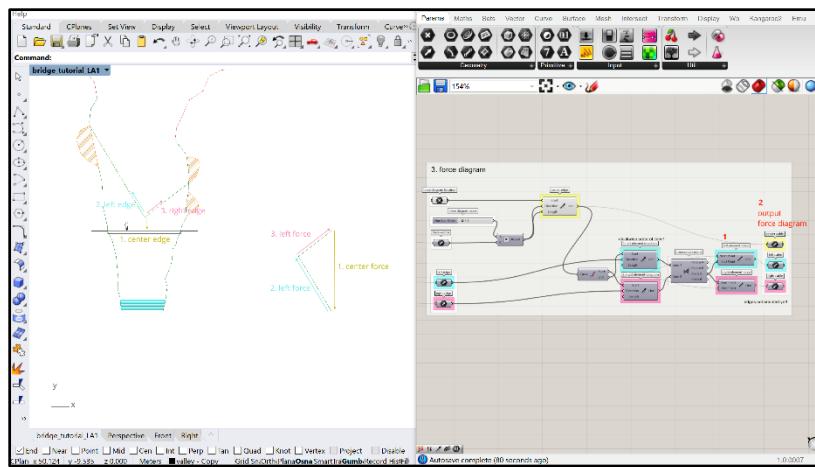
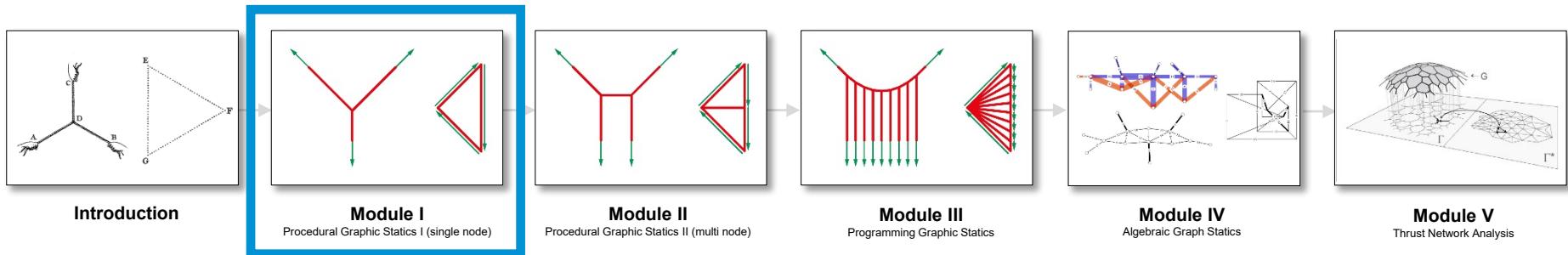
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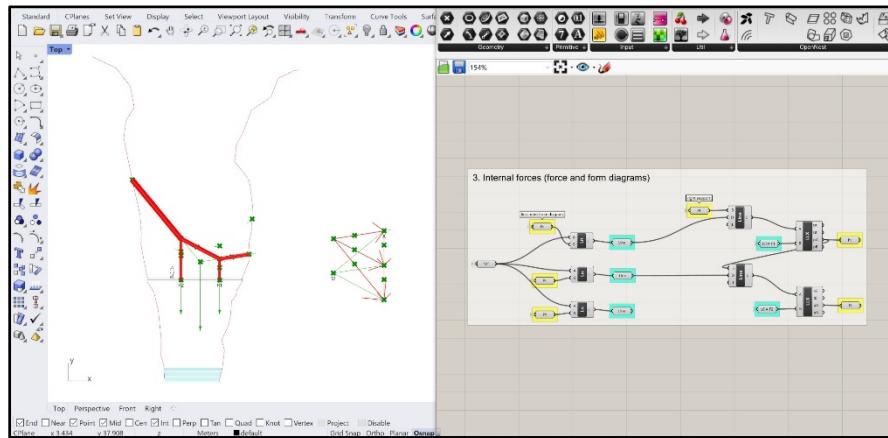
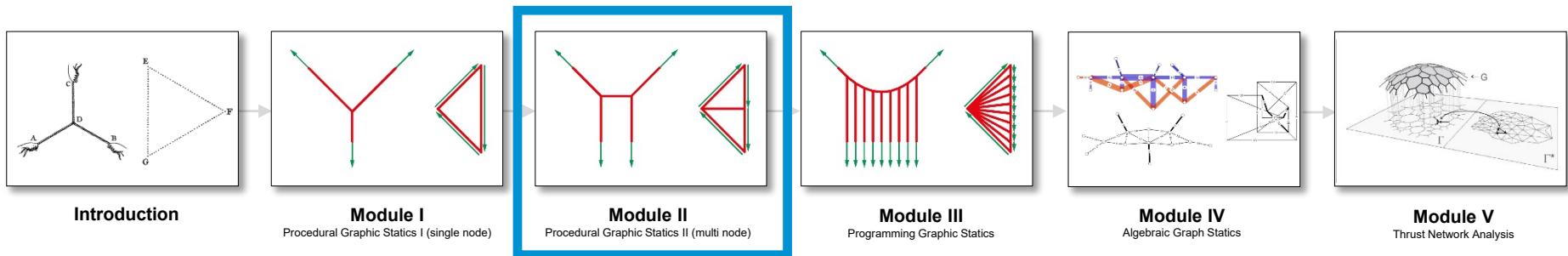


Explore new **structural design opportunities**
by combining **graphic statics** with **computational tools**



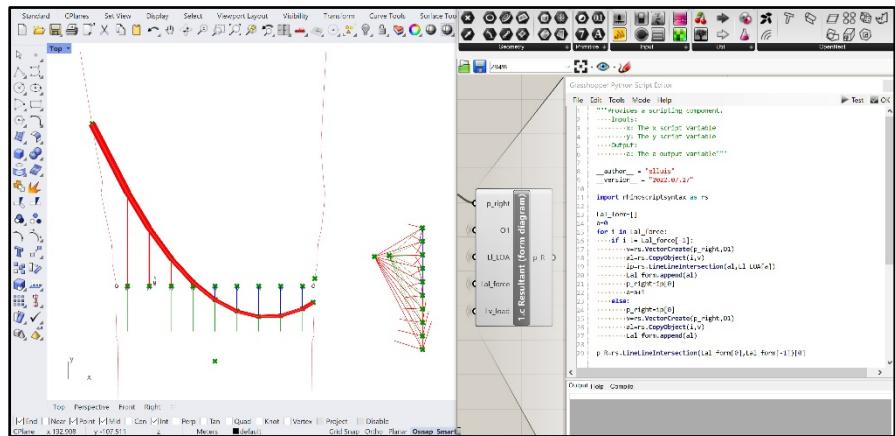
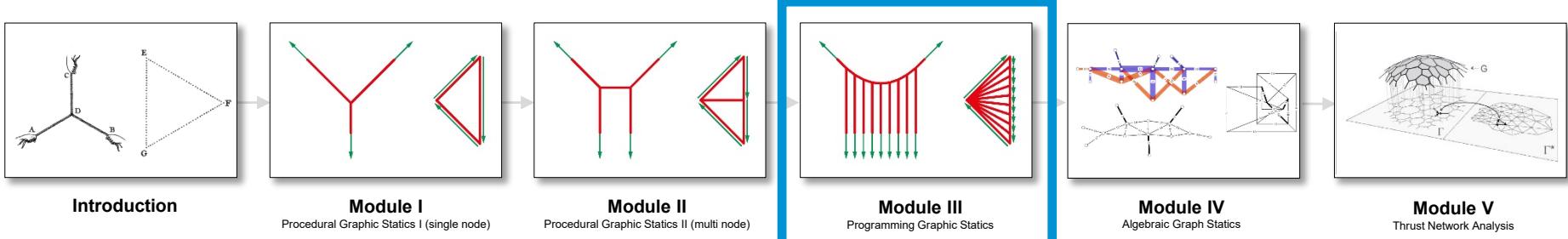


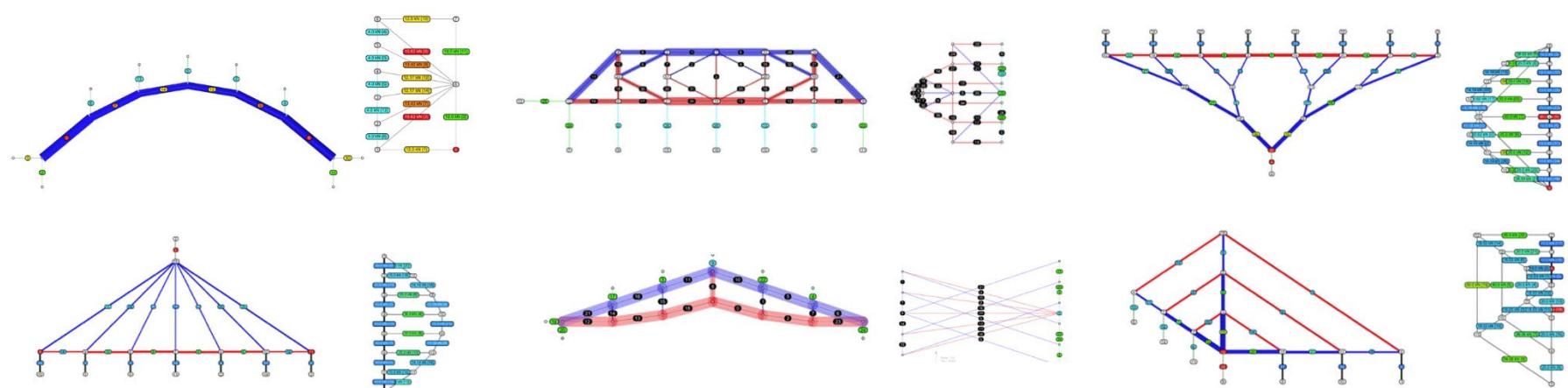
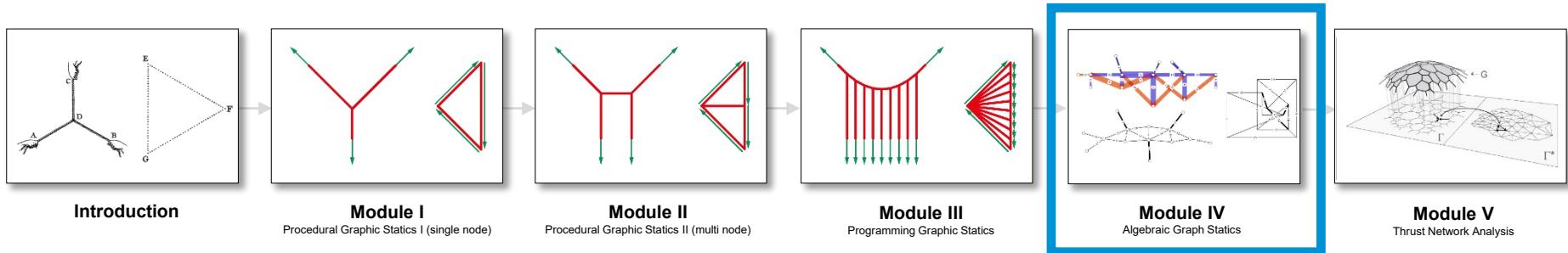


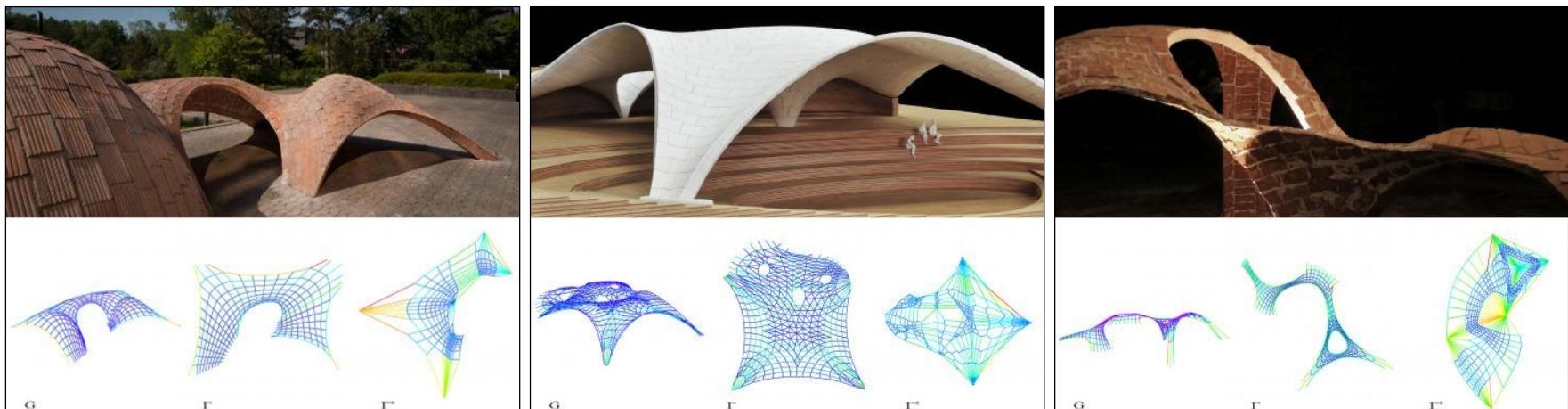
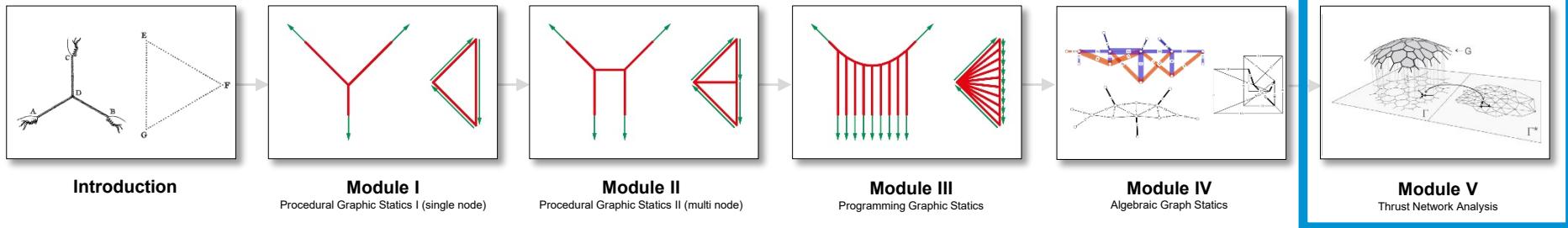


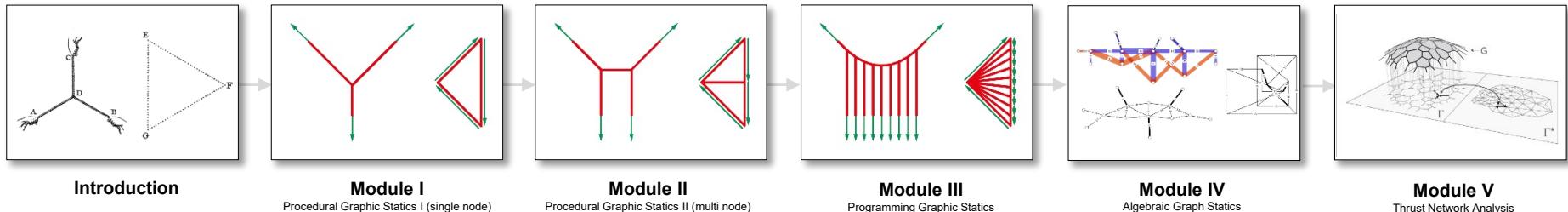
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At the conclusion of this course, you will have:

- Fundamental knowledge of graphic statics.
- Basic parametric thinking and modelling with Rhinoceros and Grasshopper.
- Elementary skills in Python scripting.
- Experience using computational tools based on graphic statics for the design and analysis of structures.
- Understanding of the potential of combining graphic statics and computational tools.

Typology	Topic	Module	Week		Topic	Lead
cables & arches	Introduction		Week 1 (23/9)	Lecture	Introduction to graphic statics	Dr. Lluis Enrique
				Tutorial	Introduction to Rhino and Grasshopper	
				Work session	graphic statics + Grasshopper	
			Week 2 (30/9)		Quick recap of last week's exercise	Dr. Lluis Enrique
				Lecture	Algorithmic design & thinking	
	Procedural GS (Grasshopper)			Tutorial	Single node bridge in Grasshopper	
		Week 3 (7/10)	Work session	Single node bridge in Grasshopper		
		Week 4 (14/10)		Quick recap of last week's exercise	Dr. Lluis Enrique	
			Lecture	Computational graphic statics		
			Tutorial	Multi-node bridge in Grasshopper		
		Week 5 (21/10)	Work session	Multi-node bridge in Grasshopper		
Week 6: Seminar week						
cables & arches	Procedural GS (Python)		Week 7 (4/11)		Quick recap of last week's exercise	Dr. Lluis Enrique
				Lecture	Programming	
			Week 8 (11/11)	Tutorial	Multi-node bridge in Python	
trusses	AGS		Week 9 (18/11)		Quick recap of last week's exercise	Dr. Lluis Enrique
				Lecture	Algebraic Graph Statics (AGS)	Dr. Lluis Enrique
				Tutorial	Interactive Graphic Statics (IGS)	Chaoyu Du
			Week 10 (25/11)	Work session	Truss analysis using IGS	
shells	TNA		Week 11 (02/12)		Quick recap of last week's exercise	Dr. Lluis Enrique
				Lecture	Thrust Network Analysis (TNA)	Dr. Lluis Enrique
			Week 12 (09/12)	Tutorial	RhinoVault 2 (rv2)	Selina Bitting
				Work session	Shell design using rv2	

063-0605-22L (CSDI) - 2022
Computational Graphic Statics

Block Research Group eQUILIBRIUM COMPAS

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COURSE MATERIAL

Introduction

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I. Procedural GS I

II. Procedural GS II

III. Programming GS

IV. Algebraic GS

V. RhinoVault 2

APPENDIX

References

Slack

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About

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OUTLINE

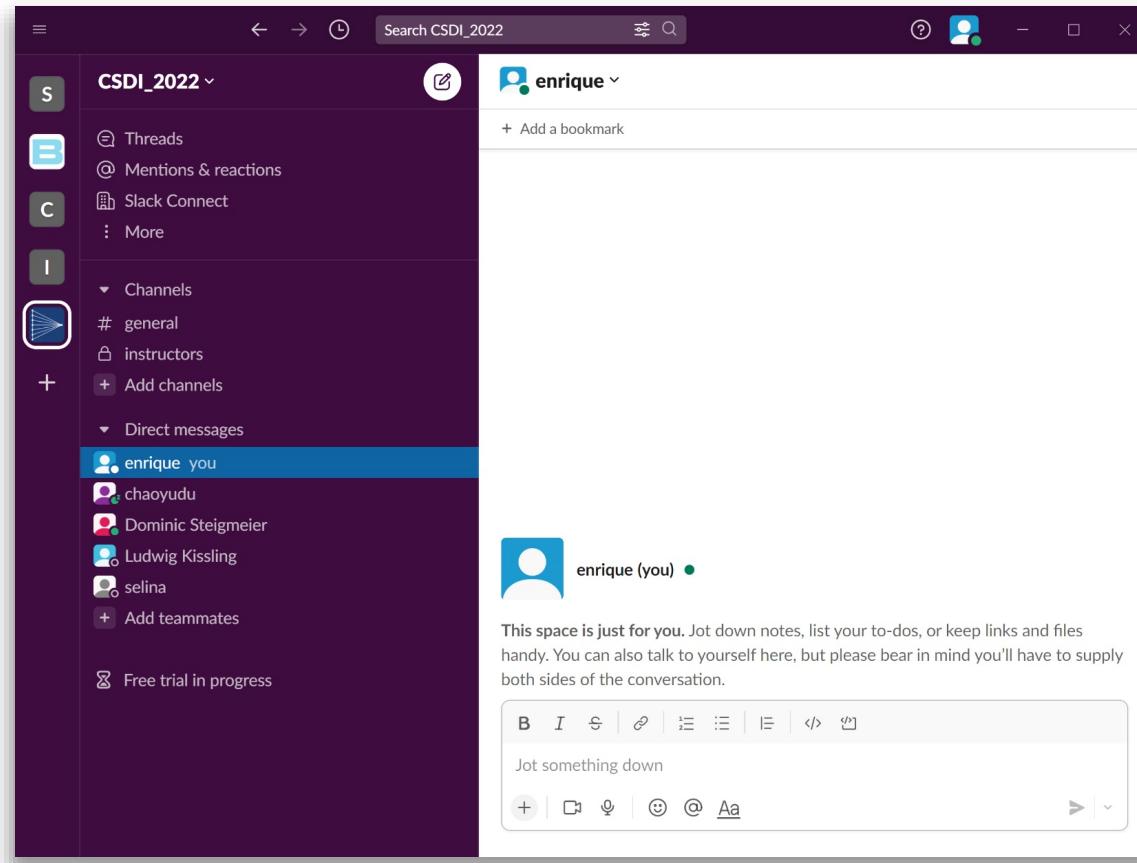
Welcome to the course Computation...
General information

**Welcome to the course Computational Structural Design I:
Computational Graphic Statics!**

This course presents new structural design opportunities that emerge when graphic statics, an intuitive equilibrium-based method for the form-finding, analysis and design of structures, is combined with computational tools. After a review of graphic statics fundamentals and an introduction to basic parametric tools, the course focuses on studying different computational approaches to program graphic statics algorithms for the form-finding and analysis of structures, from linear (procedural) algorithms to programs with more complex data structures. More specifically, the students will build linear parametric graphic statics models using Grasshopper, read and code basic graphic statics algorithms using Python, and explore the design space offered by tools developed by the Block Research Group such as Interactive Graphic Statics (IGS) and RhinoVault2 (V2). The practical potential and relevance of these methods will be demonstrated through various design-oriented tutorials and exercises.

General information

- **Name:** 063-0605-22L : Computational Structural Design I (ETH course catalogue)
- **Semester:** Autumn Semester 2022
- **Lecturer:** Dr. Lluís Enrique
- **Date/time:** Fridays, 09:45 - 12:00
- **Location:** HPT C 103



Week 1 Friday, September 23rd

9:45 – 10:30 Welcome & introduction
Lecture: Introduction to graphic statics

10:30 – 10:45 Break

10:45 – 11:30 **Tutorial: Introduction to Rhino & Grasshopper**

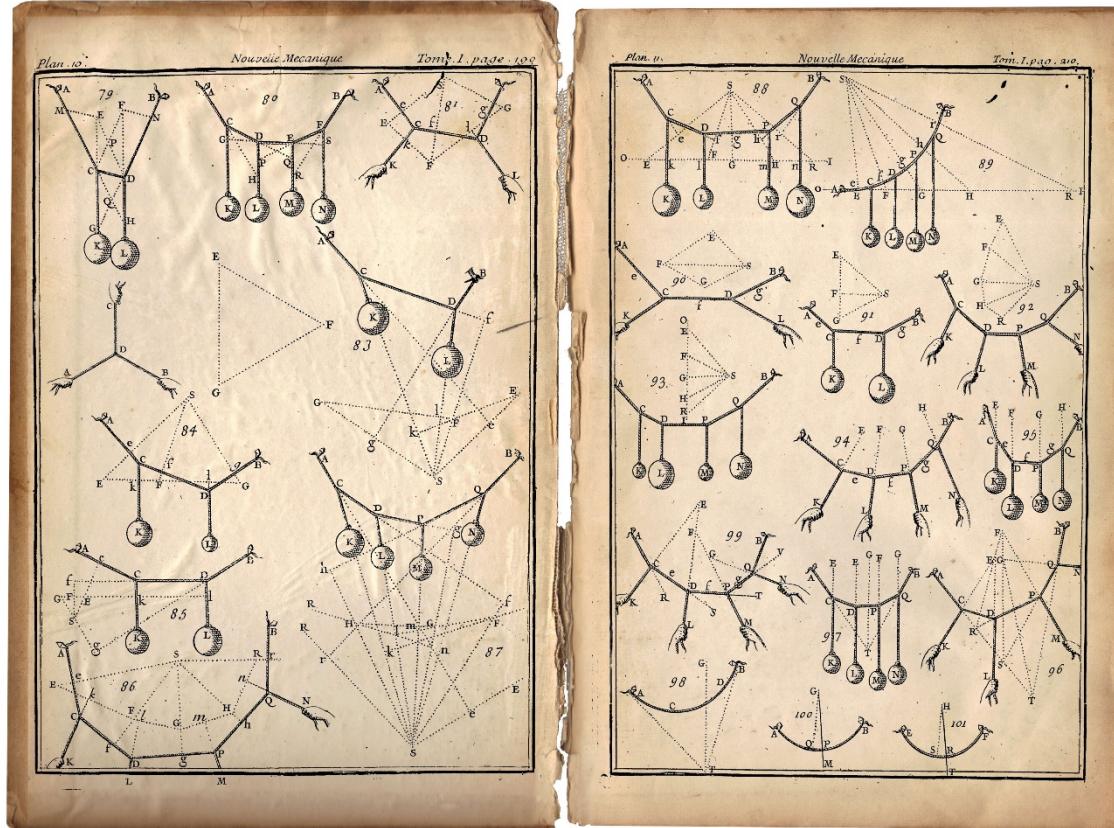
11:30 – 11:45 Break

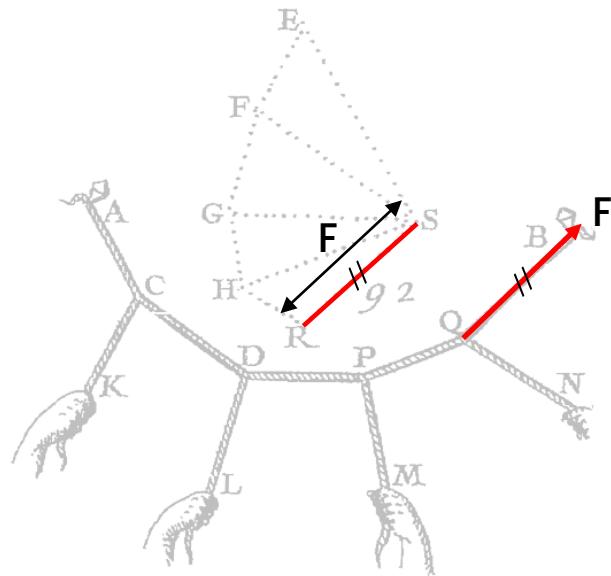
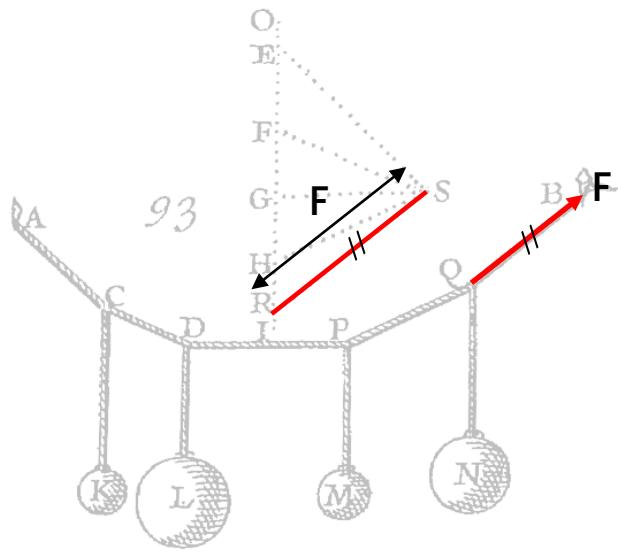
11:45 – 12:30 Exercise introduction
Work session

Introduction to Graphic Statics

Friday, September 23rd, 2022

Dr. Lluís Enrique





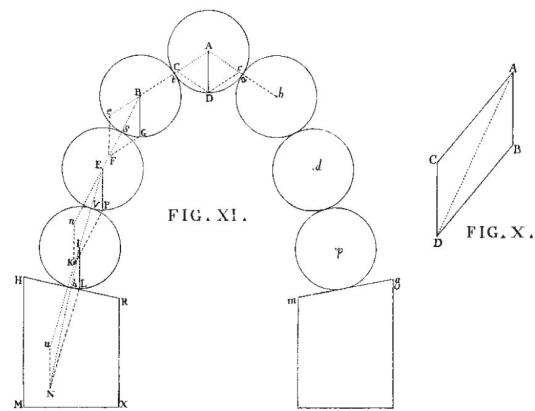


FIG. XI.

FIG. X.

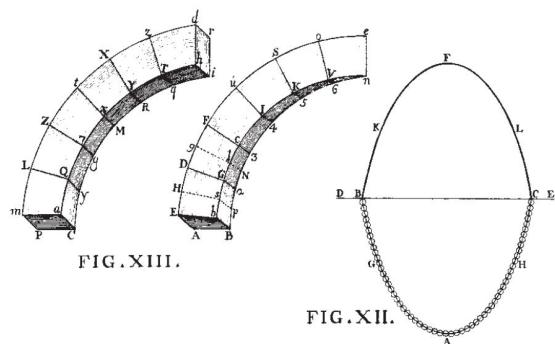
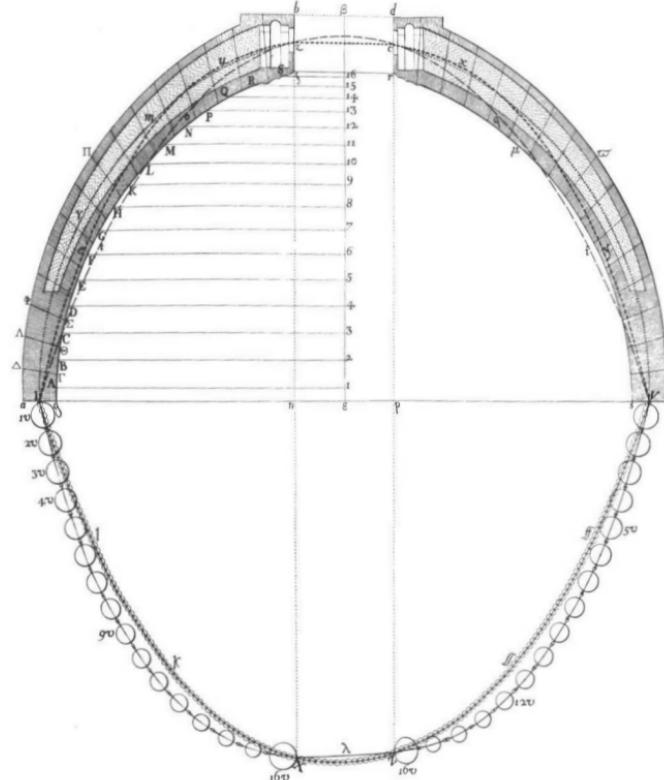
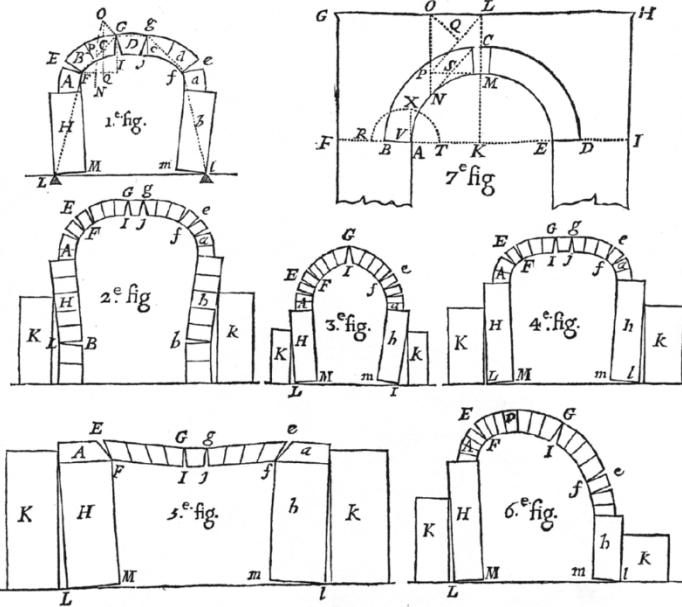


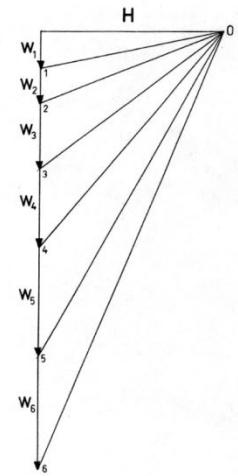
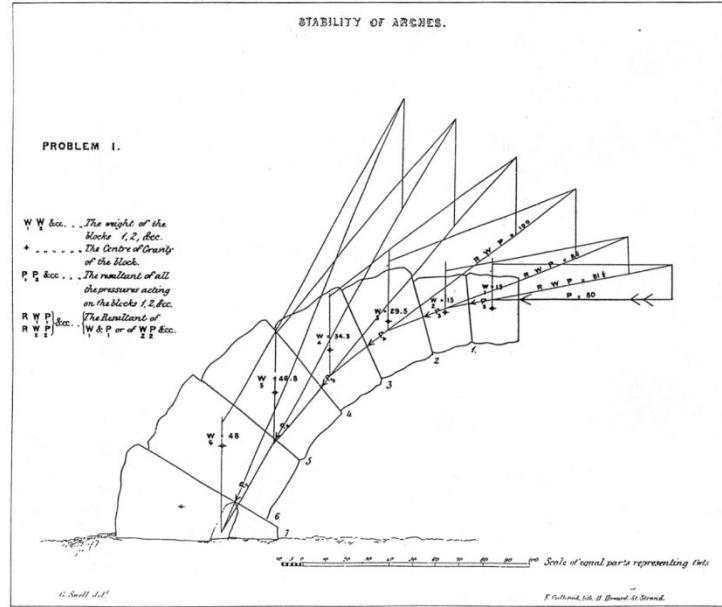
FIG. XIII.

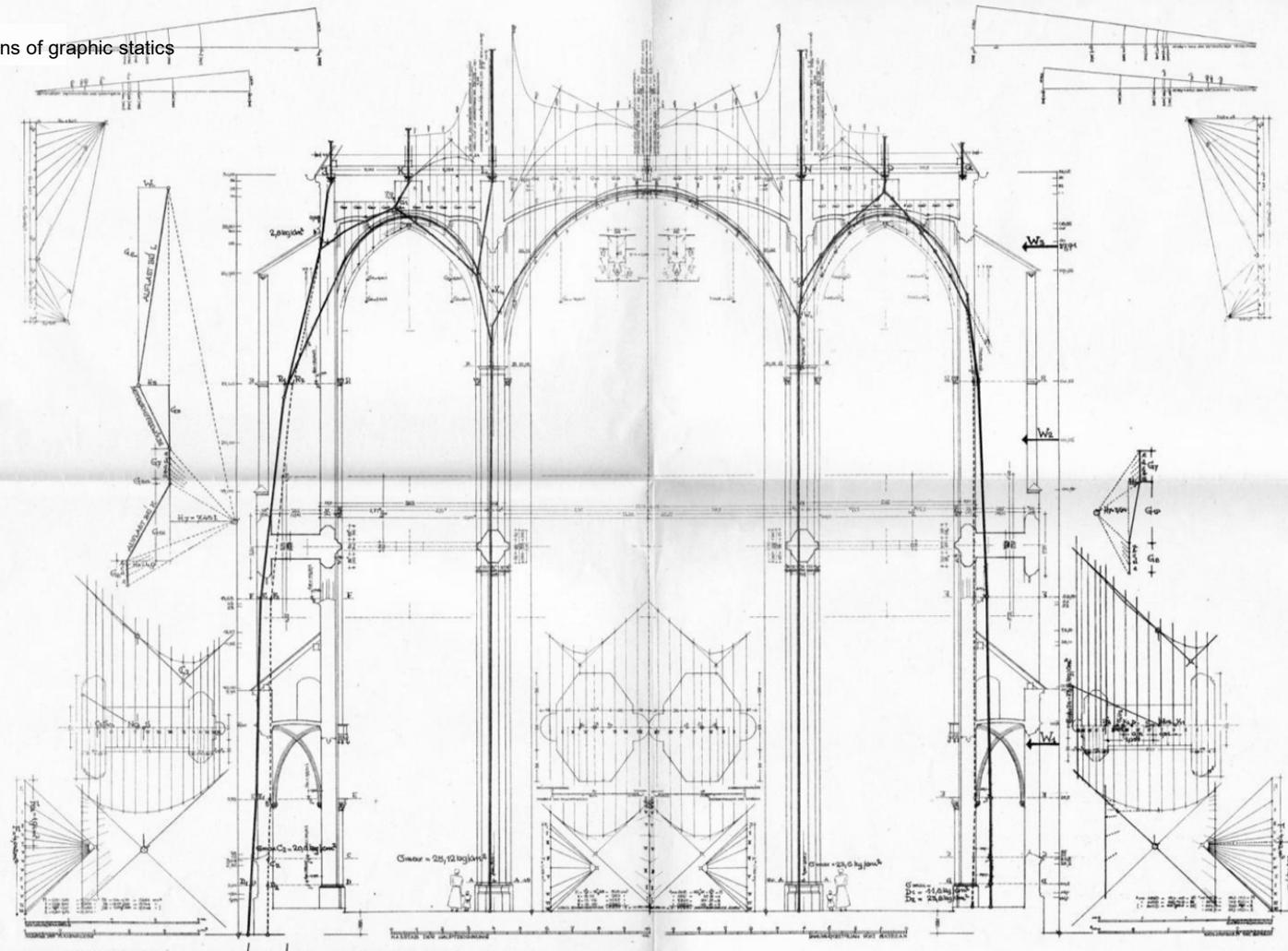
FIG. XII.



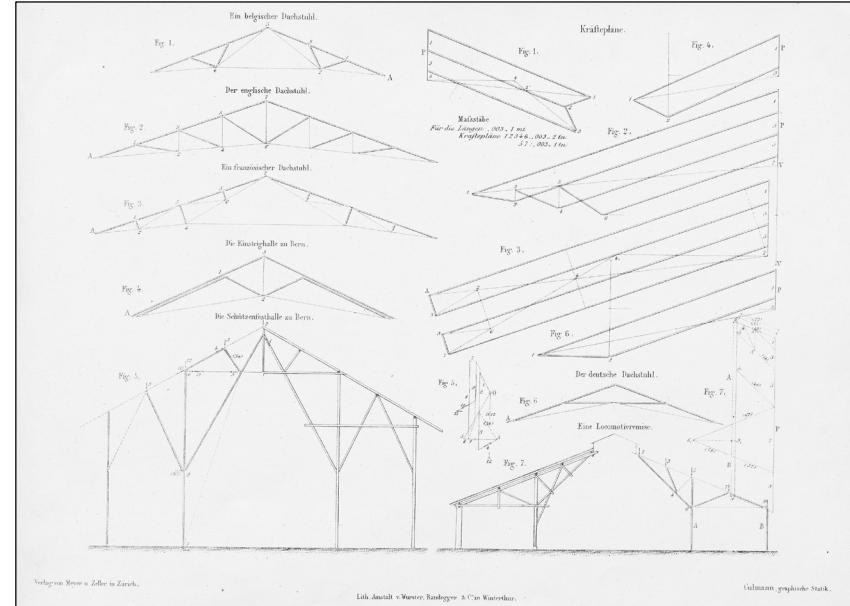
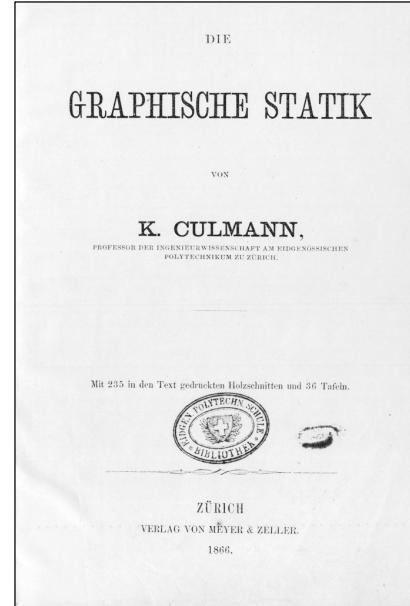


Danyzy (1732)





BELASTUNGSFALL 4: MIT WIND- UND DACHLAST



Introduction ► Rise of graphic statics

Cremona's Procedural Graphic Statics

156 EXAMPLES OF FRAME- AND STRESS- DIAGRAMS. [43-

the upper extremity of the segment 1 meets the upper extremity of the segment 2 ; and the straight line 18 through the point (16, 1), which is both the lower extremity of the segment 16 and that of the segment 1.

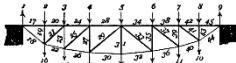


Fig. 8a.

Pass on to the joint (2, 17, 19, 20). Draw 19 through the point (17, 18), and 20 through the point (2, 3), the lower end of 2 and upper extremity of 3 ; and we obtain the polygon 2, 17, 19, 20, which is a rectangle.

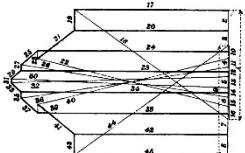


Fig. 8b.

Construct the polygon corresponding to the joint (16, 18, 19, 21, 22). For this purpose draw 21 through the point (19, 20), and 22 through the point (15, 16) ; we thus obtain a crossed pentagon. Continue to deal in the same manner with each of the points of application of the forces 3, 15, 4, 14, 13, 6, 12, 6, 11, 7, 10, 9, taken in succession.

Since the diagram *a*, which represents the skeleton of the structure and all the external forces, has for its axis of symmetry the vertical which passes through the centre of the figure, the diagram *b* has for its axis of symmetry the median horizontal line. For example, the triangle 9, 45, 44 is sym-

-44] EXAMPLES OF FRAME- AND STRESS- DIAGRAMS. 157

metrical to the triangle 1, 17, 18 ; the rectangle 8, 45, 43, 42 to the rectangle 2, 17, 19, 20 ; and so on.

All the upper bars are in compression, and all the lower ones are in tension.

The diagonals and contra-diagonals are all in compression ; finally two of the verticals 23, 39 are in tension, and all the rest in compression.

44. Figure 9a* represents one half of a locomotive shed. The external forces are the weights 1, 2, 3, 4, 5 applied at

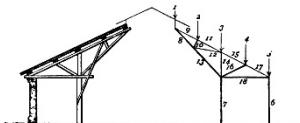


Fig. 9a.

the upper joints of the frame, and the reactions 6 and 7 of the wall and column. Again, all the external forces are parallel, and consequently the polygon of forces reduces, in diagram *b*, to one straight line. The force 6 (taken in the opposite sense to that in which it really acts) is equal to a certain part of the weight 5 ; by adding the differences to the other weights we get the magnitude of the force 7.

In the diagram *b* the direction of the lines 8 and 13 coincide ; the first is a part of the second. Here then we have for the polygon corresponding to the joint (8, 10, 12, 13) one of those degenerate forms about which we spoke in Art. 33 ; the polygon is in fact a quadrilateral 8, 10, 12, 13, having three of its vertices (13, 8), (8, 10), (12, 13) in one straight line.

The polygon 5, 17, 18, 6, corresponding to the point where

* This example is taken from Pl. xix of the atlas of *Graphische Statik* of CULMANN, 1st edition. As previously stated, the two diagrams are not rigorously reciprocal.

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the roof is supported by the wall, presents an analogous degenerate form, since the vertices (6, 5), (upper point of the segment (6), 5, 17), and (18, 6) all lie in the same straight line.

The lower bars 8, 13, 18 are in compression, as well as the diagonals 10, 14, 16, the column 7 and the wall 6 ; while the upper pieces 8, 11, 15, 17 and the diagonal 12 are in tension.

45. Diagram *a* of Fig. 10 represents a truss at the upper joints of which are applied the oblique forces 1, 2, ..., 7, which

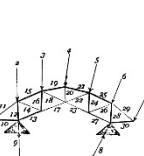


Fig. 10a.

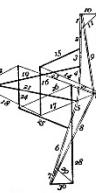
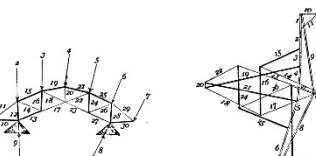


Fig. 10c.

may be considered as the resultants of the dead-loads and wind pressure ; the forces 8, 9 represent the reactions at the supports.

The polygon of external forces is drawn in diagram *b* with double lines.

We construct successively the triangle 1, 10, 11, the quadrilateral 9, 10, 12, 13, the pentagon 2, 11, 12, 14, 15, the quadrilateral 13, 14, 15, 17, the crossed pentagon 3, 15, 16, 18, 19 ; the crossed quadrilateral 4, 19, 20, 21, the pentagon 17, 18, 20, 22, 23, and so on.

The upper bars 15, 16, 21, 25 are in compression, as well as the lower bars 10, 13, 18, and the verticals 12, 16, 24, 28 ; whilst all the remaining bars of the structure are in tension.

46. The diagram *a* of Fig. 11 represents a suspension bridge, loaded at each of its upper joints with weights 1, 2, ..., 8, and at each of its lower joints with weights 10, 11, 21, ..., 18 ; the weights are kept in equilibrium by the two

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oblique reactions 9, 17 at the two extreme points of the structure*.

The polygon of external forces has its first eight sides in succession along the same vertical straight line, and its seven

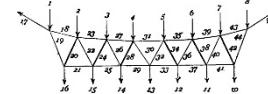


Fig. 11a.

last sides situated in another vertical straight line. The oblique sides 9 and 17 intersect, so that the polygon is a crossed one. We construct successively the polygons 1, 17, 19, 18 ; 16, 19, 20, 21 ; 2, 18, 20, 22, 23 ; 15, 21, 22, 24, 25 ; 3, 23, 24, 26, 27 ; and so on ; most of which are crossed.

Diagram *b* shows that the upper bars are all in tension, and that the tension decreases from the ends towards the

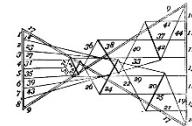
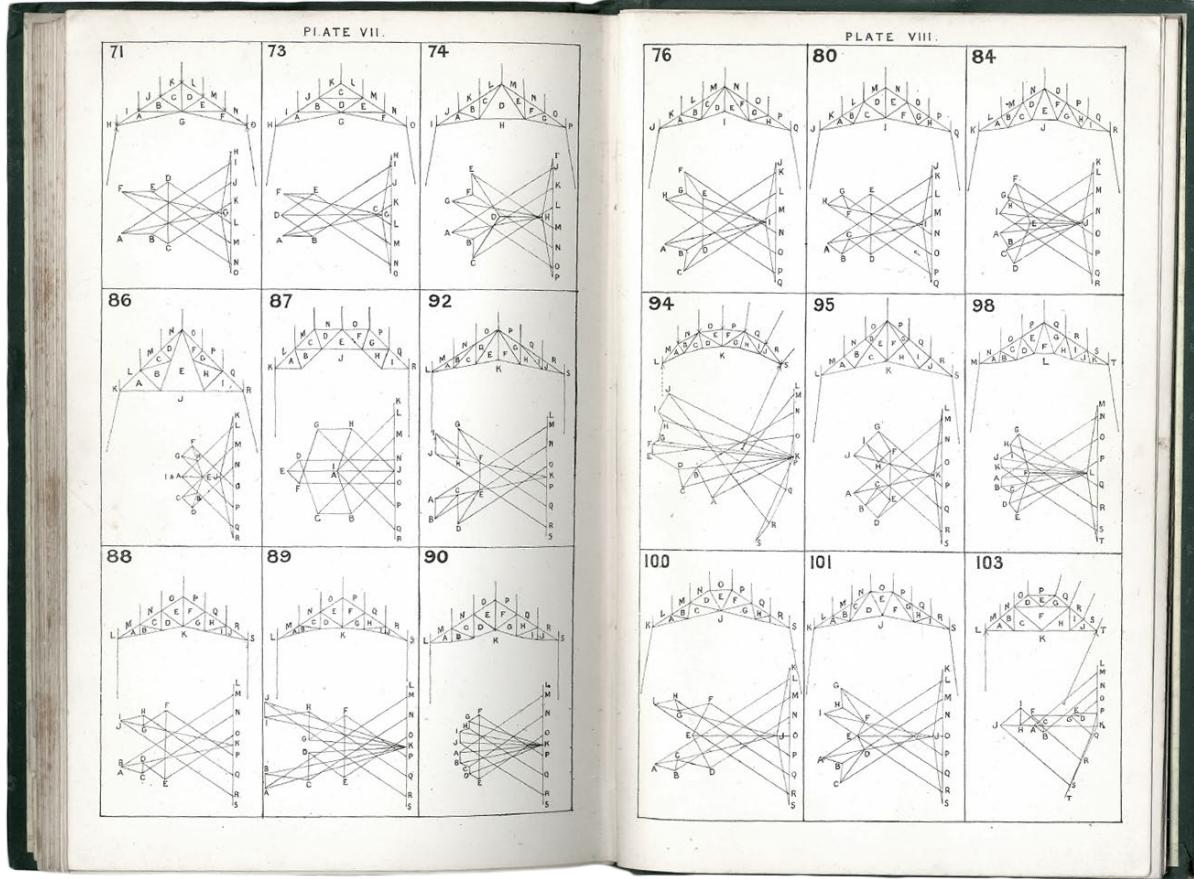


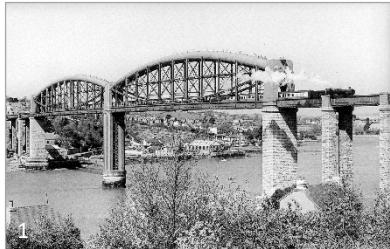
Fig. 11b.

middle of the structure ; the bars of the lower boom are also all in tension, but in them the tension decreases from the middle towards the ends.

The extreme diagonals and contra-diagonals are in tension ; in the portion situated to the left of the axis of symmetry, the diagonals or braces are alternately in tension and compression ; similarly they are on the right but in the reverse order. Considering separately the ties and struts, we see that the internal

* This example is analogous to one of those studied by Maxwell in his memoir of 1870.





Royal Albert Bridge (1859)

Isambard Kingdom Brunel



Garabit Viaduct (1884)

Maurice Koechlin



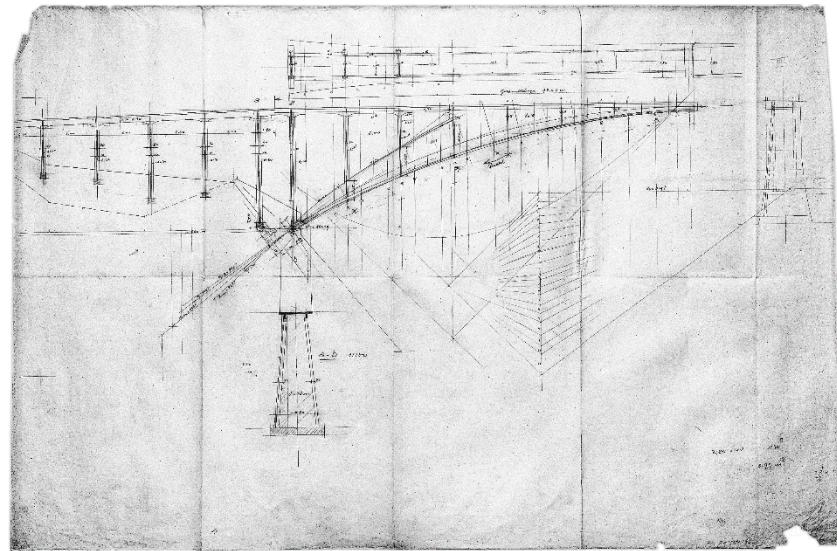
Eiffel Tower (1887)

Maurice Koechlin, Émile Nouguier



Forth Bridge (1890)

Sir John Fowler, Sir Benjamin Baker

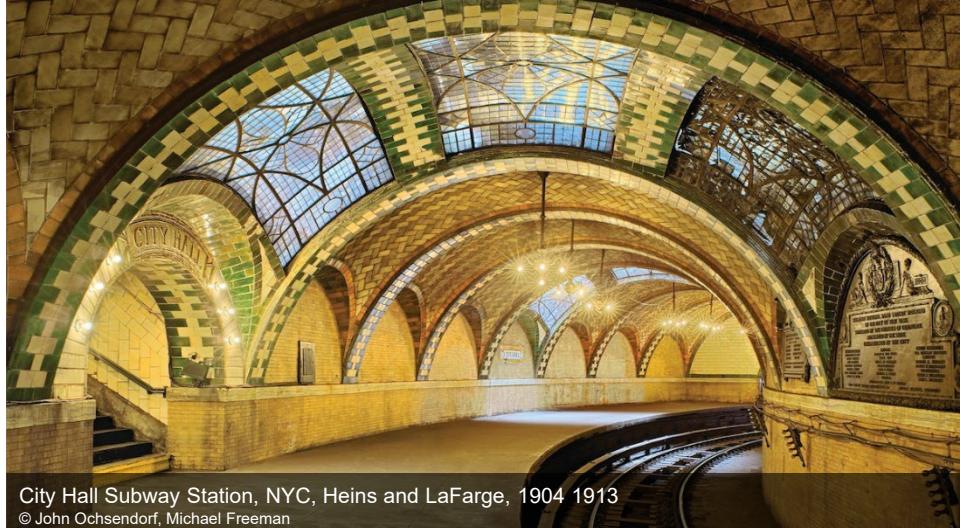


Maillart R., Salginatobelbrücke, Schiers 1930



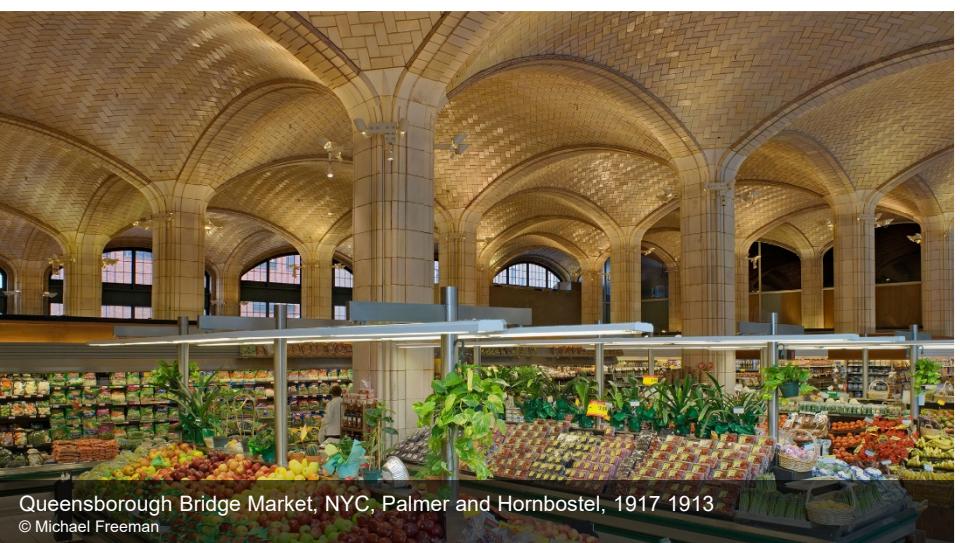
Oyster Bar, Grand Central Terminal, Warren and Wetmore, NYC, 1912-1913

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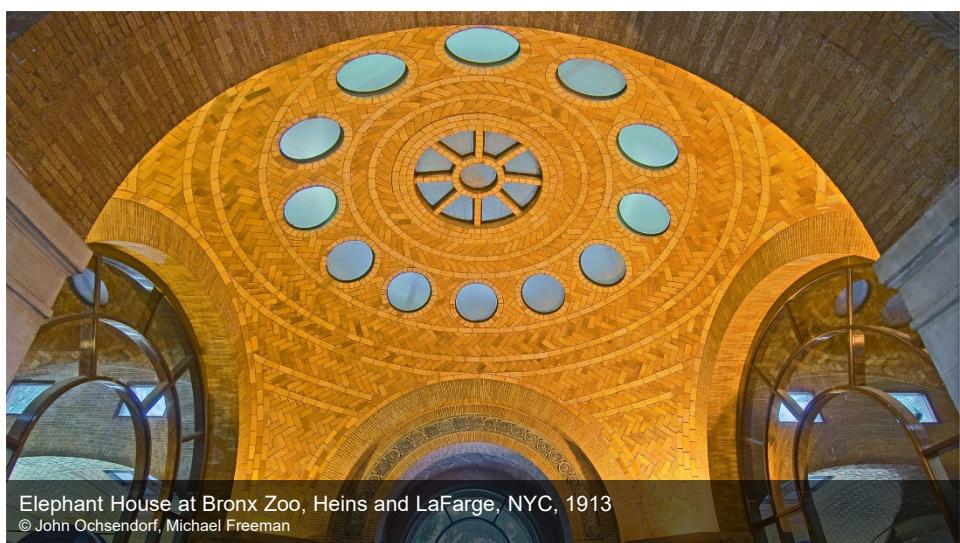
City Hall Subway Station, NYC, Heins and LaFarge, 1904 1913

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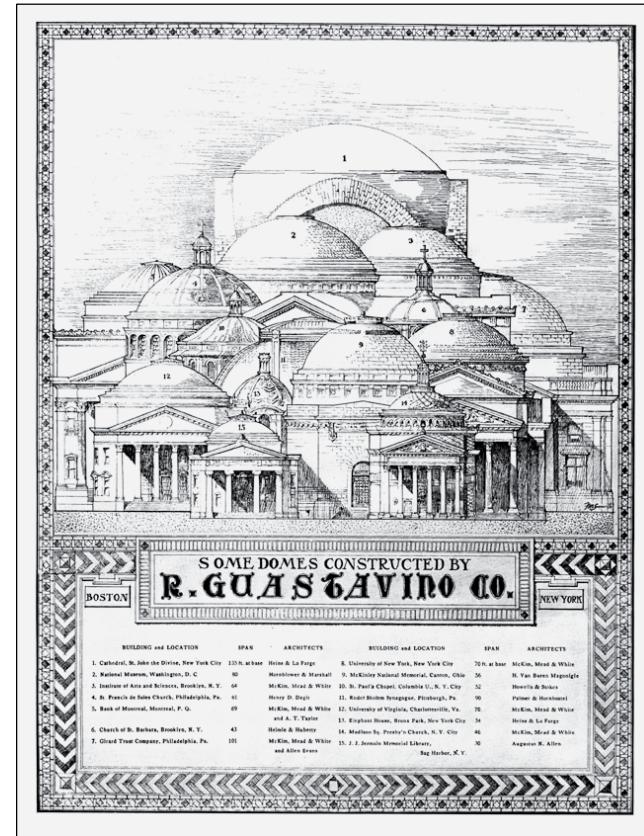
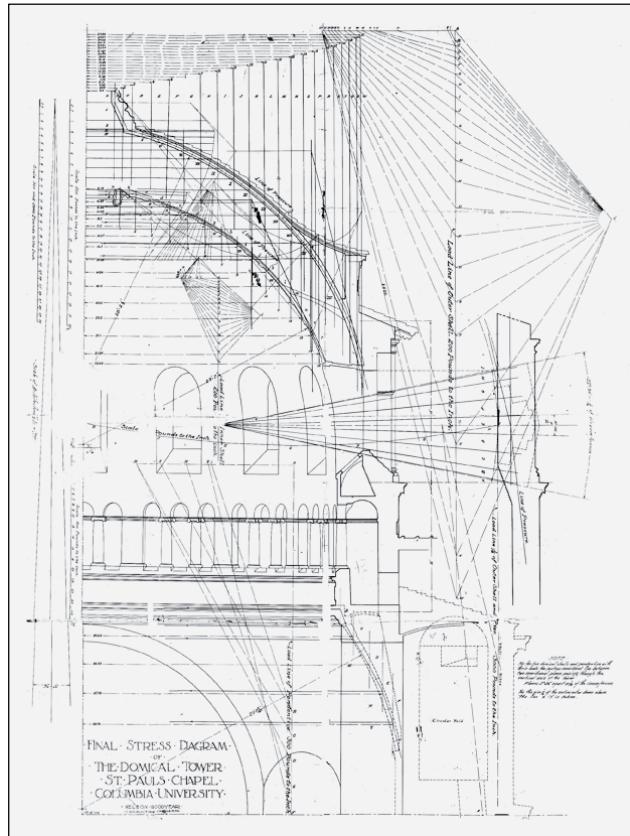
Queensborough Bridge Market, NYC, Palmer and Hornbostel, 1917 1913

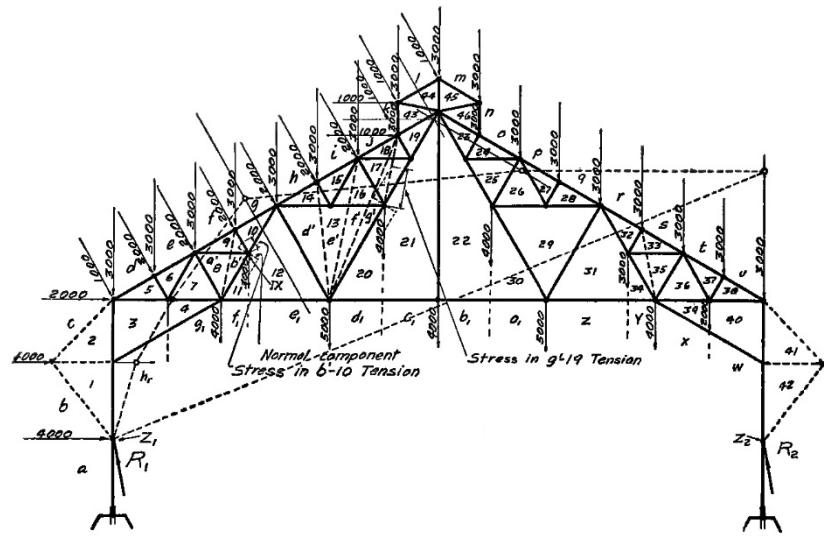
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Elephant House at Bronx Zoo, Heins and LaFarge, NYC, 1913

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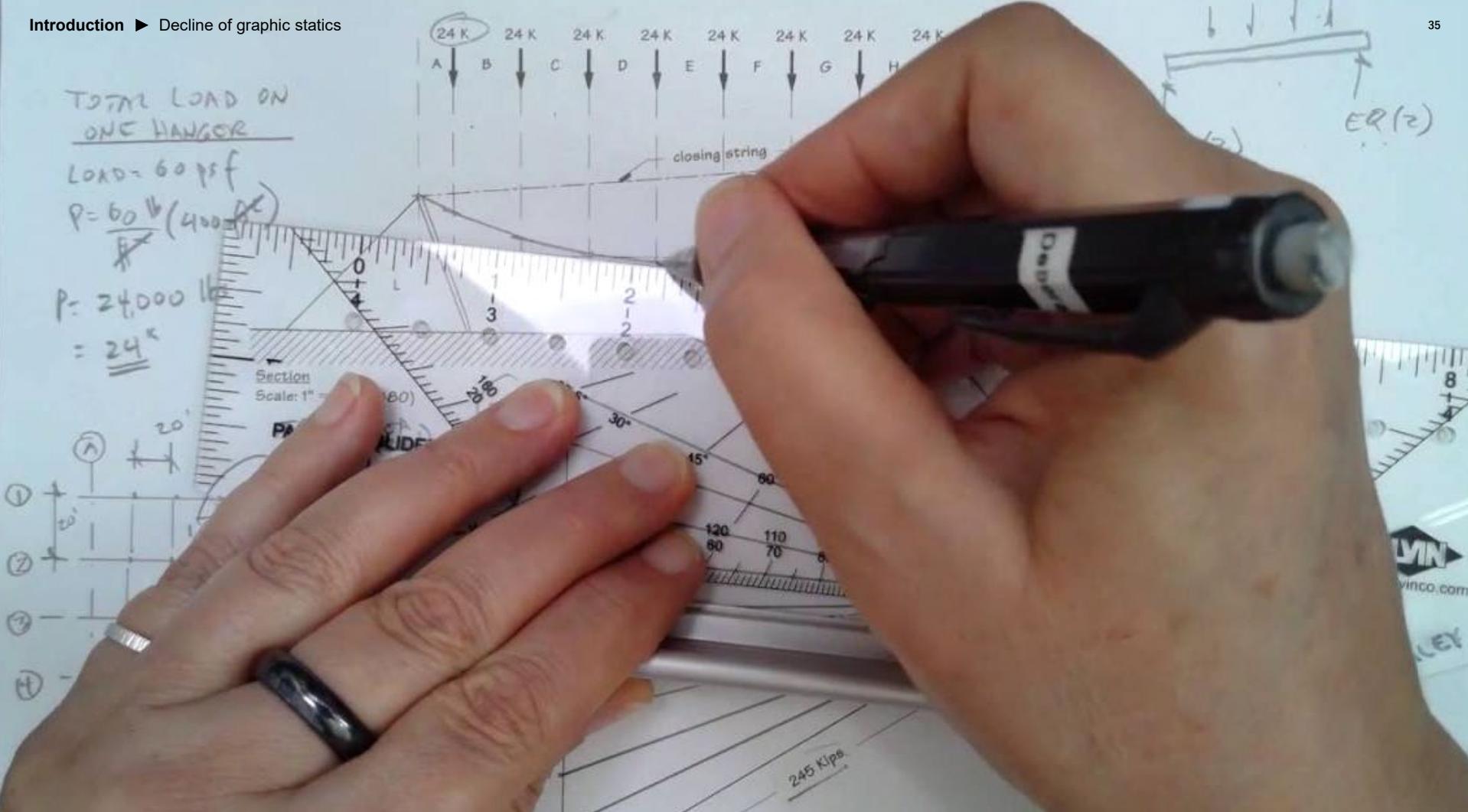
TOTAL LOAD ON ONE HANGER

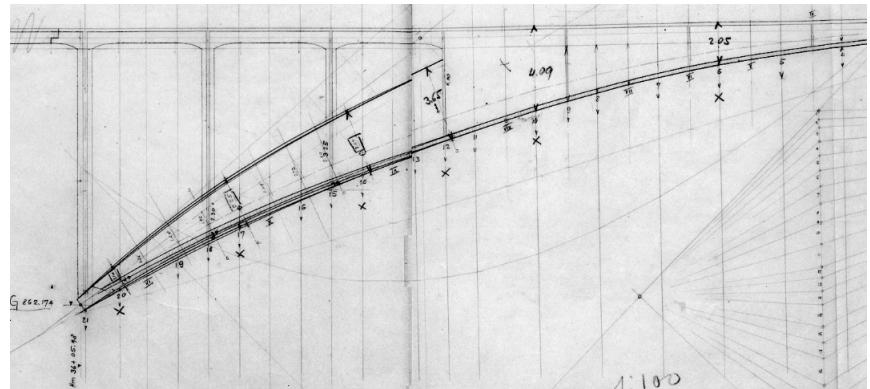
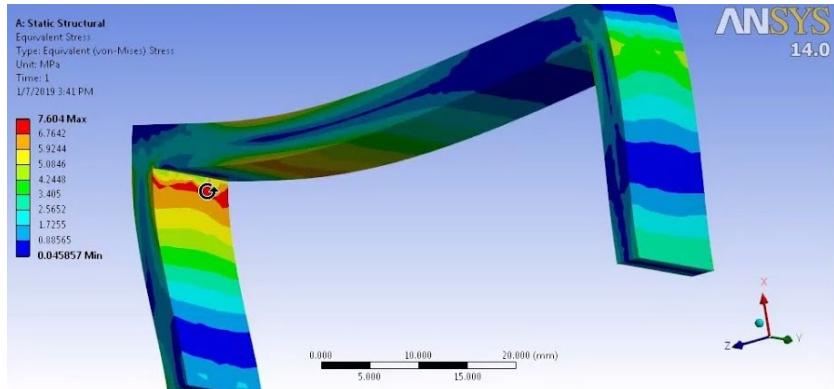
$$\text{LOAD} = 60 \text{ kip}$$

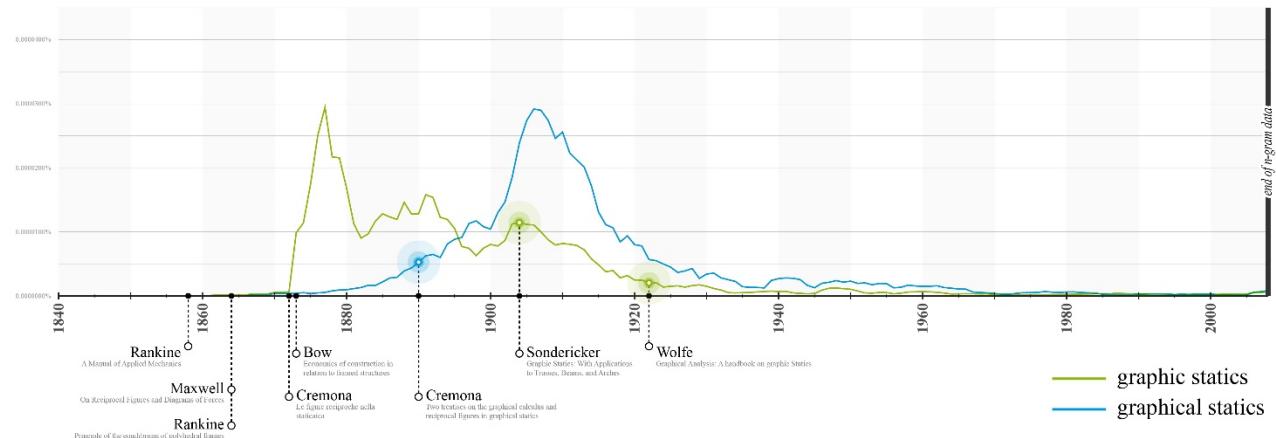
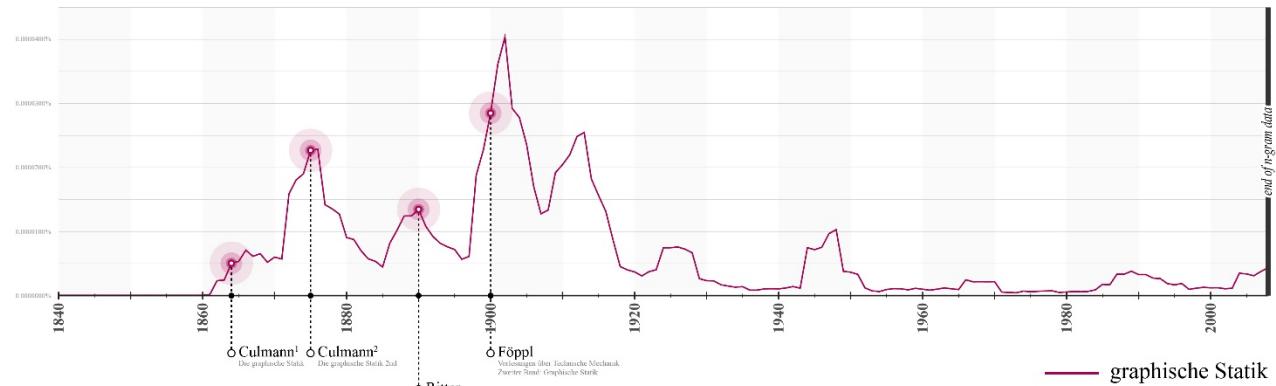
$$P = 60 \text{ kip} (400 \text{ ft})$$

$$P = 24,000 \text{ lb}$$

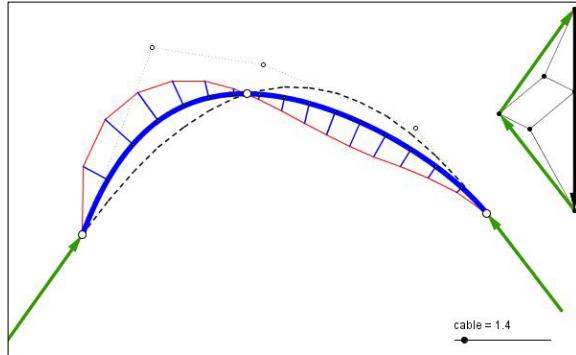
$$= 24 \text{ k}$$





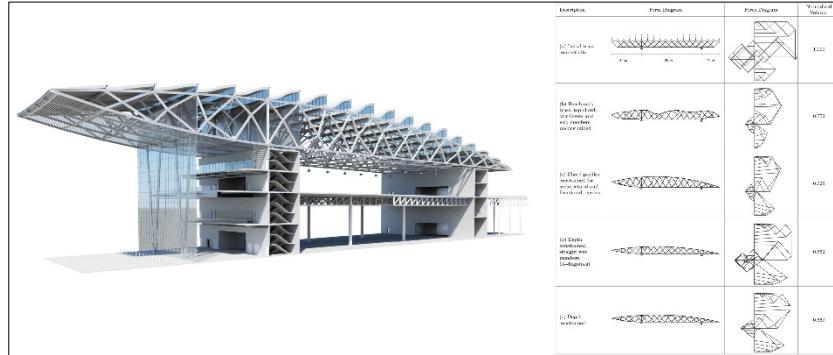






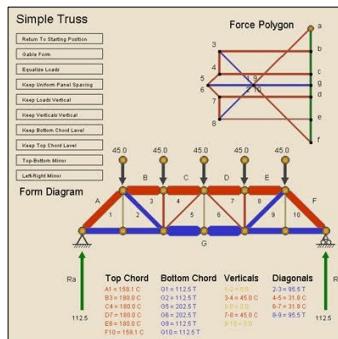
eQUILIBRIUM

Van Mele et al. (2009-)



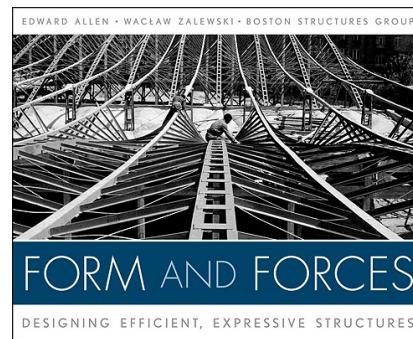
Structural Optimization using Graphic Statics

Beghini, et al. & SOM (2013)



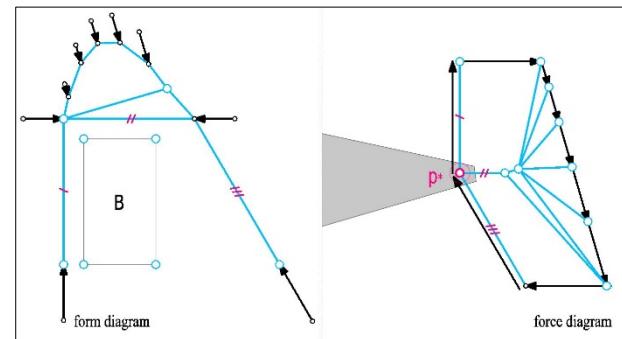
Active Statics

Greenwold & Allen (2003)



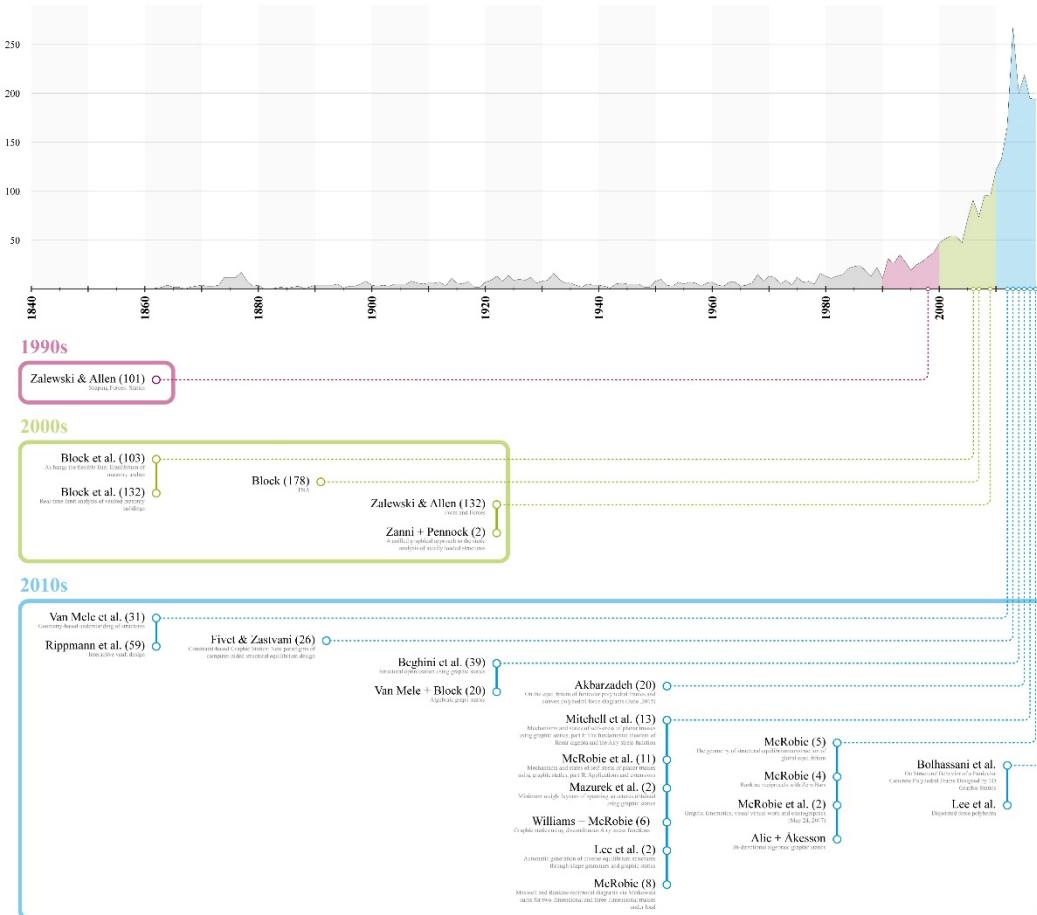
Form and Forces

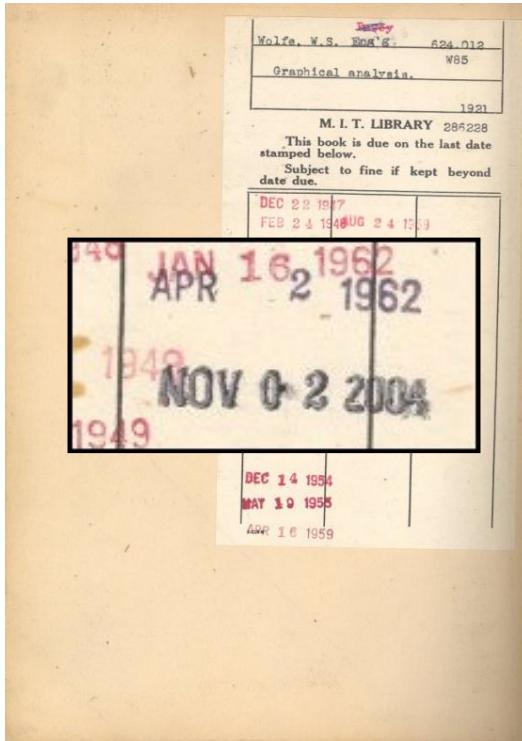
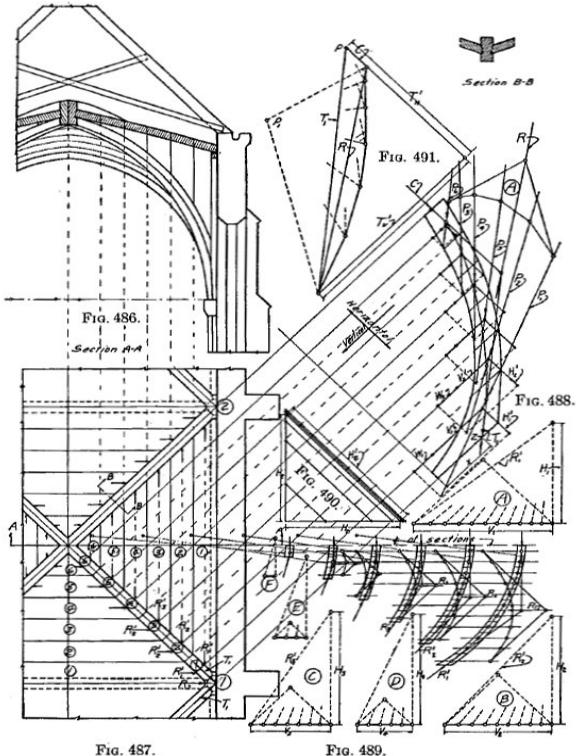
Allen & Zalewski (2009)



Constraint-based Graphic Statics

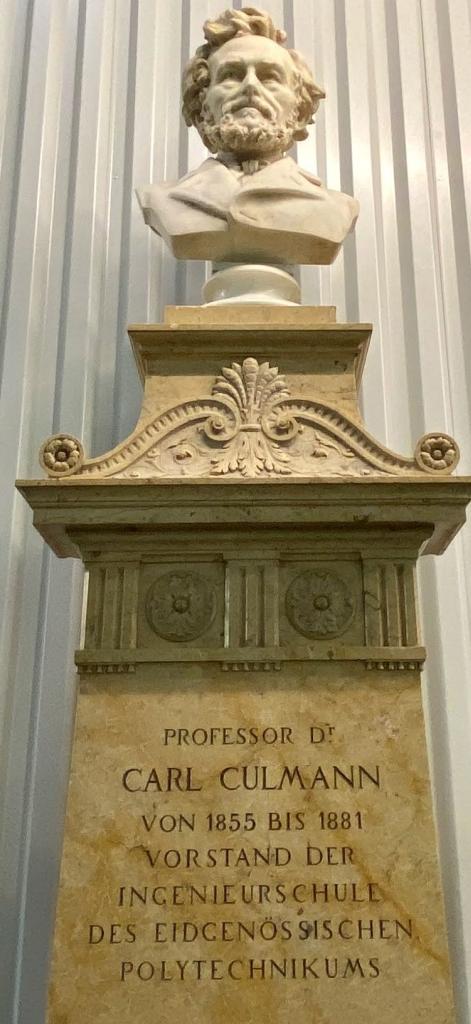
Fivet & Zastavni (2013)













Karl Culmann

- Founder of graphic statics: “Die graphische Statik” (1864-1866)
- First Professor of Civil Engineering at the ETH Zurich (1855-1883)
- Director of the Polytechnic (1872-1875)



Karl Wilhelm Ritter

(ETHZ diploma, 1868)

- Professor of graphic statics and bridge construction (appointed in 1882)
- Director of the Polytechnic (1887-1891)
- Extended applications of Culmann's graphic statics:
“Anwendungen der graphischen Statik nach Professor Dr. Culmann” (1888-1906)



Robert Maillart
(ETH diploma, 1894)



Othmar Ammann
(ETH diploma, 1902)



Pierre Lardy
(ETH diploma, 1928)



Heinz Isler
(ETH diploma, 1950)



Christian Menn
(ETH diploma, 1950)



Joseph Schwartz
(ETH professor, 2008-)



Philippe Block
(ETH professor, 2009-)

