An Introduction to Graphic Statics and its Relation to Optimal Structural Form

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Why design for optimal form?

Walt Disney Concert Hall, Los Angeles, 2003 | Frank Gehry

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Walt Disney Concert Hall, Los Angeles, 2003 | Frank Gehry

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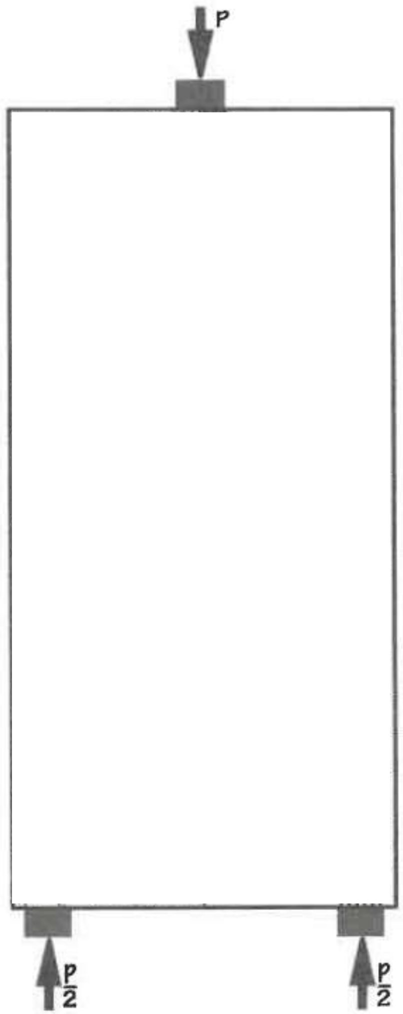
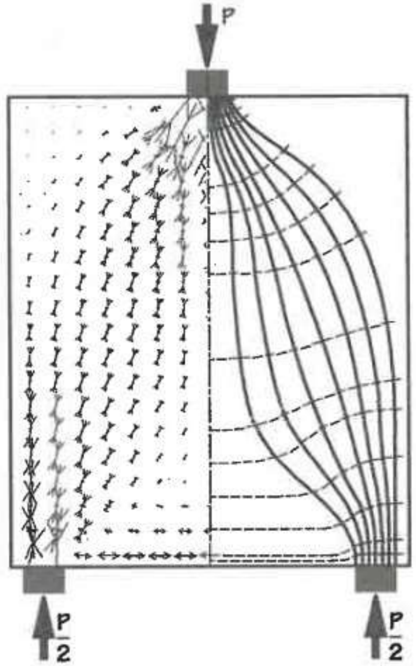
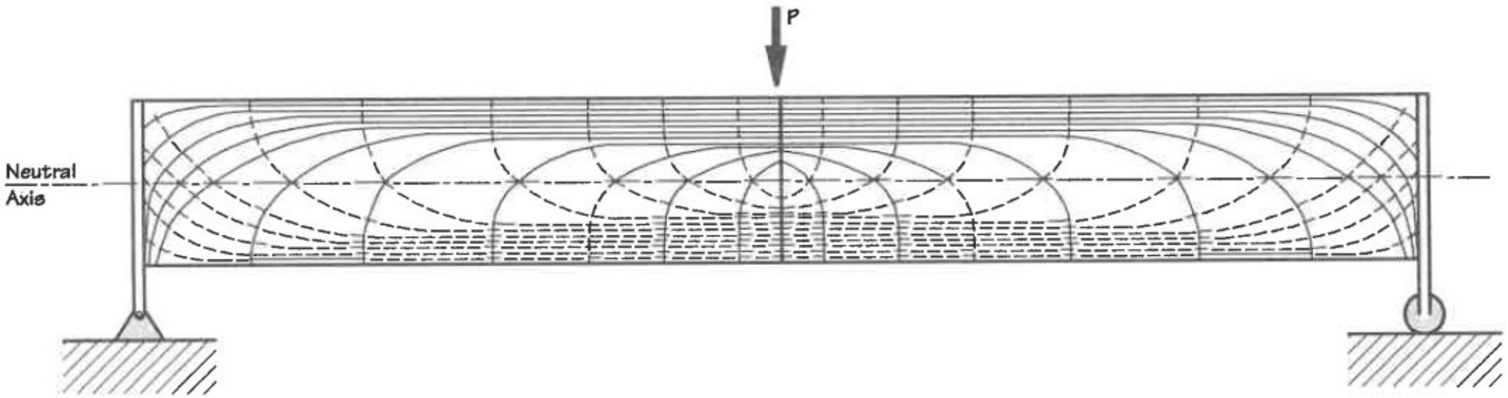
How forces (want to) flow



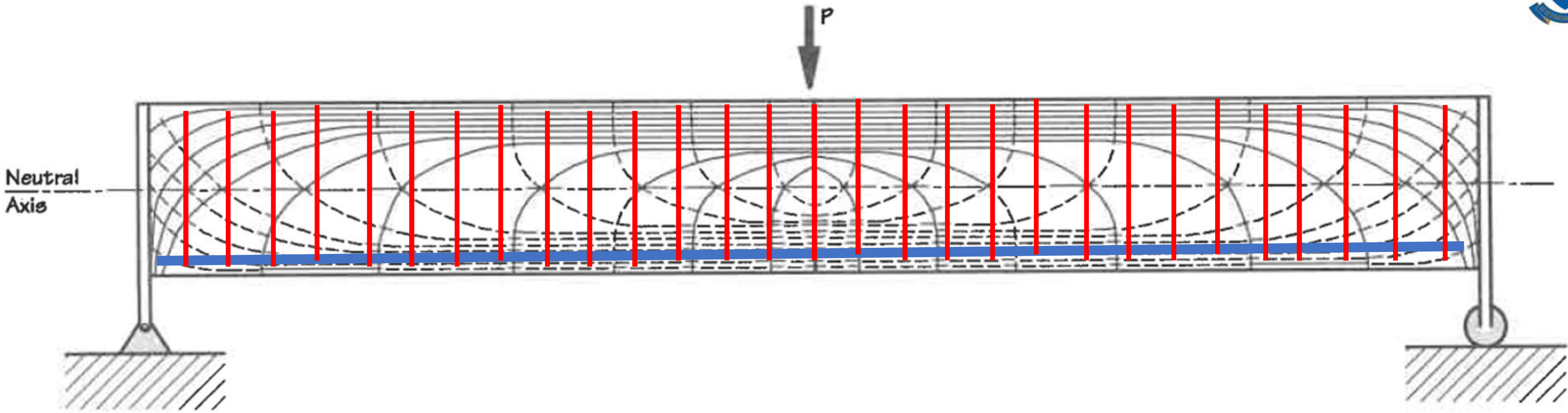
Allen et al. (2010). Form and Forces



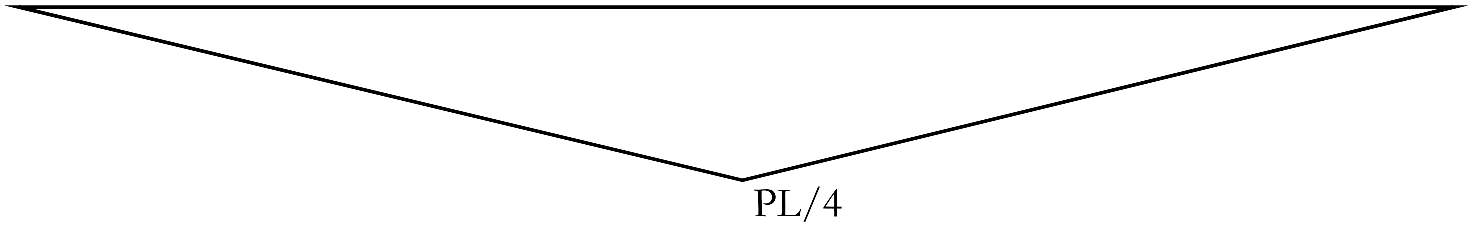
Allen et al. (2010). Form and Forces



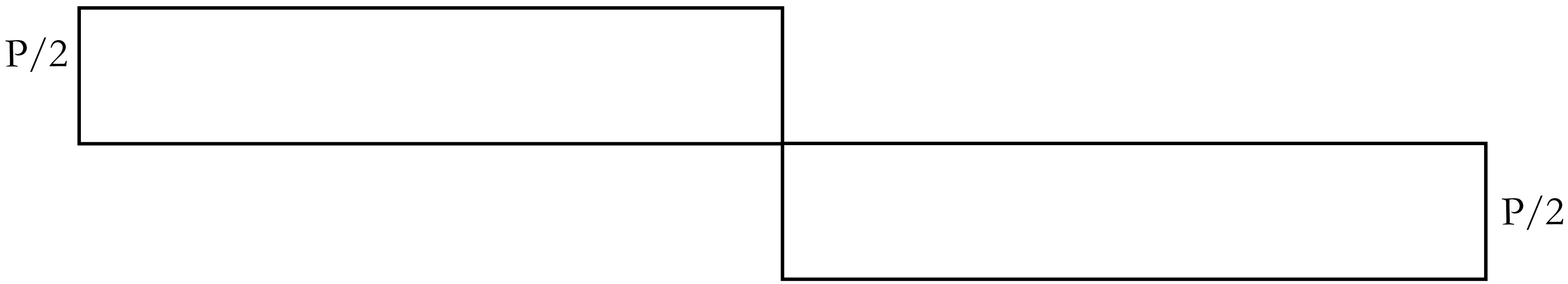
Allen et al. (2010). Form and Forces



Bending moment diagram



Shear force diagram



In the above formula, by the term *statical moment* is meant the product of the area mentioned by the distance between its center of gravity and the neutral axis. For example, the longitudinal shearing intensity at a point c in a rectangular beam, Fig. 2, may be expressed as follows:

$$v = \frac{VA'r}{Ib}$$

For rectangular beams and all beams of uniform width, the largest value of v for any given section will occur at the neutral axis since the statical moment Q has its maximum value for a point on this axis, and b is constant.

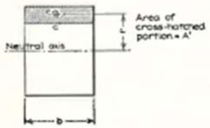


Fig. 2.

6. If a beam is of constant cross-section throughout, the maximum values of f and v will occur at the section where M and V respectively have maximum values.

7. In addition to the longitudinal or horizontal shear at any point there coexists a vertical shear and the intensity of this vertical shear is equal to the intensity of the horizontal shear.

8. The intensity of the shear at the top and bottom of a beam is zero and the intensity of shear (horizontal and vertical) along a vertical cross-section for a rectangular beam varies as the ordinates to a parabola, as shown graphically in Fig. 3. The maximum value occurs at the neutral axis and is 3/2 the average intensity, or $\frac{3}{2} \cdot \frac{V}{bd}$.

9. At the neutral plane there exists a tension and compression at angles of 45 deg. to the horizontal, and the intensity of these forces is equal to that of the shear.

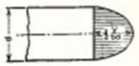


Fig. 3.

10. At the end of a simply supported beam where the shear is a maximum and the bending moment a minimum, the stresses lie practically at 45 deg. to the horizontal throughout the entire depth of beam.

11. At the section of maximum moment, the shear is zero and the stresses are horizontal.

12. If f represents the intensity of horizontal fiber stress and v the intensity of vertical or horizontal shearing stress at any point in a beam, the intensity of the inclined stress will be given by the formula

$$t = \frac{1}{2}f \pm \sqrt{\frac{1}{4}f^2 + v^2}$$

and the direction of this stress by the formula

$$\tan 2K = \frac{2v}{f}$$

where K is the angle of the stress with the horizontal.

13. At any given point maximum compressive stress and maximum tensile stress make an angle of 90 deg. with each other.

14. The directions of the maximum stresses for a simply supported beam uniformly loaded are as given in Fig. 4. The general direction of the stresses in a beam with any given loading may be determined by means of the formulas for t and K given above.

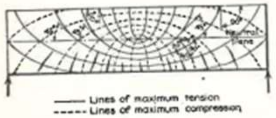
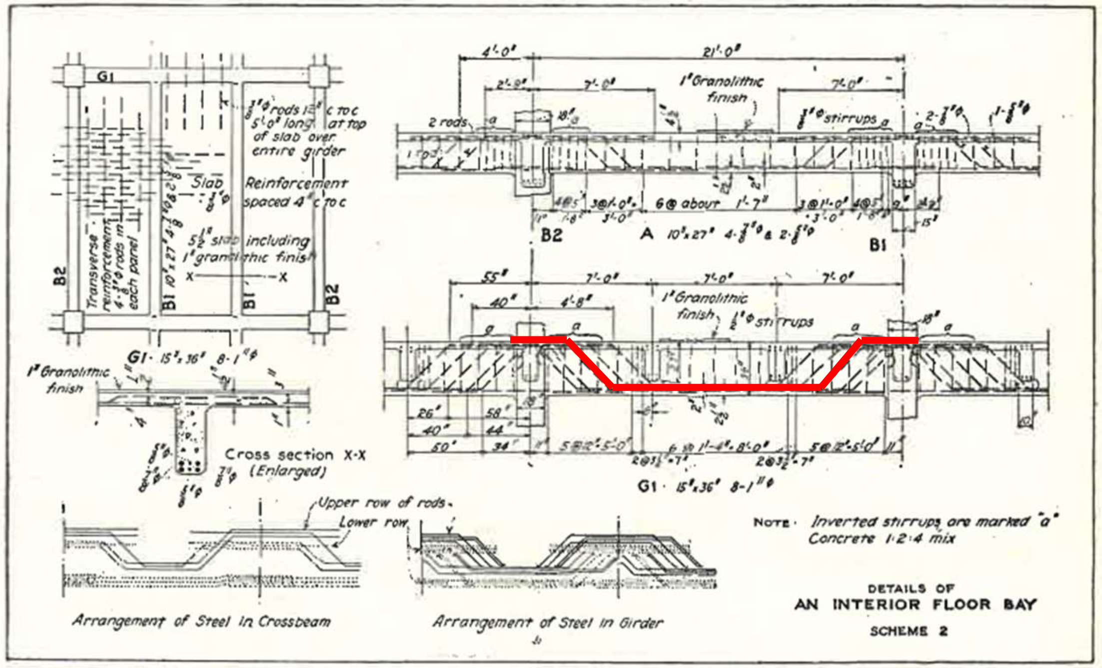
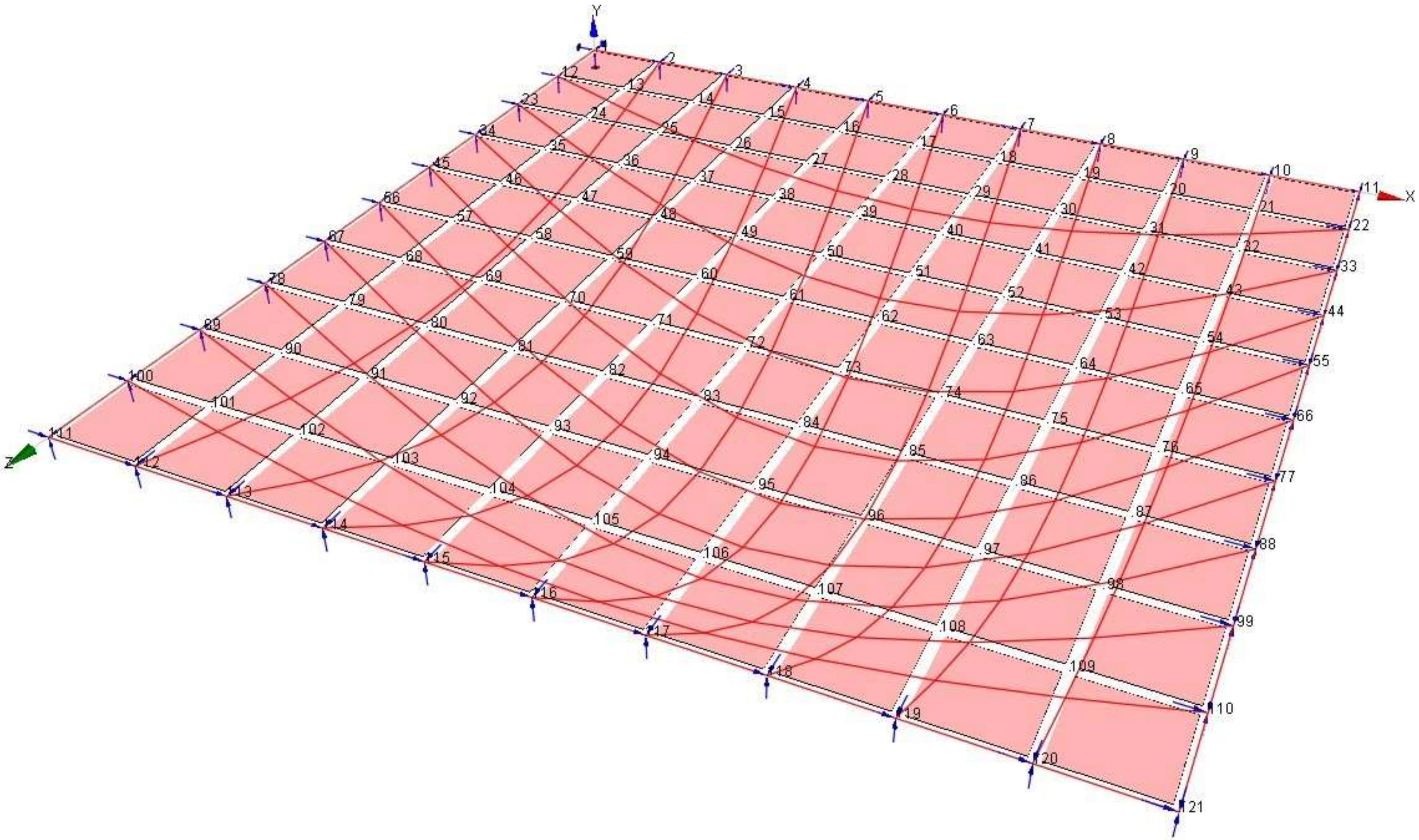


Fig. 4.

15. The common theory of flexure gives the unit stress correctly at the important section of maximum moment and also for the extreme fibers in other sections, since at these points the shear is zero. Where the shear is not zero an inclined stress is the result and the flexure formula gives only the horizontal component of this stress—namely, the fiber stress.



Hool and Johnson (1918). Concrete Engineers Handbook


Y
X
Z

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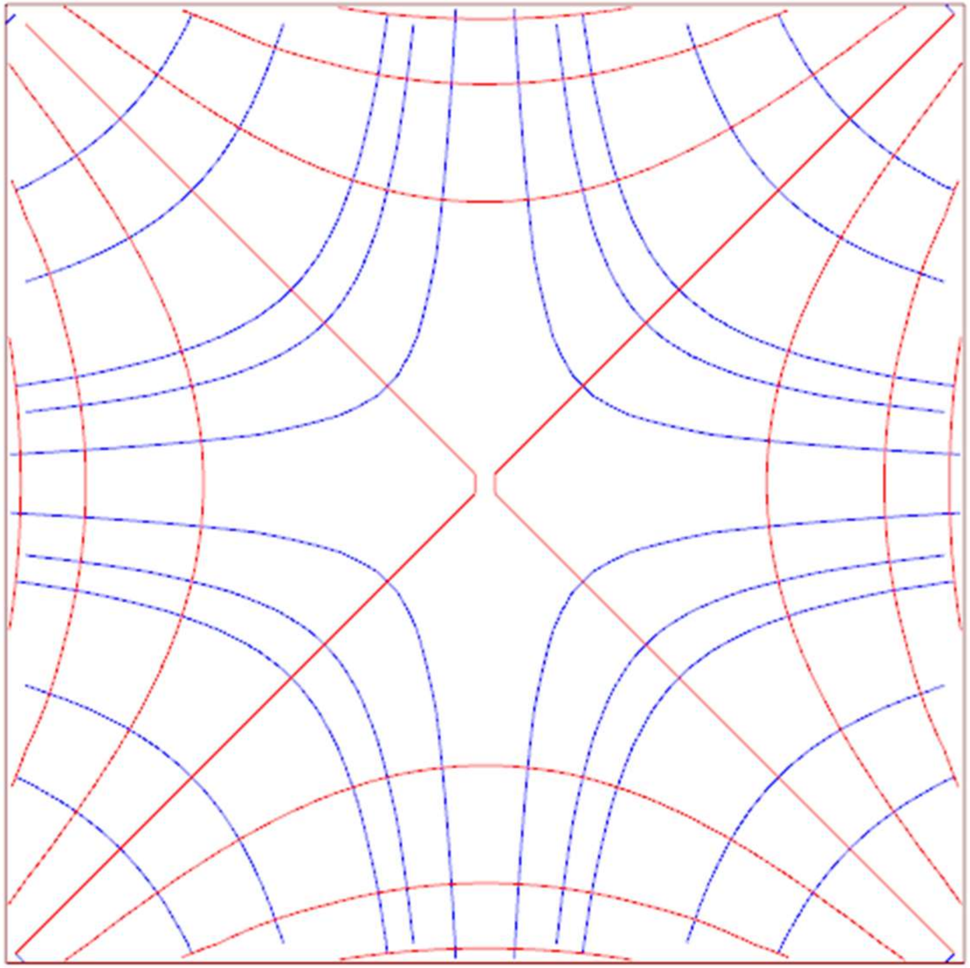

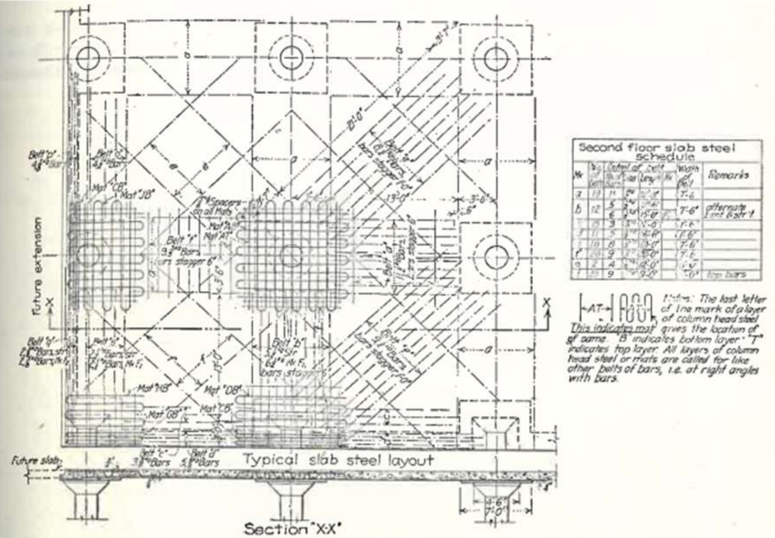

FIG. 42.

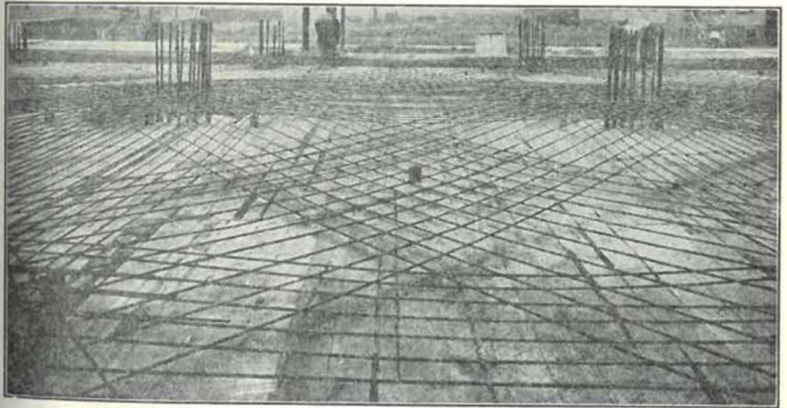

FIG. 43.

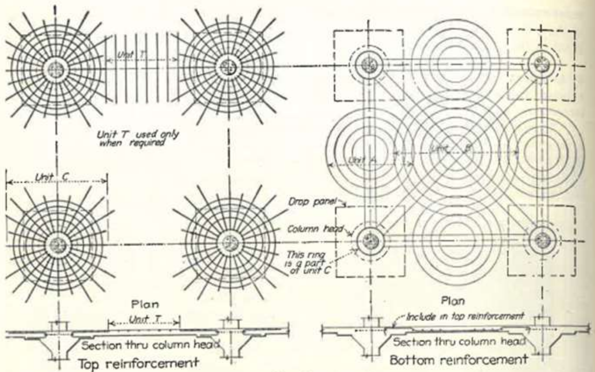

FIG. 50.

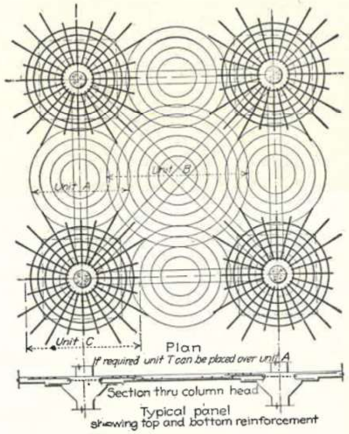

FIG. 51.

The trussed bar extends into the column head a sufficient distance beyond the point of maximum stress (*i.e.*, the edge of the column head) to develop, in combination with the hook, their full tensile strength. The ring which they engage serves to distribute the bearing stresses laterally on to a large area of concrete.

Position of Units.—Units *A* and *B* are placed near the bottom while unit *C* is near the top of the slab.

Compression Reinforcement.—By introduction of compression reinforcement in the shape of lower prongs of the radials, the slab is stiffened at the support, and the compression stresses in concrete reduced. If desired, therefore, it is possible to omit the drop panel at the column head and use an altogether flat ceiling. This is often desirable either for the sake of appearance or to simplify shafting or piping.

Secondary Reinforcement.—Sometimes to prevent cracks on the top of the slab between columns, additional secondary reinforcement consisting of short straight bars, and called Units *T*, is used. These bars are usually placed after the concrete of the slab is poured.

FIG. 52.

THEORETICAL DISCUSSION

The scientific basis of the S-M-I system is evident from the following discussion of the action of a flat slab under load.

Shape of the Slab after Deflection.—After deflection a flat slab assumes a composite shape, namely, the shape of an umbrella at the column head, and the shape of a saucer in the central portion.

Lines of Equal Deflection.—The shape of a deflected slab can be seen better from Fig. 53, which shows in sections the deflection curve along the side and the diagonal of the panel, and in plan the lines of equal deflection. The lines of equal deflection, which are based on tests, were obtained by connecting the points which deflected an equal distance below their original position.

Direction of Stresses and Reinforcement.—By referring to the plan and the sections, it is evident that deformation of fibers are equal and therefore the fiber stresses act perpendicularly to the lines of equal deflection as indicated by arrows in Fig. 53. The best method of resisting these stresses, or preventing the deformation, is either by placing the bars perpendicularly to the lines of equal deflection, or by enclosing them by means of a ring, the hooping action of which is explained later. Fig. 54 shows the deflection lines in light dash lines and the reinforcement according to the S-M-I system in heavy lines. The radials and trussed bars are perpendicular to the lines of equal deflection. The rings either intersect the deflection lines at angles close to 90 deg., or they enclose the same and prevent the enclosed concrete from spreading. The combination therefore fulfills all the requirements of efficient and economical reinforcement.

Hool and Johnson (1918). Concrete Engineers Handbook

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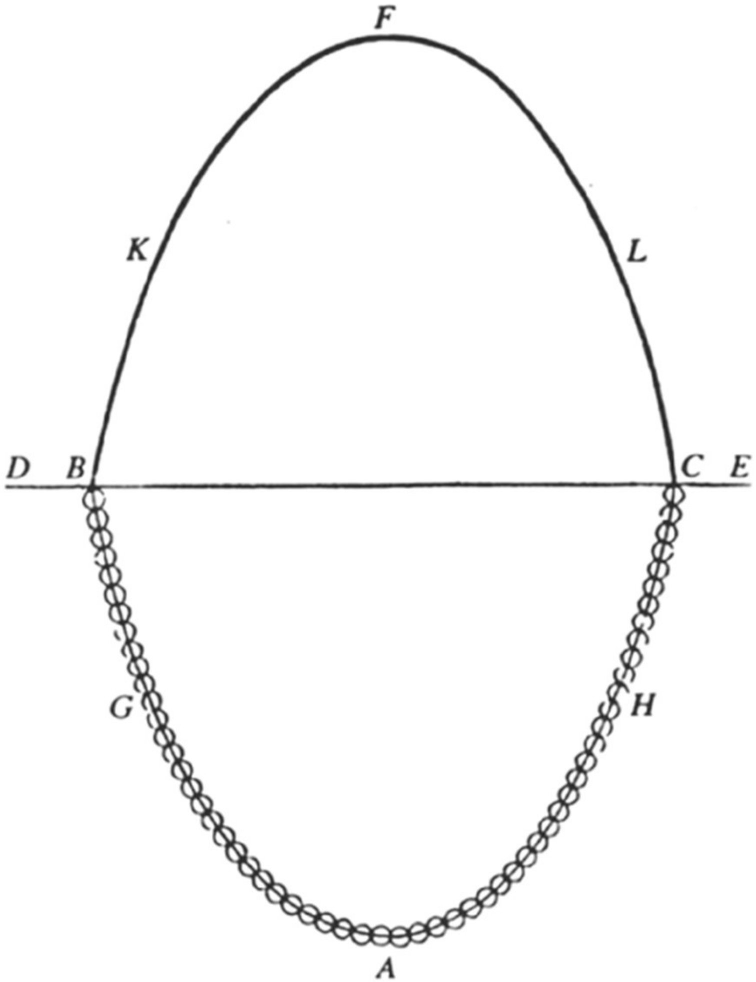
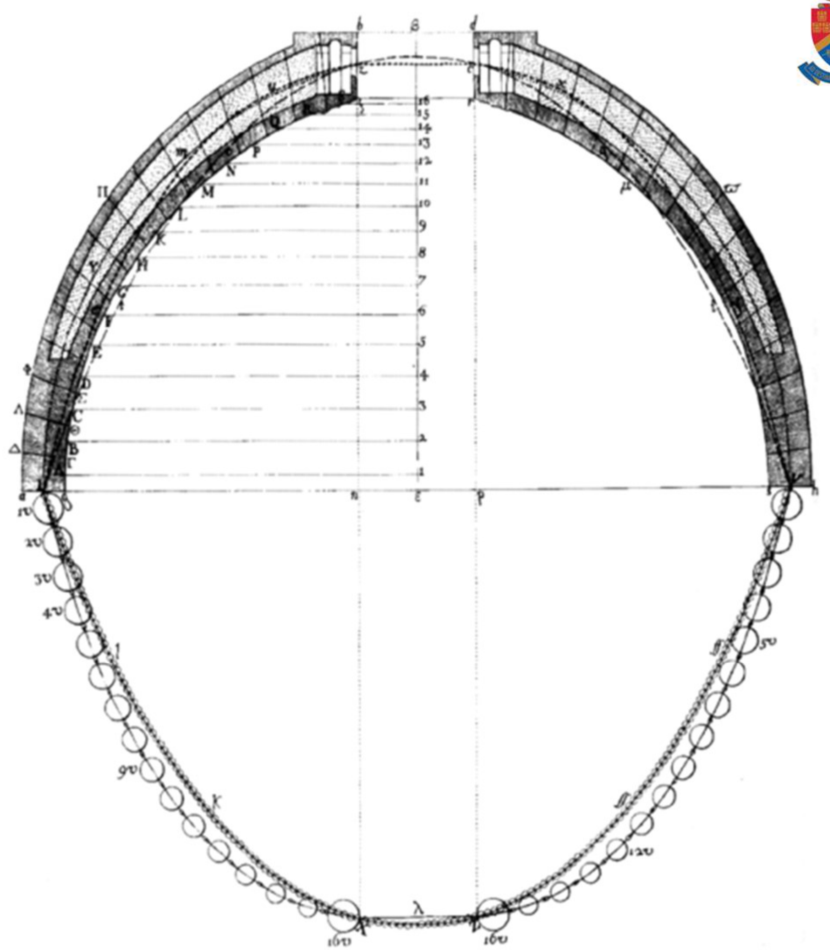
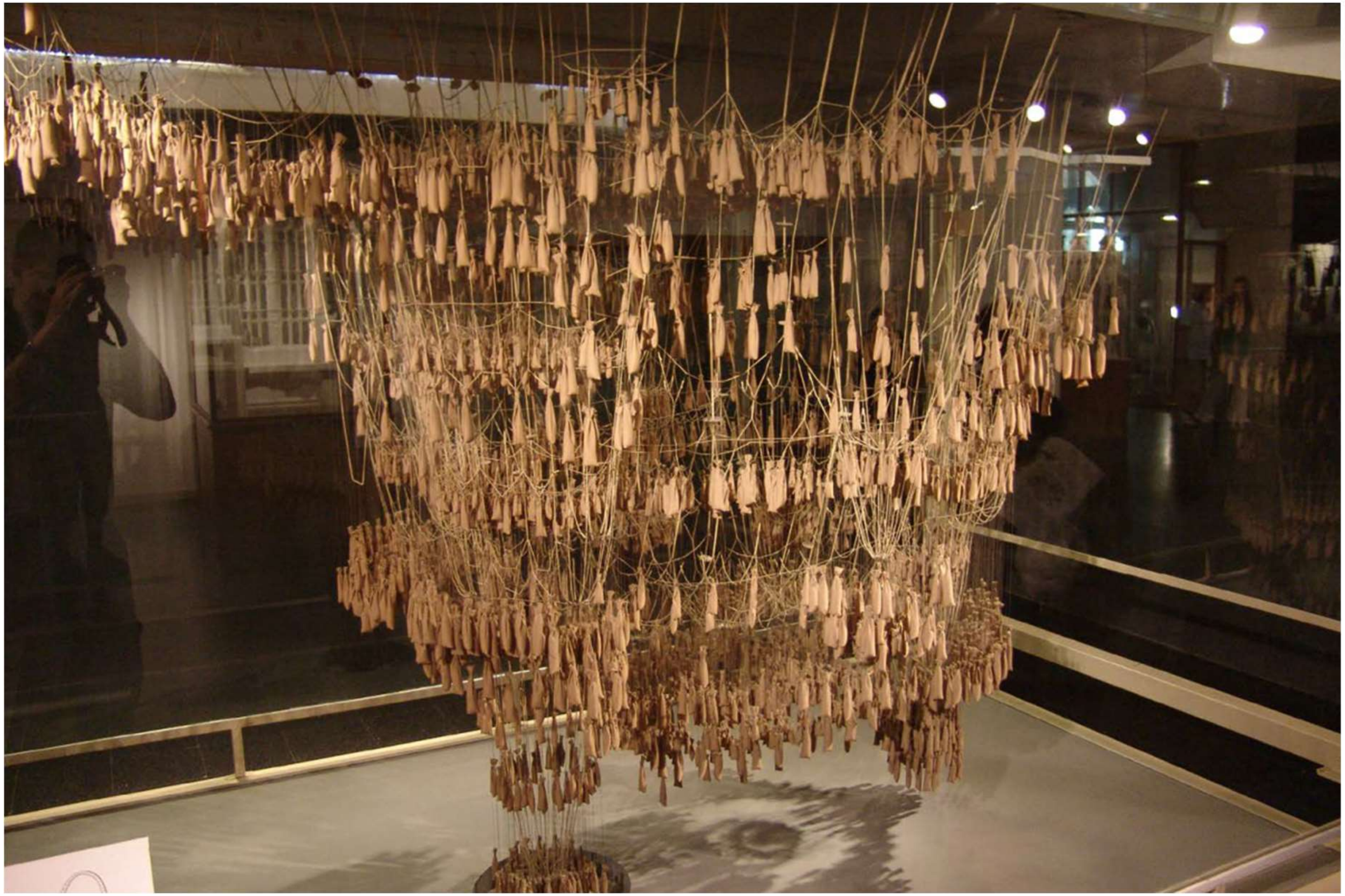
Gatti Wool Factory, Rome, 1951 | Pier Luigi Nervi



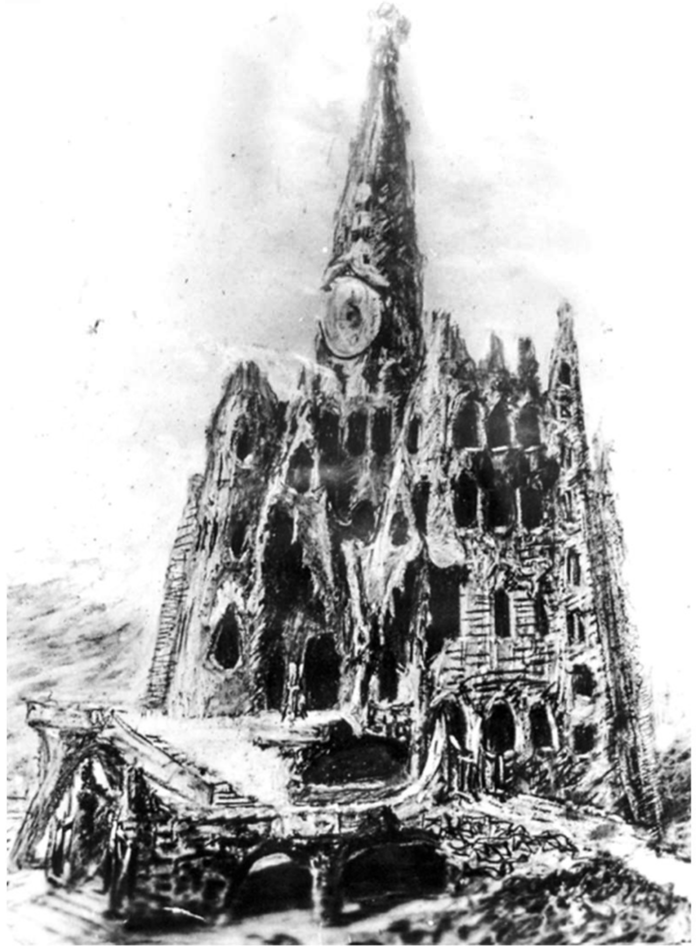


"As hangs the flexible line, so but inverted will stand the rigid arch."
Robert Hooke

Giovanni Poleni, 1748: Hooke's guiding principles

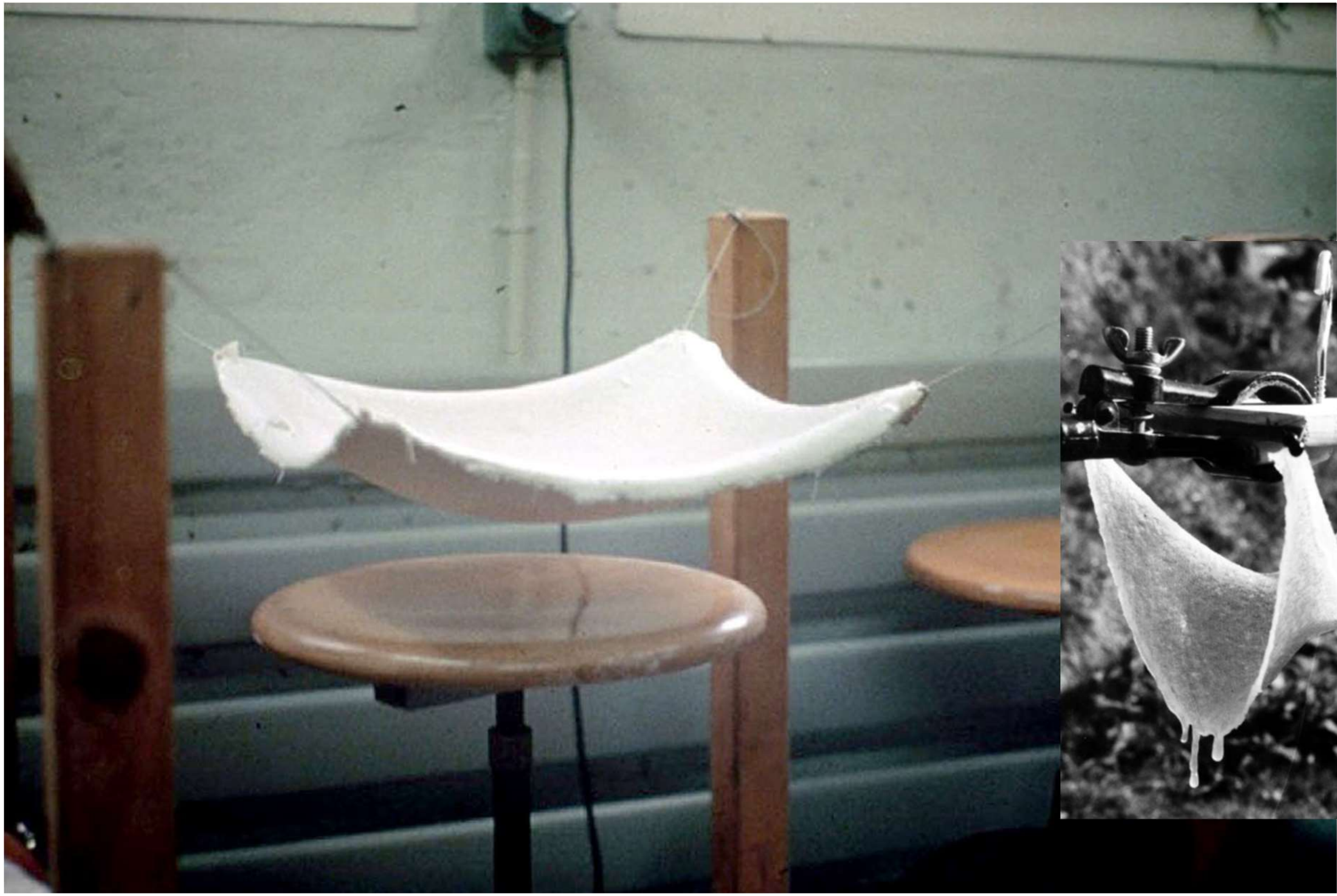


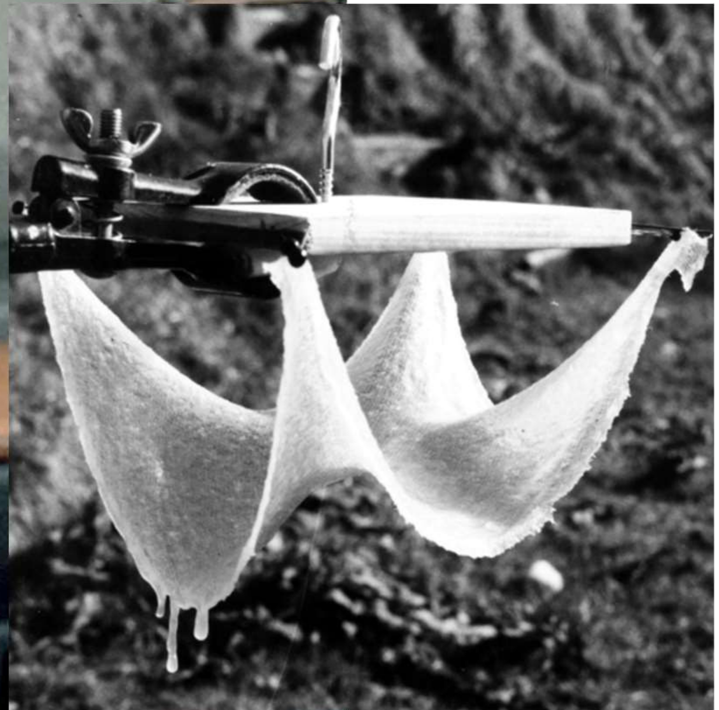
Model of Familia Sagrada, Barcelona, 1908 | Antoni Gaudi



Model of Familia Sagrada, Barcelona, 1908 | Antoni Gaudi

Heinz Isler





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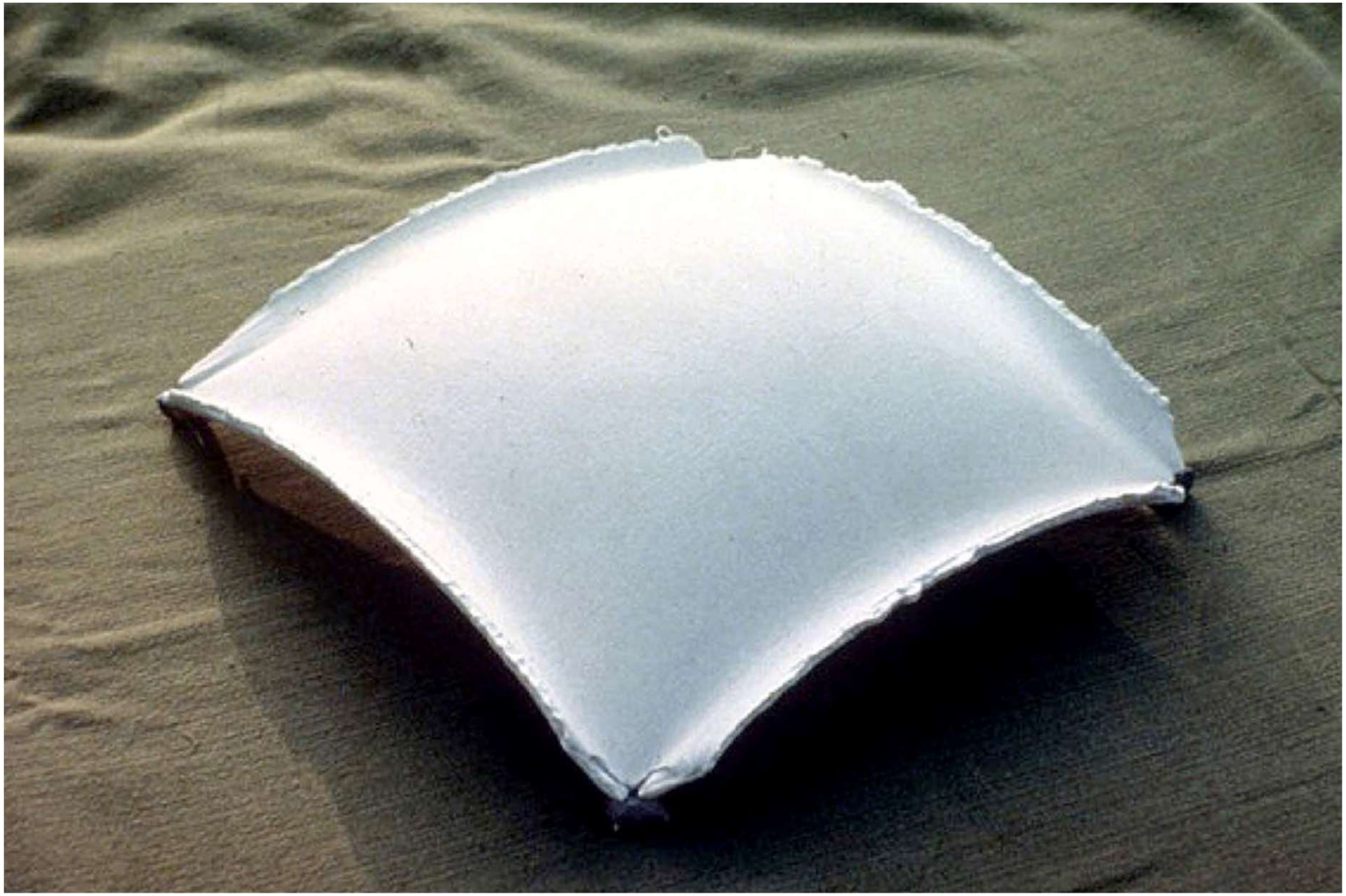
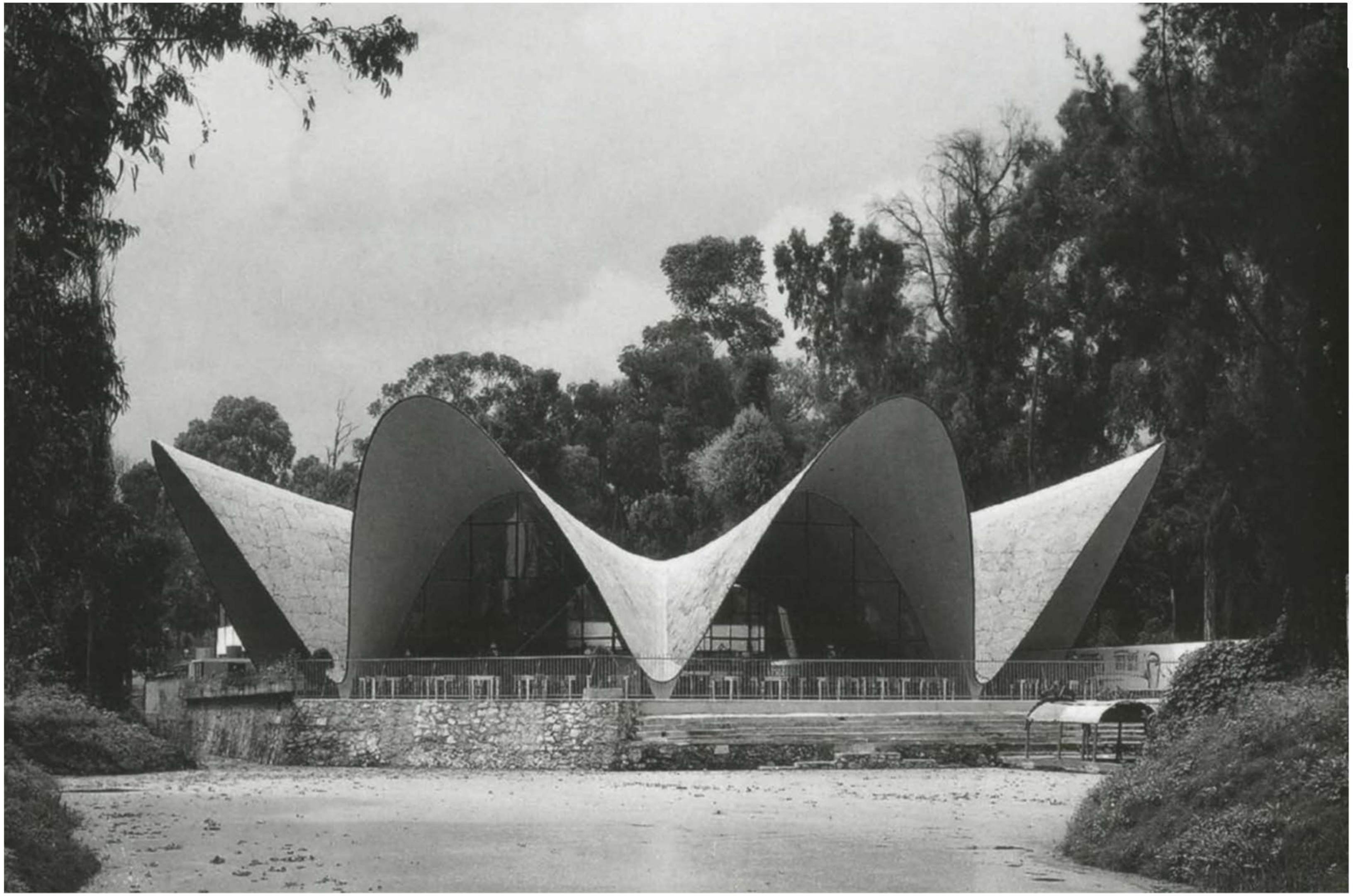


Heinz Isler

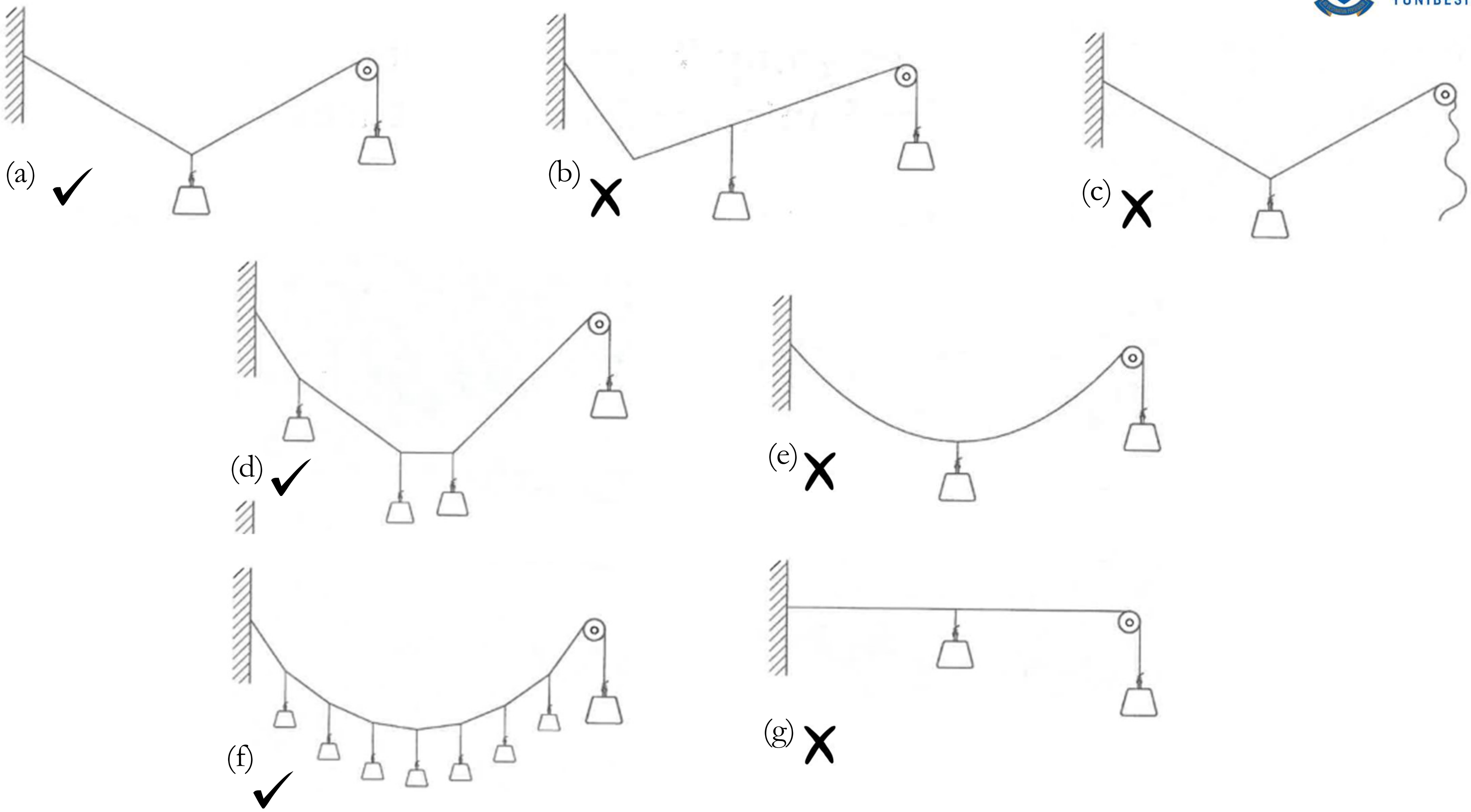
Filling station, Deitingen Süd, 1968 | Heinz Isler

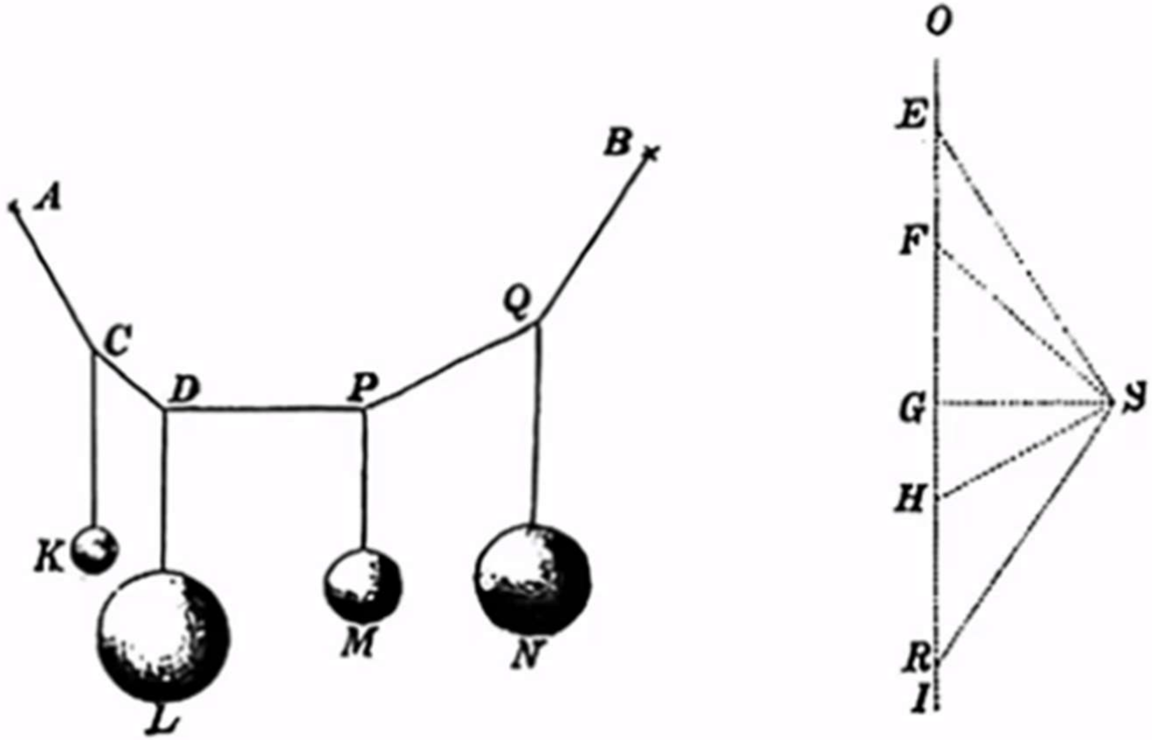


Los Manantinales Restaurent, Xochimilco, 1958 | Felix Candela

Cadyl Horizontal Silo, Young, 1978 | Eladio Dieste

Graphic statics


(a) ✓
(b) ✗
(c) ✗
(d) ✓
(e) ✗
(f) ✓
(g) ✗



Varignon, 1725

Carl Culmann 1821-1881

DIE

GRAPHISCHE STATIK

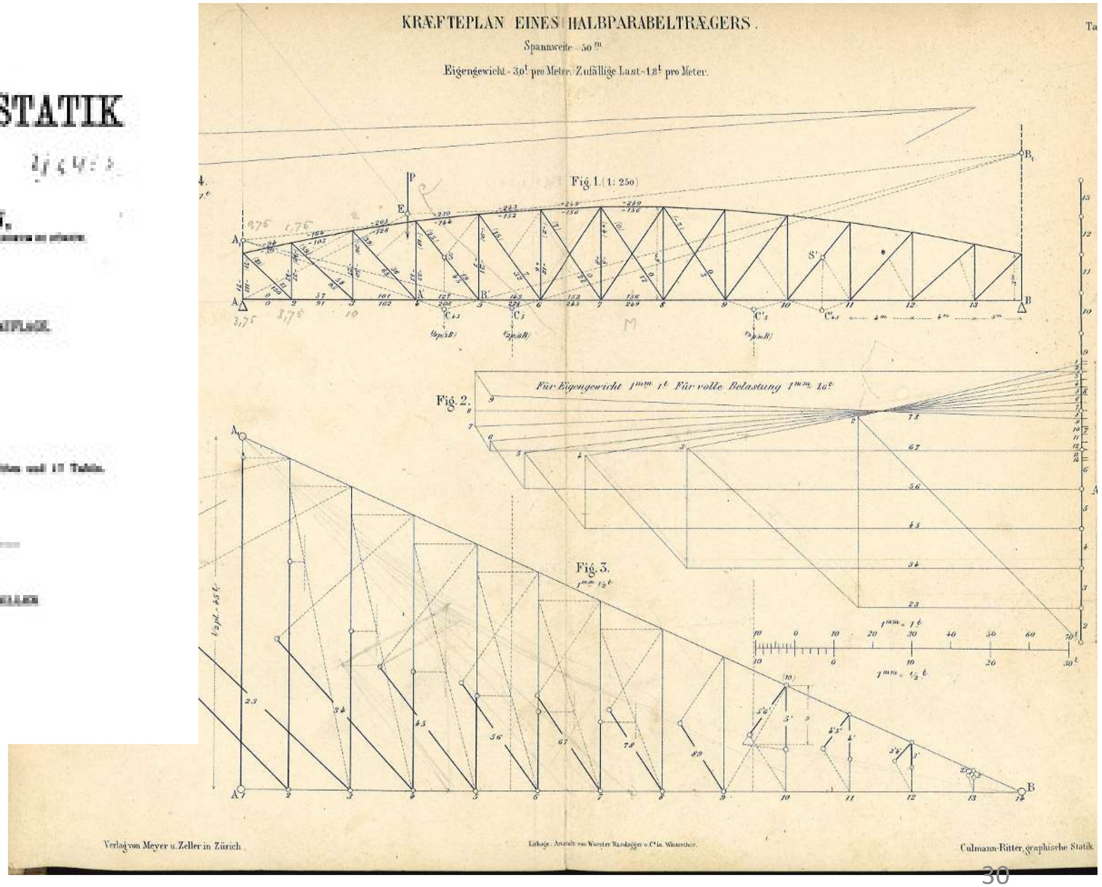
VON

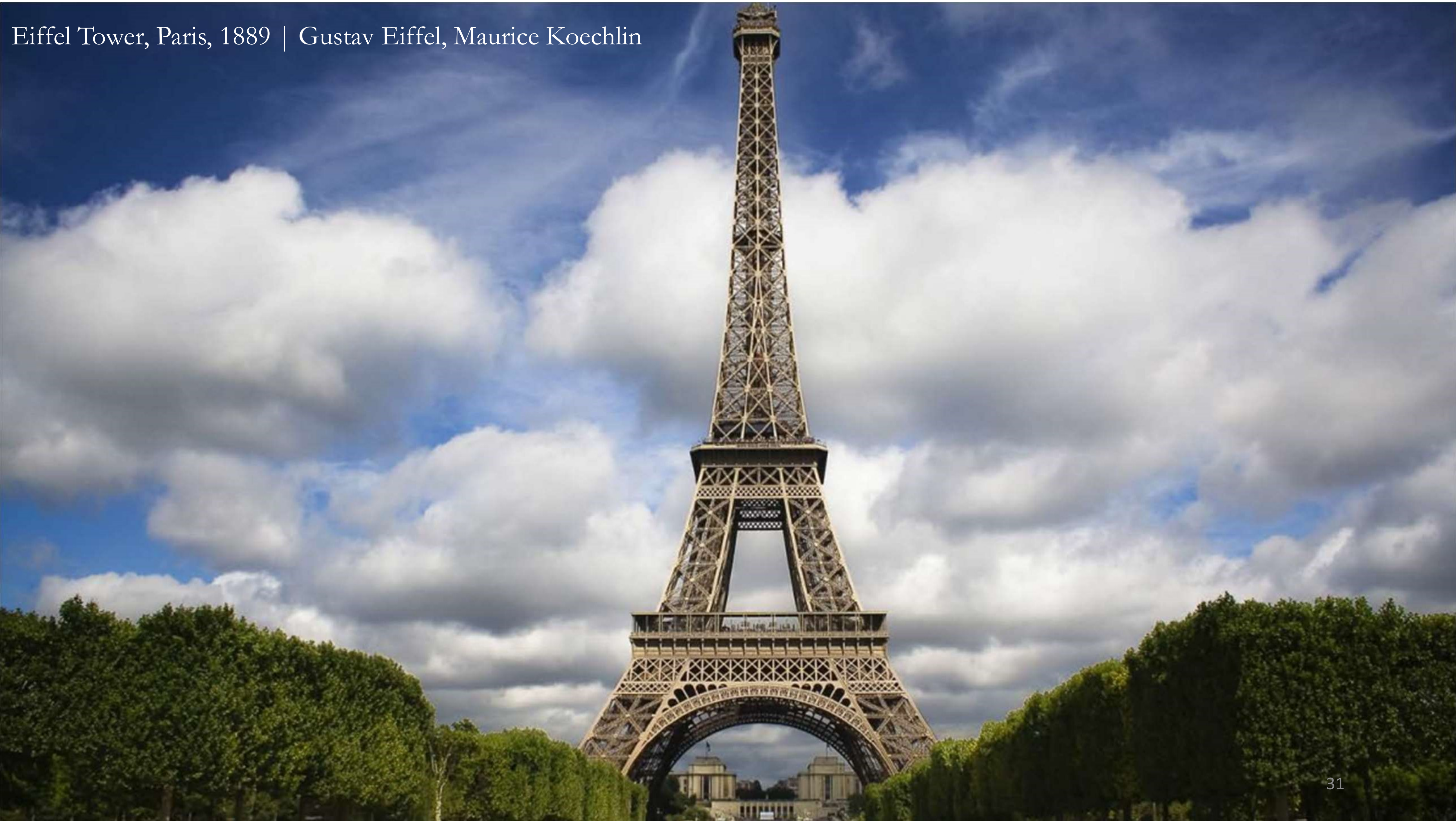
C. CULMANN,

ZWEITE NEU BEARBEITETE AUFLAGE.

ERSTER BAND.

ZÜRICH
VERLAG VON MEYER & ZELLER




Eiffel Tower, Paris, 1889 | Gustav Eiffel, Maurice Koechlin

Epure de résistance au vent

1er Cas : *Vent de 300 kg de la base au sommet.*
2e Cas : *Vent croissant de 200 k à la base jusqu'à 400 kg au sommet.*

Surfaces et efforts correspondants.

N° des divisions	Hauteurs des divisions de surfaces	Surfaces des divisions	1er cas de surcharge : effort par m²	1er cas : effort total du vent	2e cas de surcharge : effort par m²	2e cas : effort total du vent
Sommet	-	-	-	-	400k	-
1	28m	350m²	300k	285.000k	375	358.[illegible]
2	65,5	1048	300	313.200	338	346.332
3	18,5	583	300	174.800	300	174.800
4	11,5	391	300	117.300	290	113.890
5	33	1236	300	370.800	275	338.[illegible]
6	2	360	300	108.000	258	92.880
7	42	3098	300	900.300	242	226.728
8	41,5	6361	300	1.908.300	215	722.815
	300m			[illegible]		3.174.412

Détermination des efforts dans les arbalétriers.

Le prolongement du montant coupé par la section AB rencontre l'axe au point O où agit la résultante des forces 1, 2, 3, 4, 5. On peut donc en ce point O décomposer cette force de 1.287.200k suivant la direction des montants.

Ce qui donne pour chacun d'eux un effort de $\frac{2.490.000^{k}}{2}$

De même :

L'effort à la partie inférieure d'un montant est 2.462.000k

L'effort à la partie supérieure d'un montant est 2.602.000k

Calcul de la section d'un montant à sa base.

Poids total de la construction au niveau des appuis 6.500.000k

Moment de renversement à la base 503.150.120

Charge à la base d'un montant due au poids propre $\frac{6.500.000}{4}$ *= 1.625.000k*

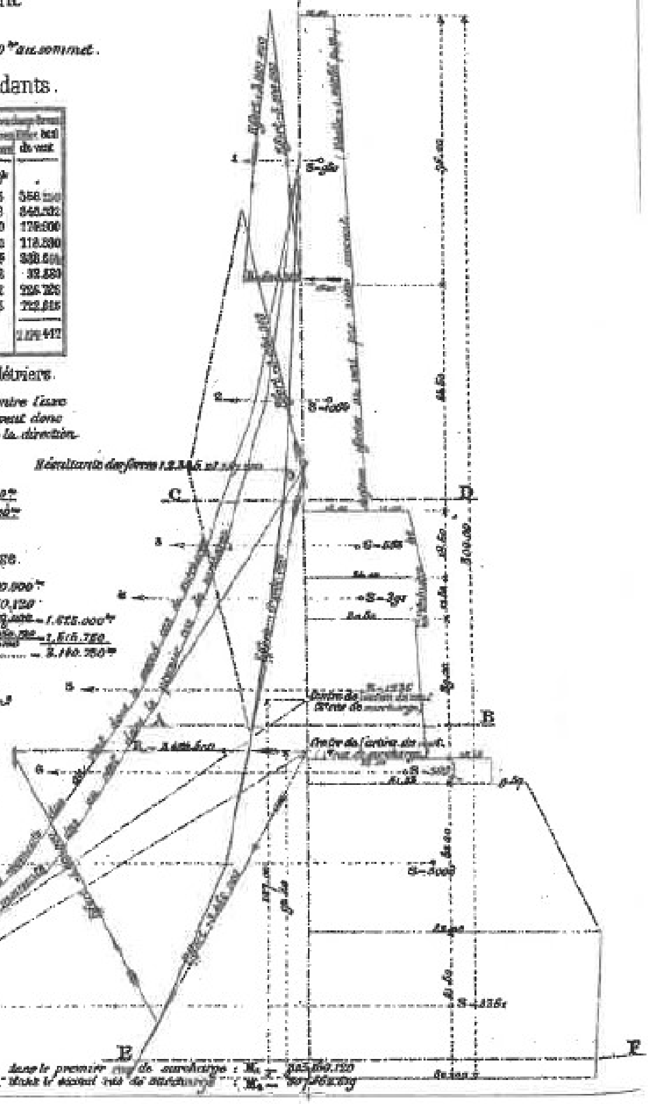
Charge à la base d'un montant due à l'effet du vent [illegible] *= 1.515.750*

Charge totale .... = 3.140.750k

Section d'une membrure à sa base .... 80.188 c.m²

Section d'un montant : 80.188×4 .... = 320.752 c.m²

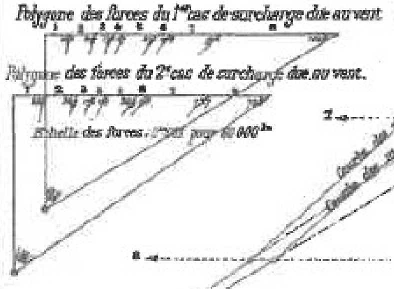
Coefficient de travail à la base $\frac{3.140.750}{320.752}$ *= 9k,8 par m.m²*



Polygone des forces du 1er cas de surcharge dû au vent.

Polygone des forces du 2e cas de surcharge dû au vent.

Echelle des forces



Garabit Viaduct, Ruynes, 1884 | Gustav Eiffel, Maurice Koechlin, Léon Boyer

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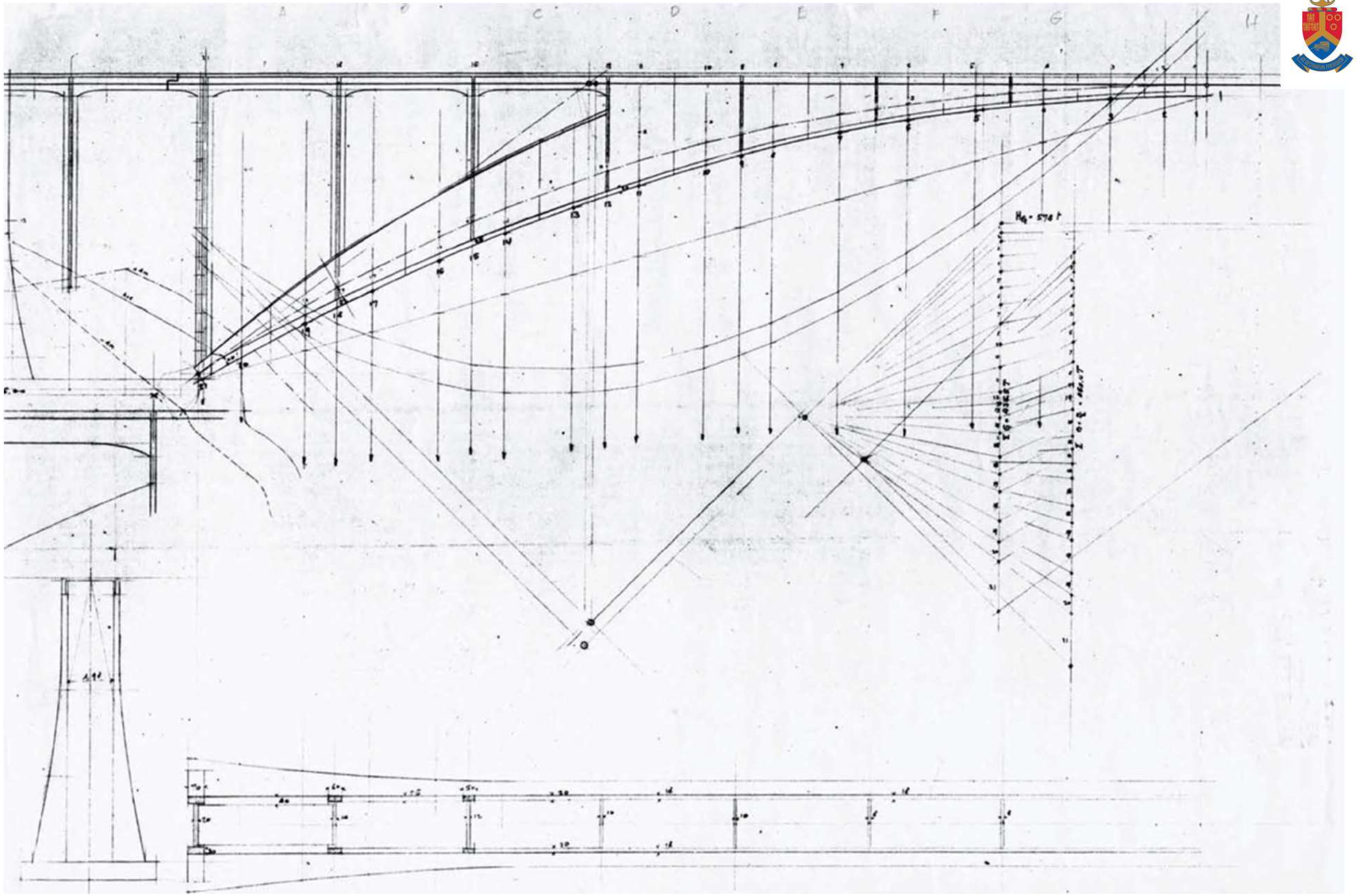
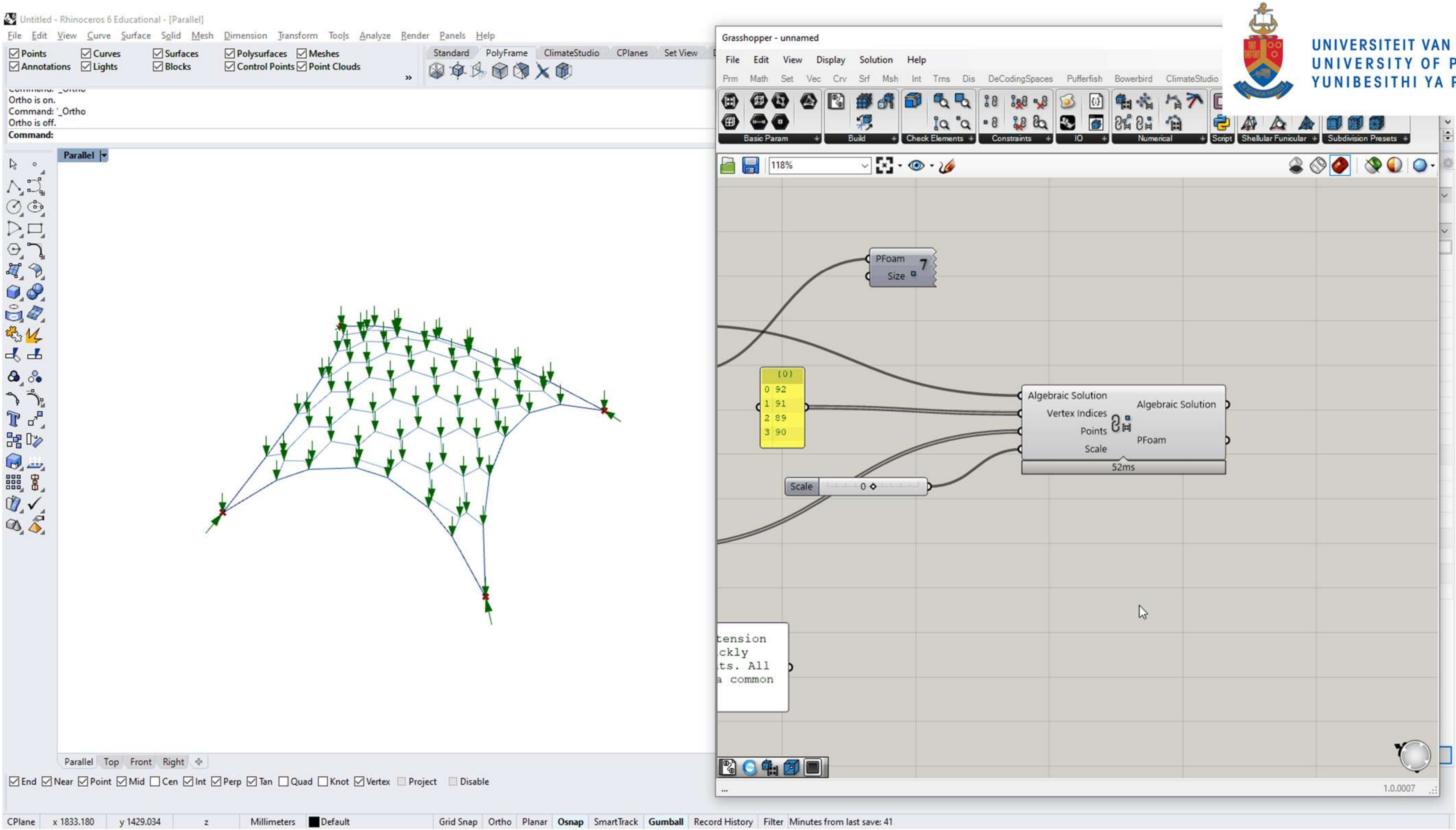
Salginatobel Bridge, Schiers, 1930 | Robert Maillart



Salginatobel Bridge, Schiers, 1930 | Robert Maillart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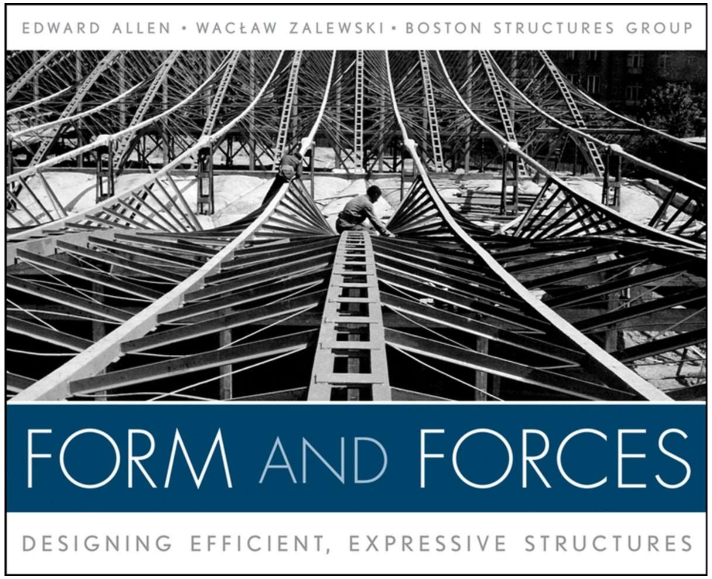
Example



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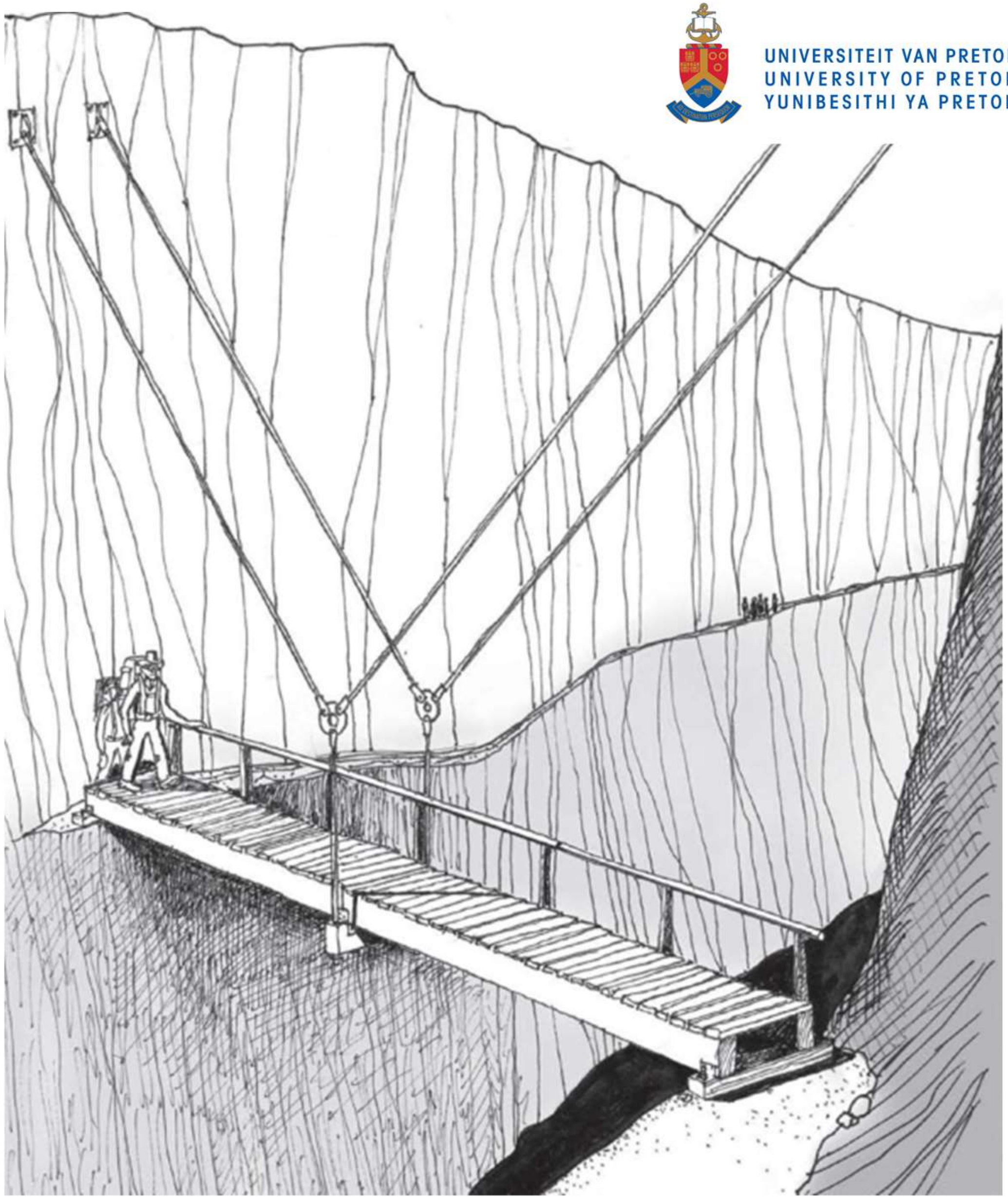

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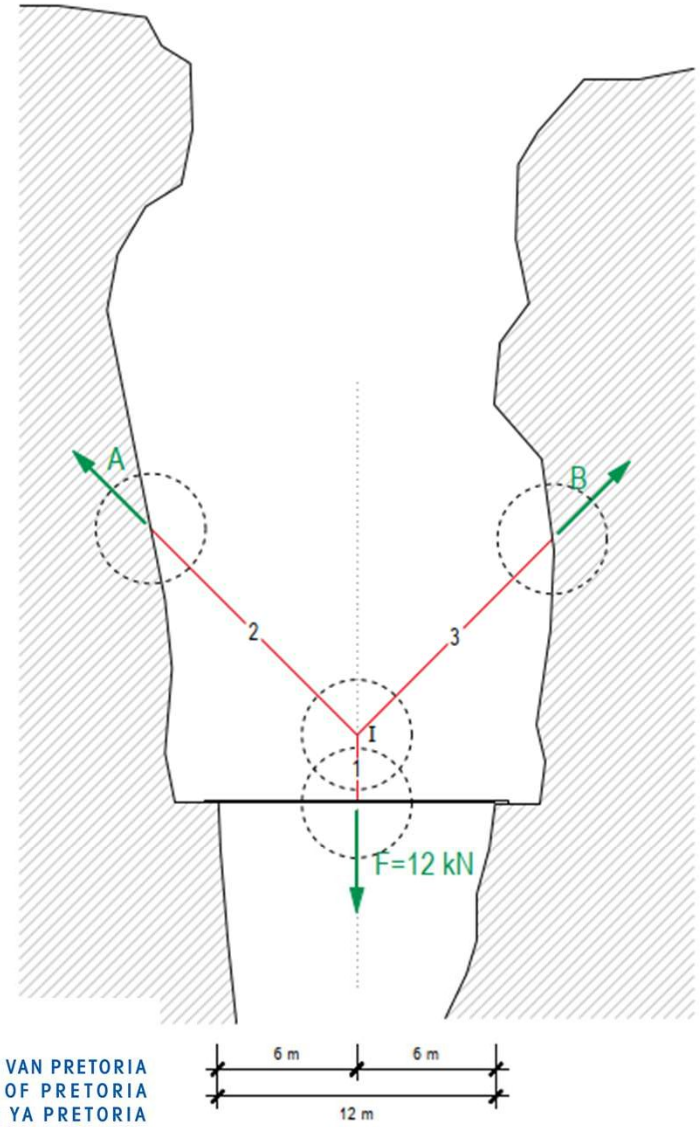
A
B
2
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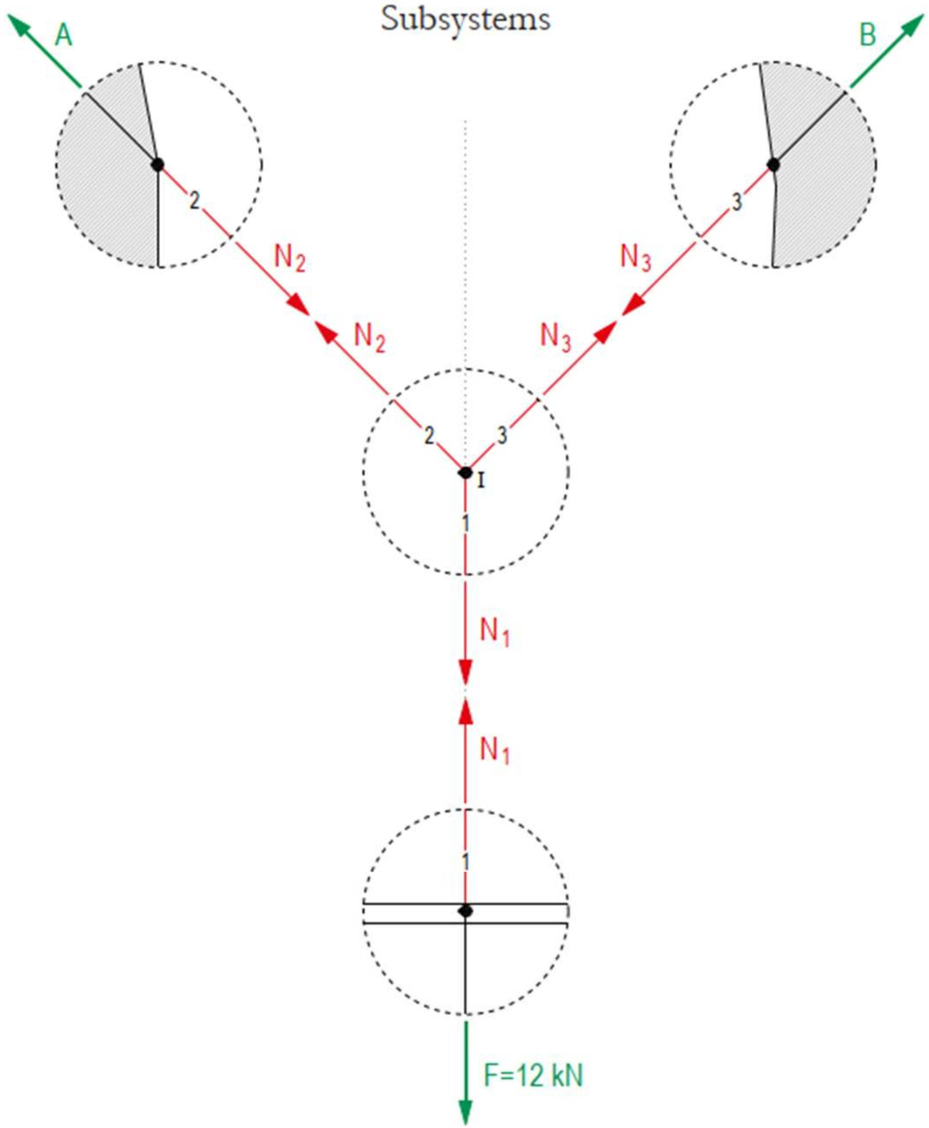
F=12 kN
6 m
6 m
12 m


Subsystems
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B
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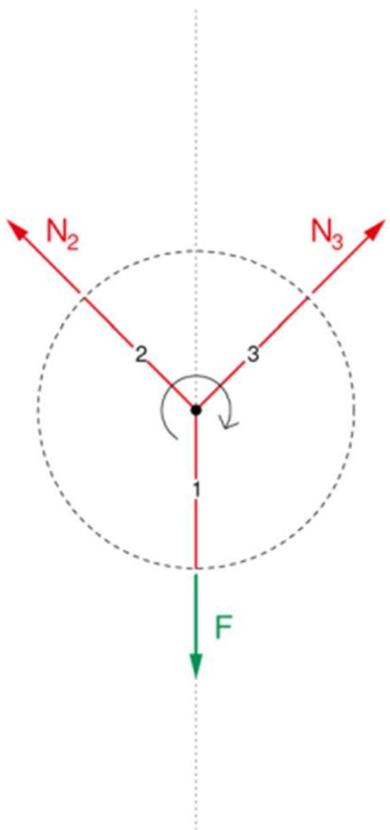
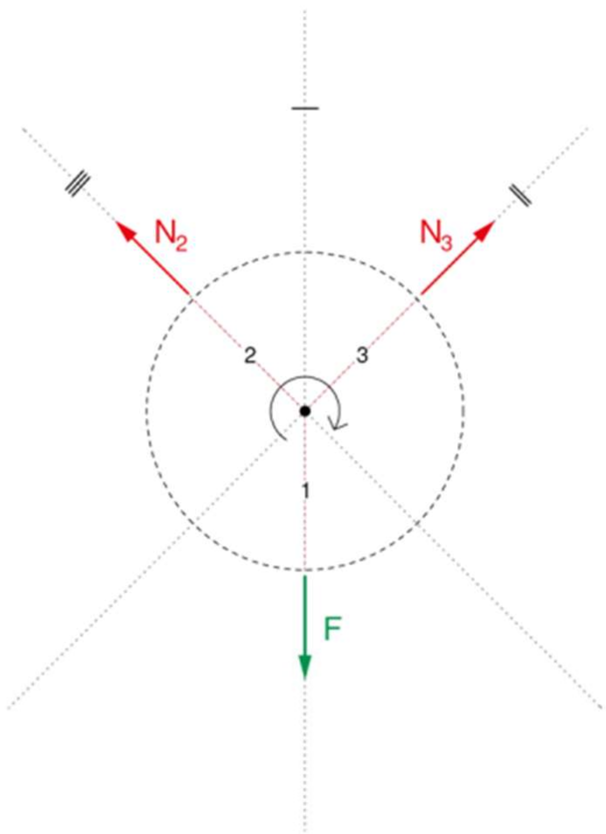
N$_1$
1
F=12 kN

Subsystem

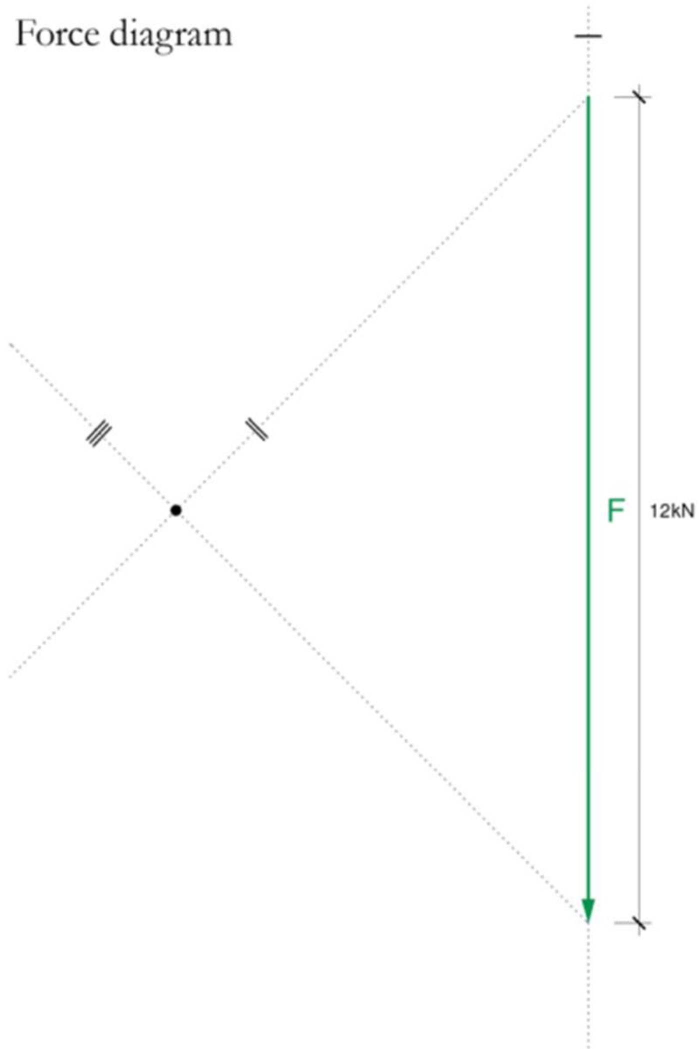


Force diagram

Subsystem



Force diagram



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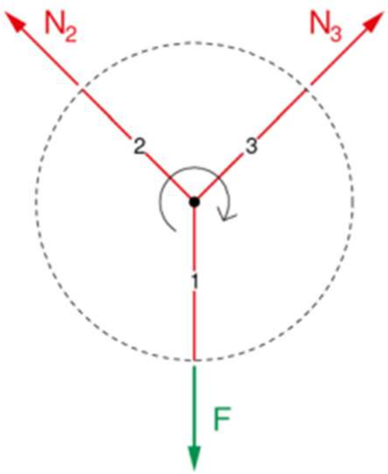
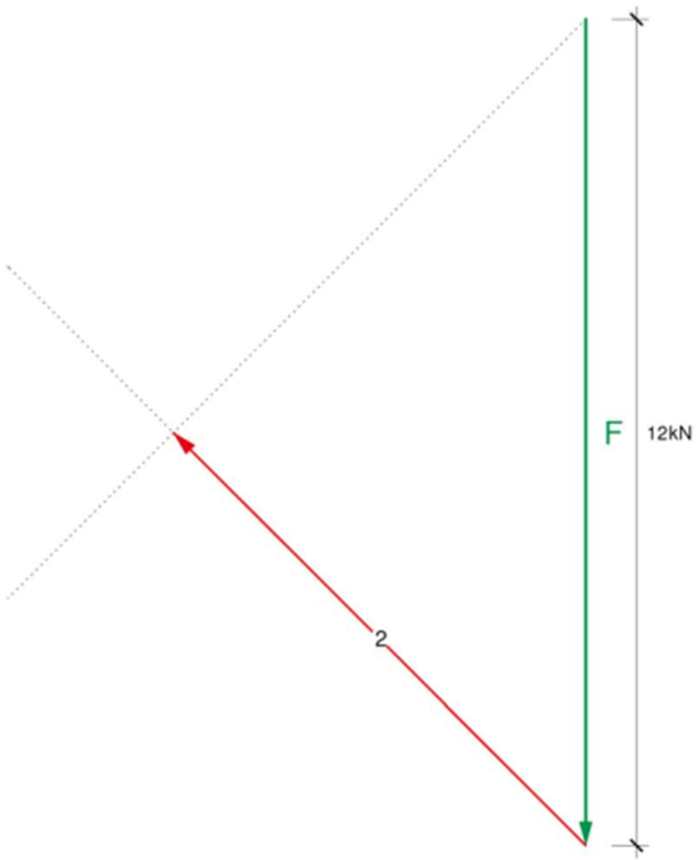


Force diagram



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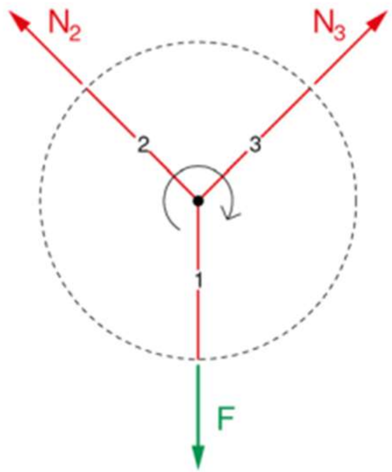
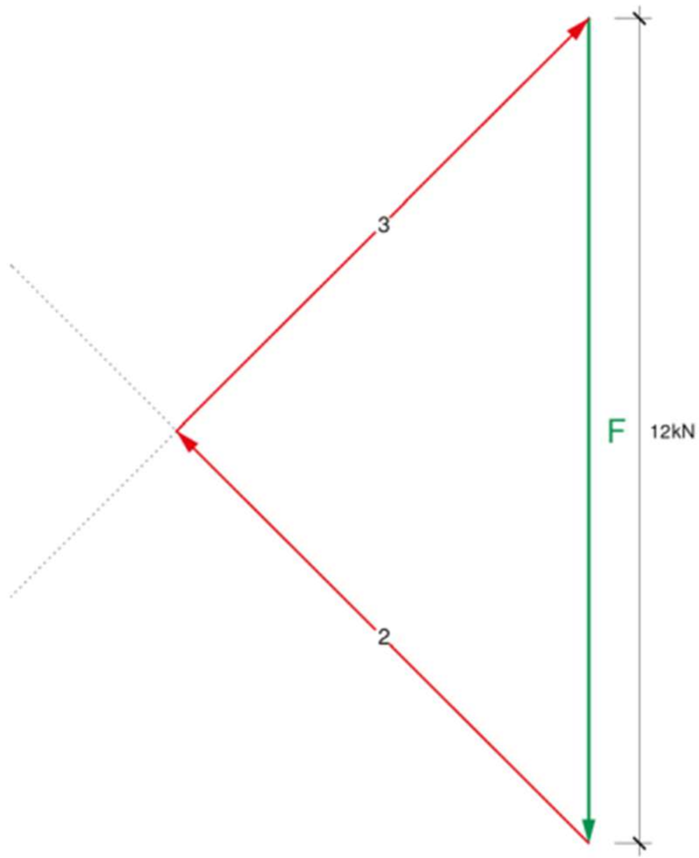


Force diagram



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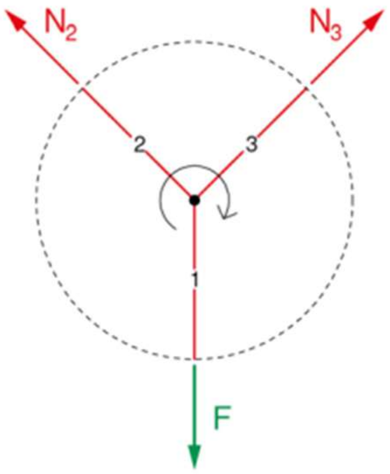
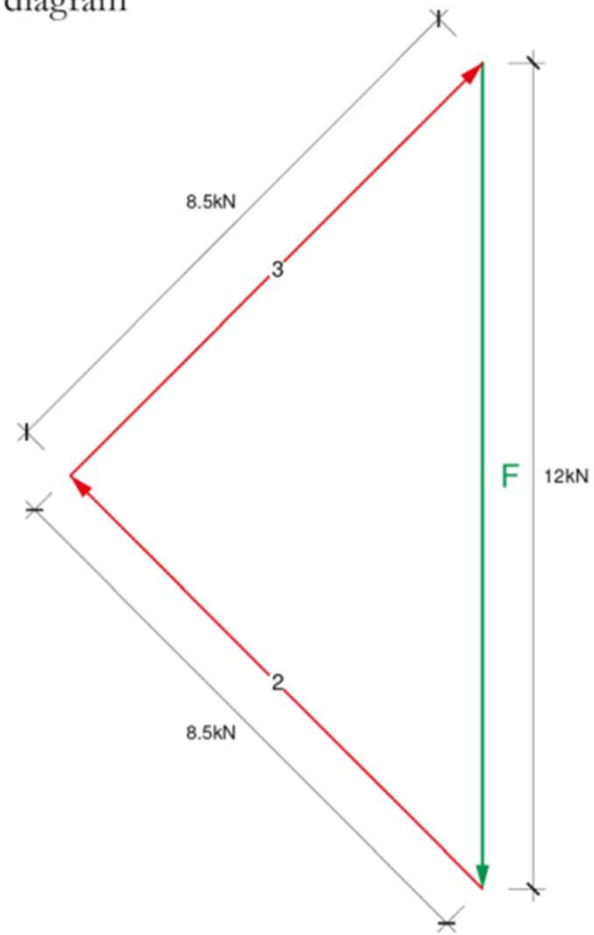
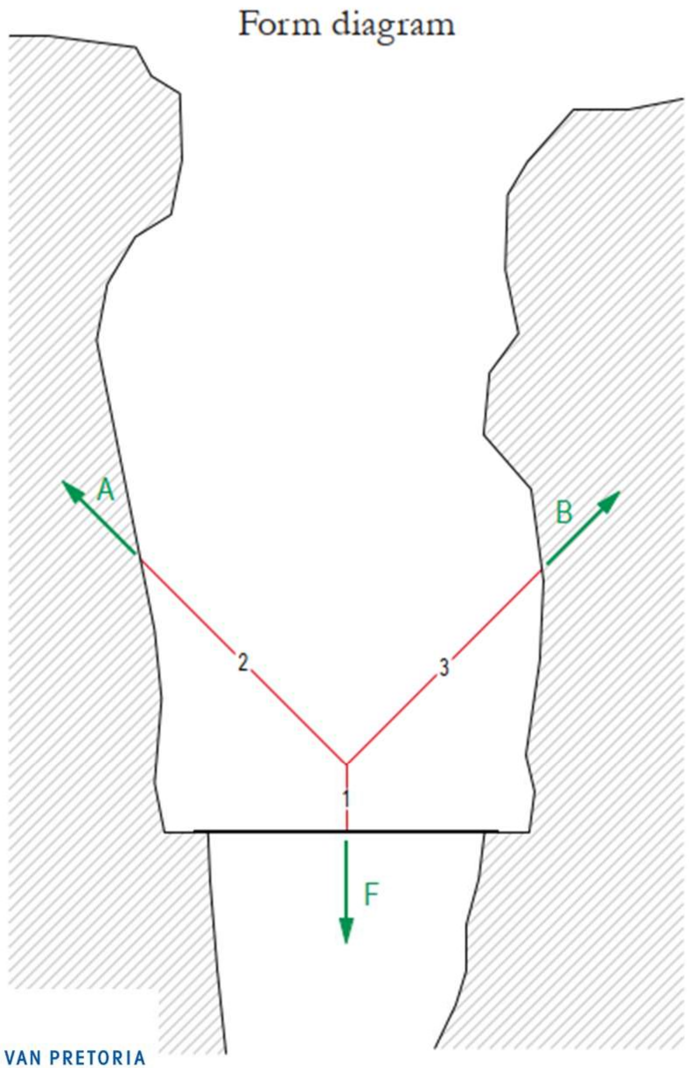
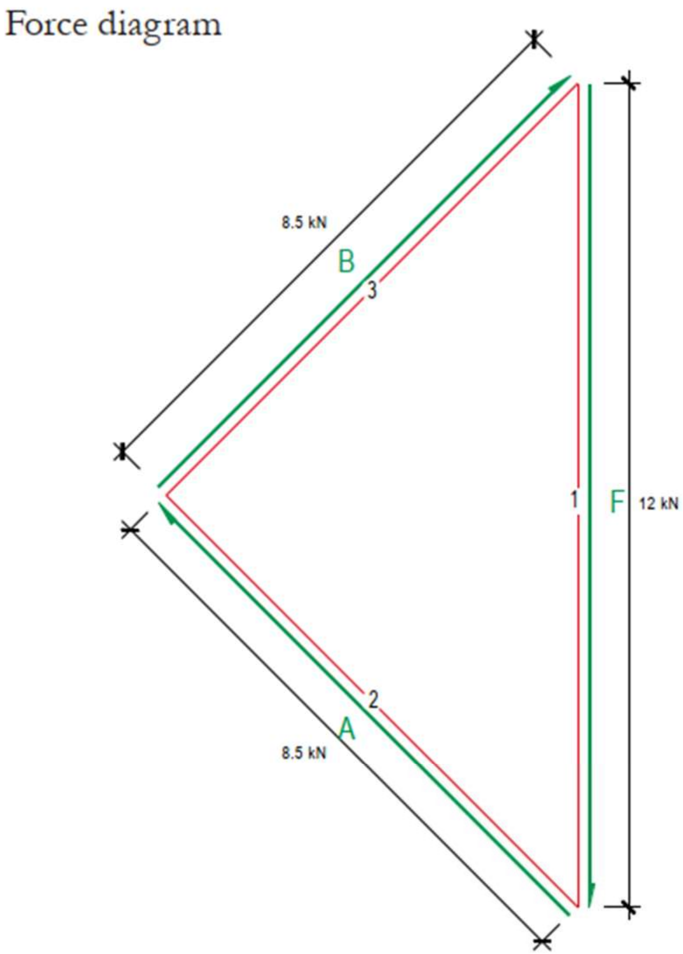


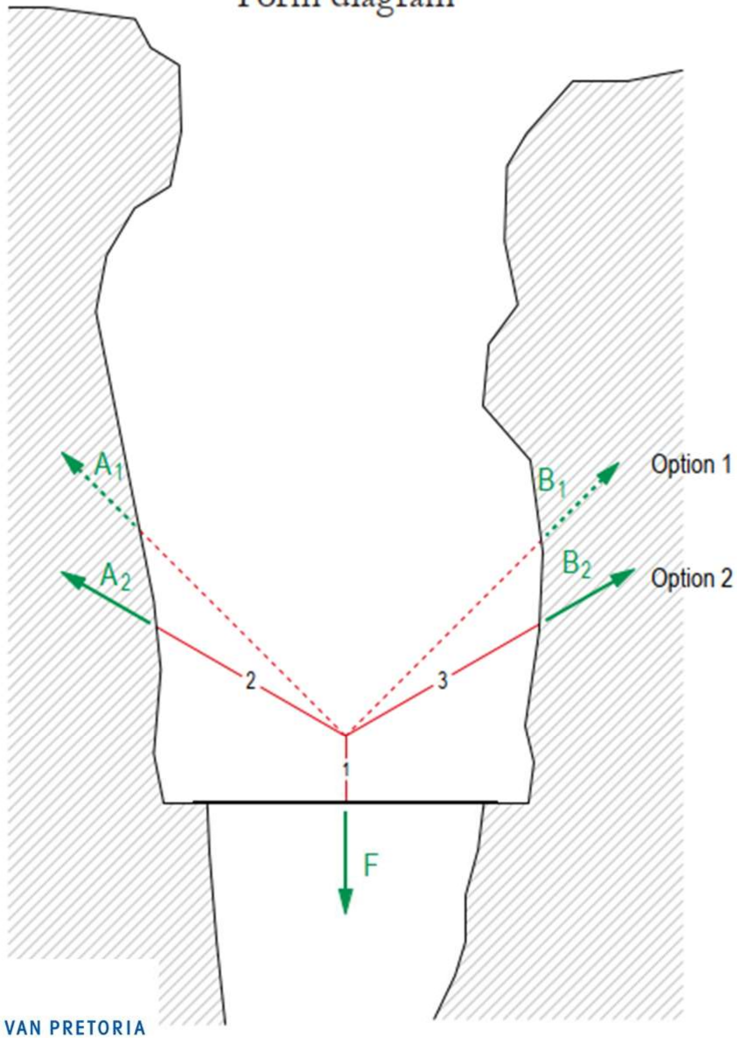
Force diagram




Form diagram
A
B
2
3
1
F


Force diagram
8.5 kN
B
3
1
F
12 kN
2
A
8.5 kN

Form diagram



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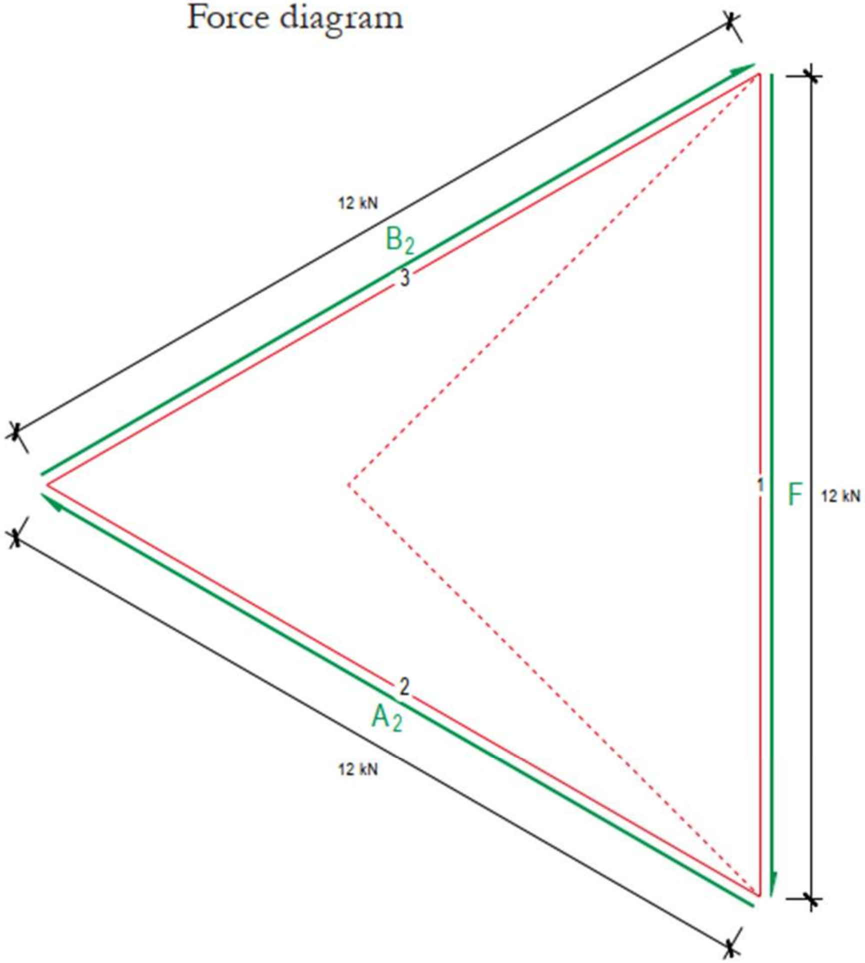

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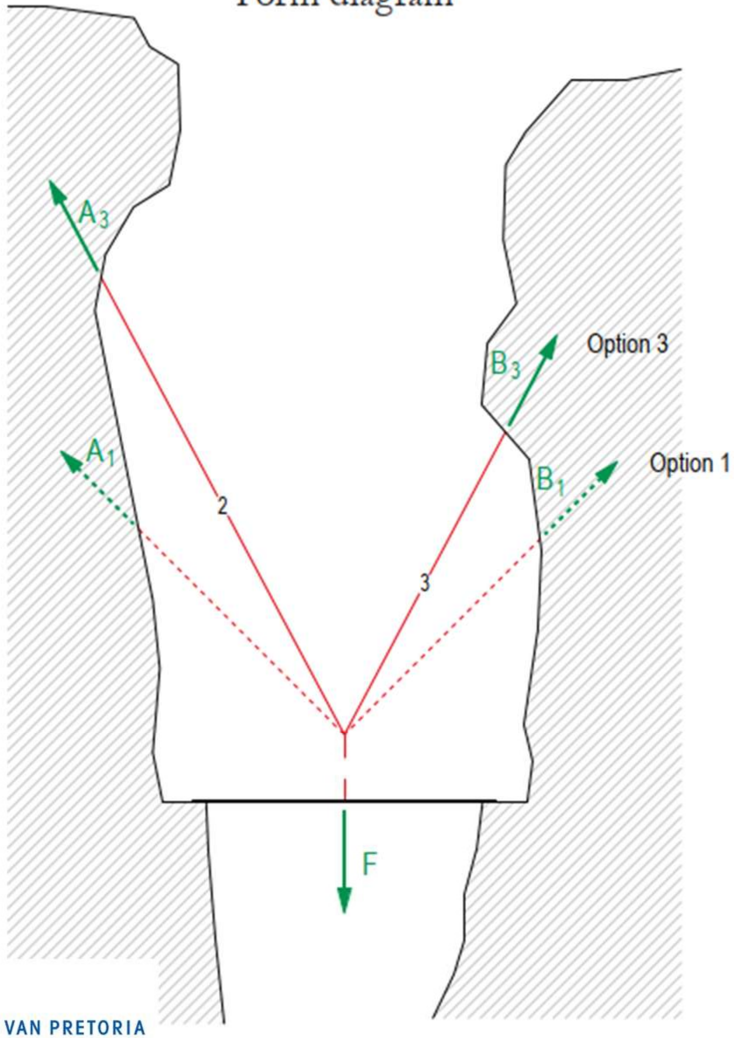

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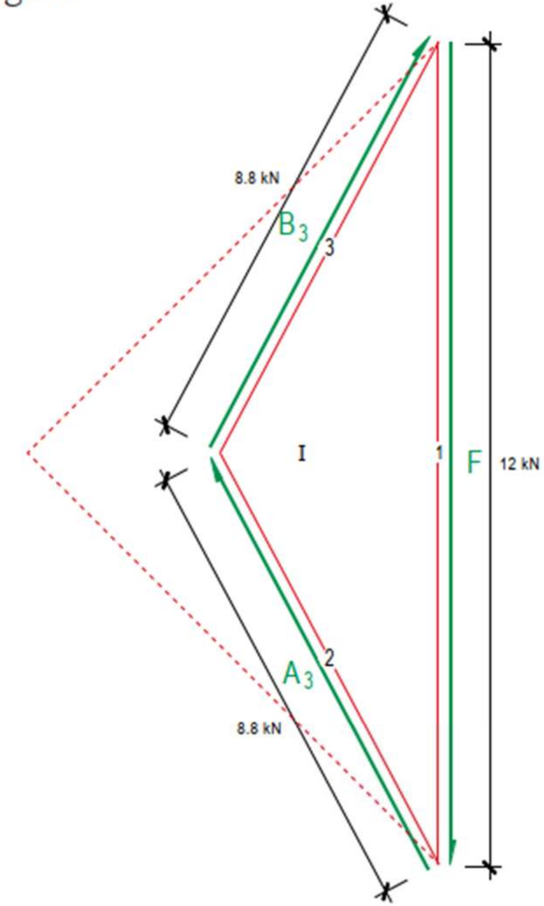
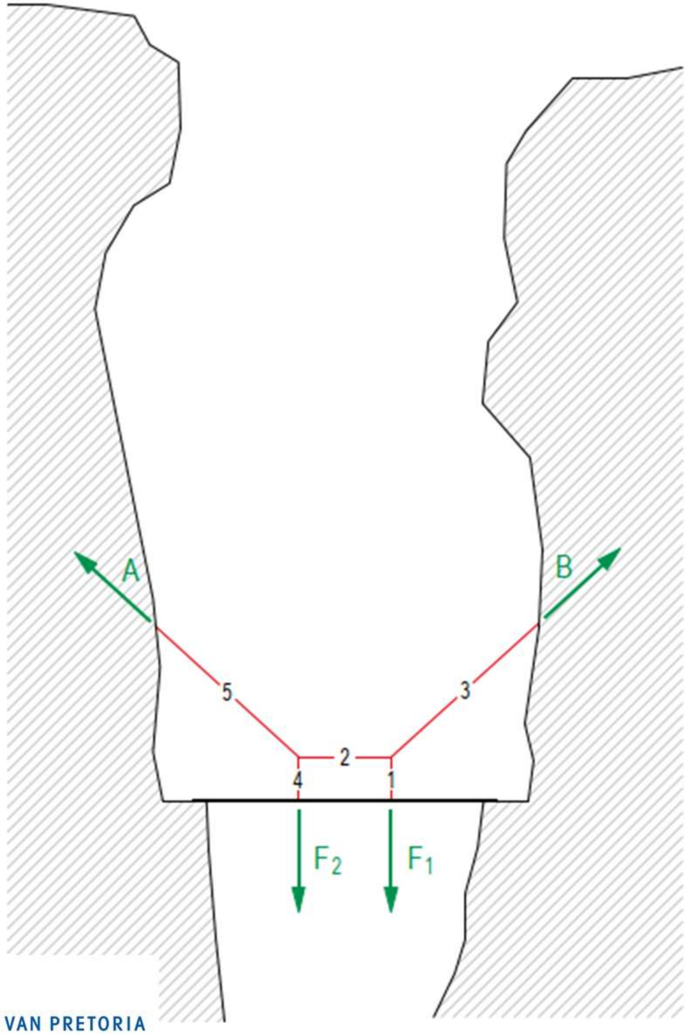
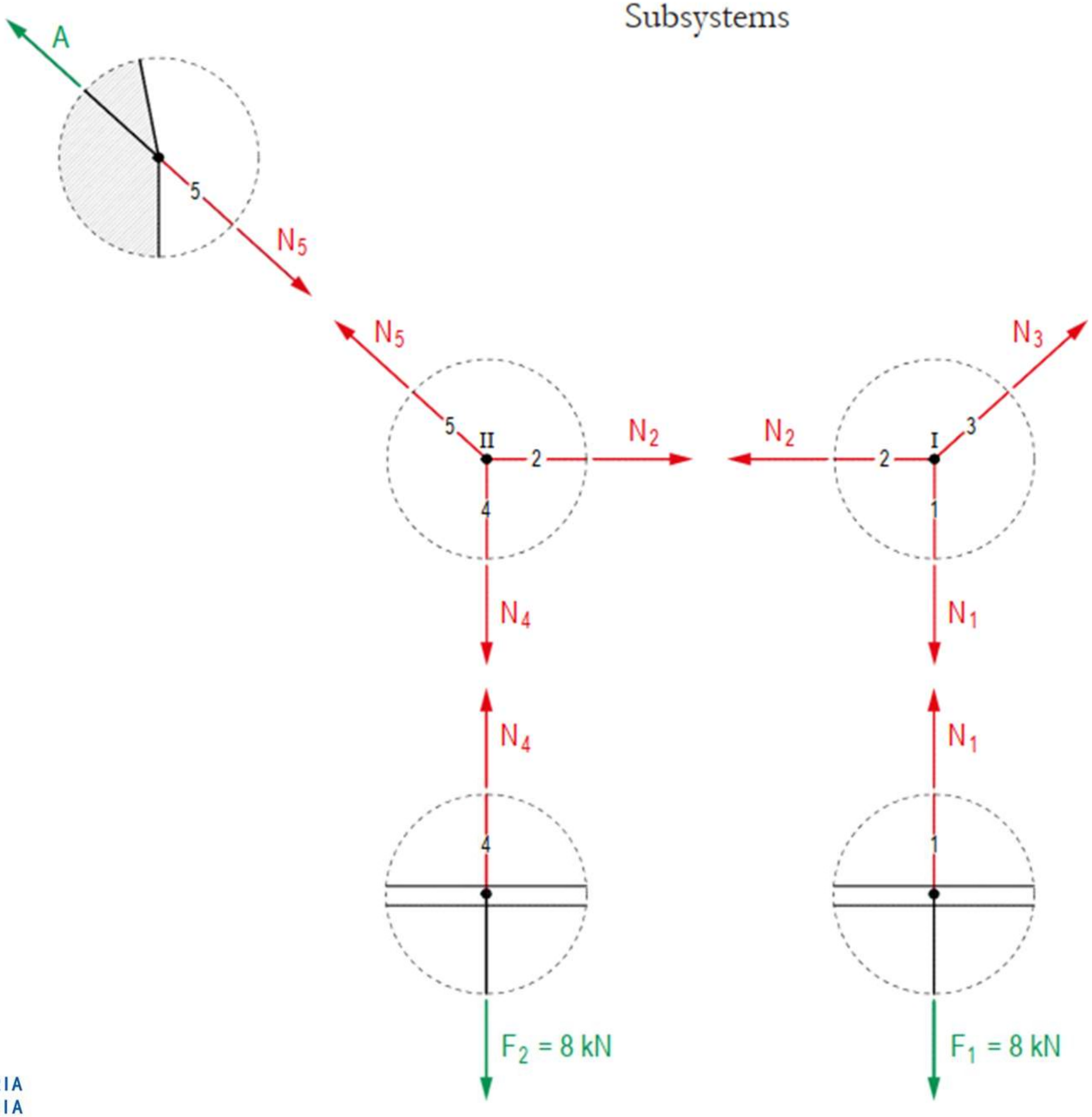



A
B
5
3
2
4
1
F_2
F_1

Subsystems



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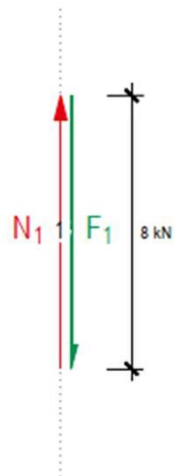

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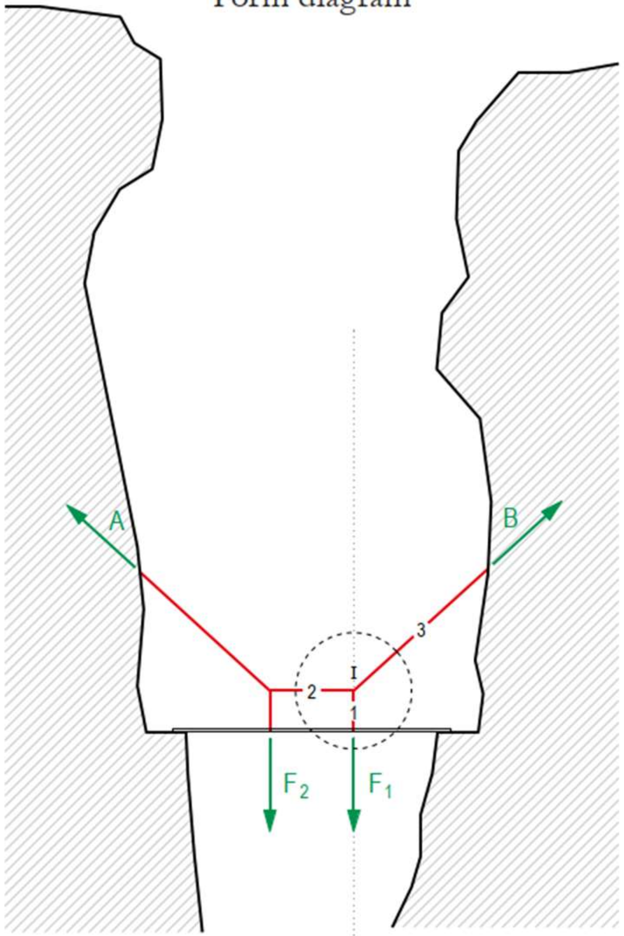

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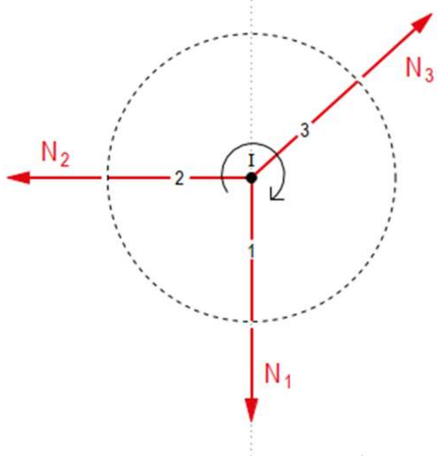

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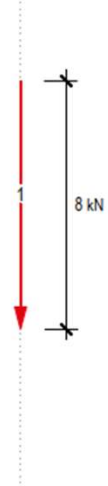

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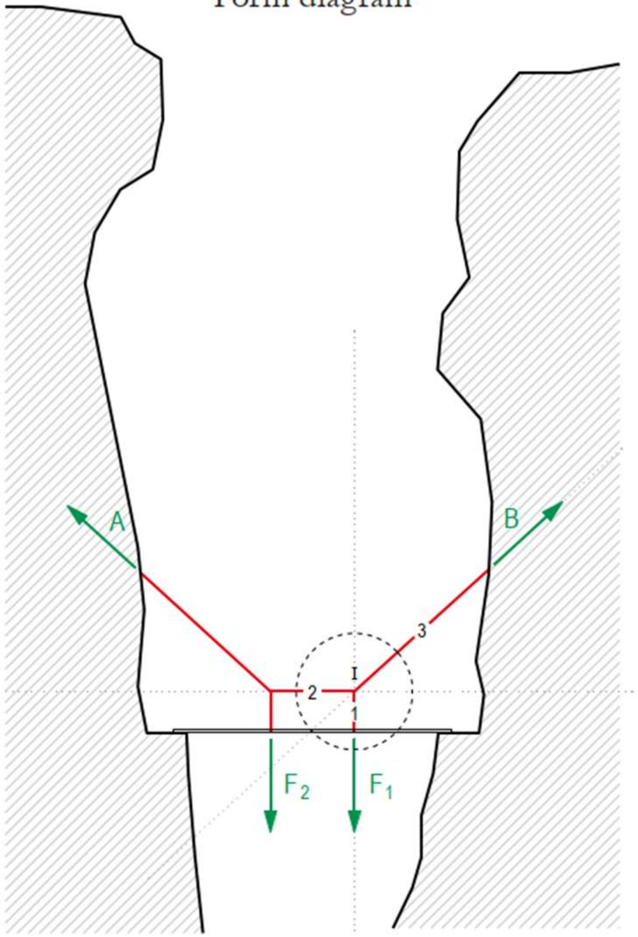

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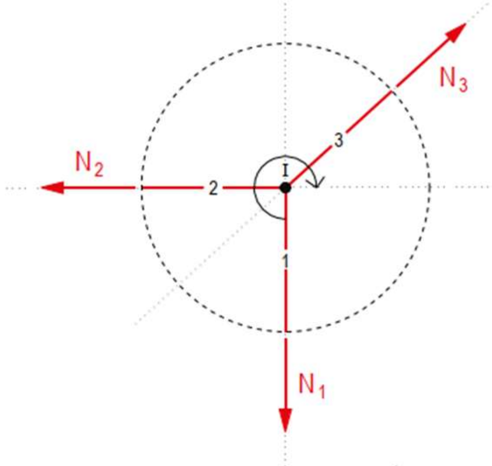

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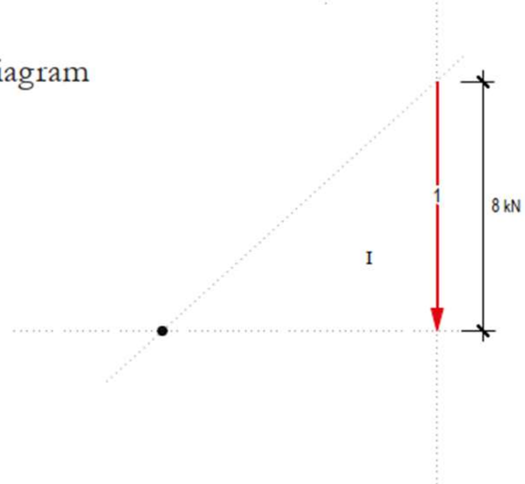

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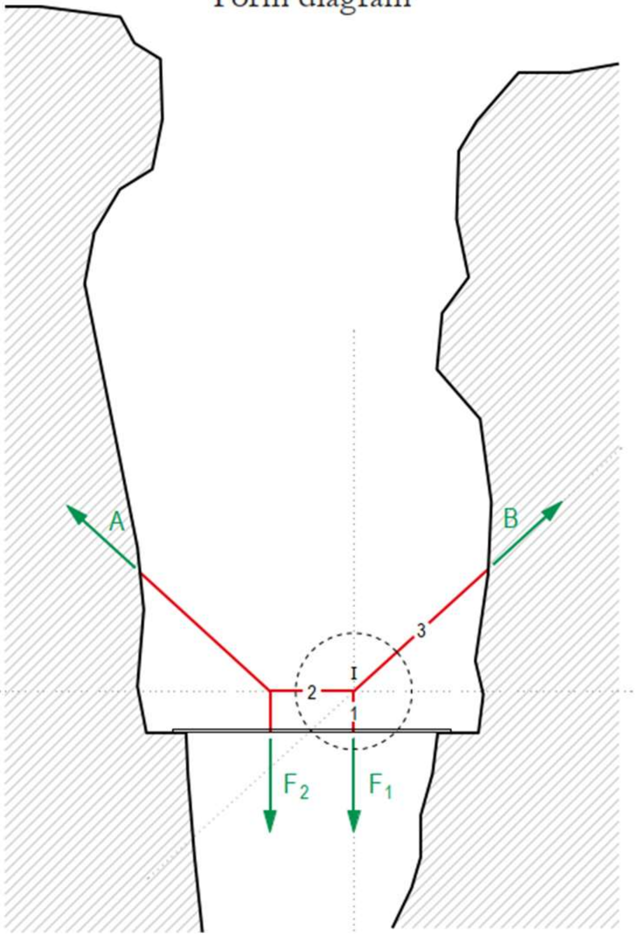

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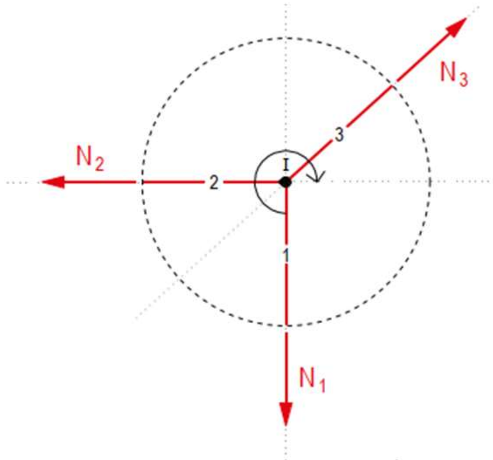

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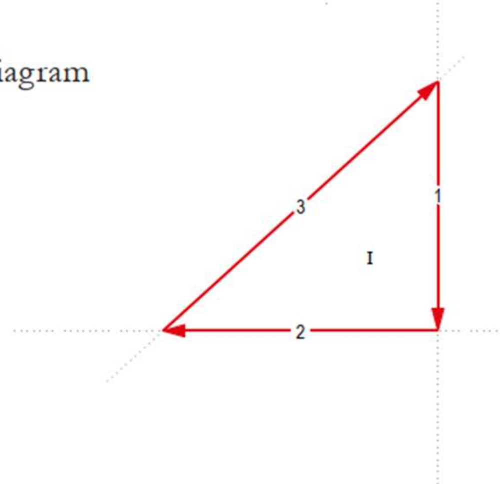

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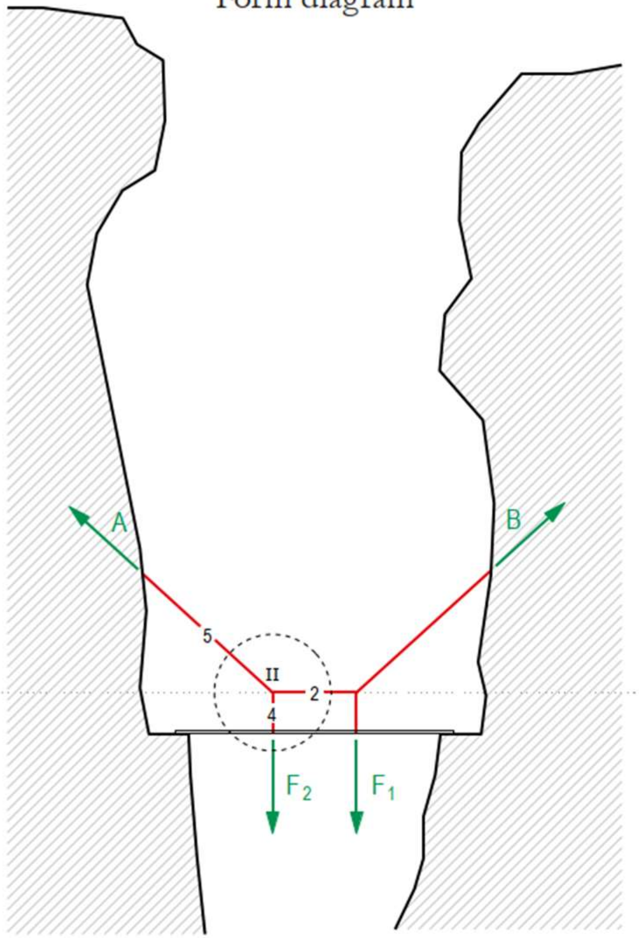

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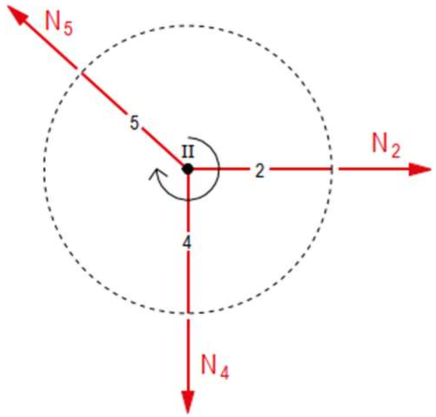

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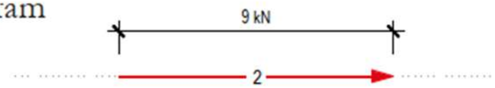

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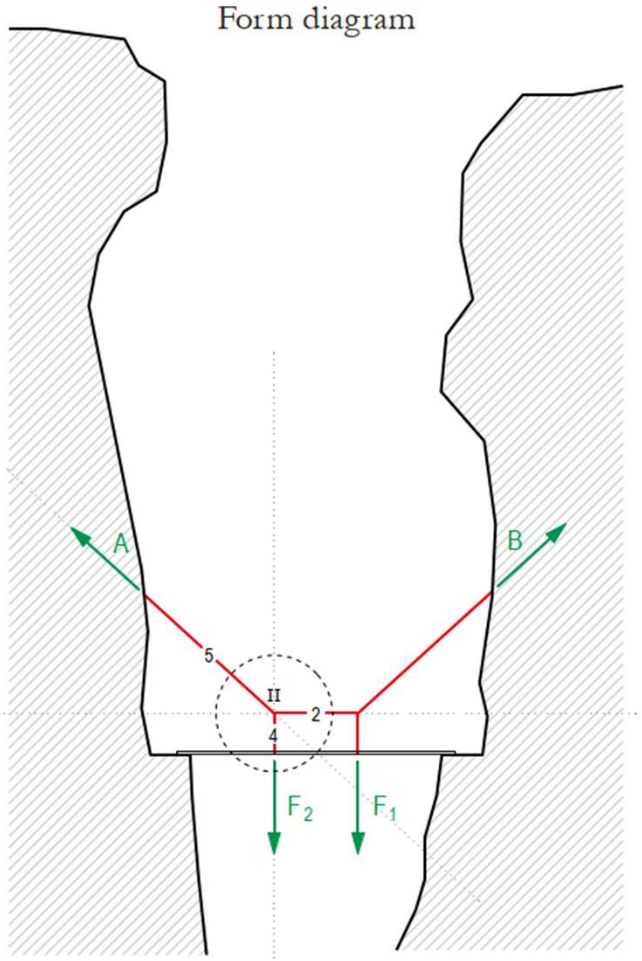
Form diagram
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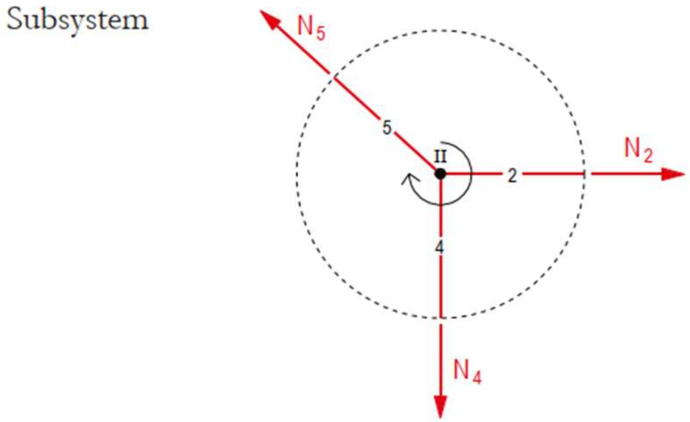
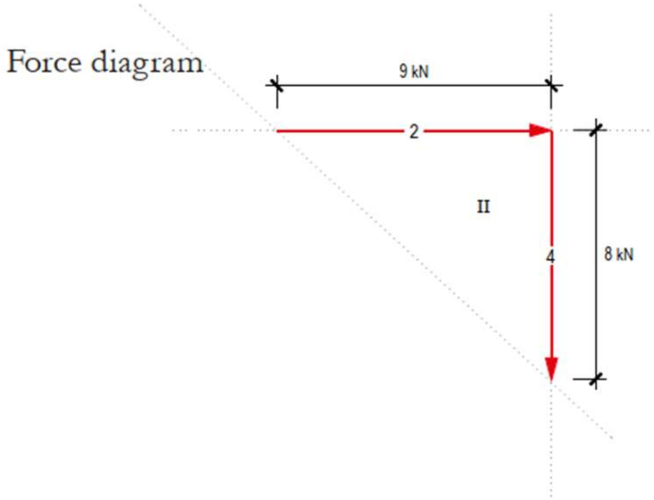
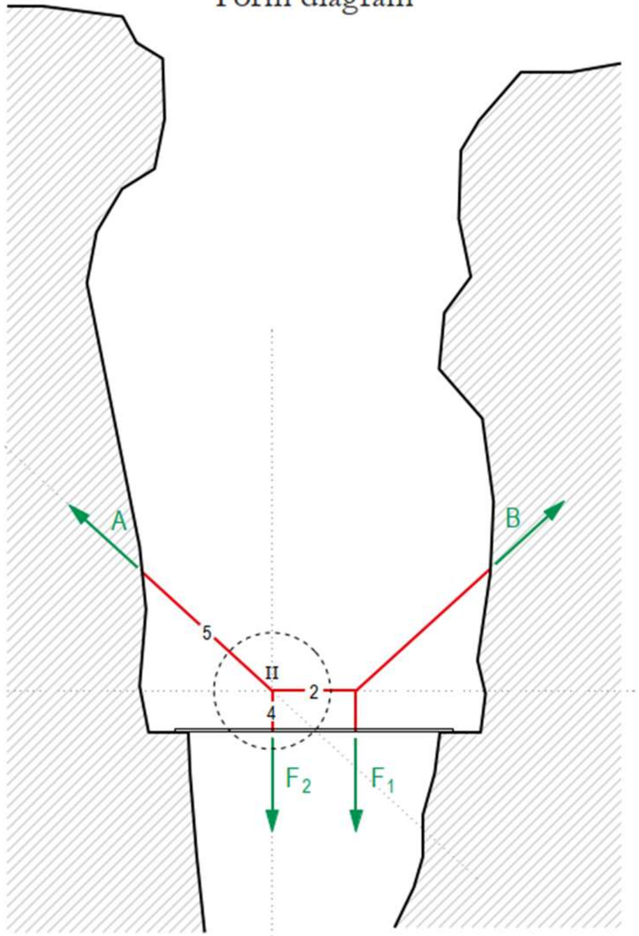
II
2
4
F2
F1


Subsystem
N5
5
II
2
N2
4
N4


Force diagram
9 kN
2
II
4
8 kN

Form diagram



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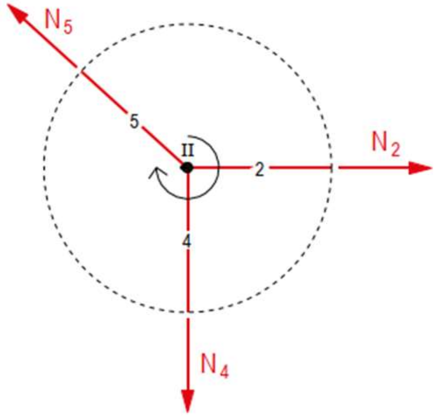

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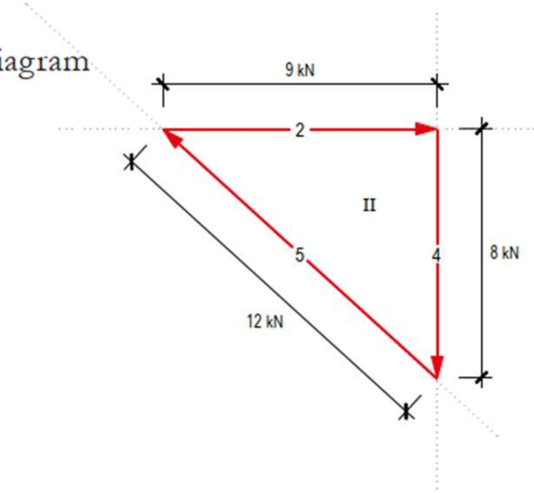

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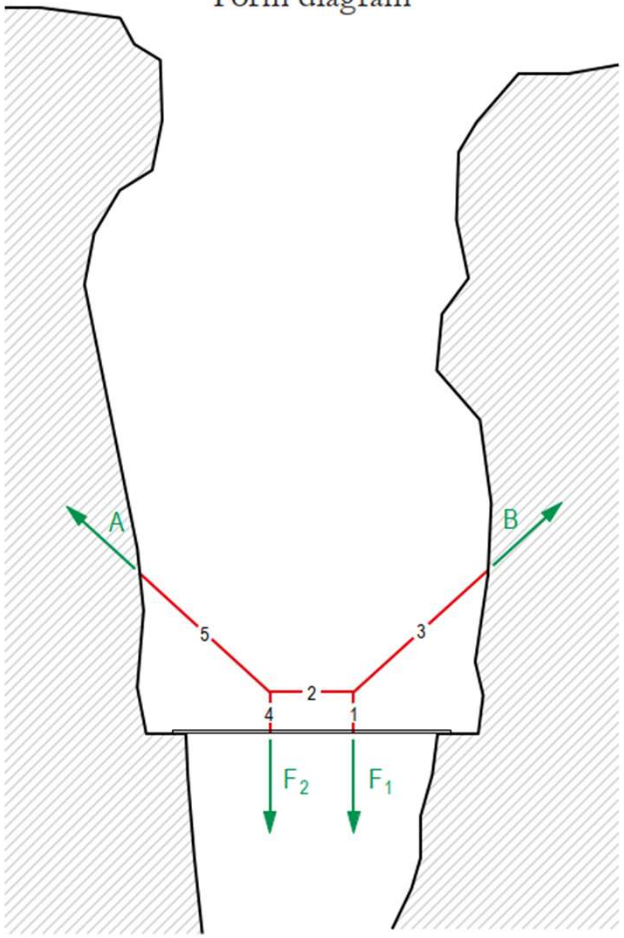

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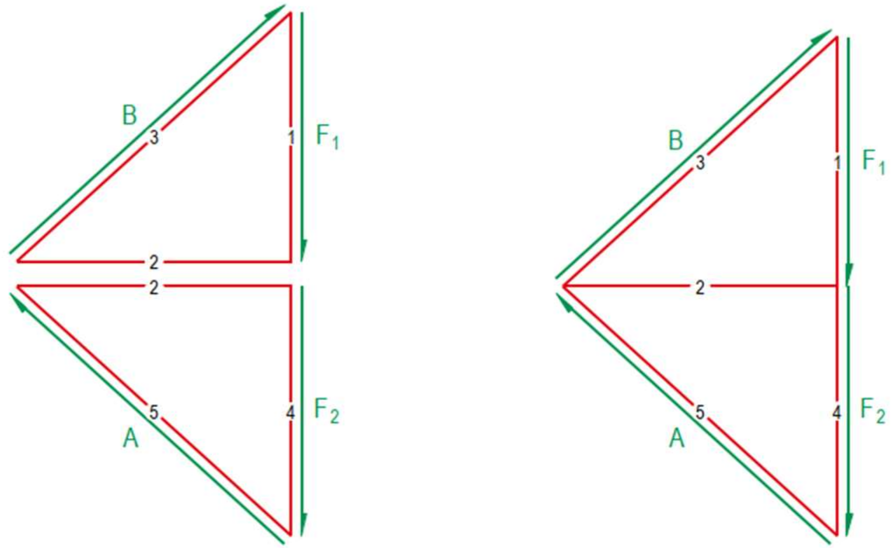

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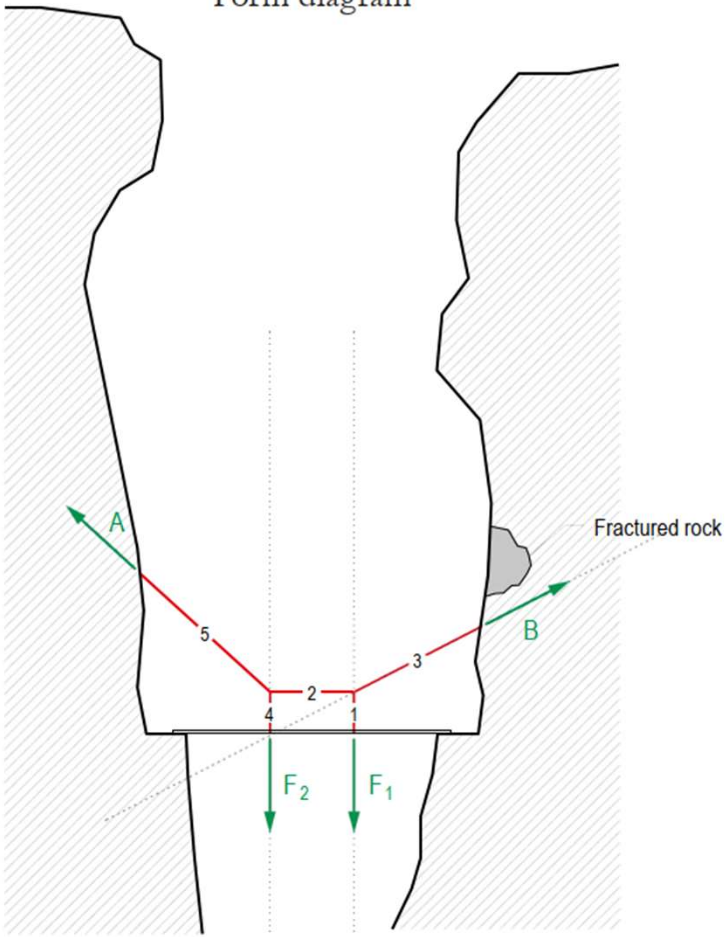

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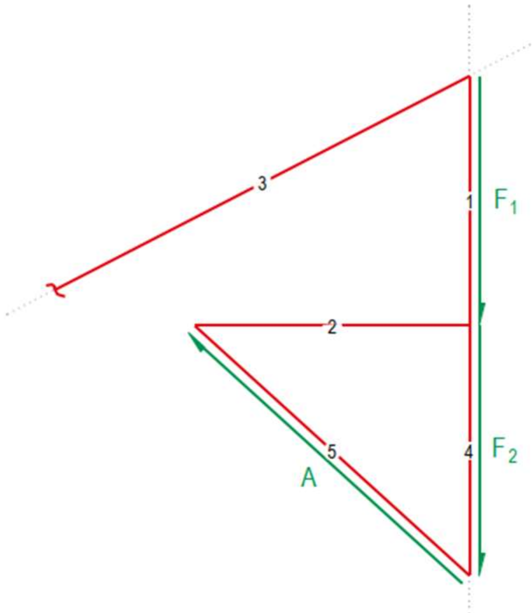

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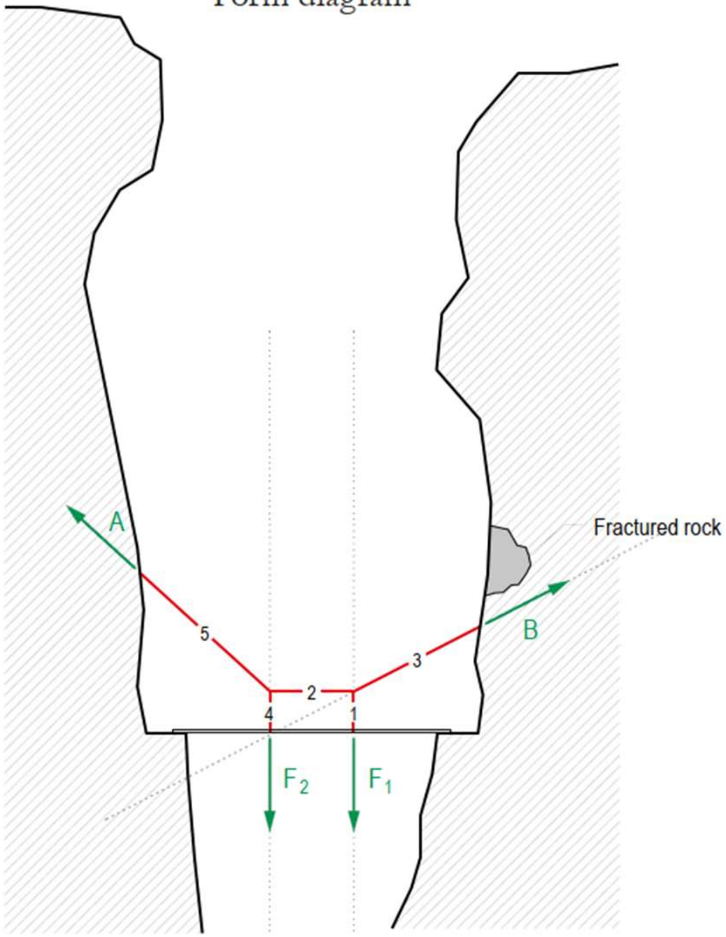

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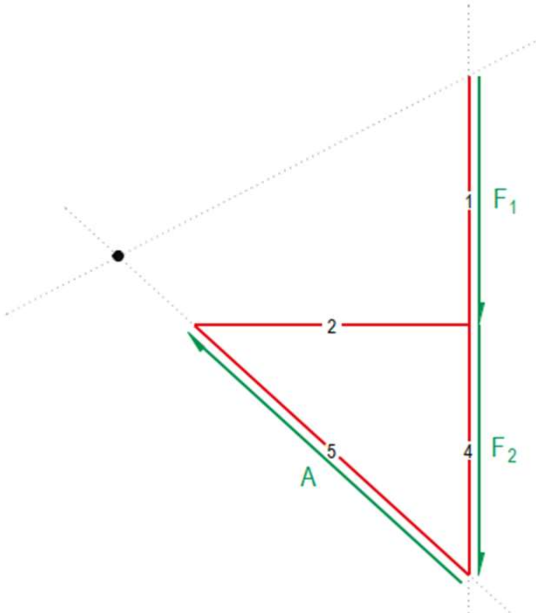

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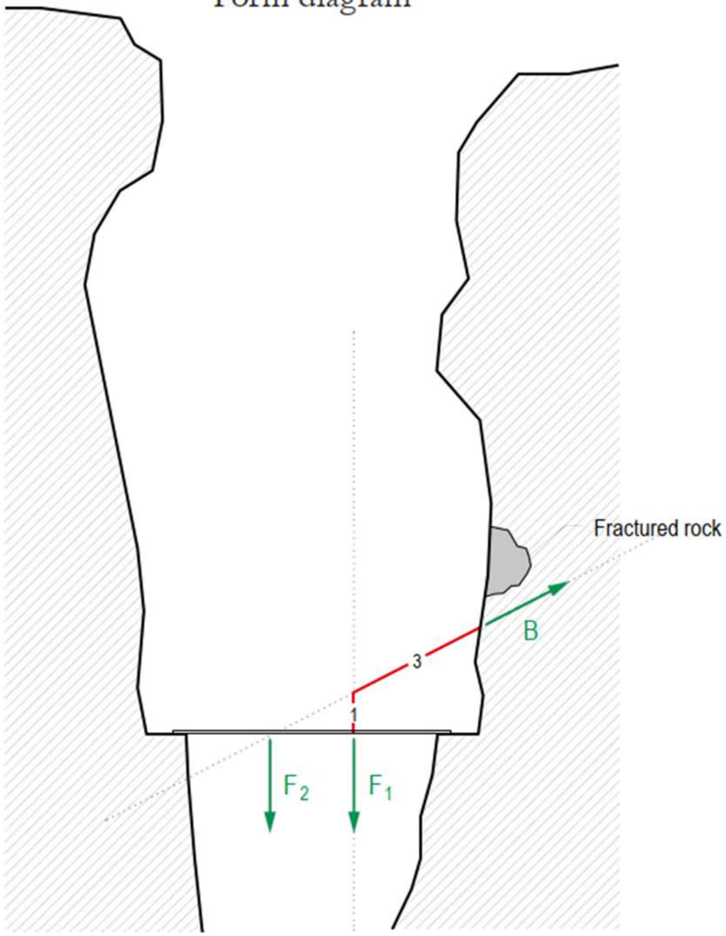

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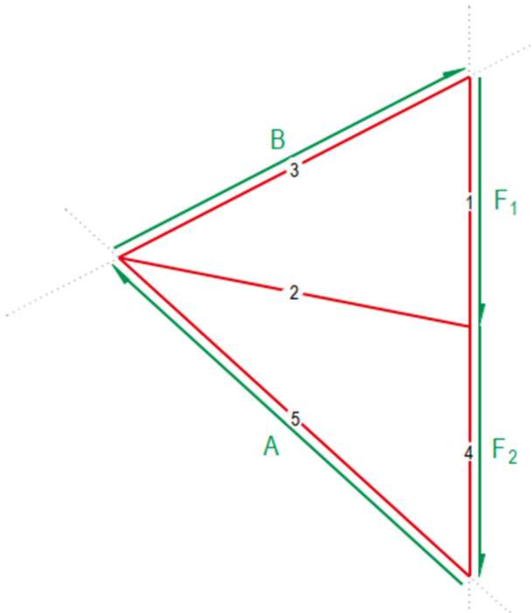

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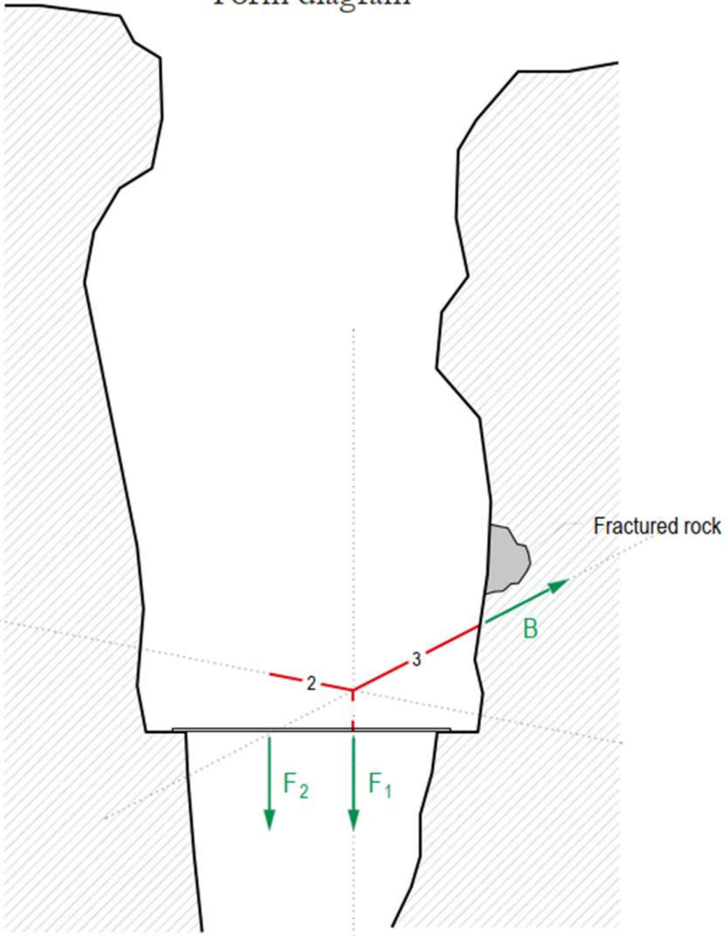

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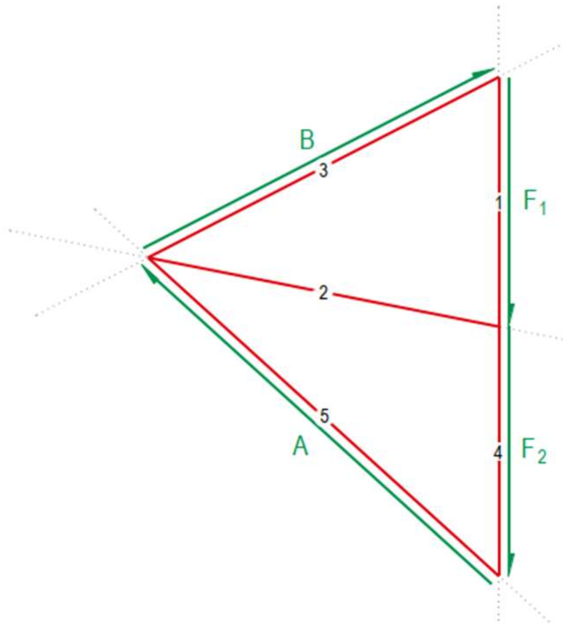

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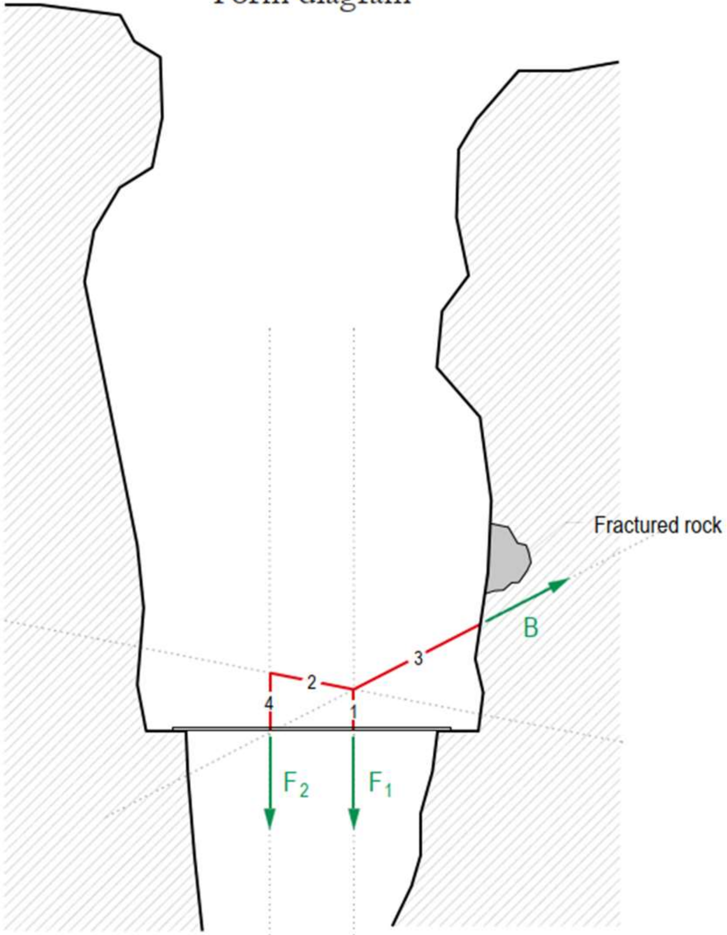

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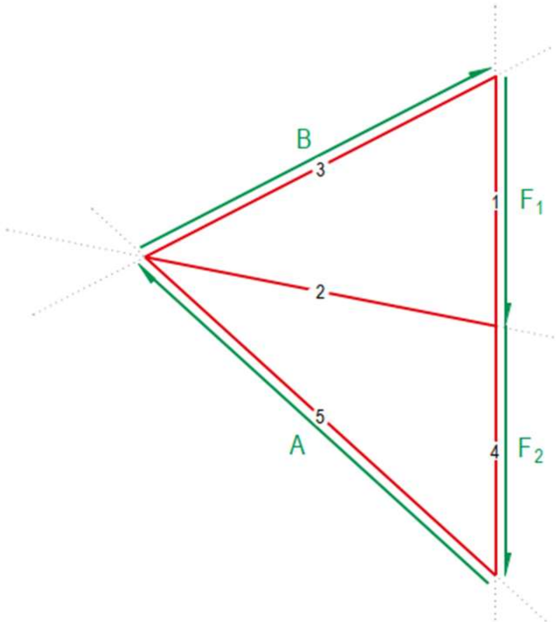

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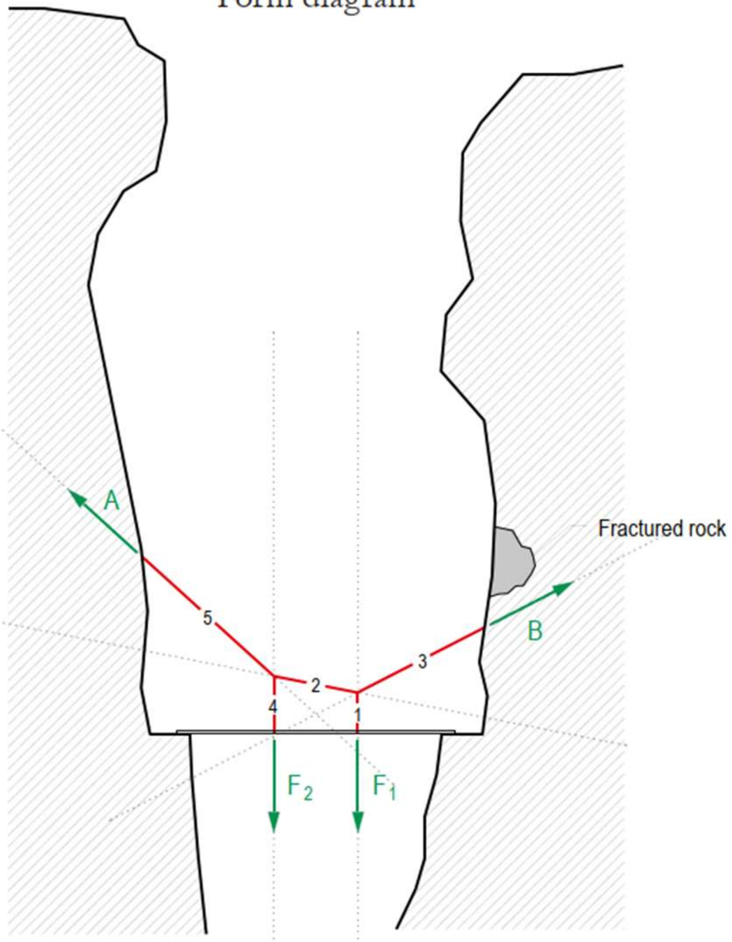

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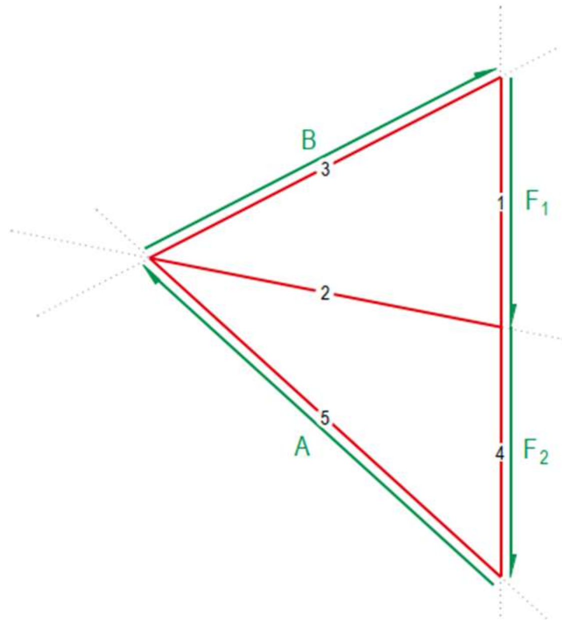

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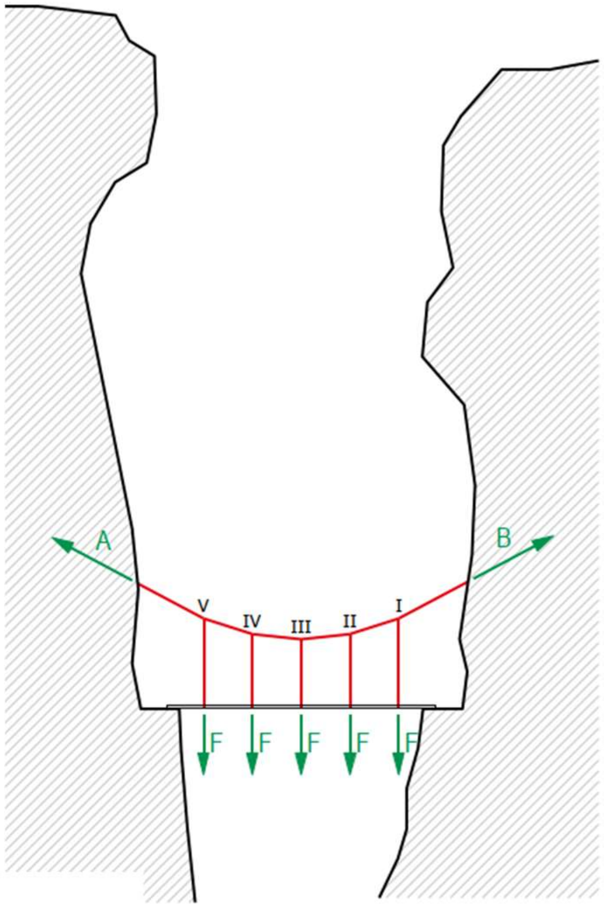

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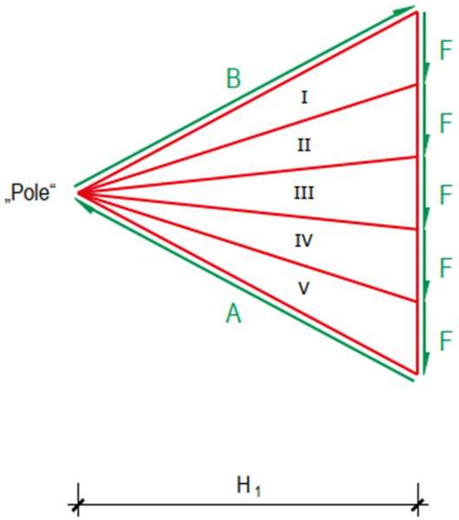
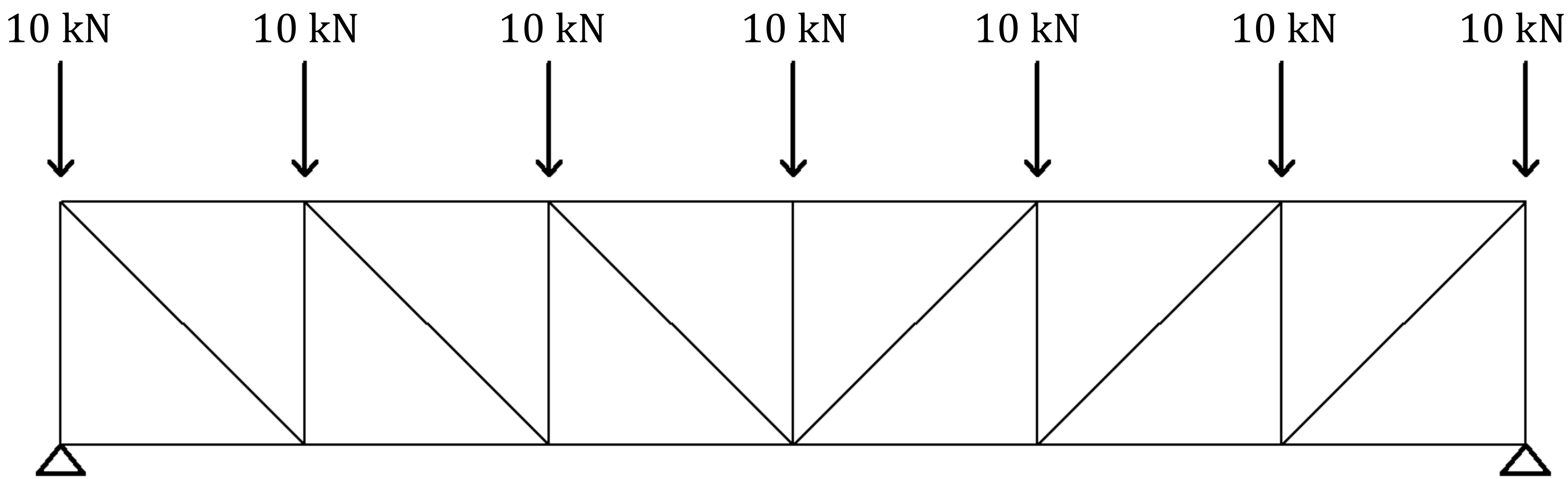
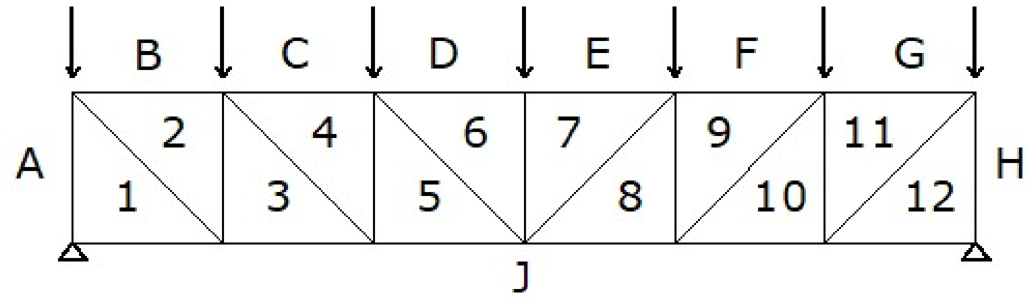


Example

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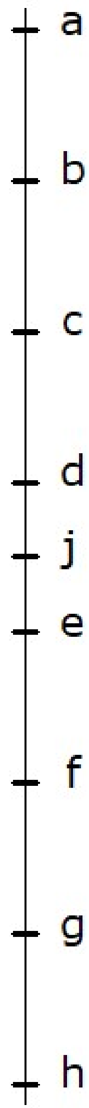
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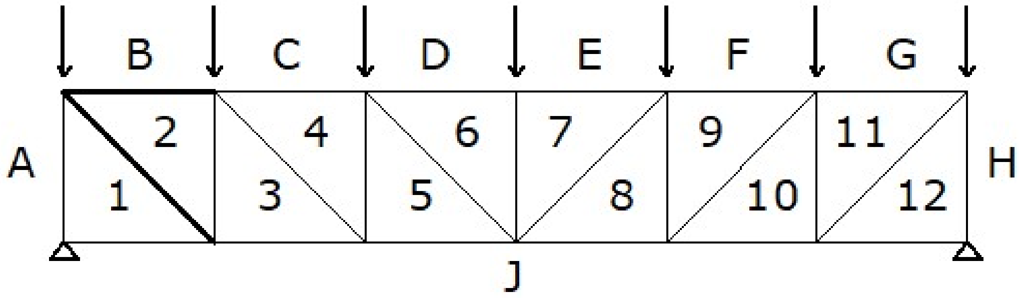
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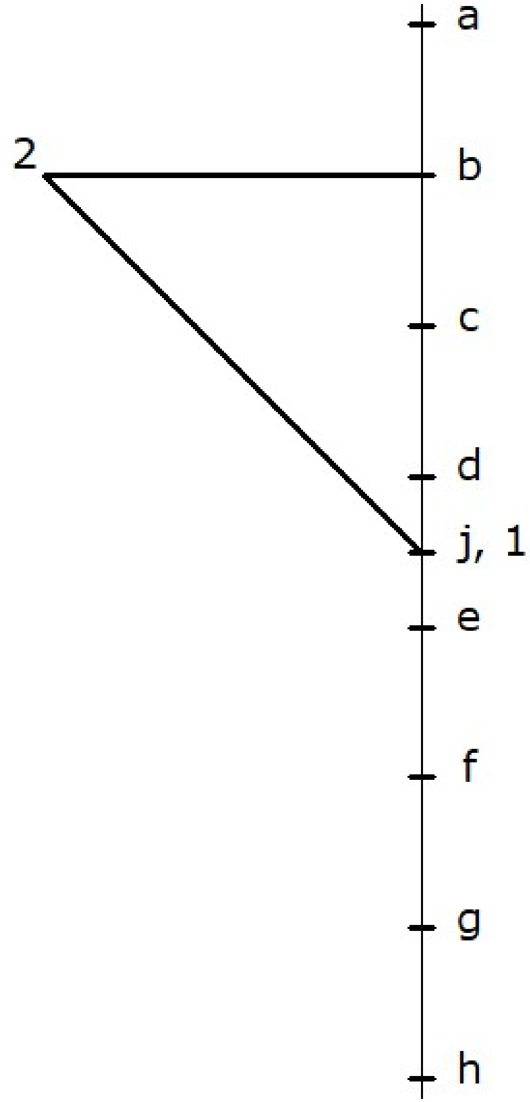
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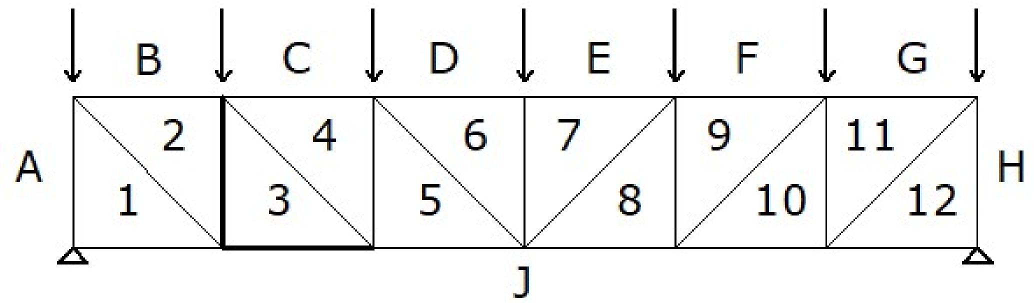
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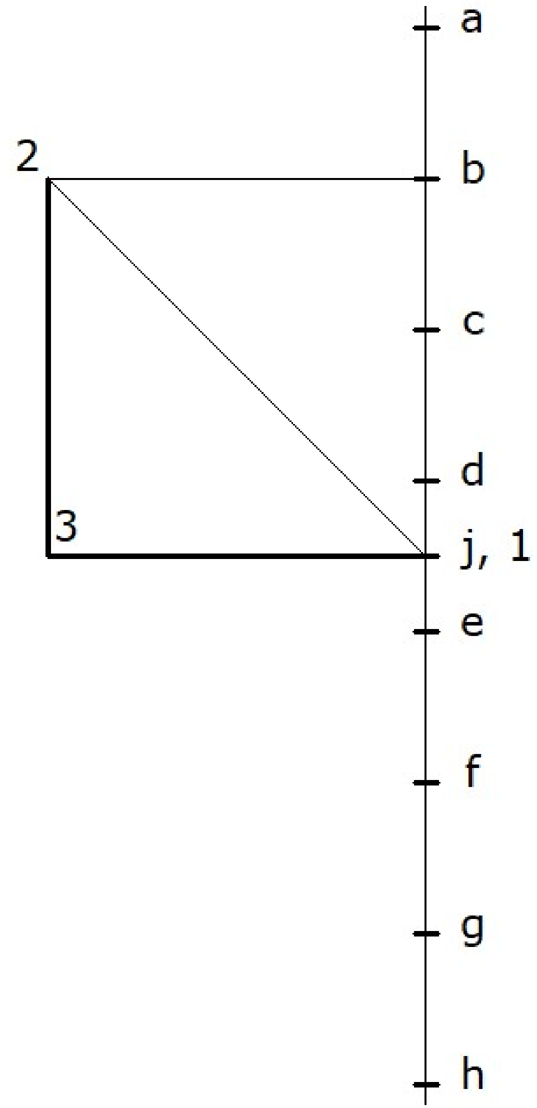
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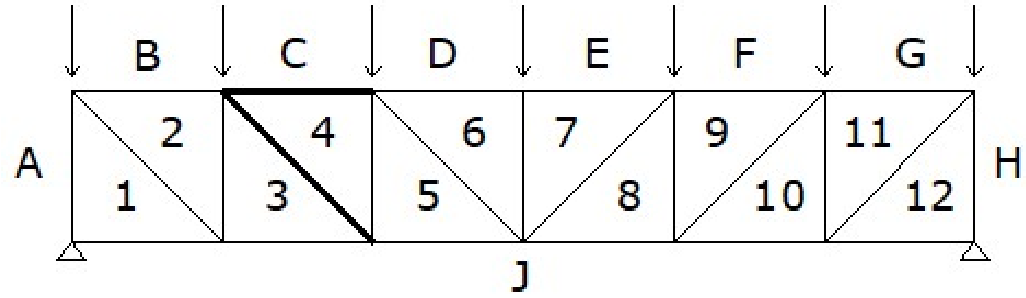
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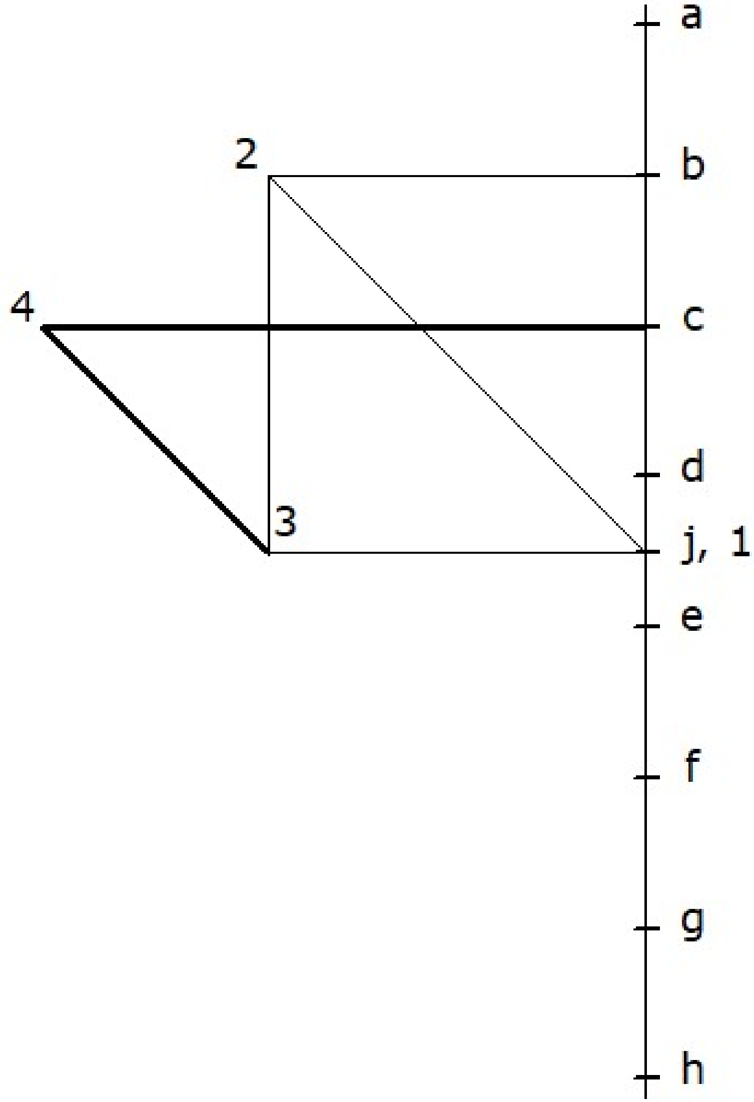
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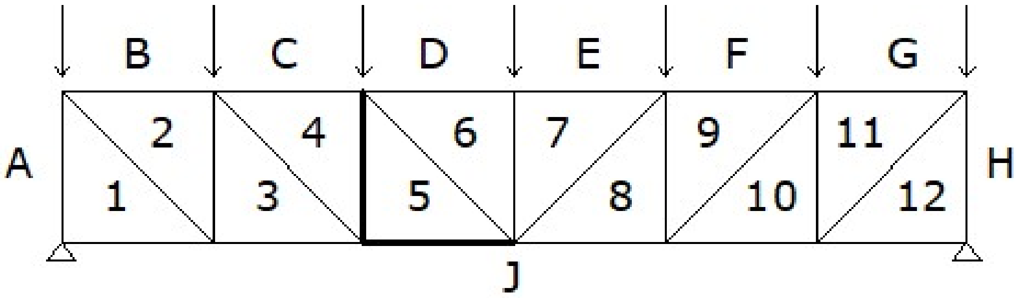
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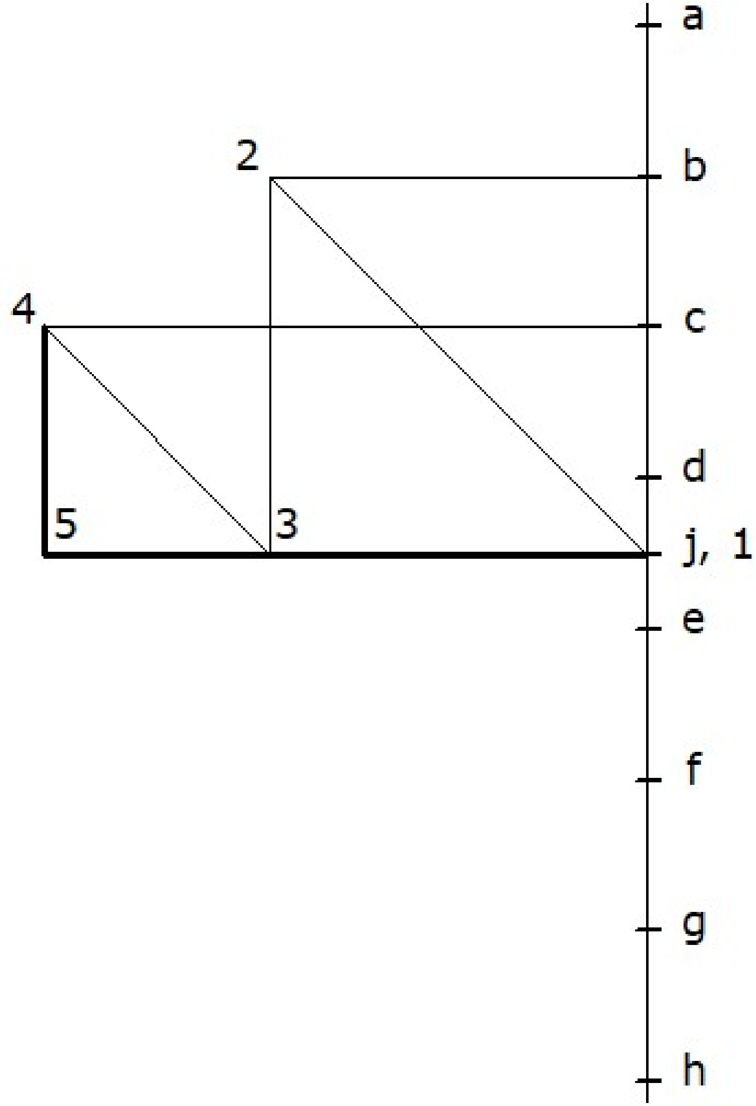
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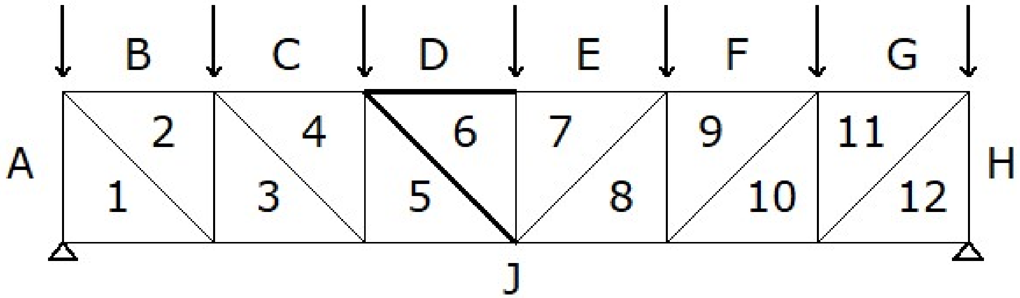

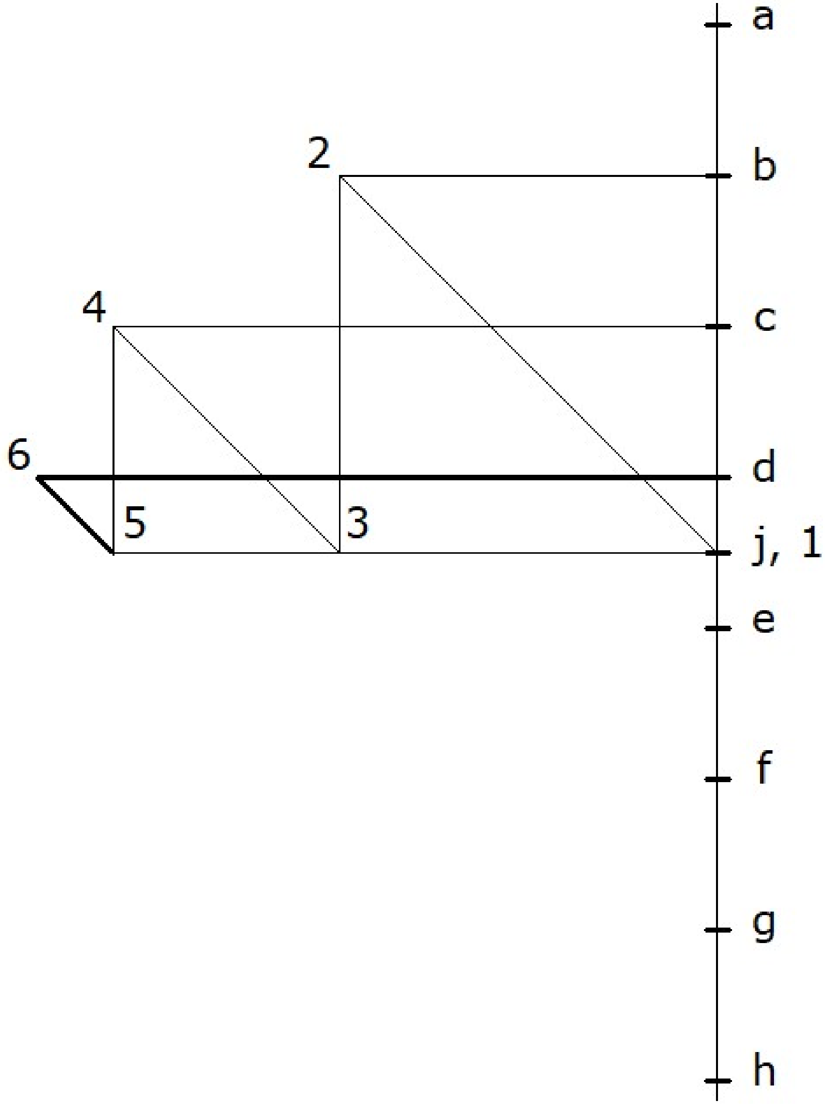

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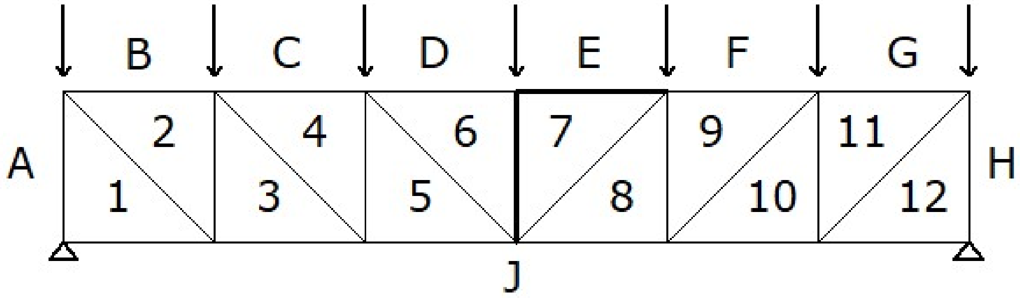
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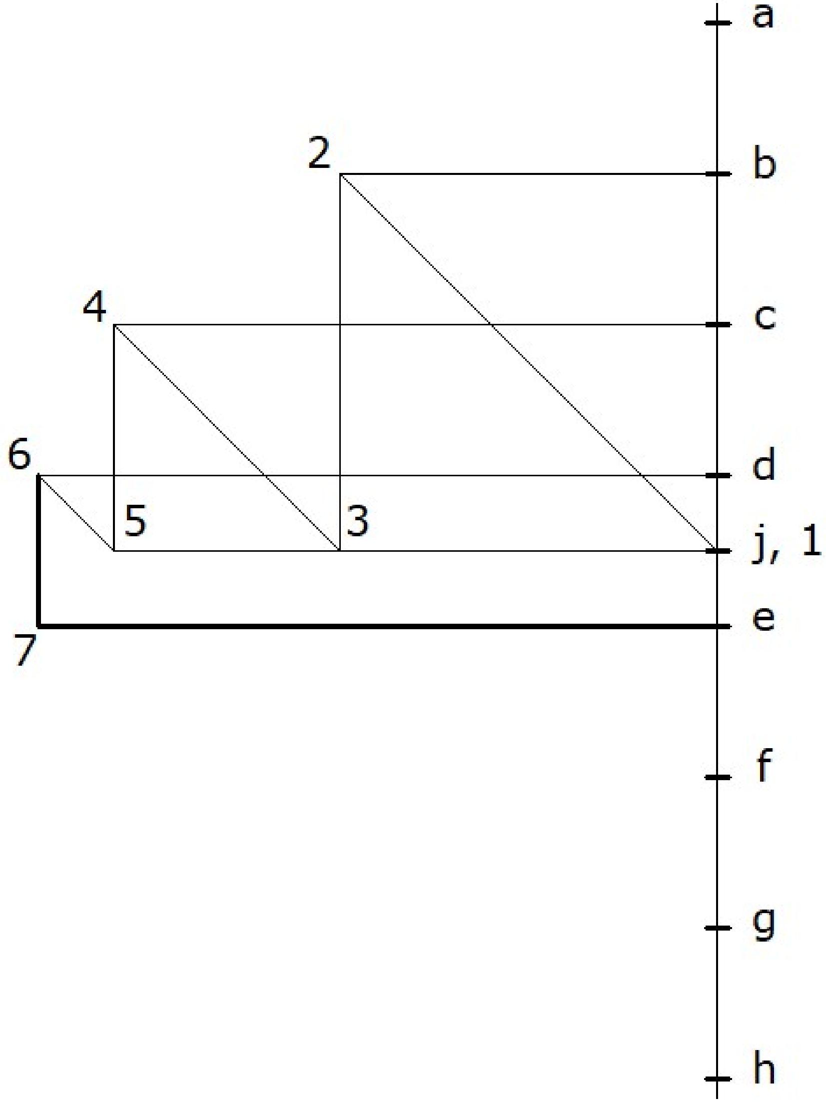
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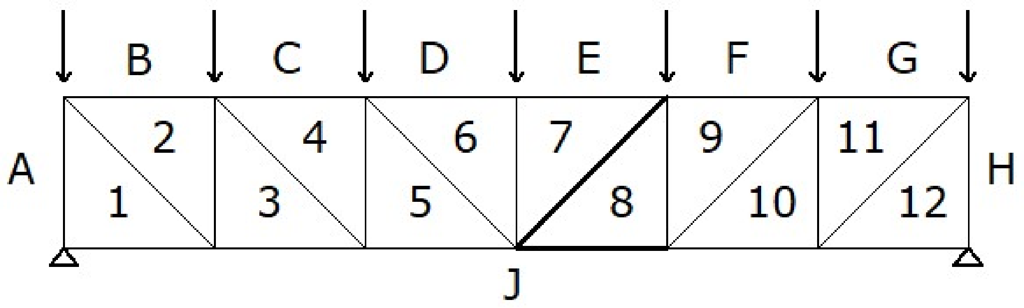
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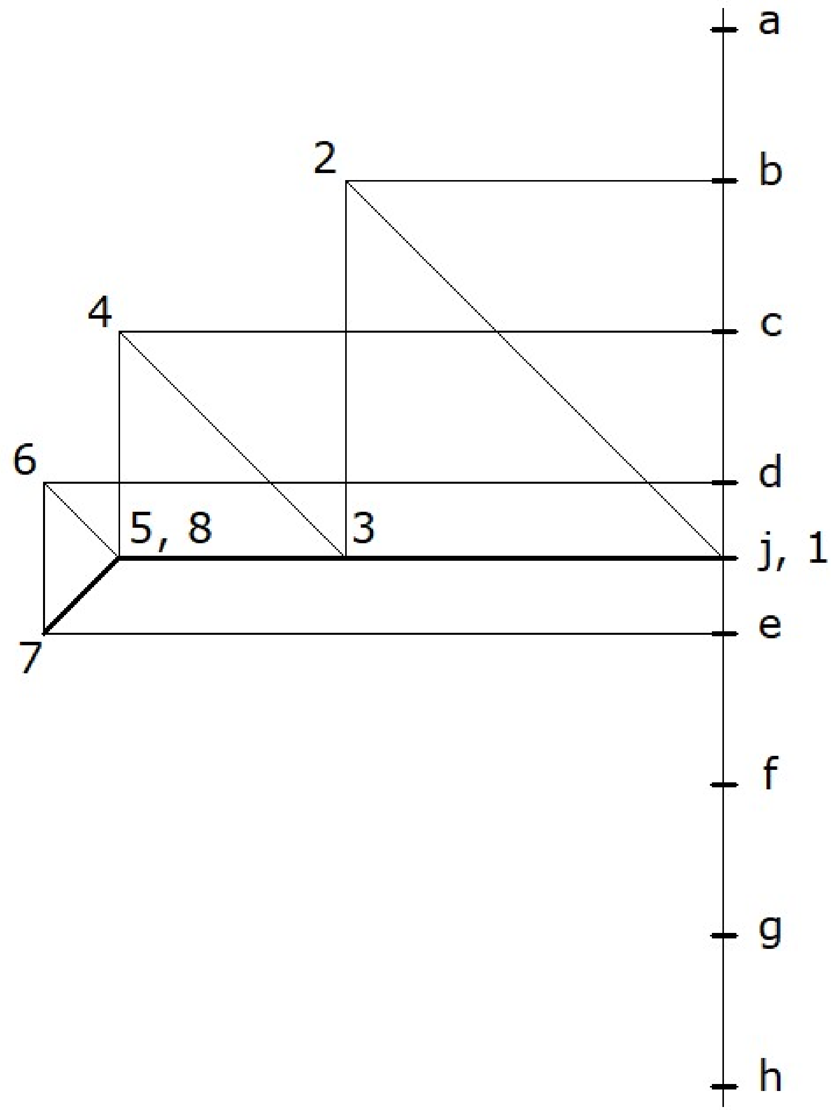
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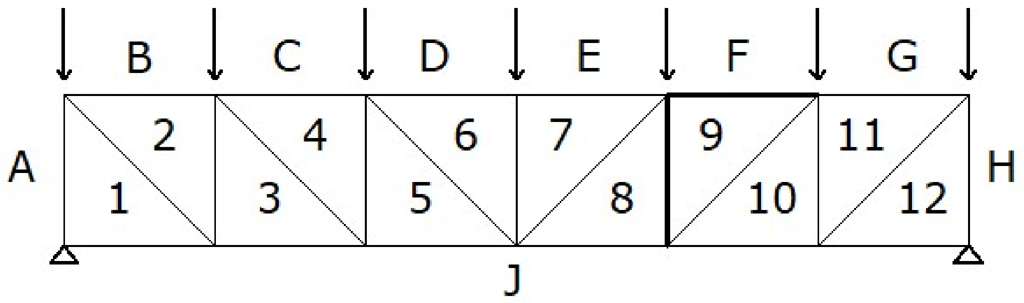
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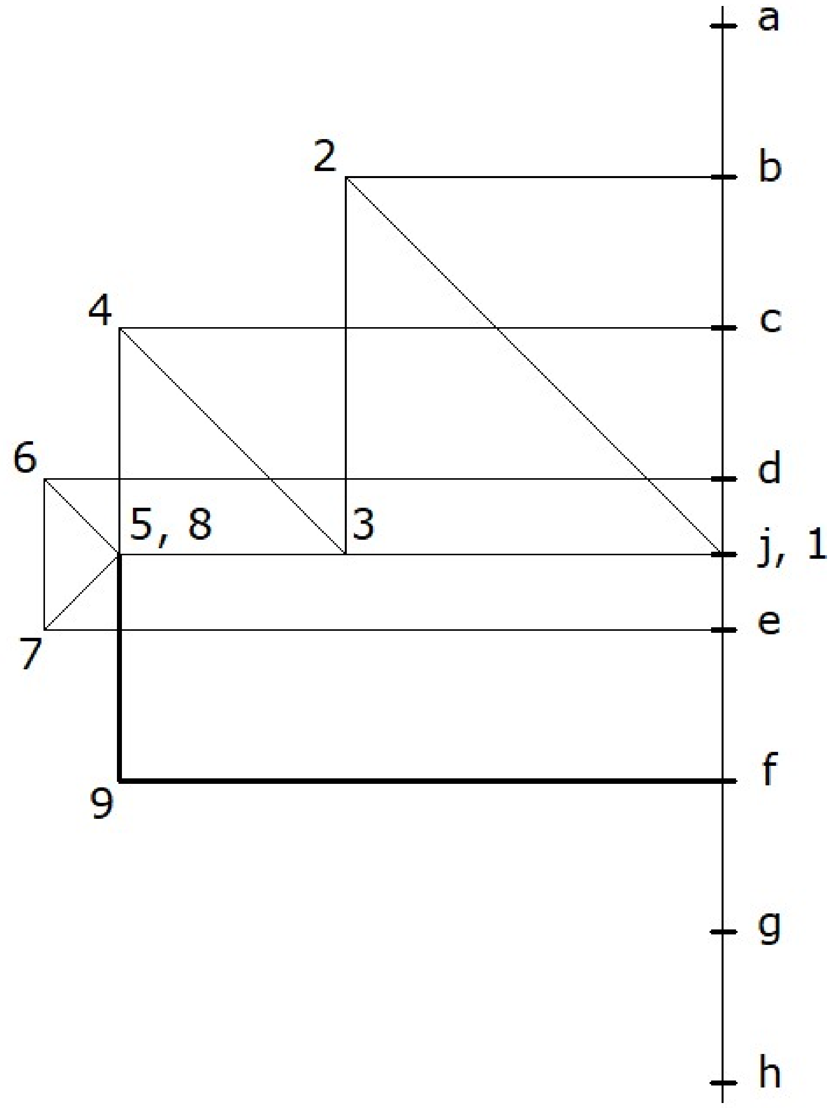
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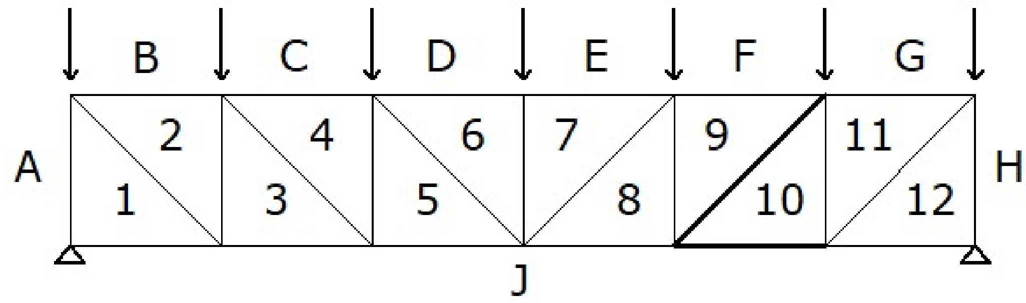
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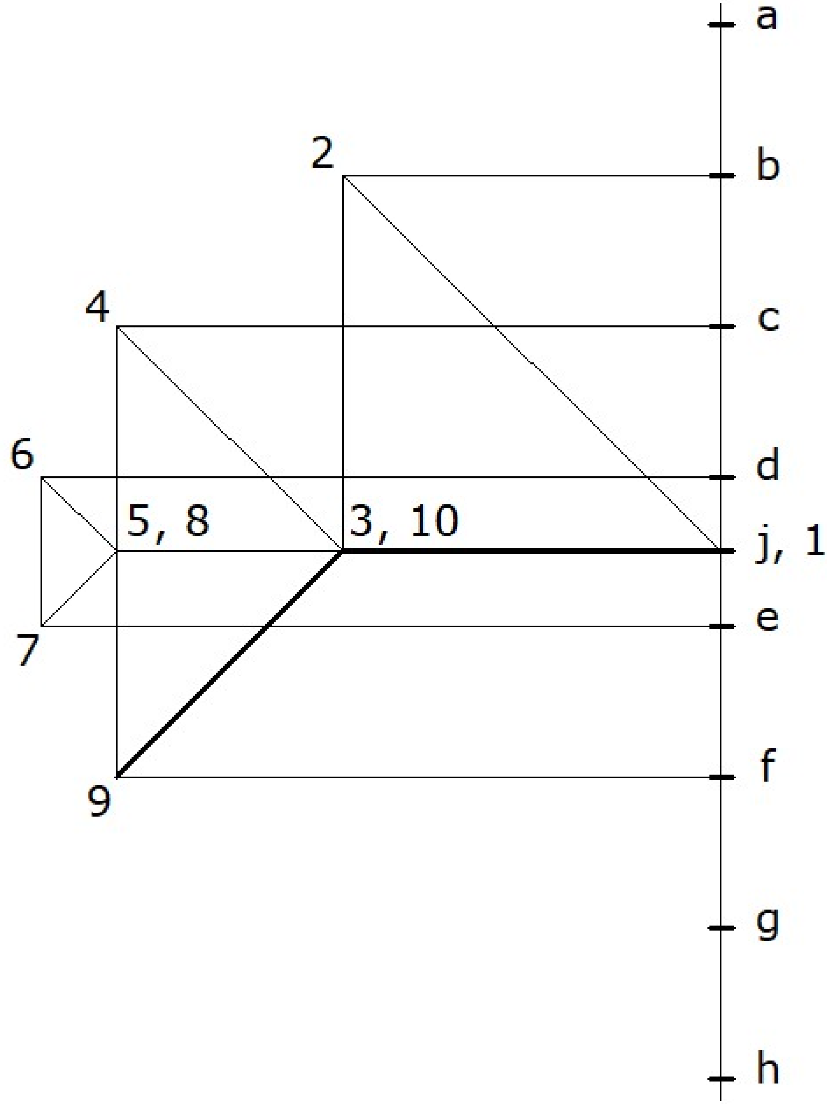
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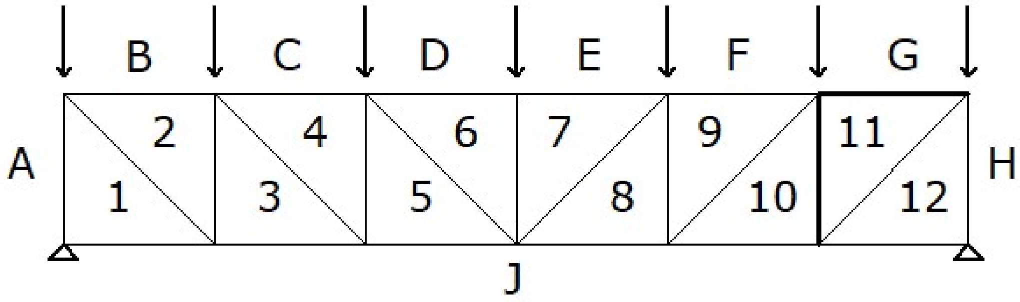

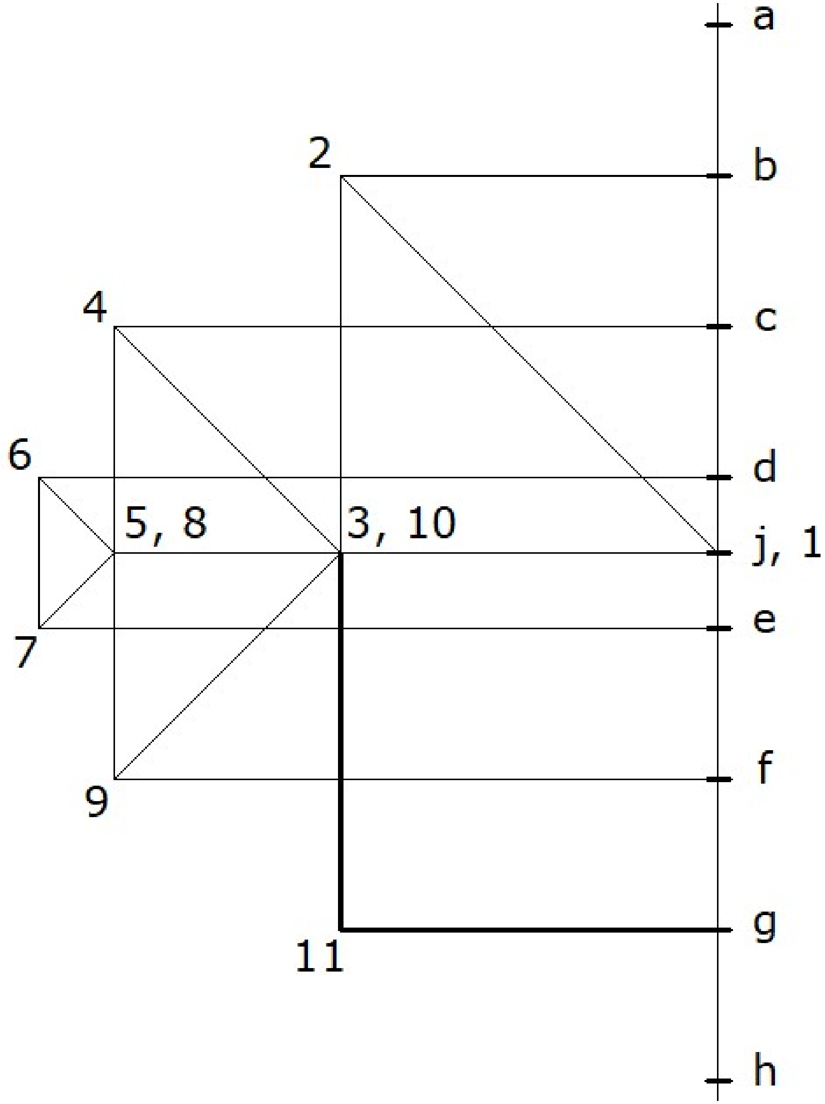

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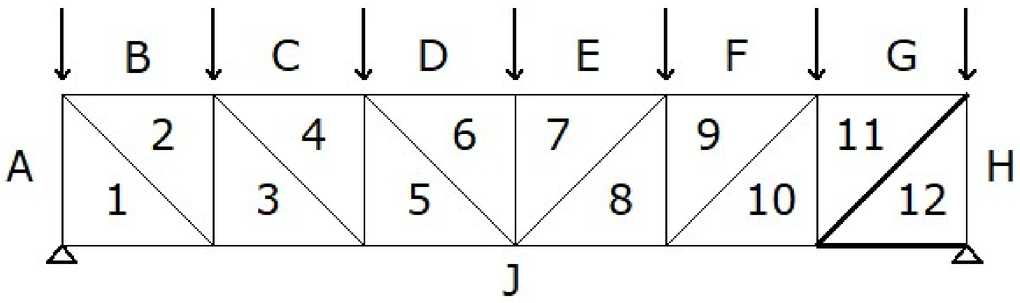
B
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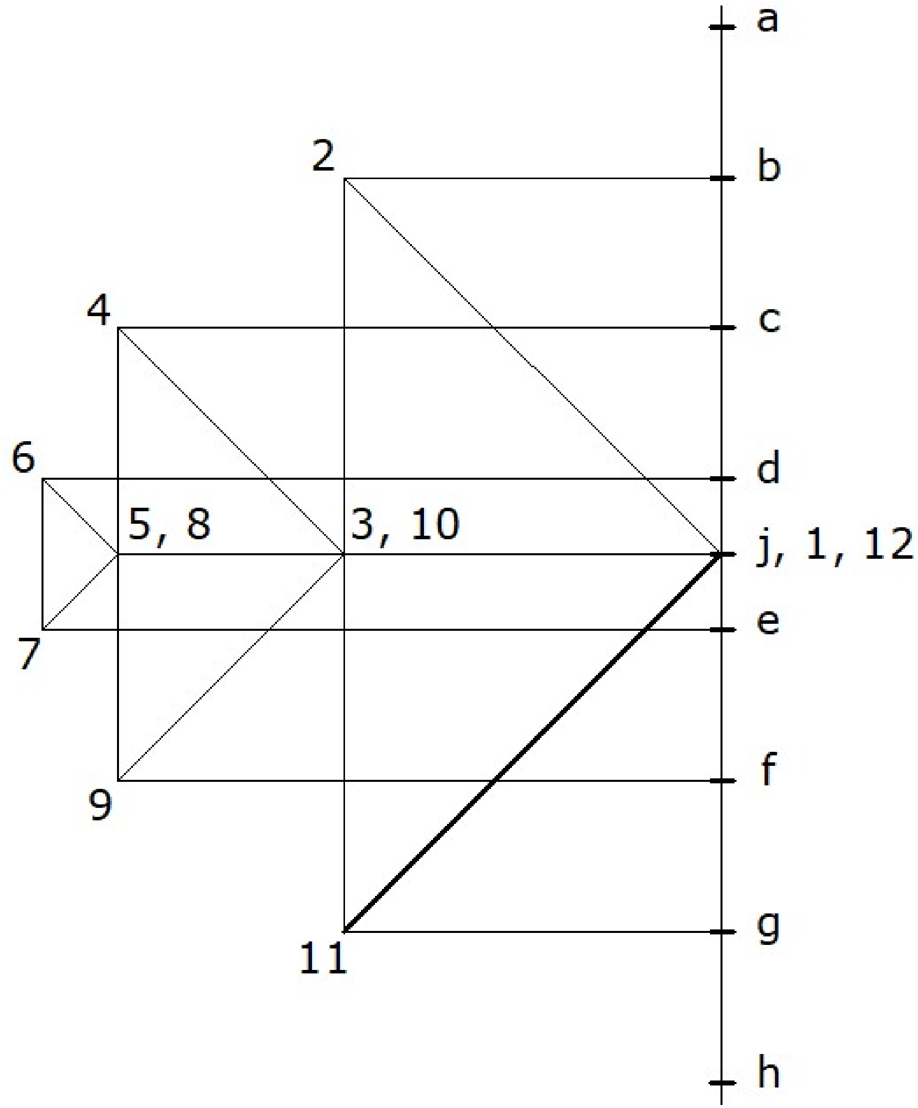
12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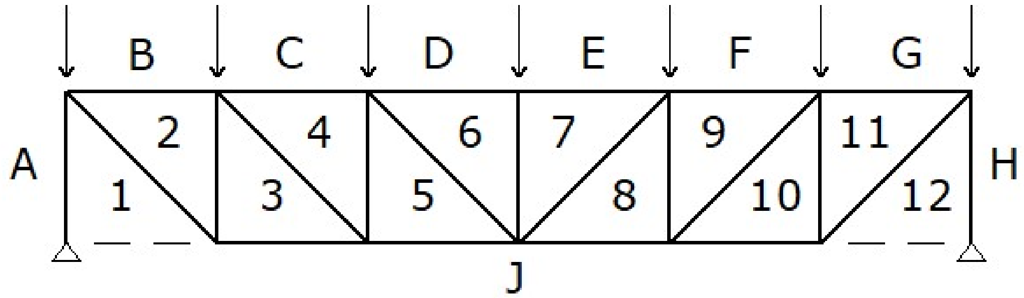
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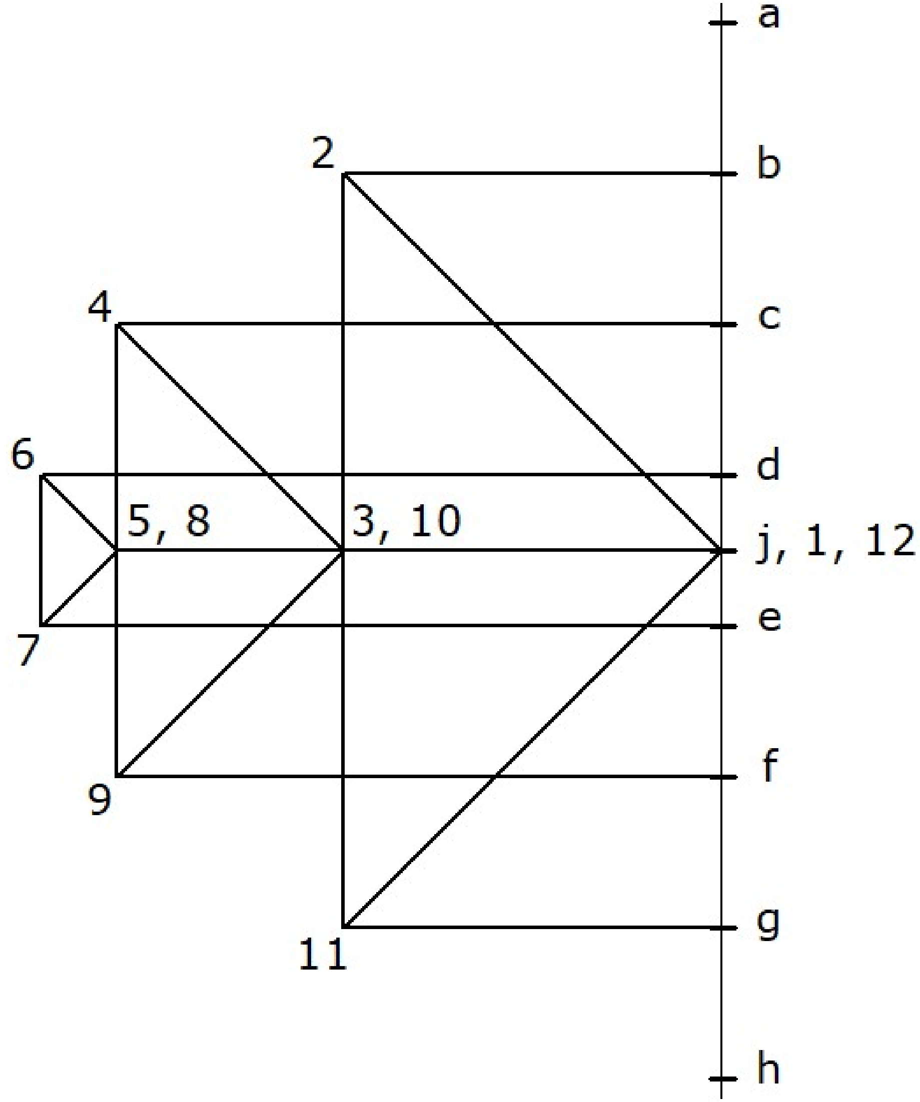
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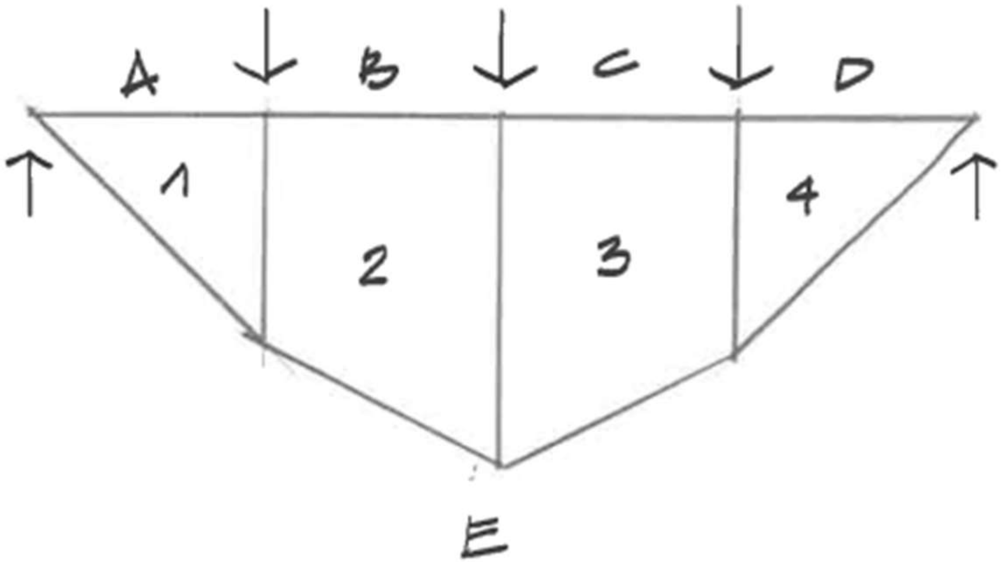
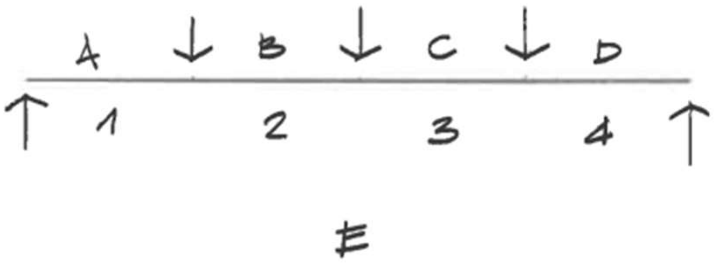
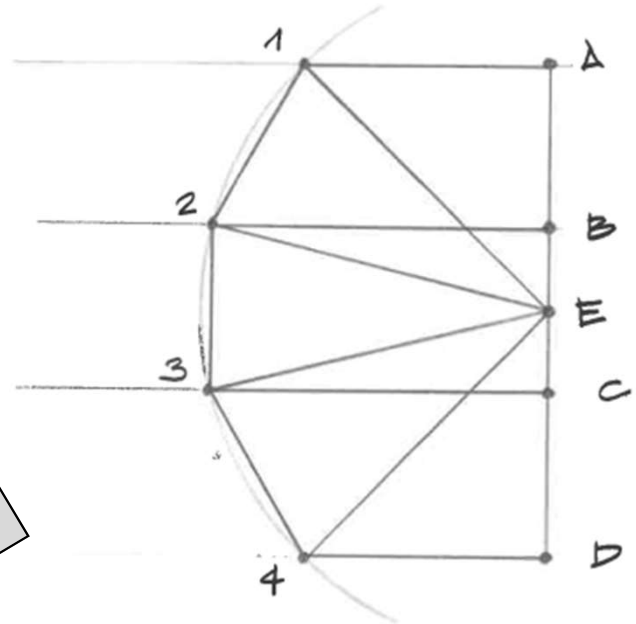
Example

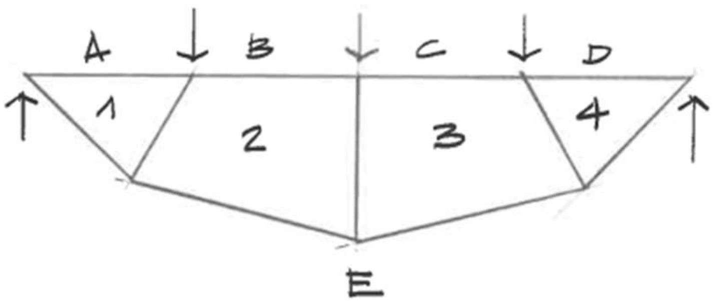


Form diagram

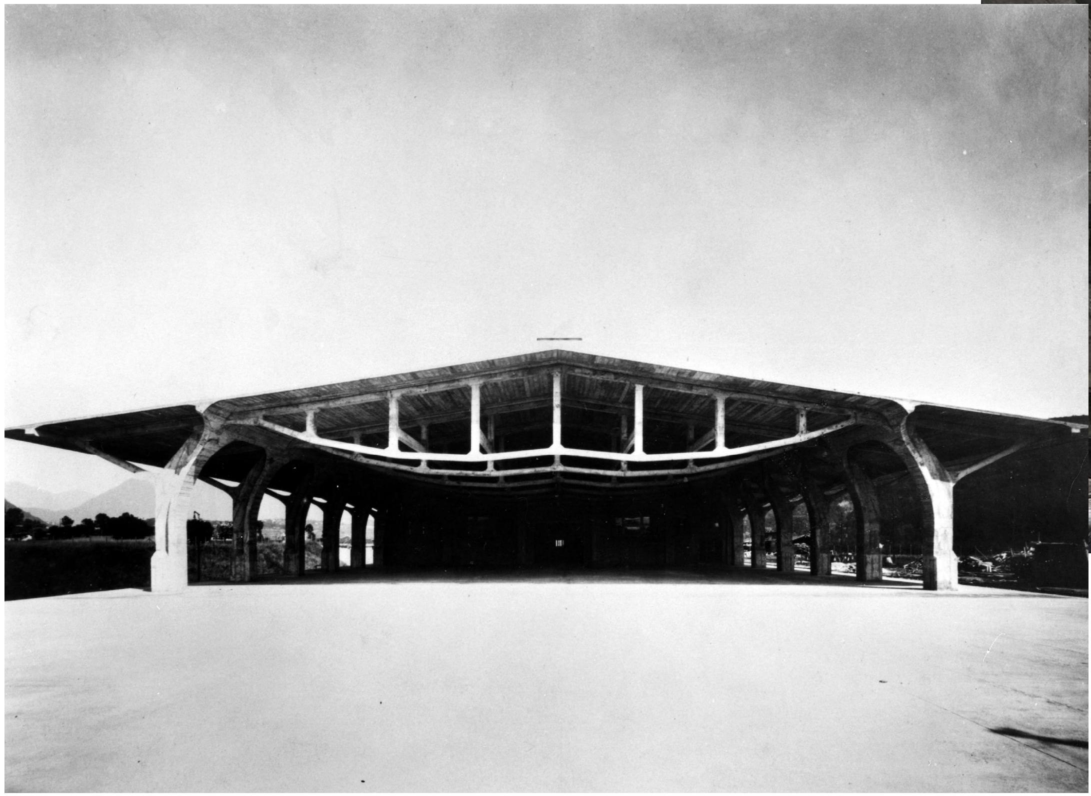
Force polygon





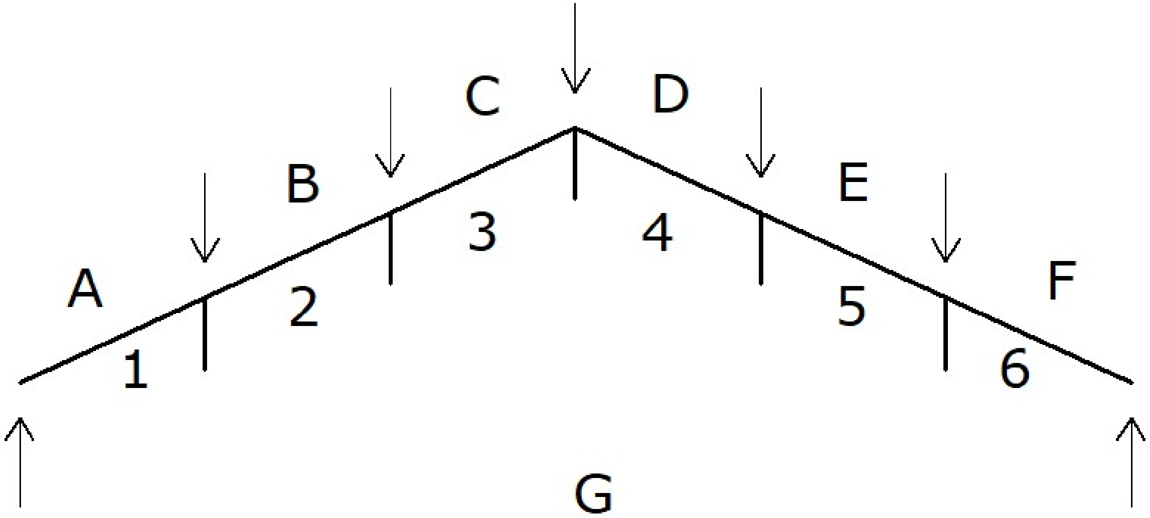


Example

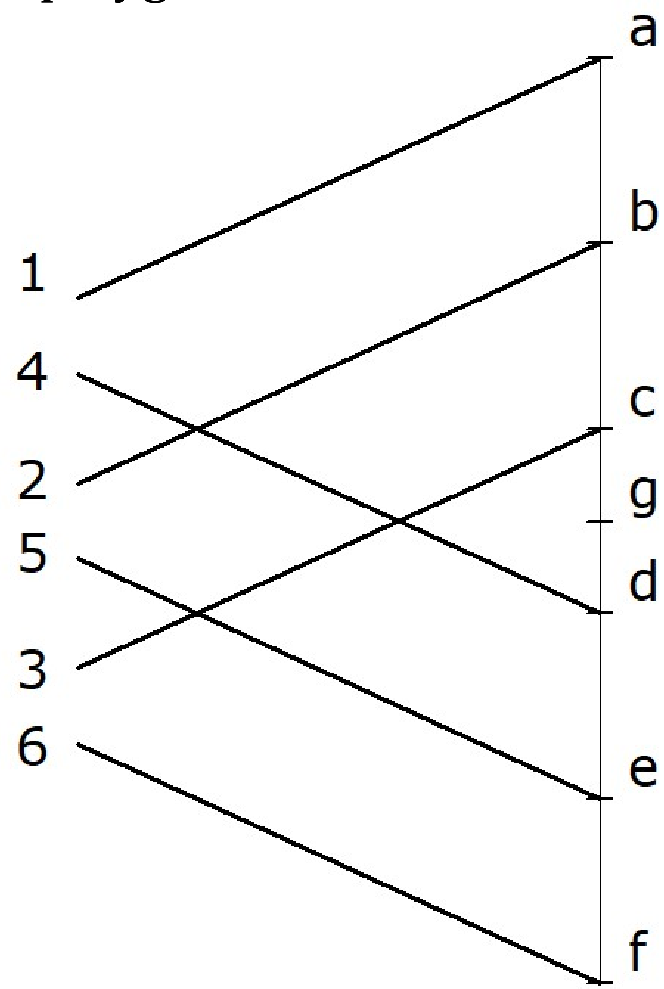


Magazzini Generali warehouse
Chiasso, Switzerland
Robert Maillart (1924)

Form diagram



Force polygon



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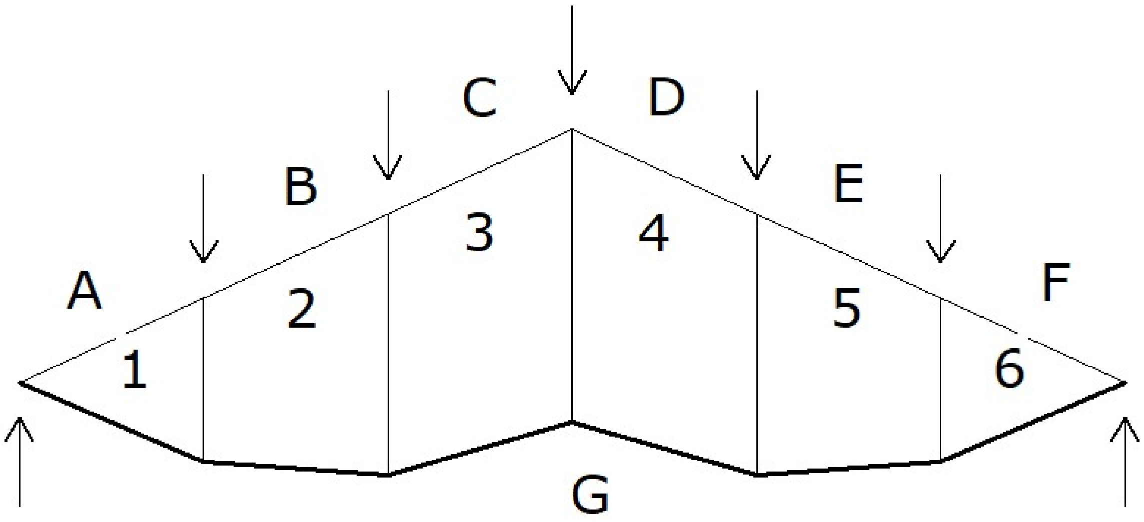
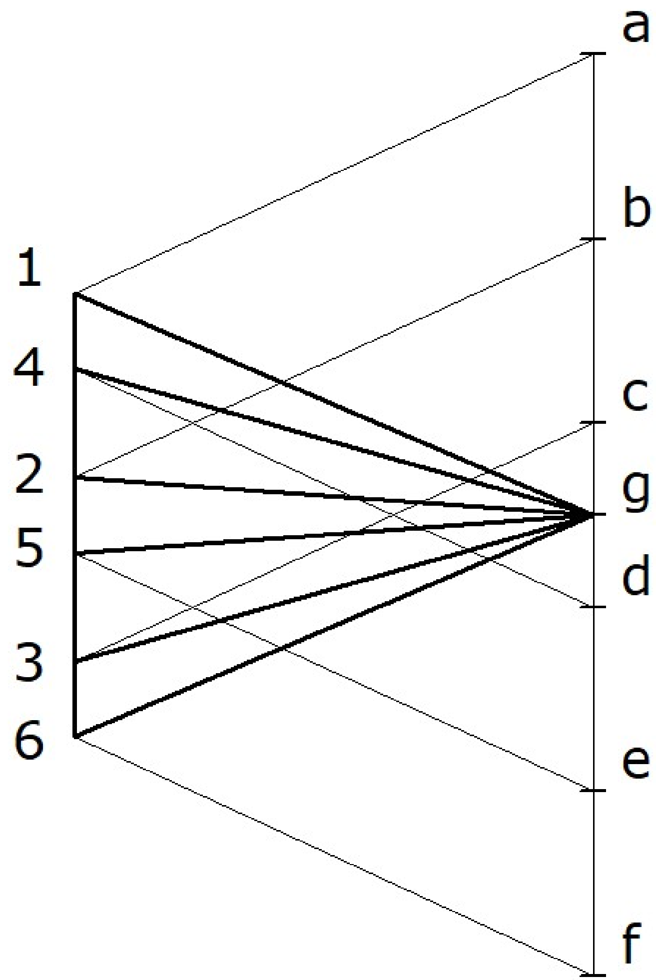
Form diagram



Force polygon



Relationship between form and force

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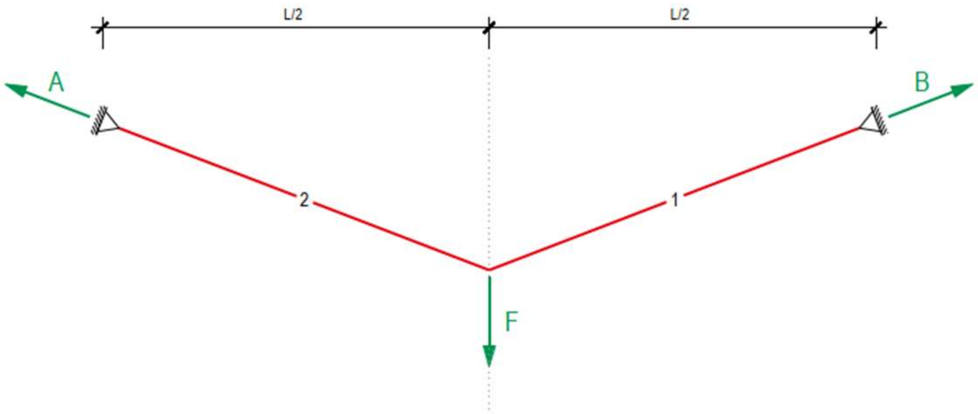
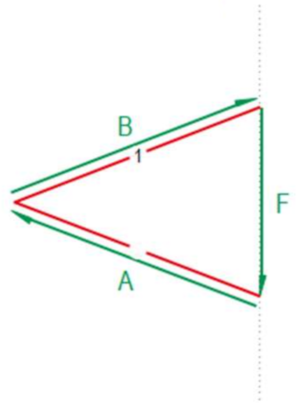
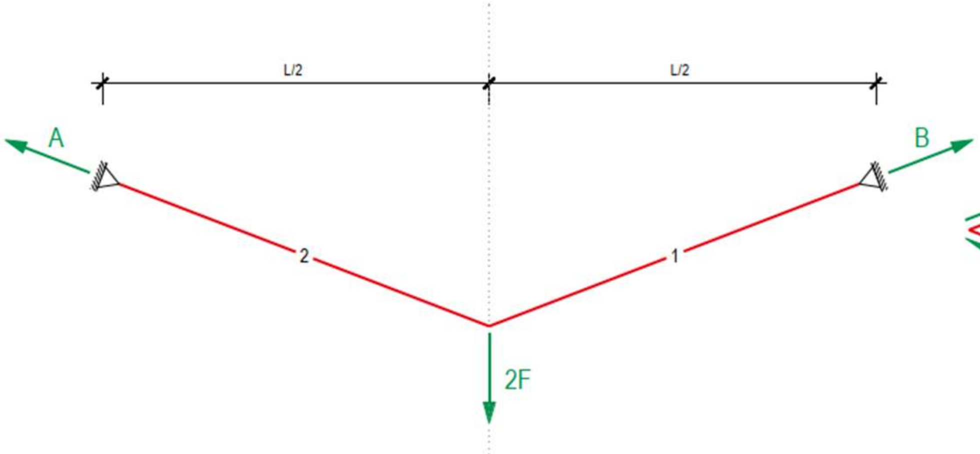
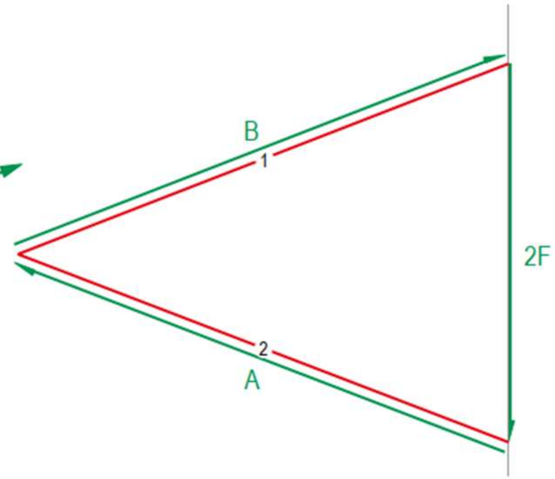
Form diagram

Force diagram

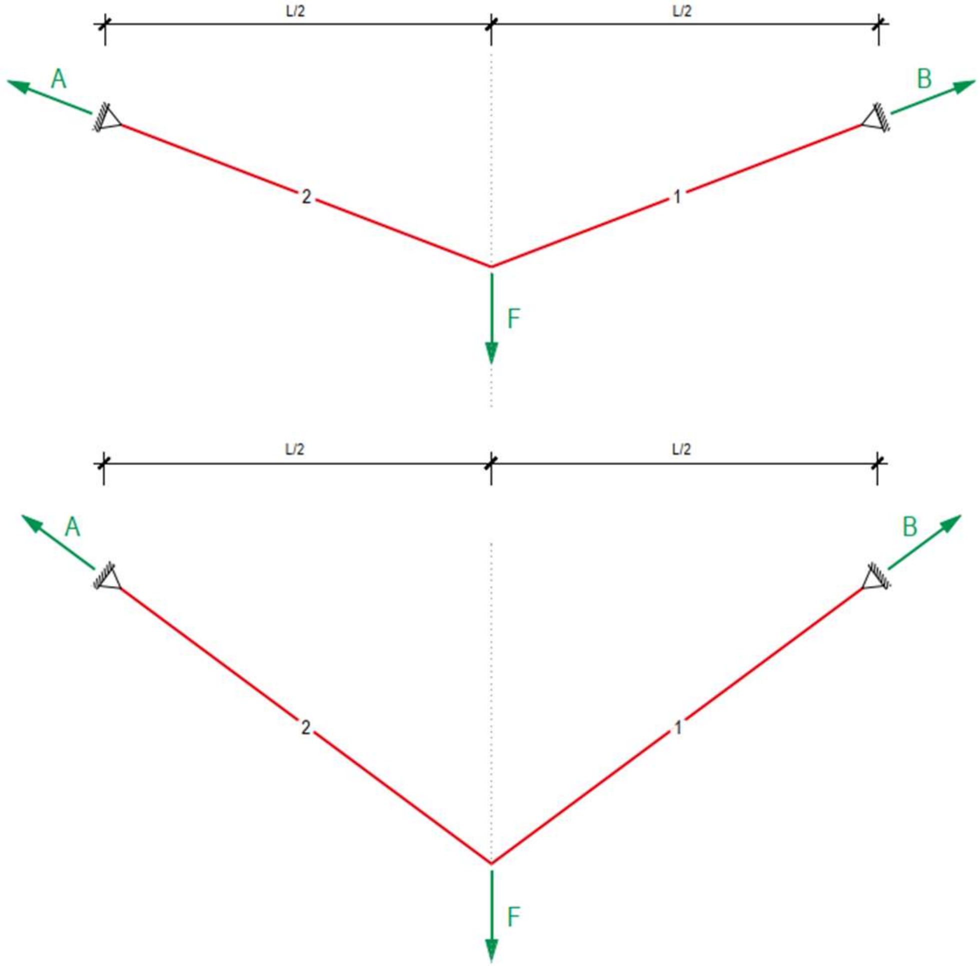




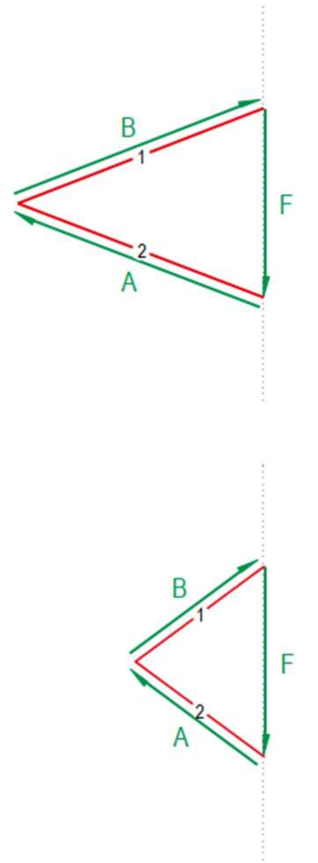




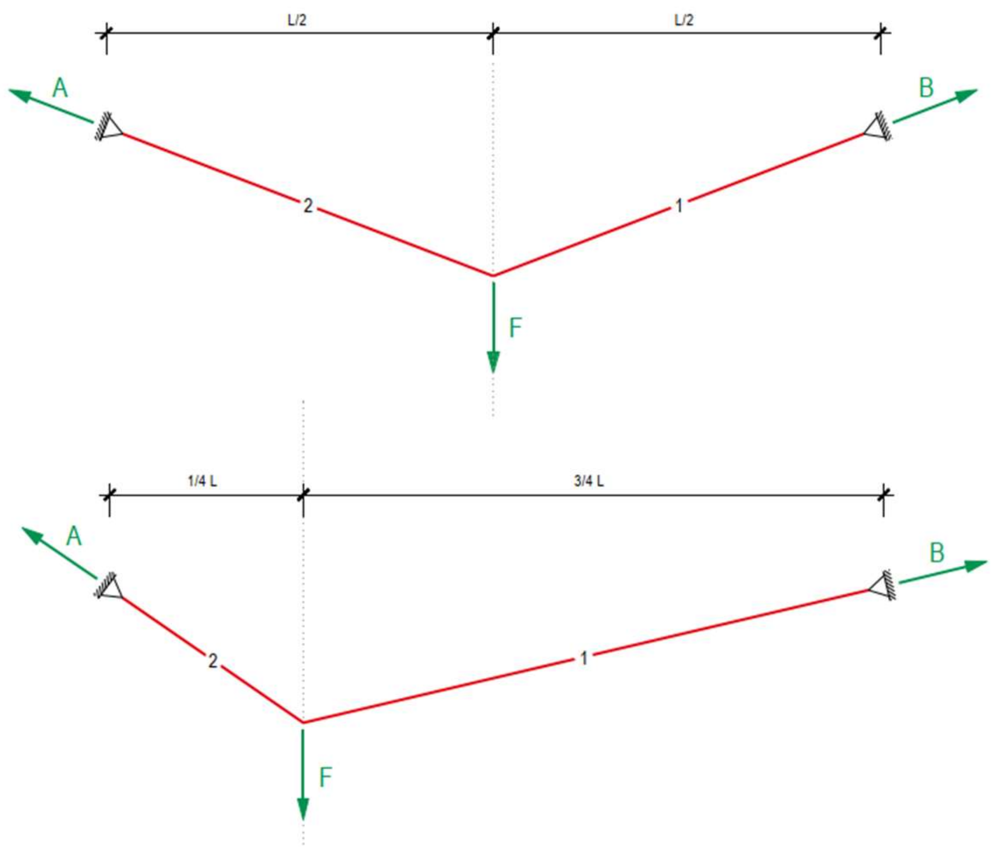
Form diagram



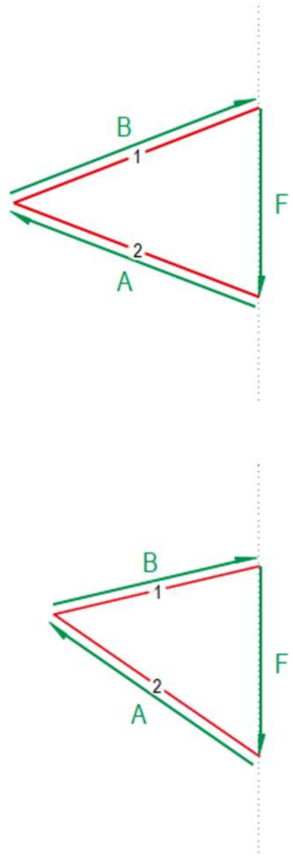
Force diagram



Form diagram



Force diagram



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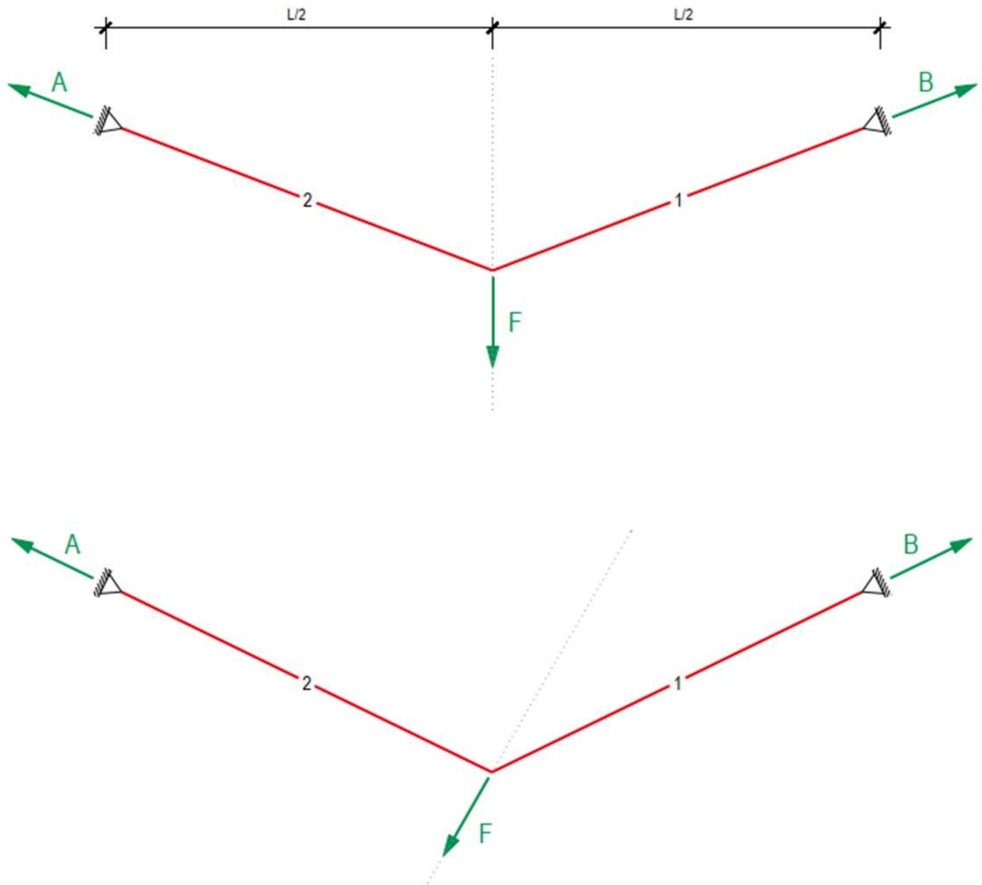

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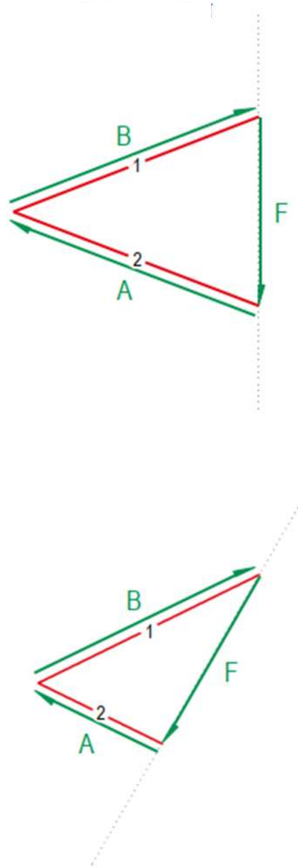
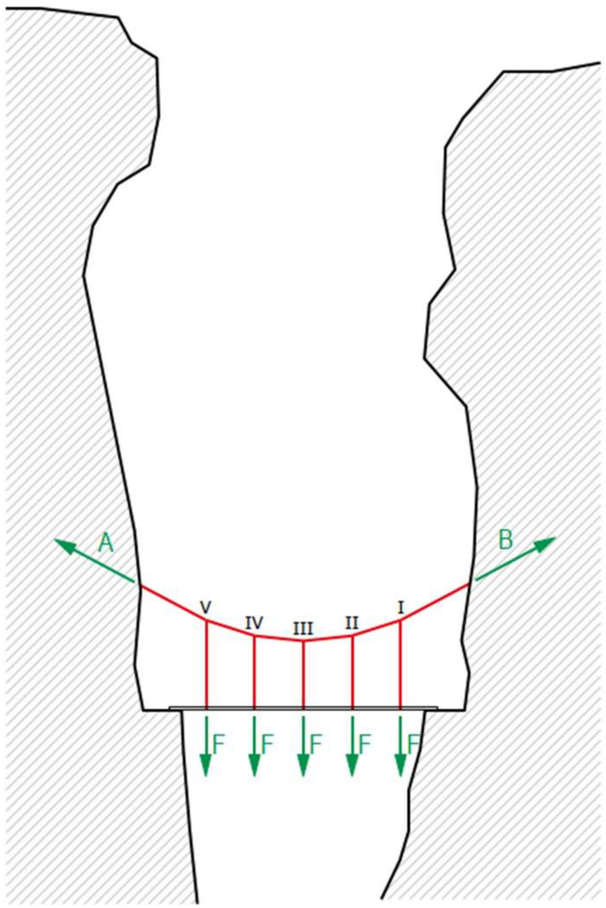
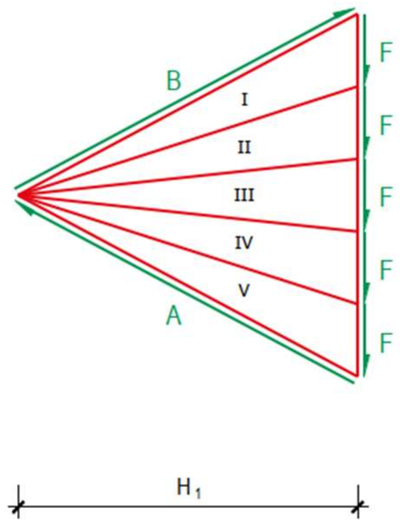


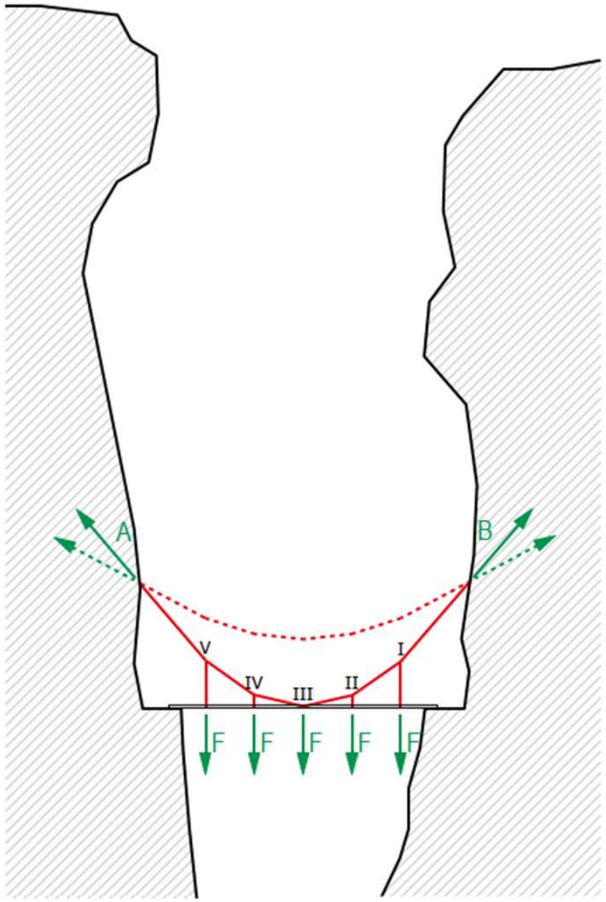
Form diagram



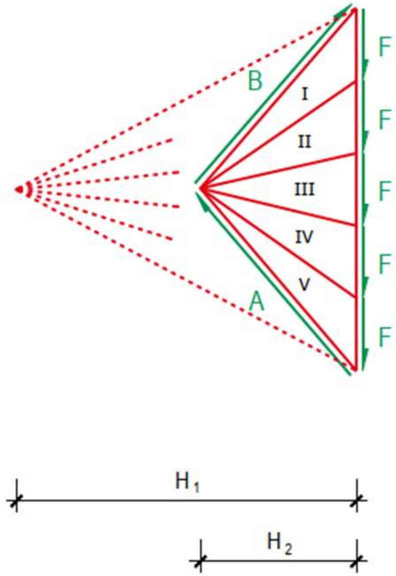
Force diagram



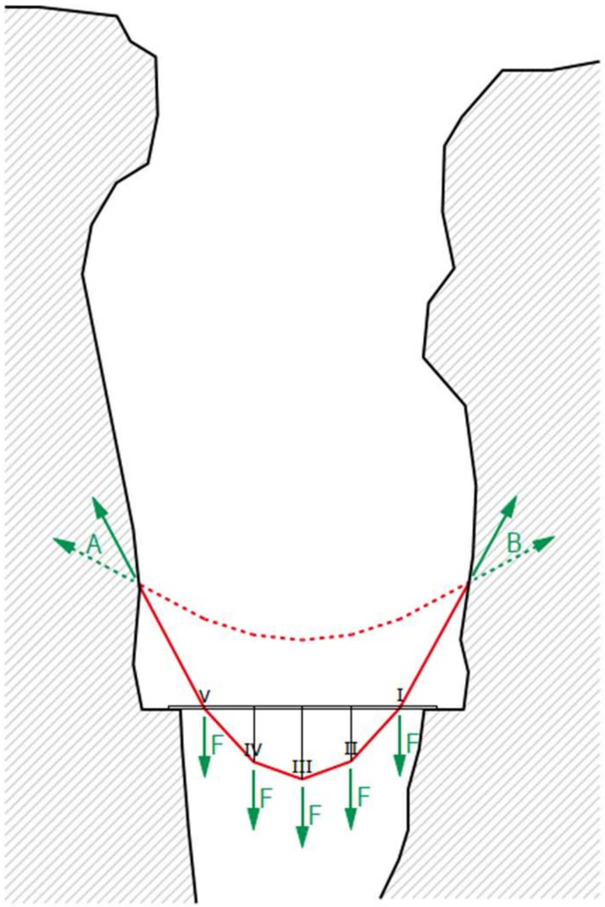
Form diagram



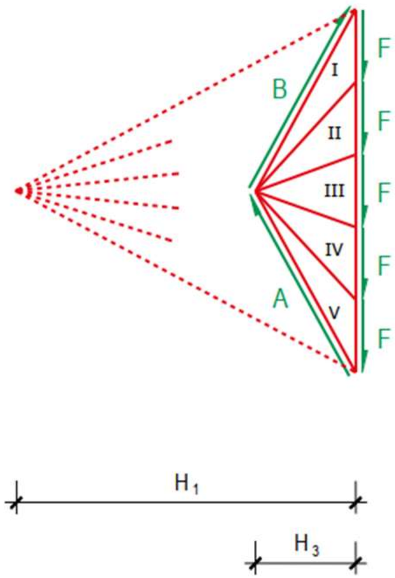
Force diagram

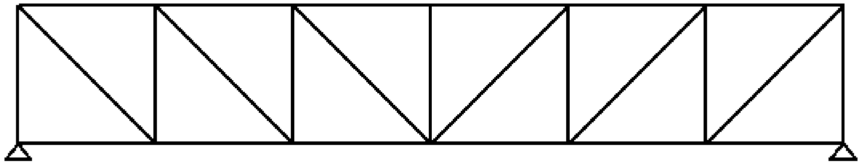


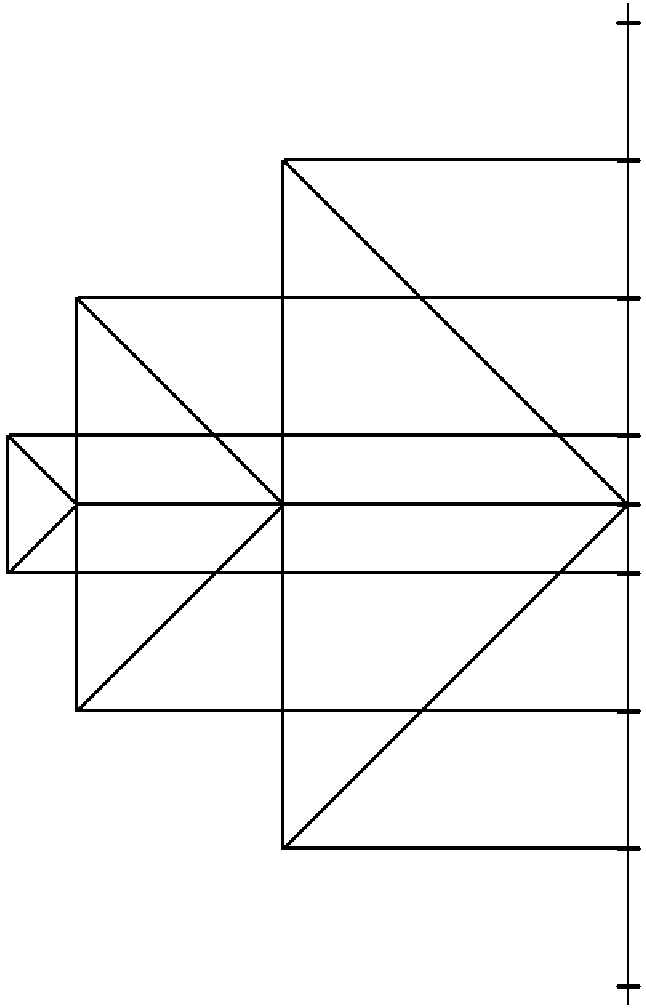
Form diagram

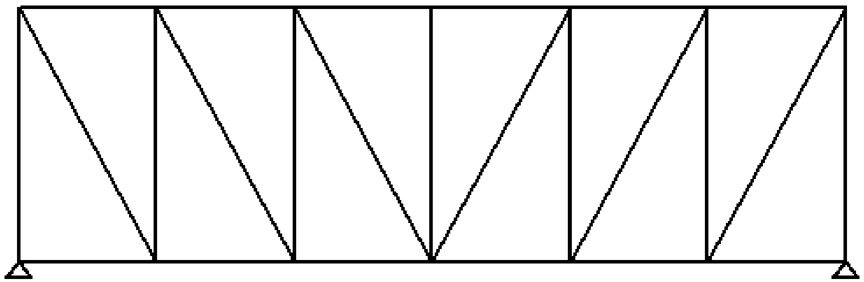


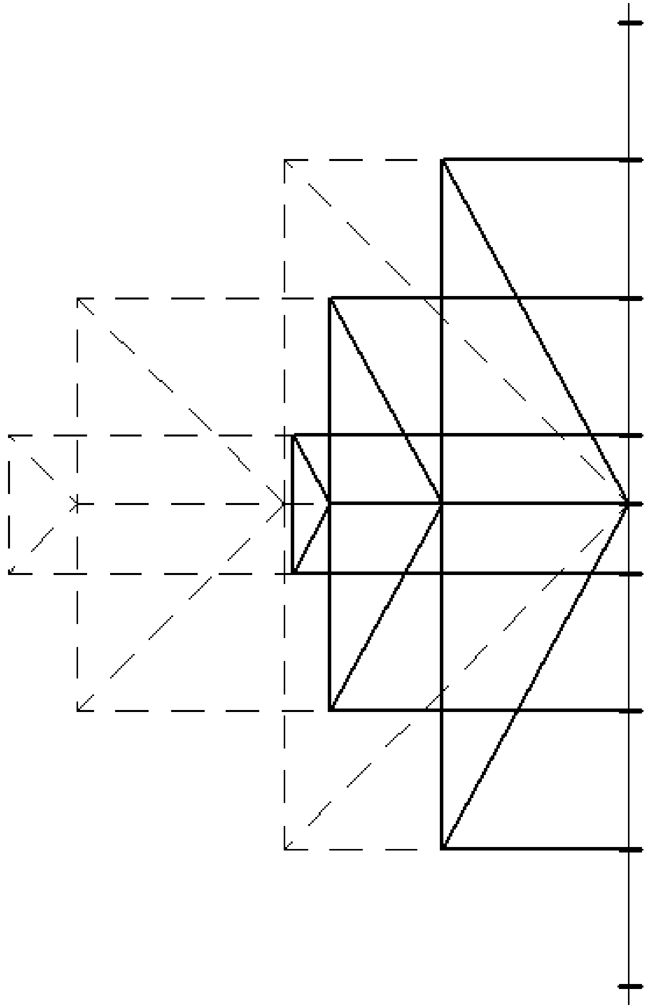
Force diagram

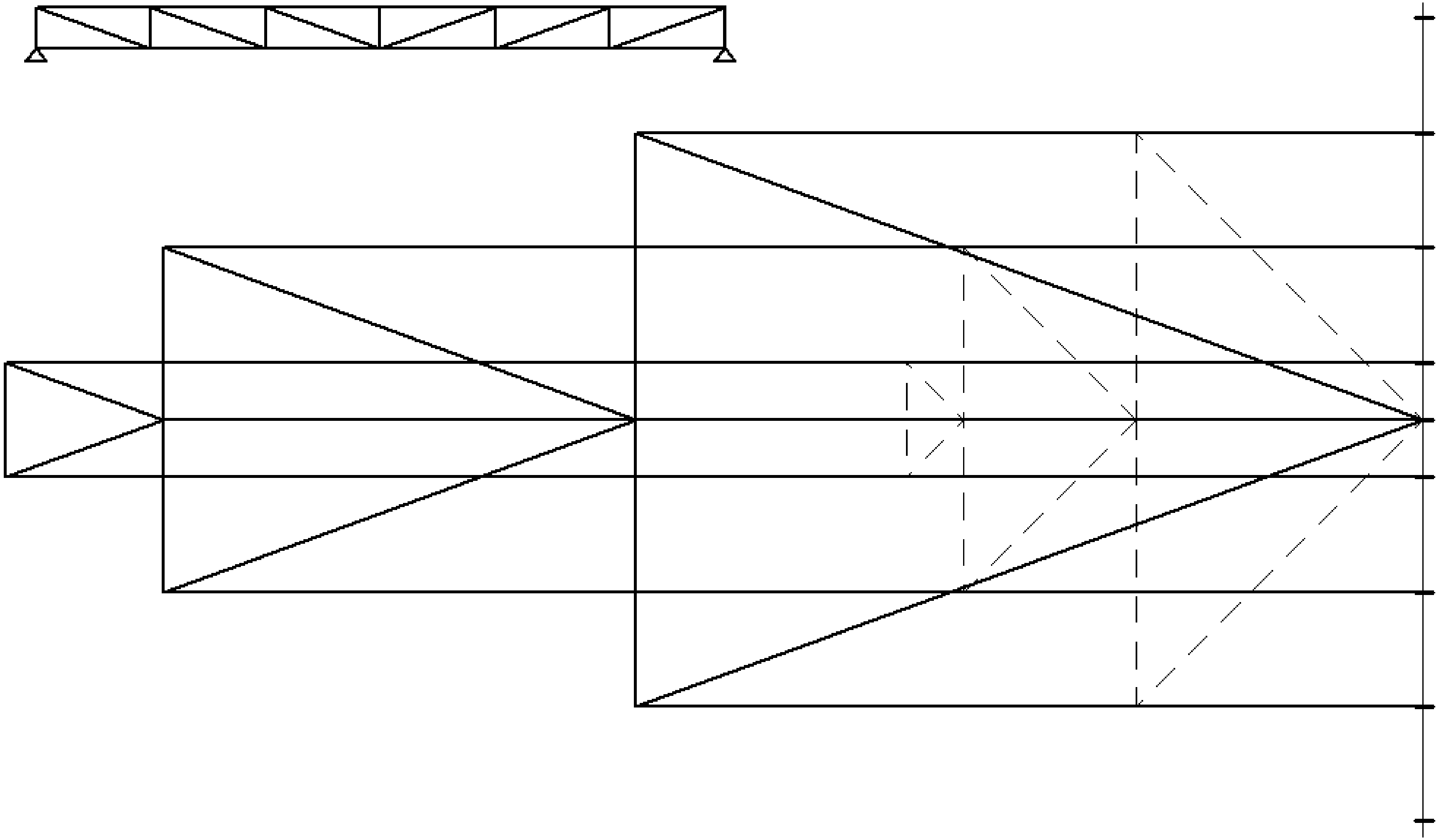






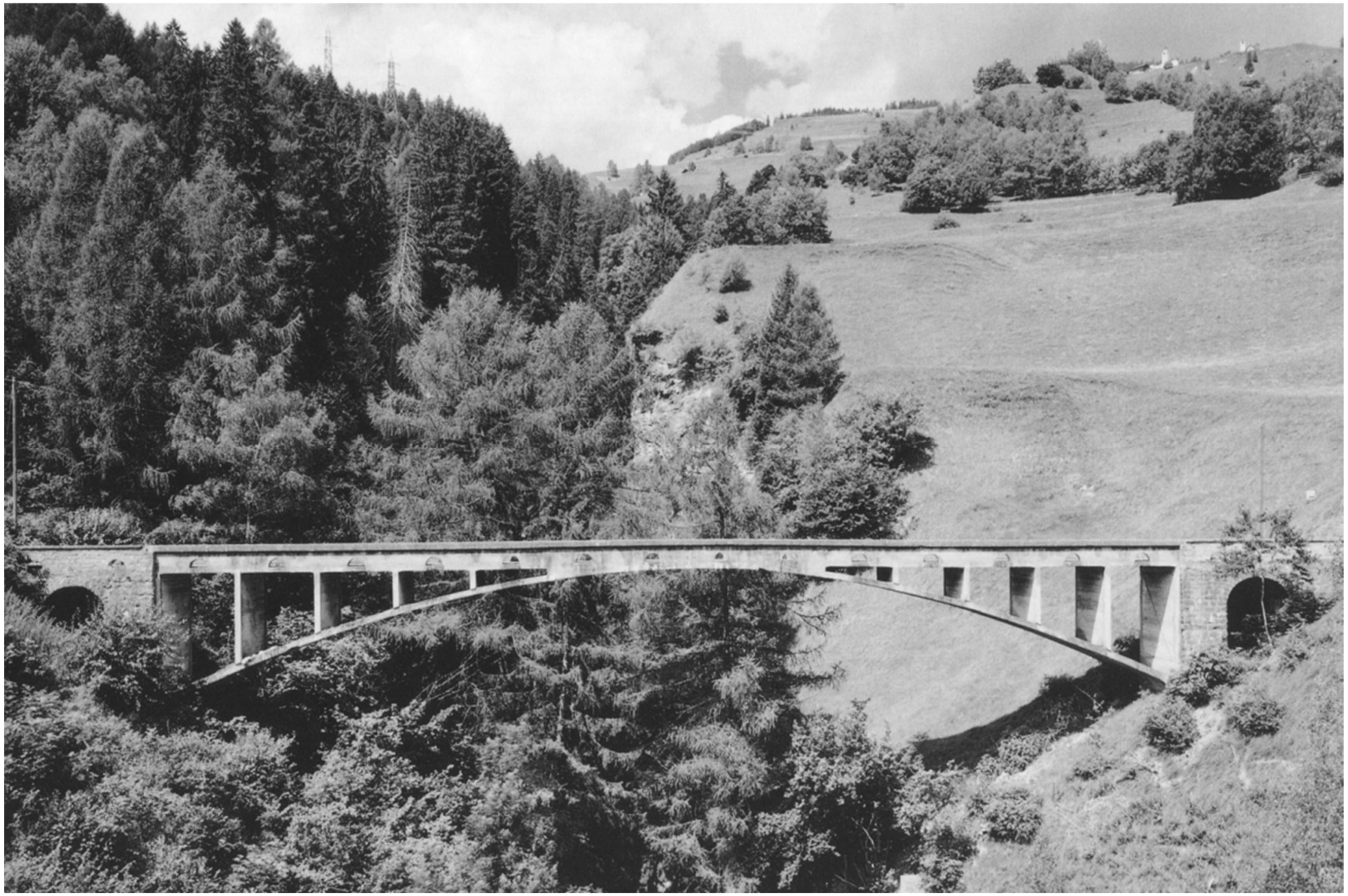




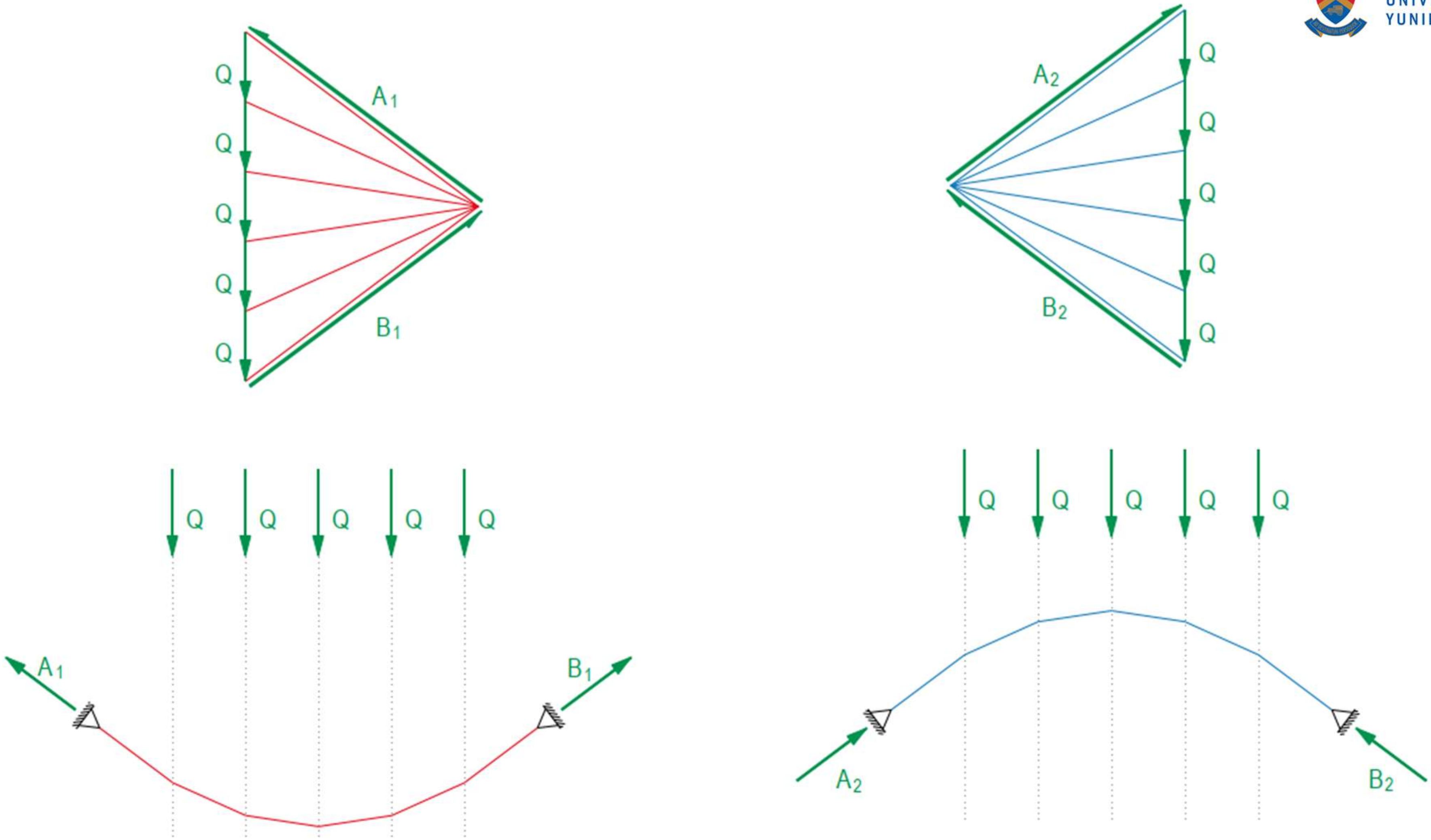


Arches

Mülheimer bridge, Cologne, 1951 | Wilhelm Riphahn & Fritz Leonardt



Valtschielbach bridge, Donath, 1925 | Robert Maillart


Q
Q
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B1
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B2

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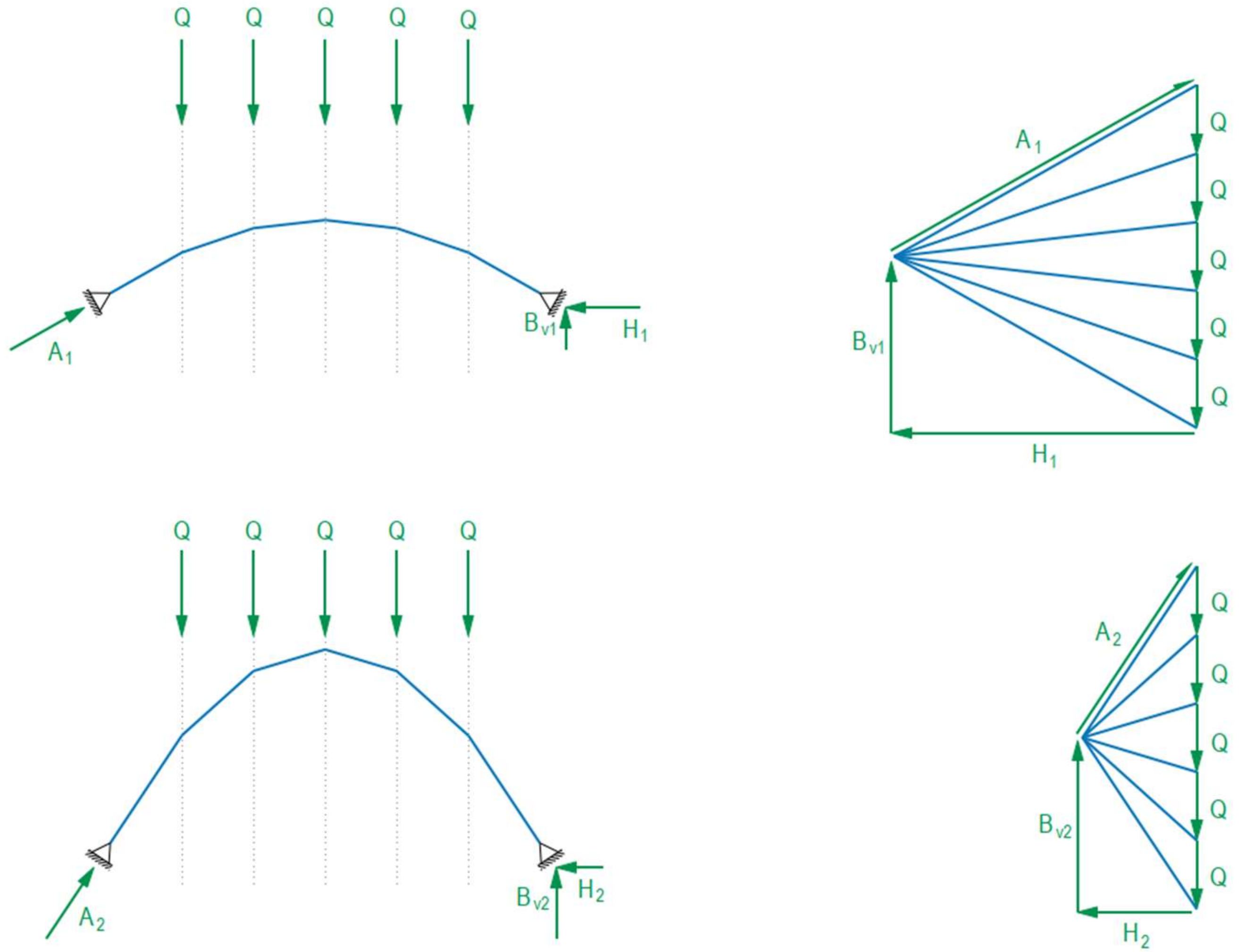
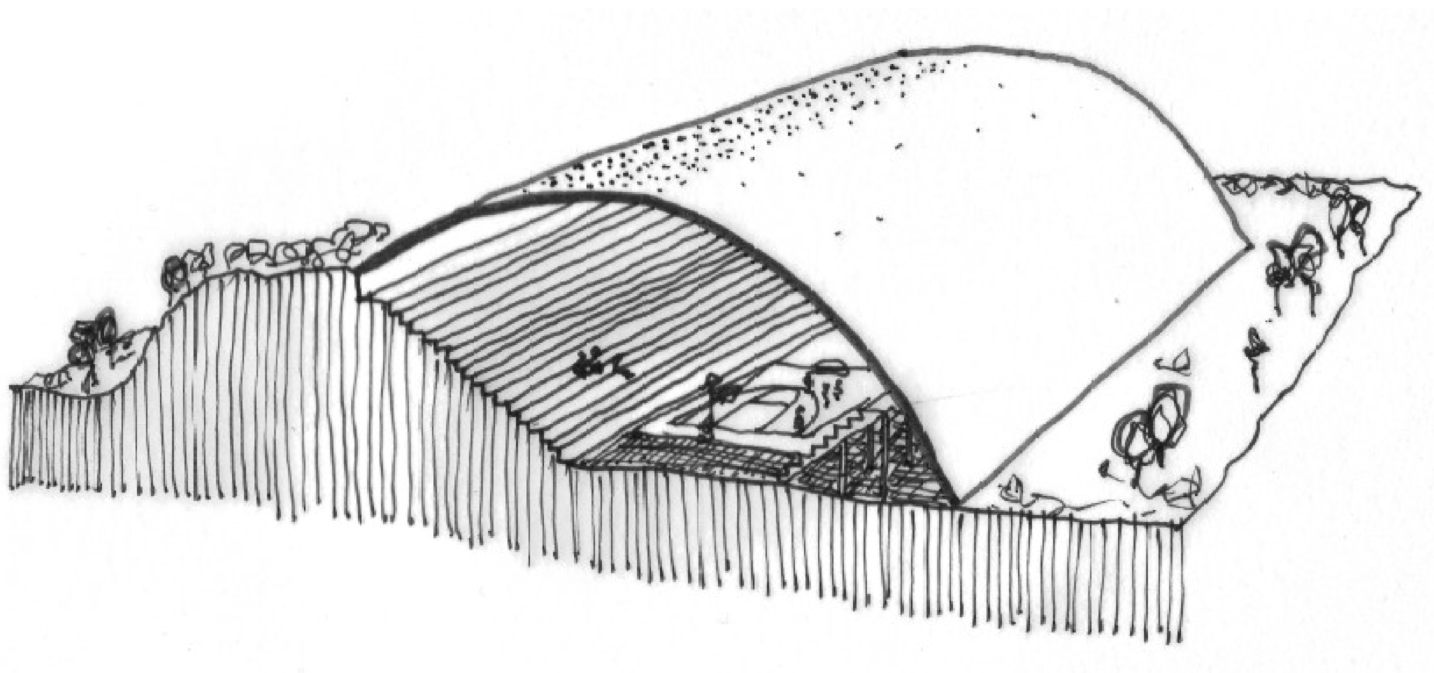


Example



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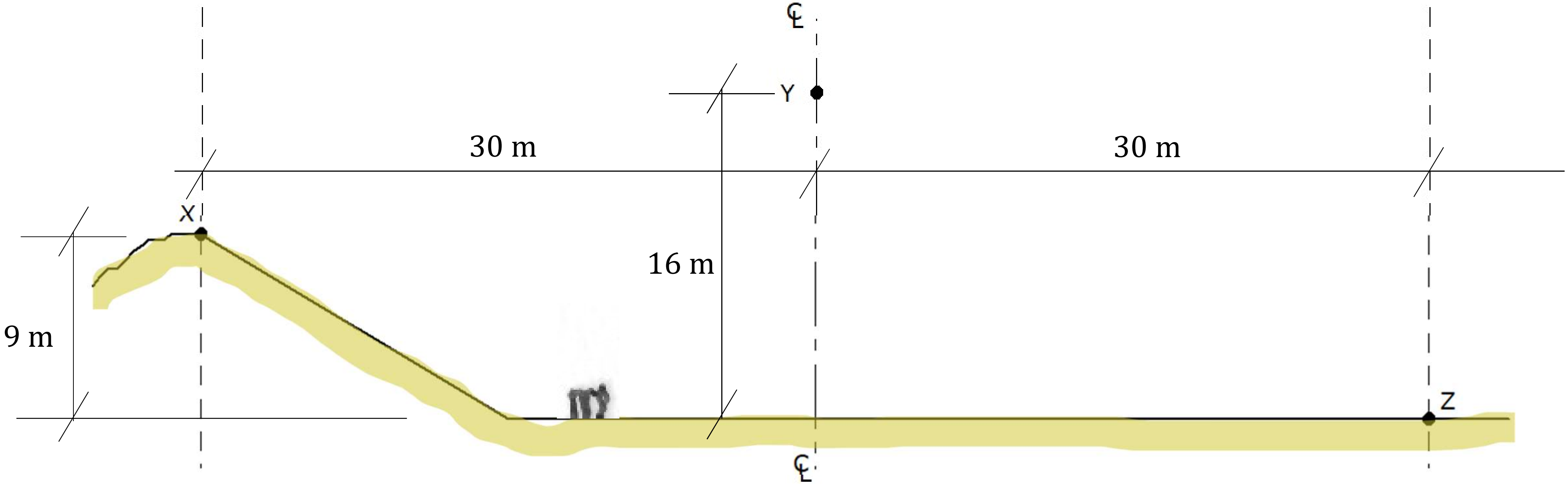
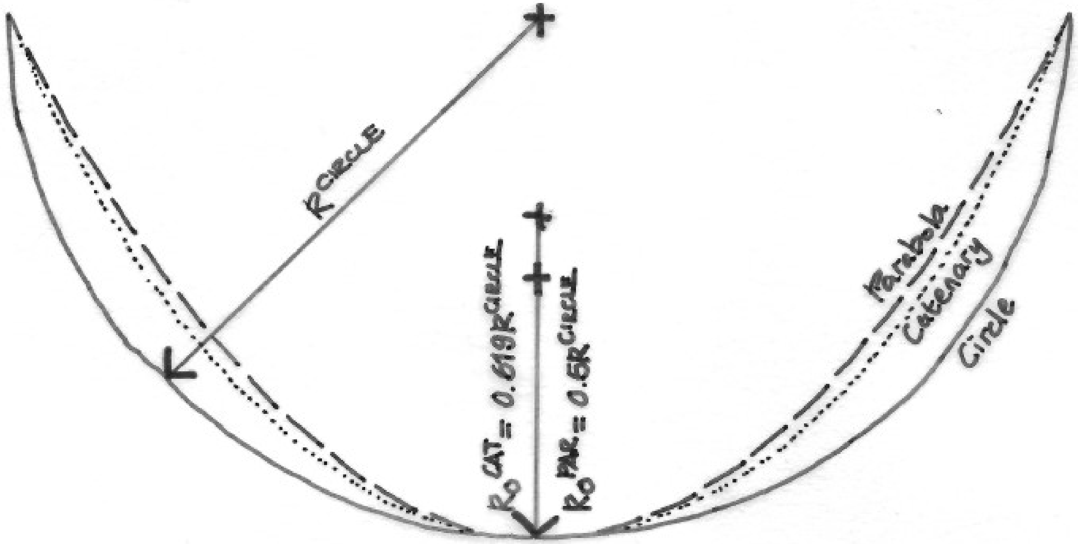
Total load ≈ 450 kN (per 1m width of roof)

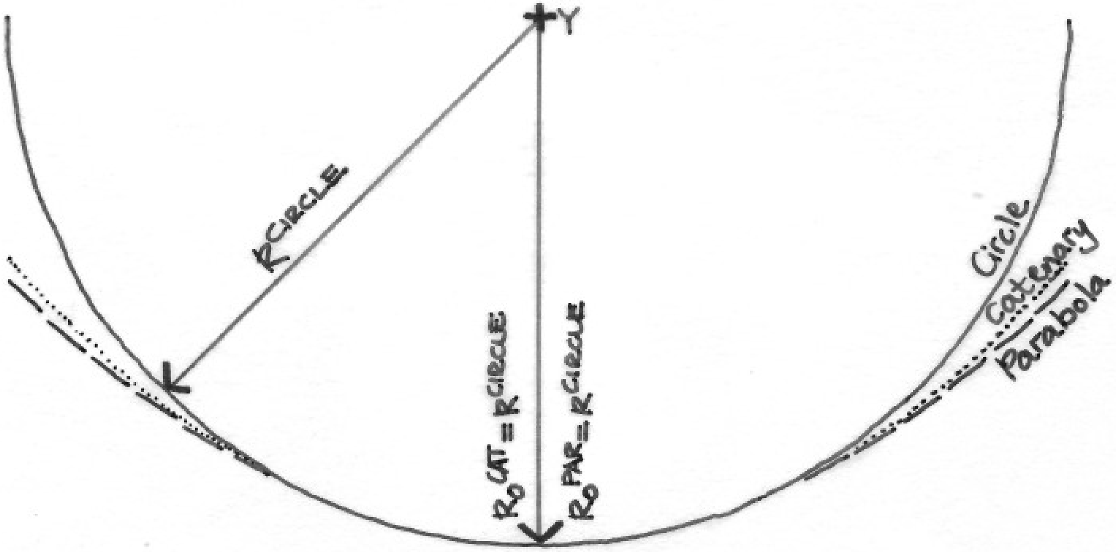
SW ≈ 5 kPa
Waterproofing & insulation ≈ 0.4 kPa
Services ≈ 0.2 kPa
So, DL = 5.6 kPa

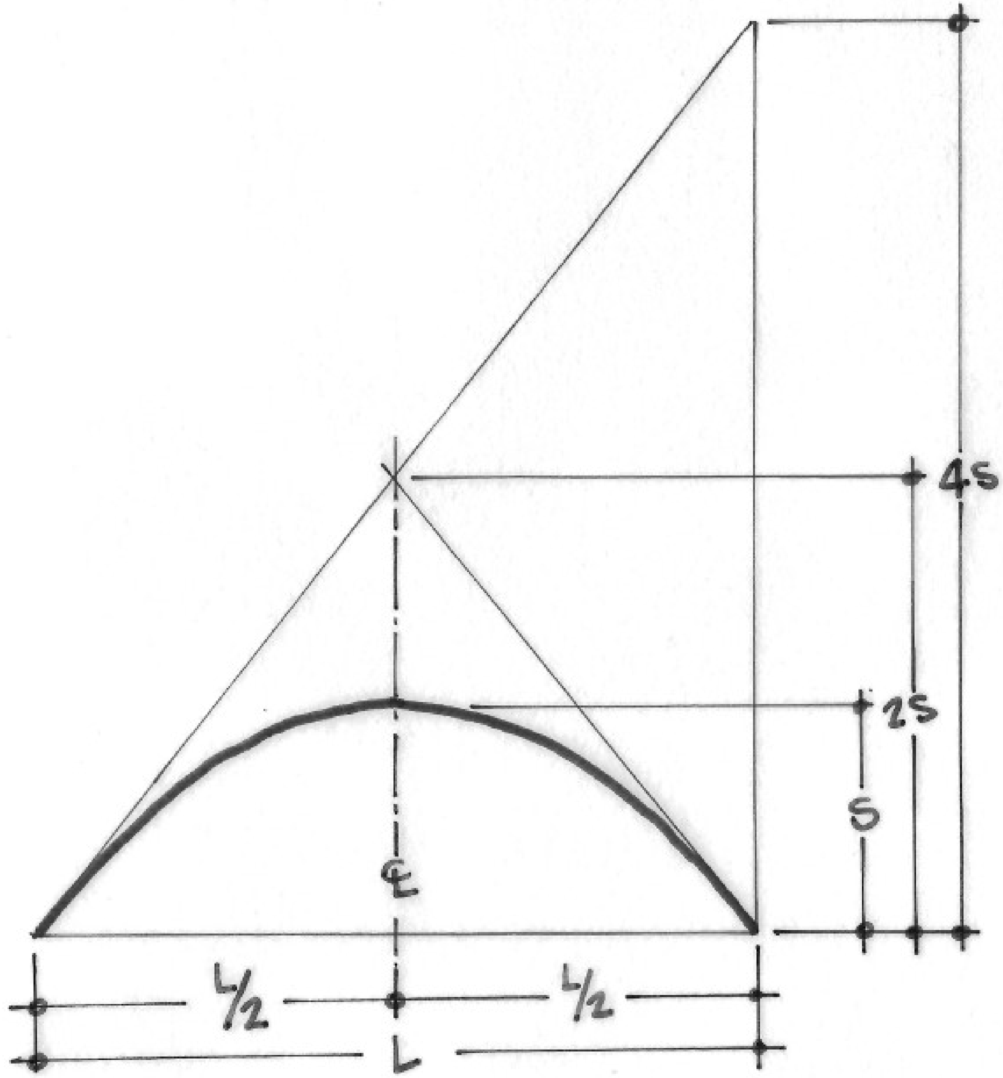
LL = 0.5 kPa

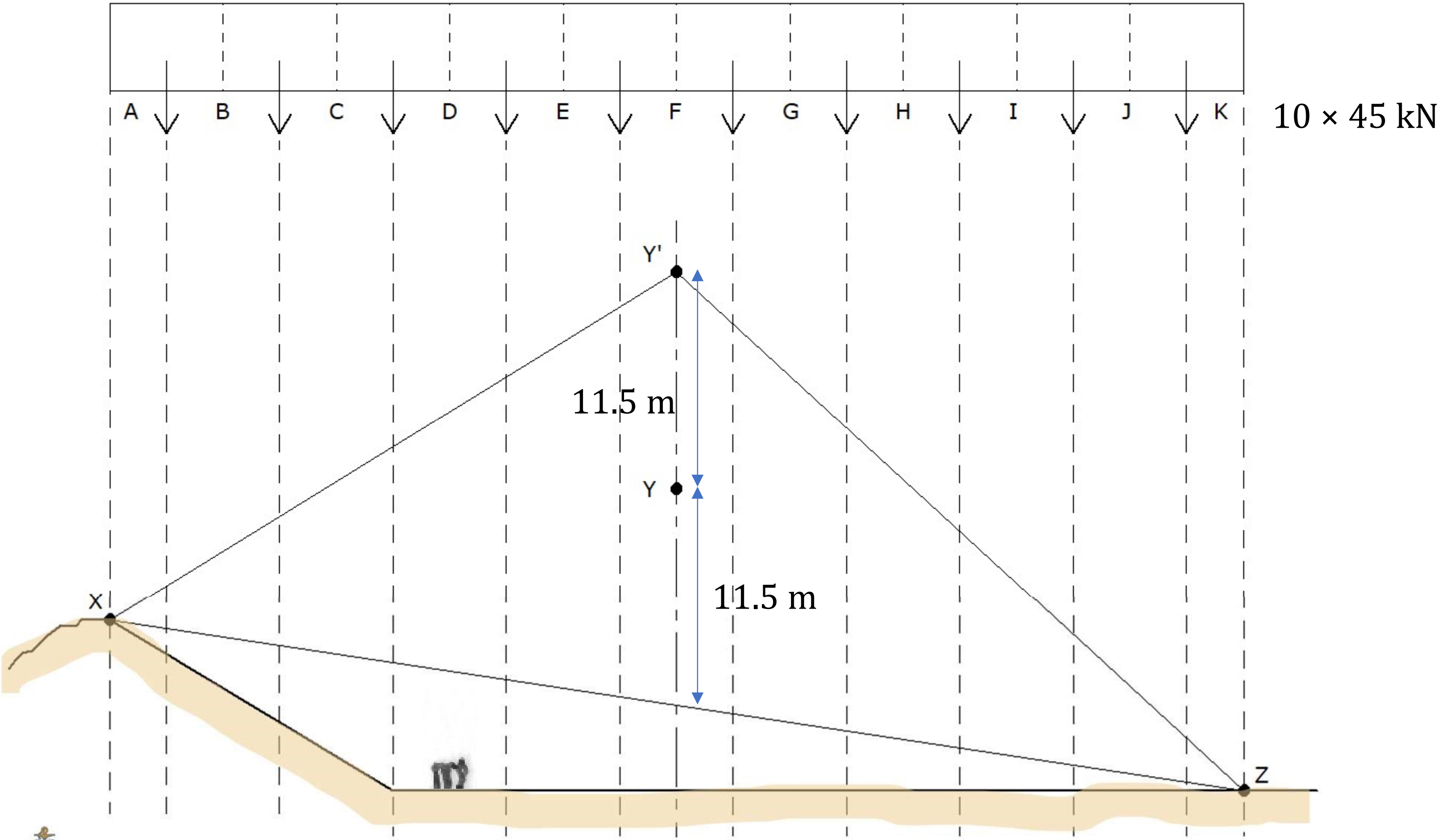
ULS = 1.2DL + 1.6 LL = 7.52 kPa




R^{CIRCLE}
$R_O^{CAT} = 0.619R^{CIRCLE}$
$R_O^{PAR} = 0.5R^{CIRCLE}$
Parabola
Catenary
Circle


Y
R^{CIRCLE}
$R_O^{CAT} = R^{CIRCLE}$
$R_O^{PAR} = R^{CIRCLE}$
Circle
Catenary
Parabola


4s
2s
s
L/2
L/2
L


A
B
C
D
E
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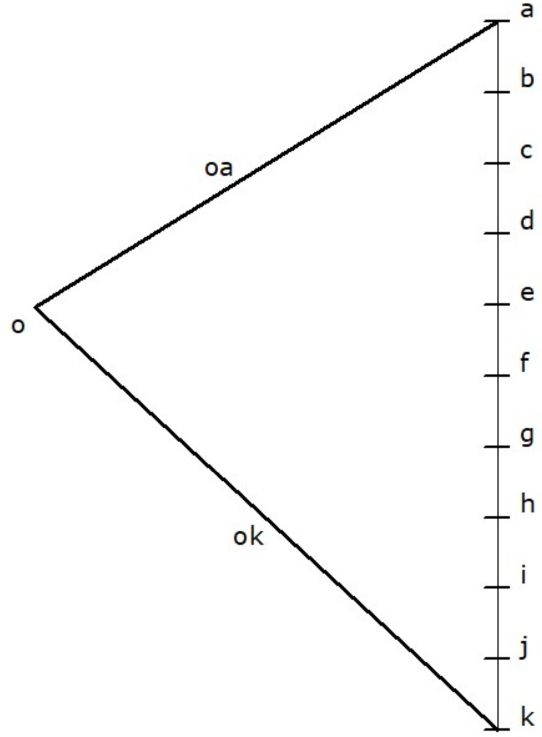
G
H
I
J
K
10 × 45 kN
Y'
11.5 m
Y
11.5 m
X
Z


a
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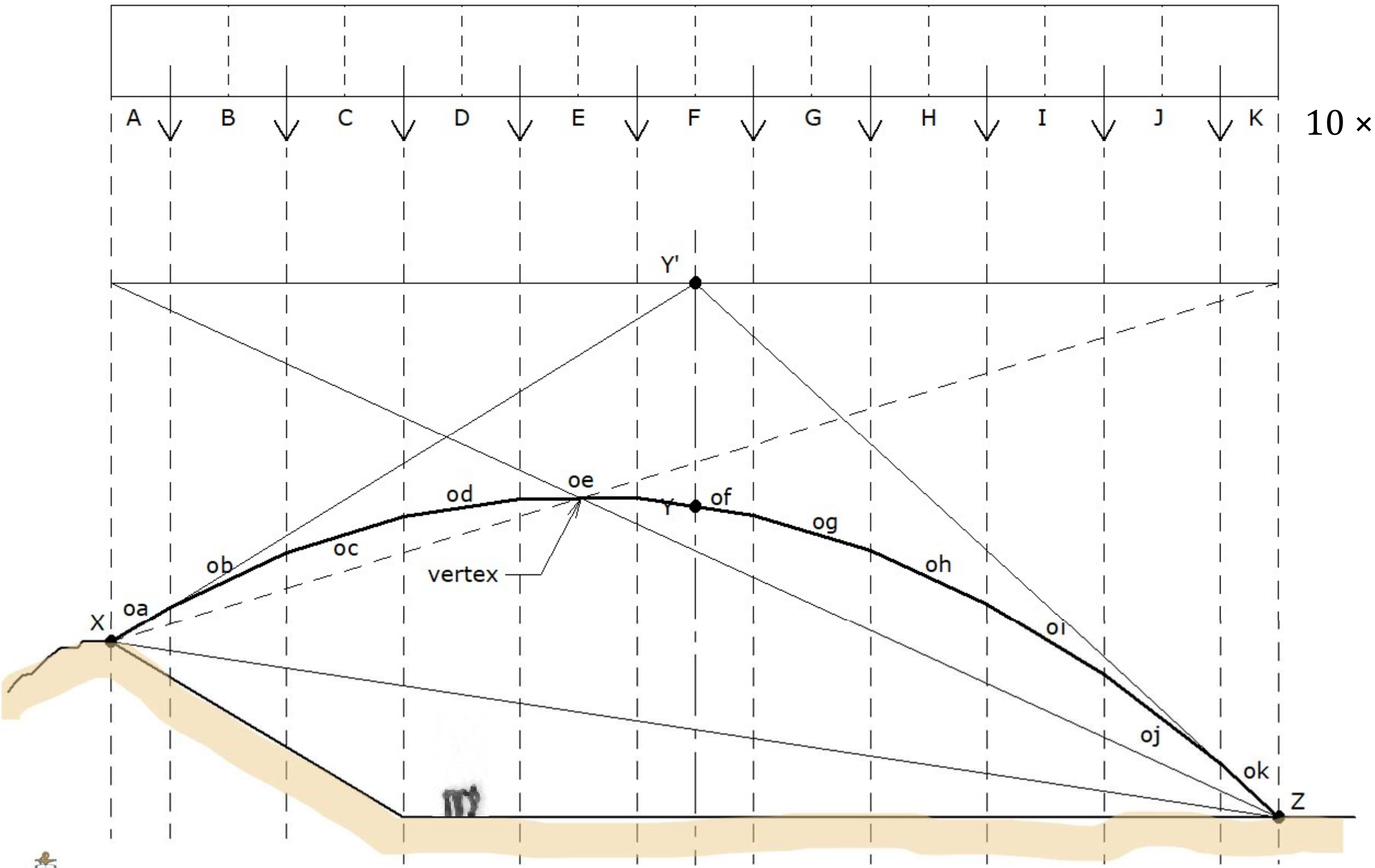
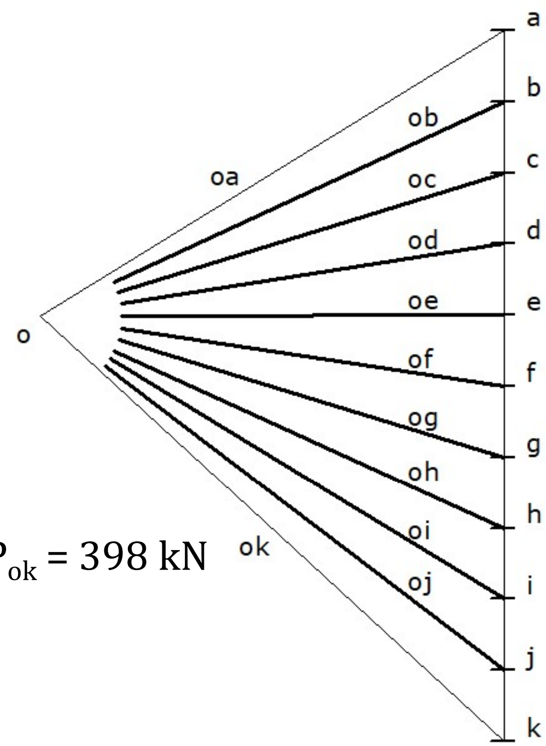
o
ok



10 × 45 kN



P_{ok} = 398 kN

$F_{allow} = P/A$

4 MPa = 398 kN / (1000 mm × t)

So, t = 100 mm

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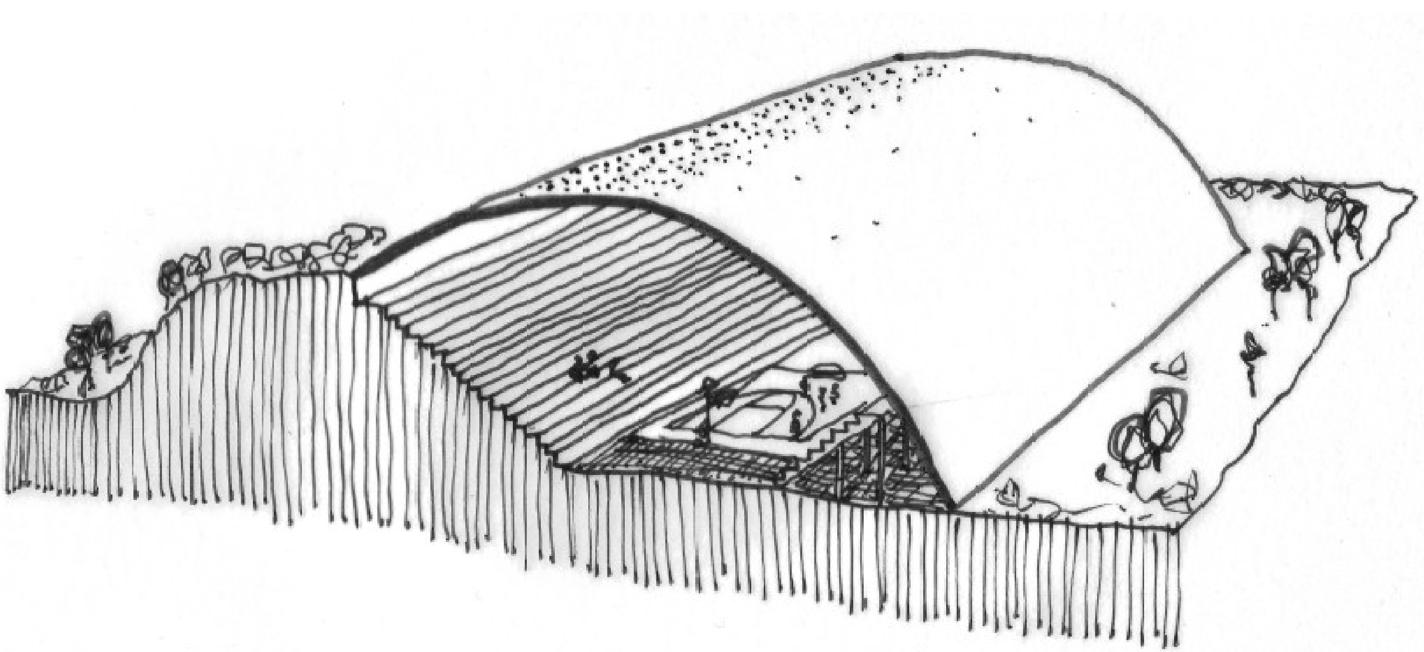

100mm??!!

Thrust lines

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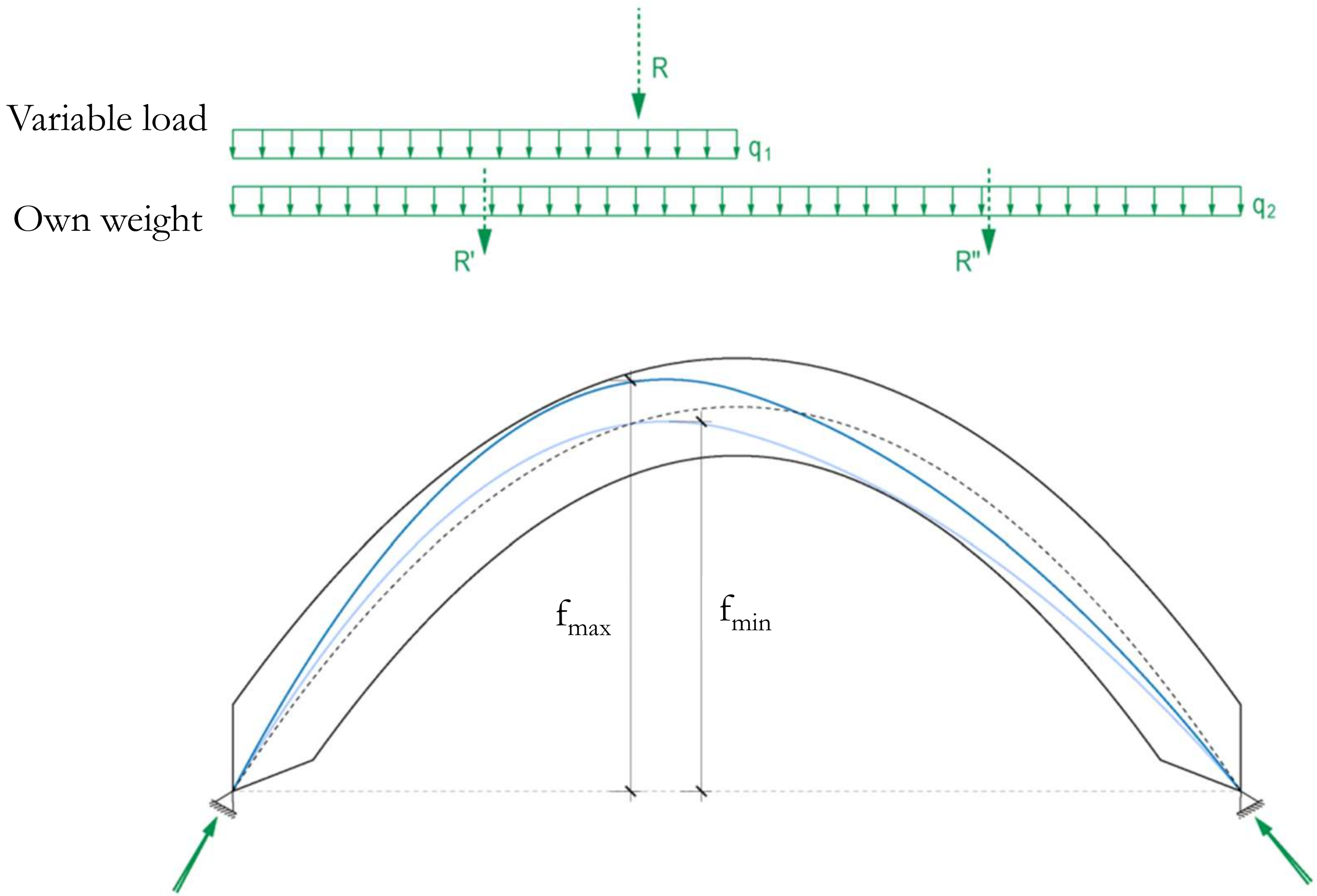
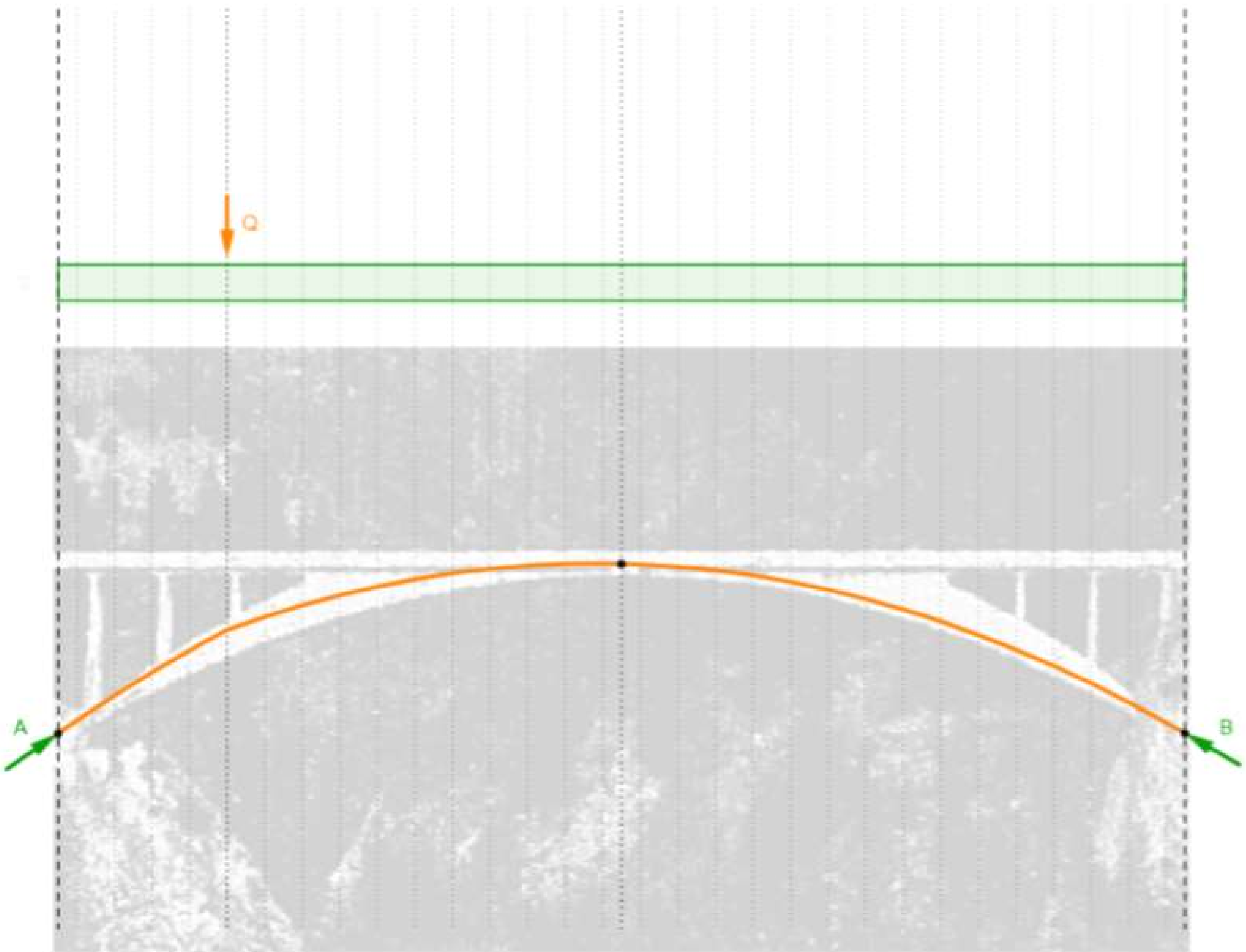
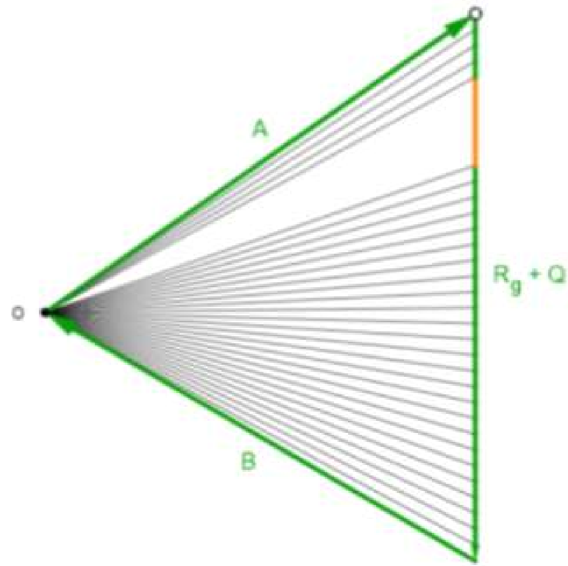


Salginatobel Bridge, Schiers, 1930 | Robert Maillart

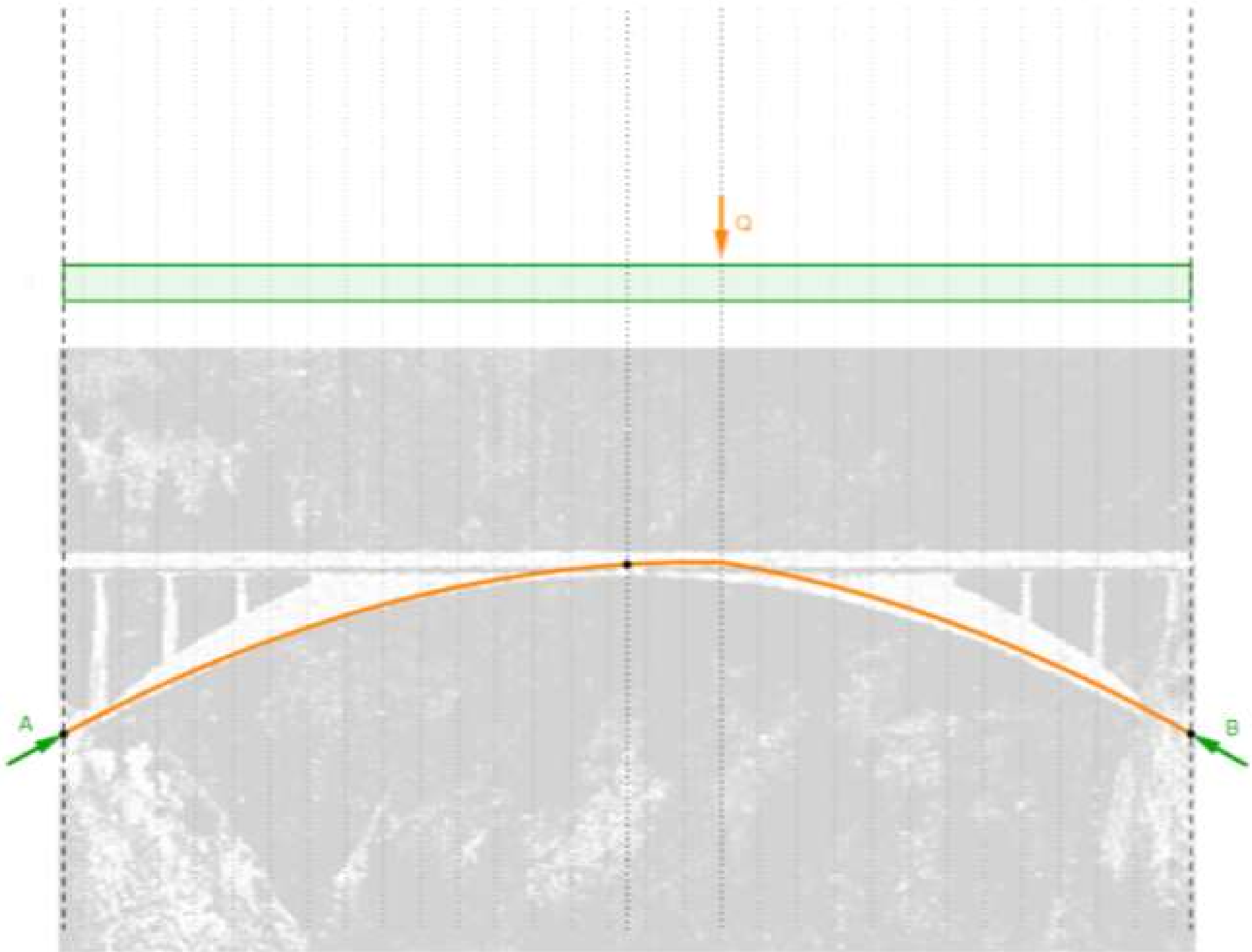
Form Diagram



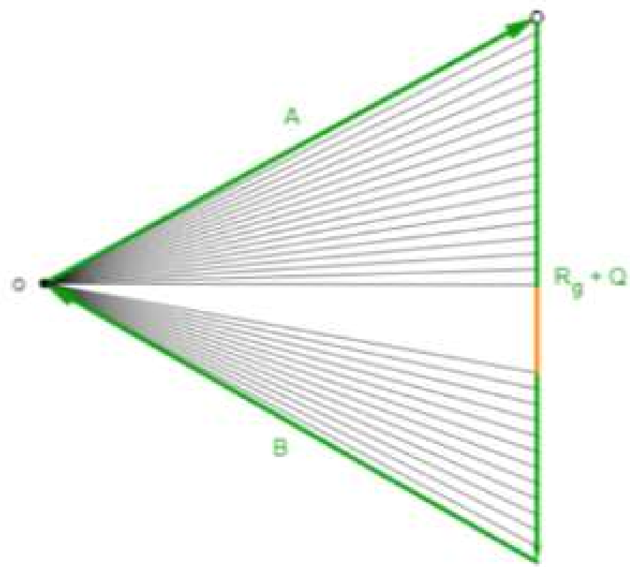
Force Diagram

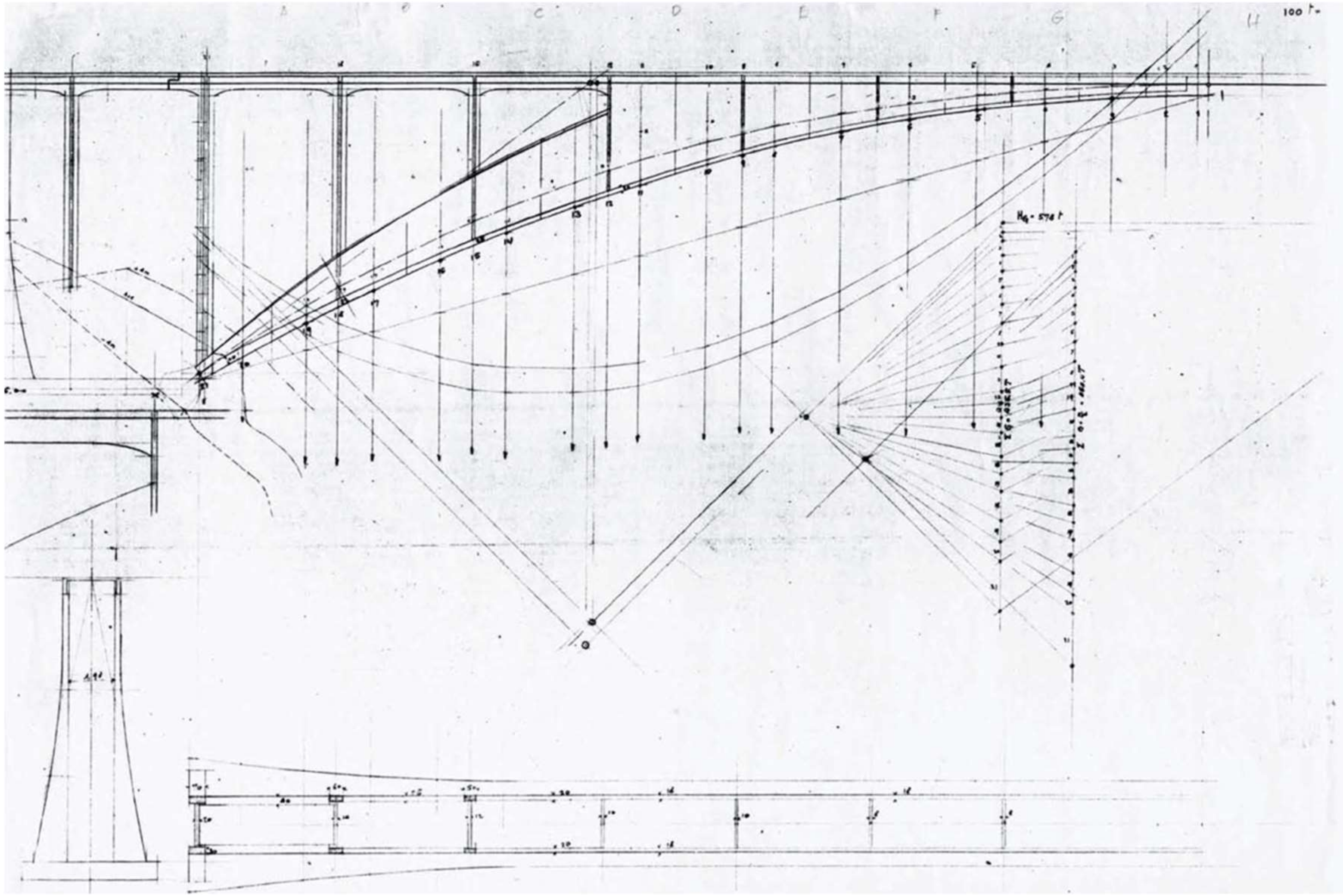


Form Diagram



Force Diagram





Salginatobel Bridge
Schiers, Switzerland
Robert Maillart (1930)

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Tower Bridge
London, UK
Sir Horace Jones & Sir John Wolfe Barry (1894)

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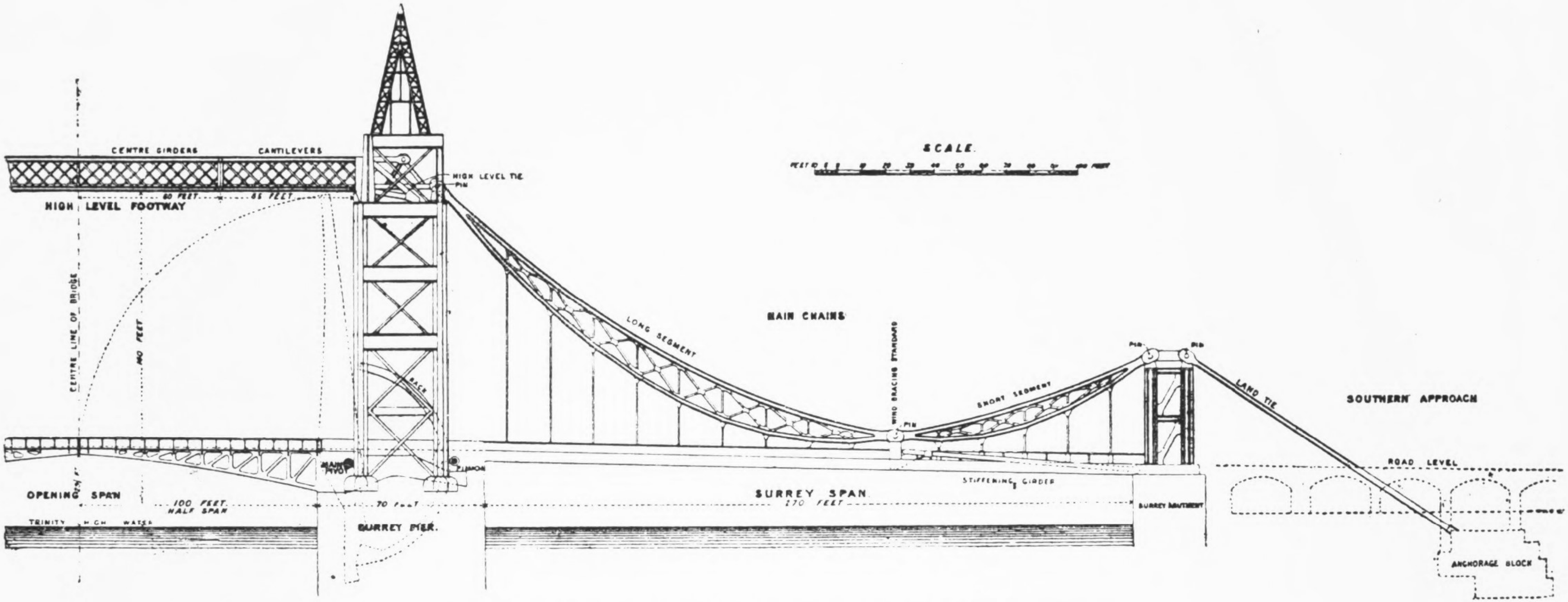


FIG. X. SKELETON HALF ELEVATION OF TOWER BRIDGE.

Tower Bridge, London, 1894 | Sir Horace Jones & Sir John Wolfe Barry

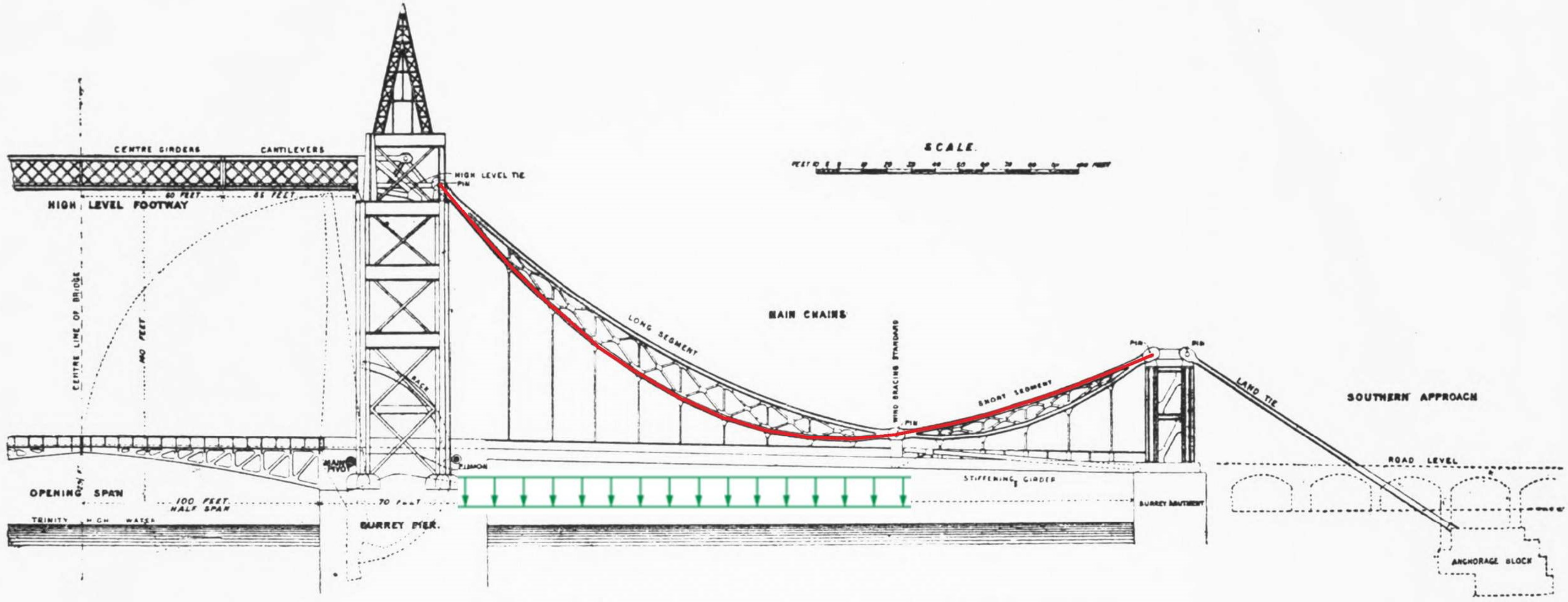


FIG. X. SKELETON HALF ELEVATION OF TOWER BRIDGE.

Tower Bridge, London, 1894 | Sir Horace Jones & Sir John Wolfe Barry

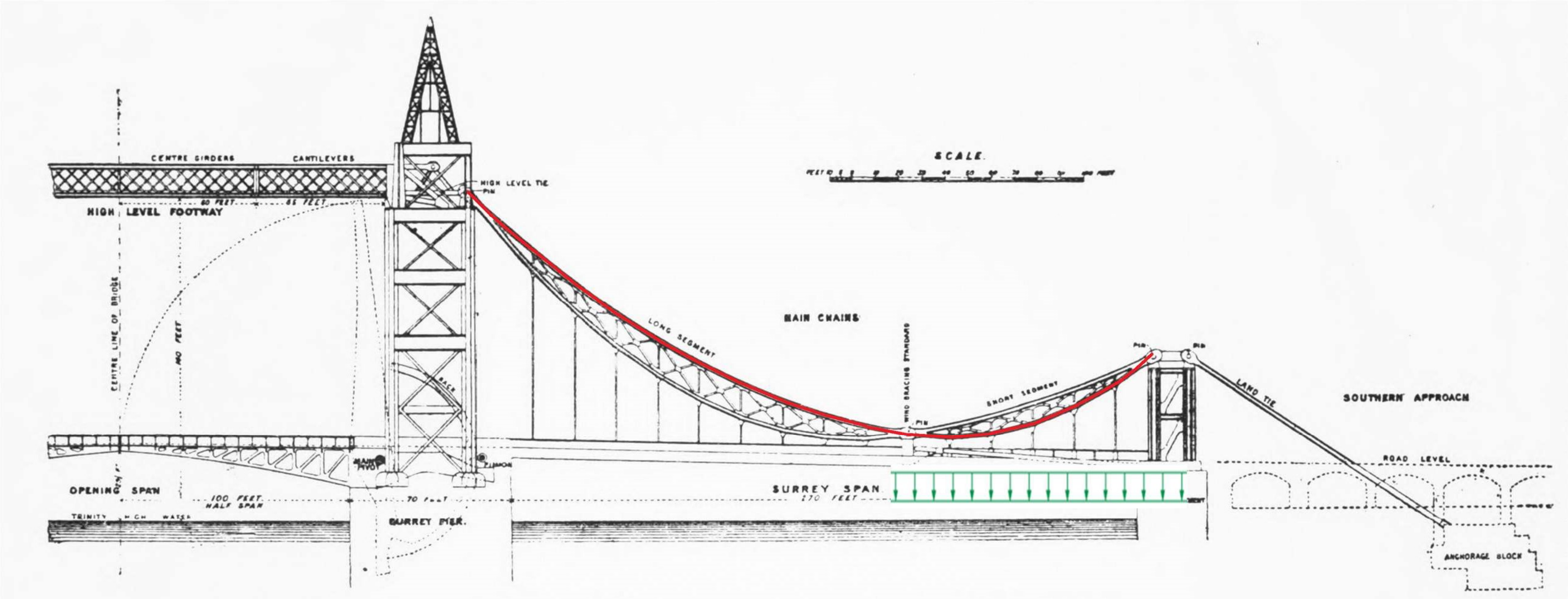
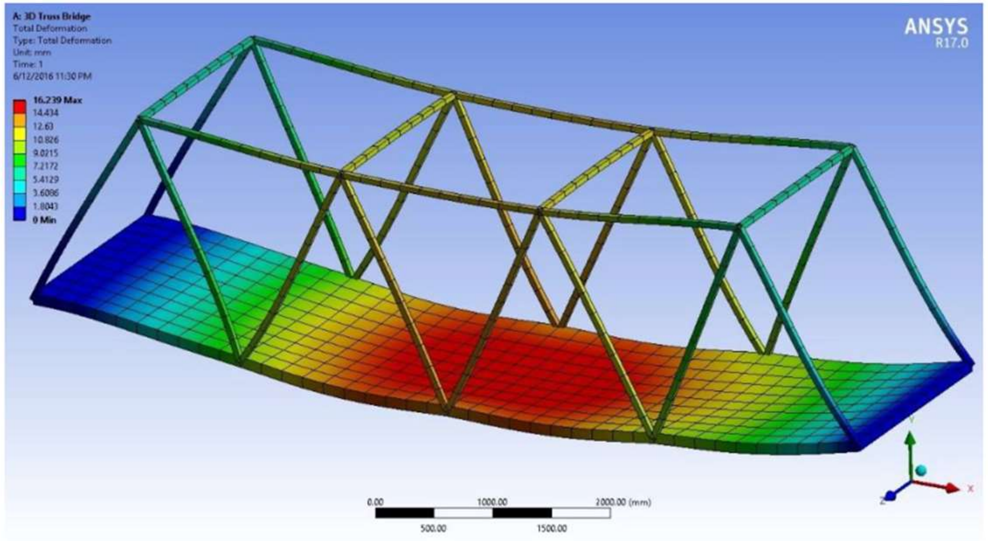
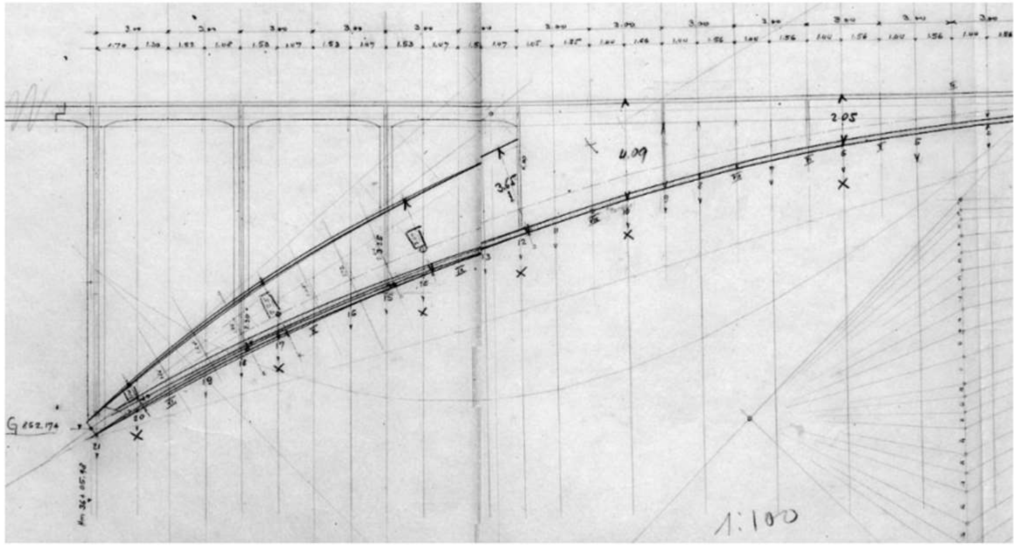


FIG. X. SKELETON HALF ELEVATION OF TOWER BRIDGE.

Tower Bridge, London, 1894 | Sir Horace Jones & Sir John Wolfe Barry

Concluding remarks





Structural Engineering
= analysis of forces
= reactive
= architectural monologue

Structural Design
= design with forces
= proactive
= dialog between architect and engineer

Thank you

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Dr. Johann van der Merwe | Pr.Eng, Dr.sc. ETH Zürich
Senior Lecturer, Dept. of Civil Engineering
University of Pretoria