

# Tragwerksentwurf II

## *Structural Design II*

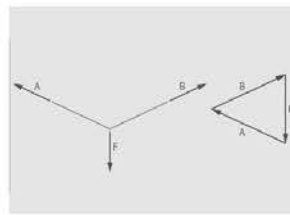
Prof. Philippe Block



Tragwerksentwurf  
*Structural Design*



1. Gleichgewicht  
*1. Equilibrium*



2. Graphische Statik  
*2. Graphic statics*



3. Seile  
*3. Cables*



4. Bogen  
*4. Arches*



5. Bogen-Seil  
*5. Arch-cables*

## Tragwerksentwurf I *Structural Design I*

## Tragwerksentwurf II *Structural Design II*



6. Fachwerke  
*6. Trusses*



7. Balken  
*7. Beams*



8. Rahmen  
*8. Frames*



9. Platten  
*9. Plates*



10. Stützen  
*10. Columns*

# Fachwerke

## *Trusses*

>> Von Bogen-Seiltragwerken zu Fachwerken

*From arch-cable-structures to trusses*

Das Fachwerk als Kombination von Bogen-Seilen

*The truss as a combination of arch-cables*

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*Geometric variation*

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Variation der Randbedingungen

*Variation of boundary conditions*

Schlankheit von Fachwerken

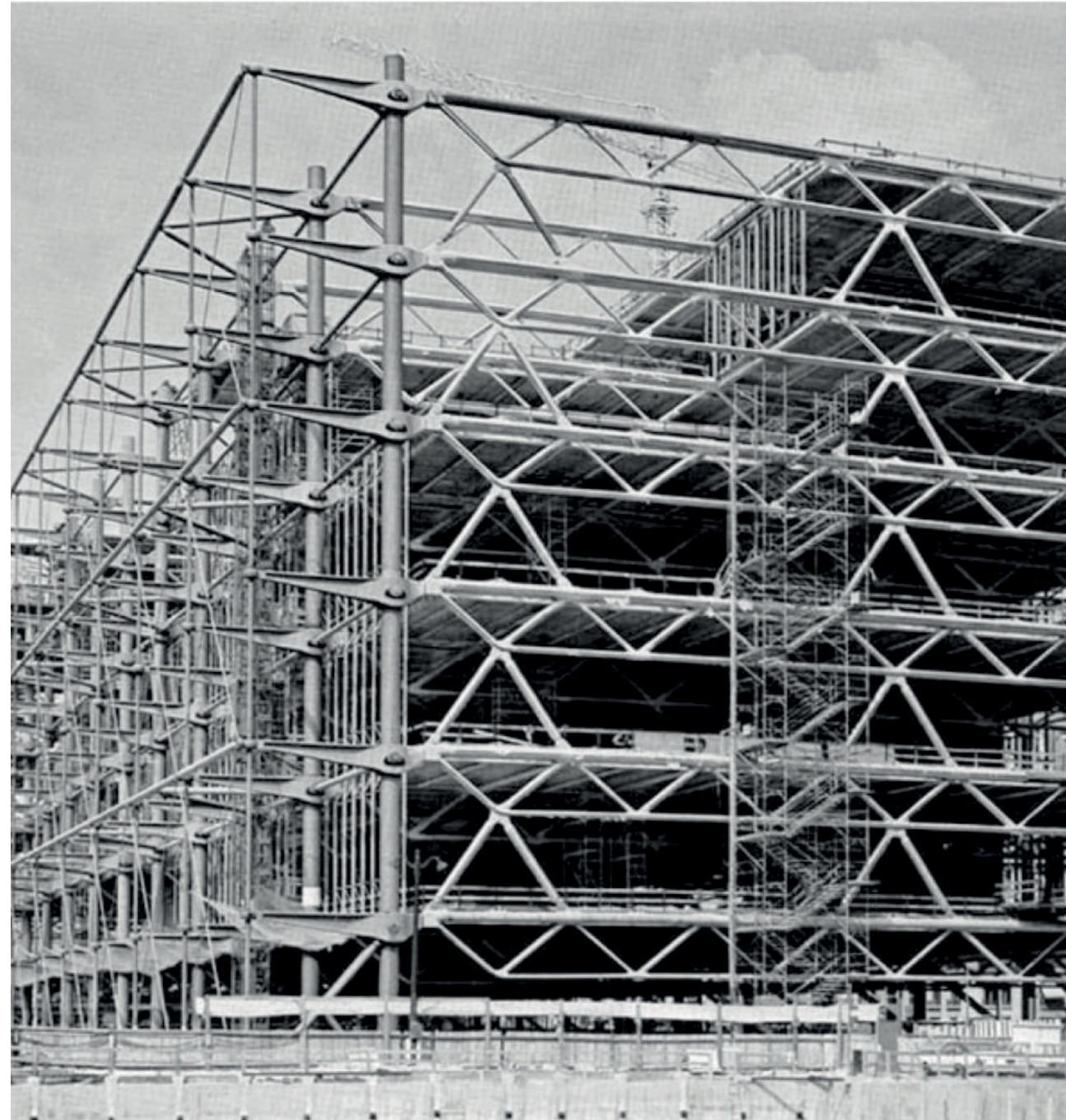
*Slender trusses*

Konstruktion von Fachwerken

*Construction of trusses*

Räumliche Fachwerke

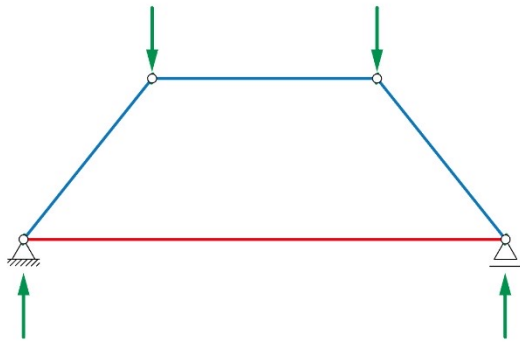
*Spatial trusses*



Renzo Piano, Richard Rogers, Peter Rice: Centre Pompidou, Paris, 1977

Bogen-Seil

*Arch-cable*



Nur für den gegebenen Belastungsfall stabil

*Only stable for the given loading case*

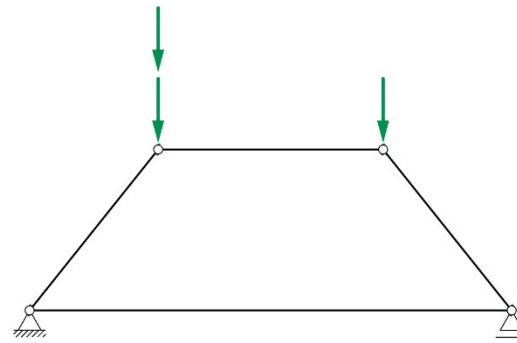
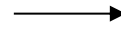
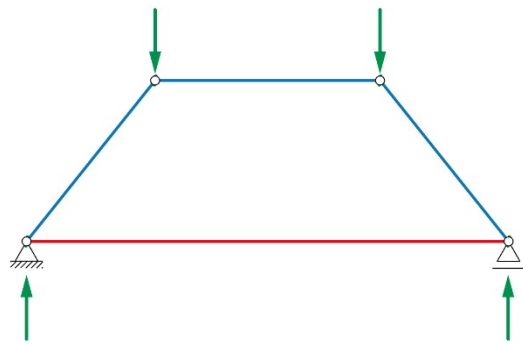


Formfindung

*Form-finding*

Bogen-Seil

*Arch-cable*

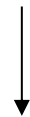


Nur für den gegebenen Belastungsfall stabil

*Only stable for the given loading case*

Instabil!

*Unstable!*

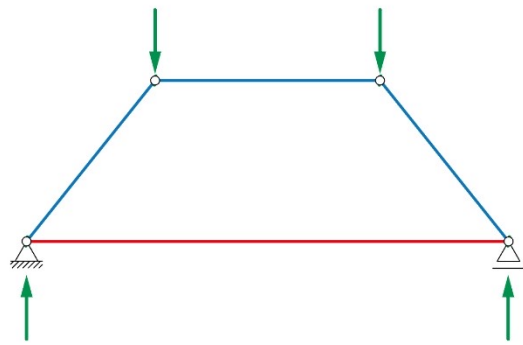


Formfindung

*Form-finding*

Bogen-Seil

*Arch-cable*



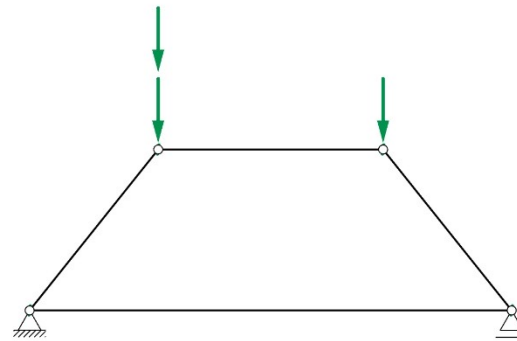
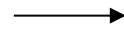
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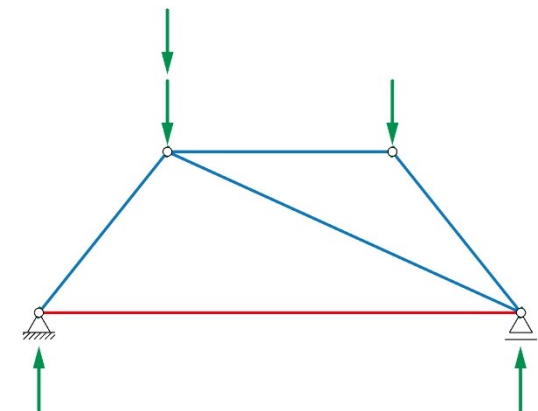
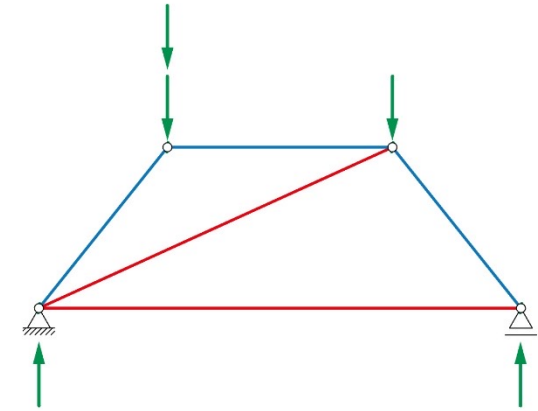
Zusätzliches Element

*Additional Element*



Fachwerk

*Truss*



Für beliebige Belastungen stabil

*Stable for any loading case*



Analyse

*Analysis*

# Fachwerke

## *Trusses*

Von Bogen-Seiltragwerken zu Fachwerken

*From arch-cable-structures to trusses*

>> Das Fachwerk als Kombination von Bogen-Seilen

*The truss as a combination of arch-cables*

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Variation der Randbedingungen

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Schlankheit von Fachwerken

*Slender trusses*

Konstruktion von Fachwerken

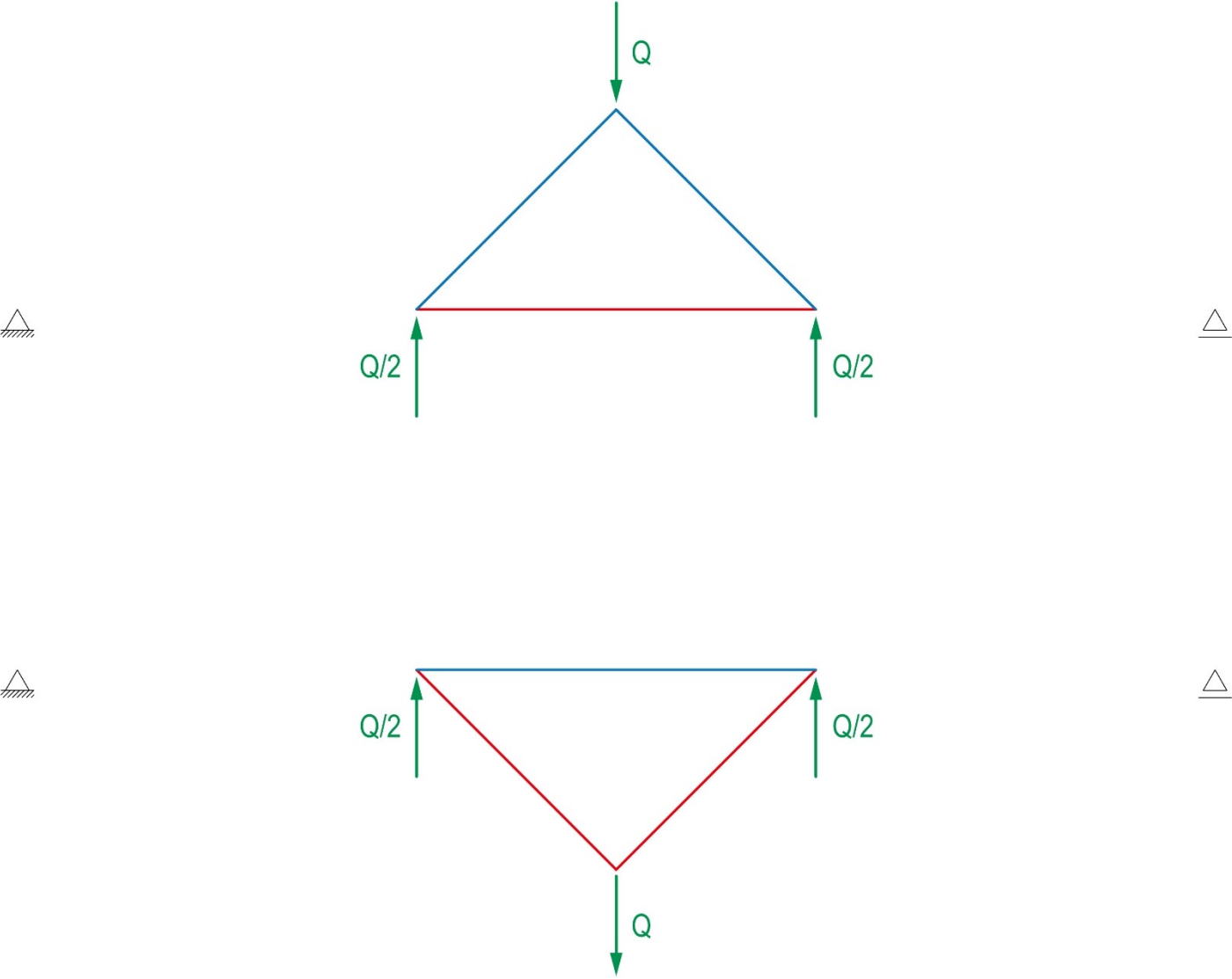
*Construction of trusses*

Räumliche Fachwerke

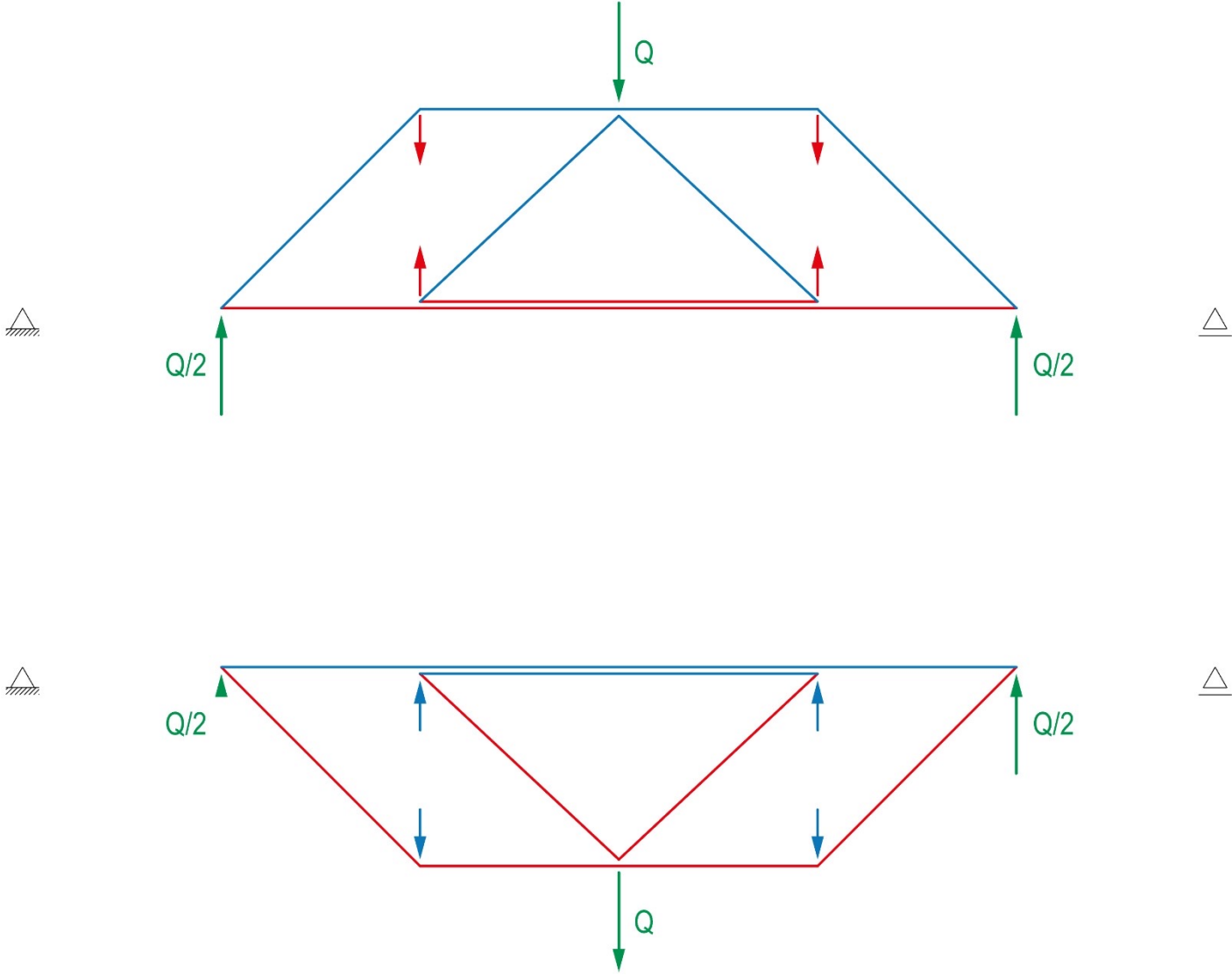
*Spatial trusses*



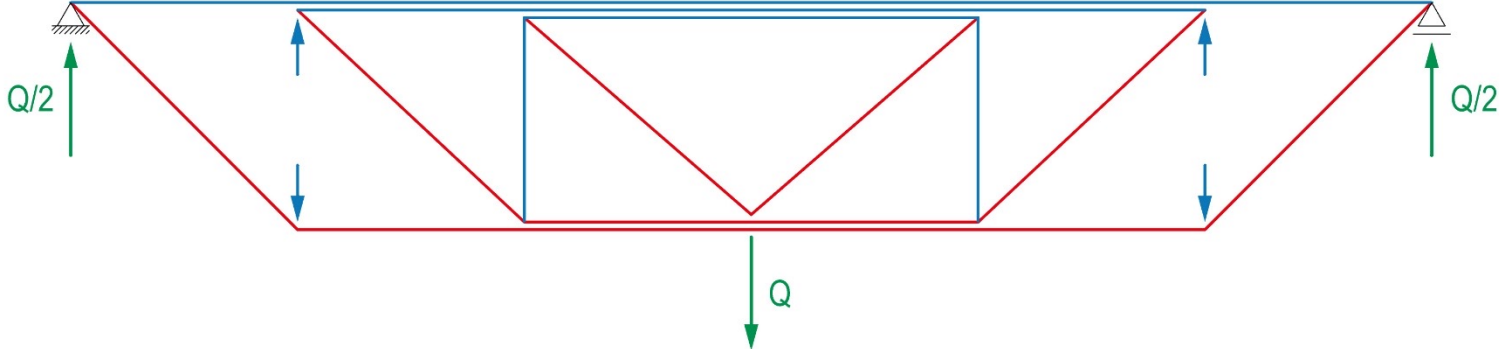
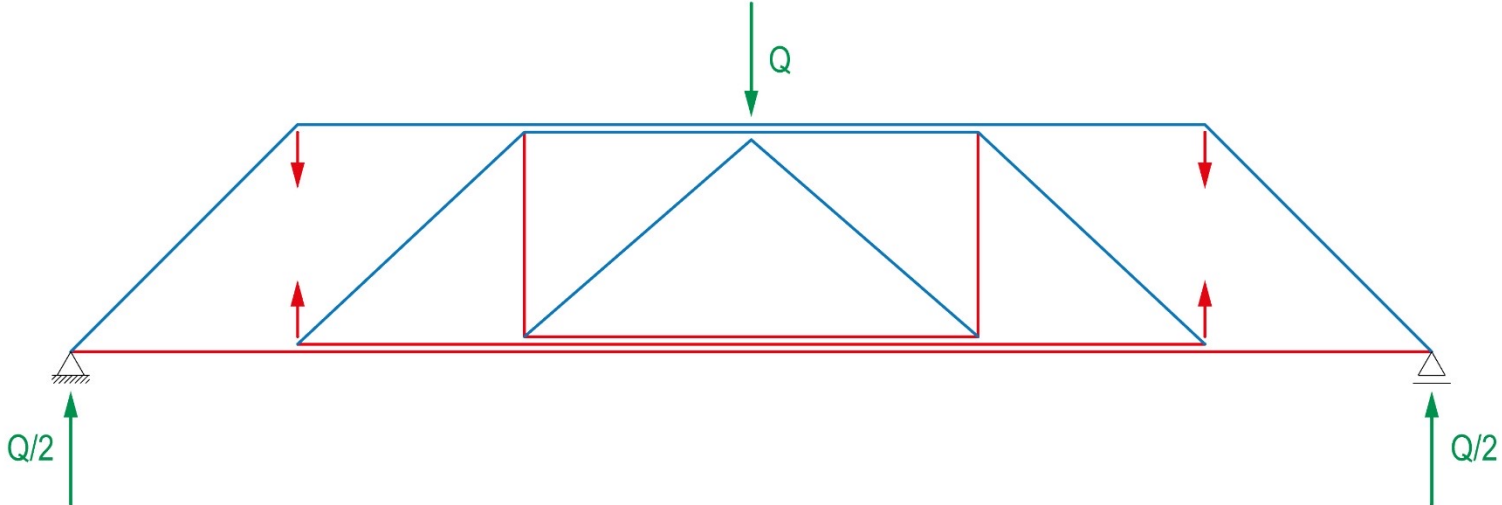
*The truss as a combination of arch-cables*



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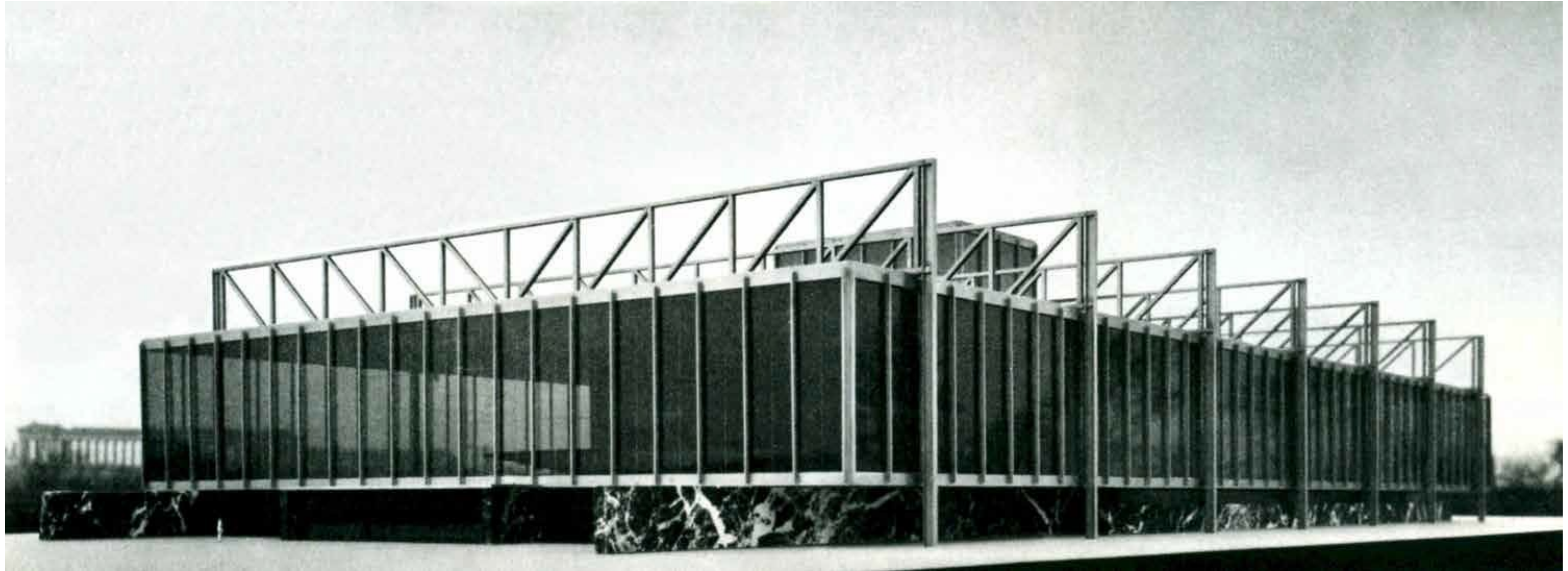


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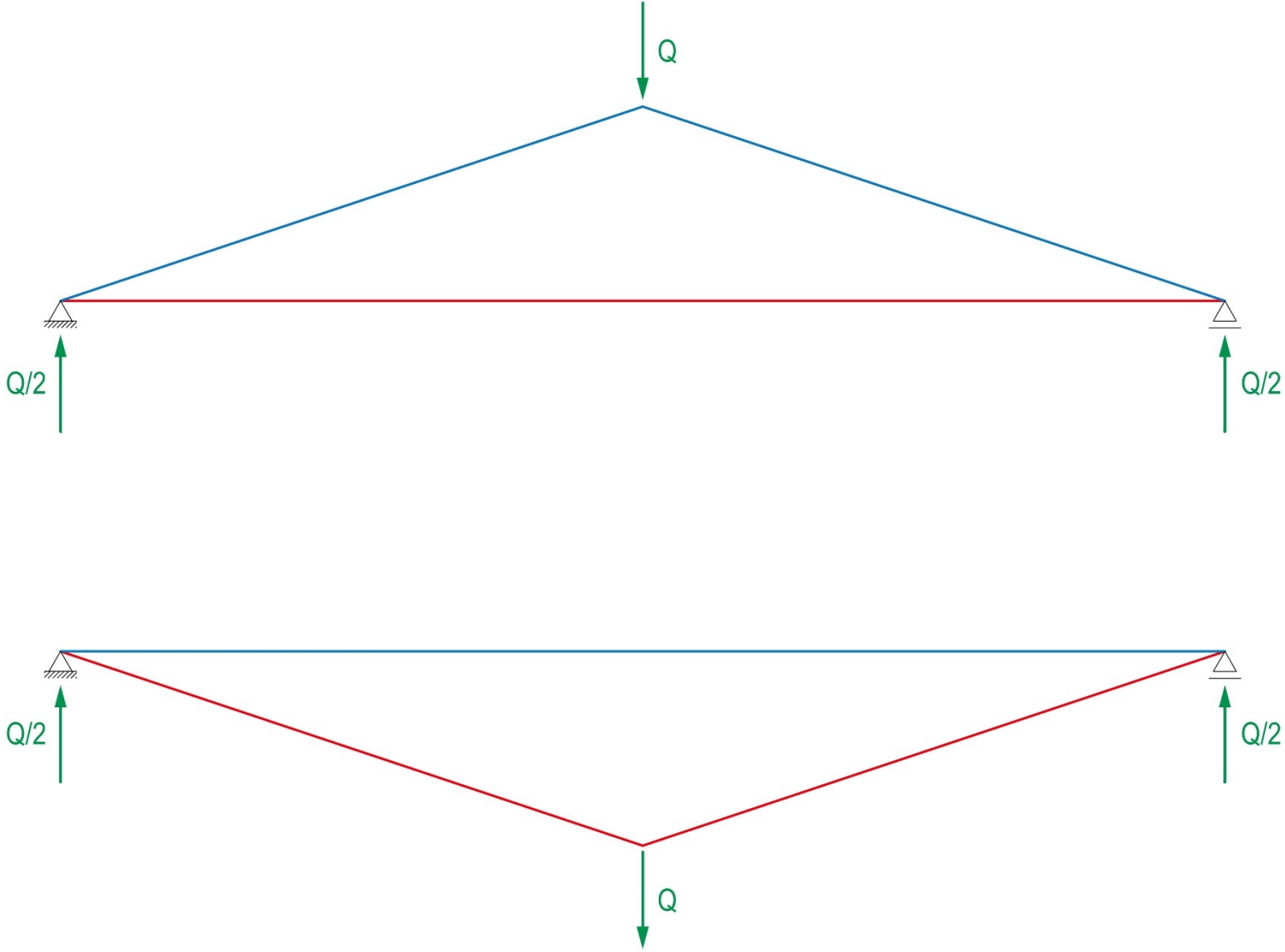




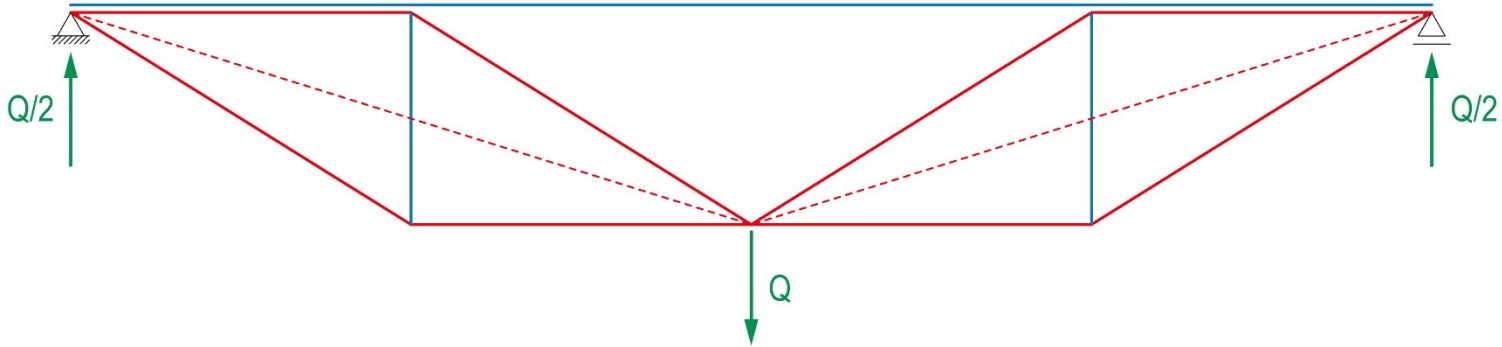
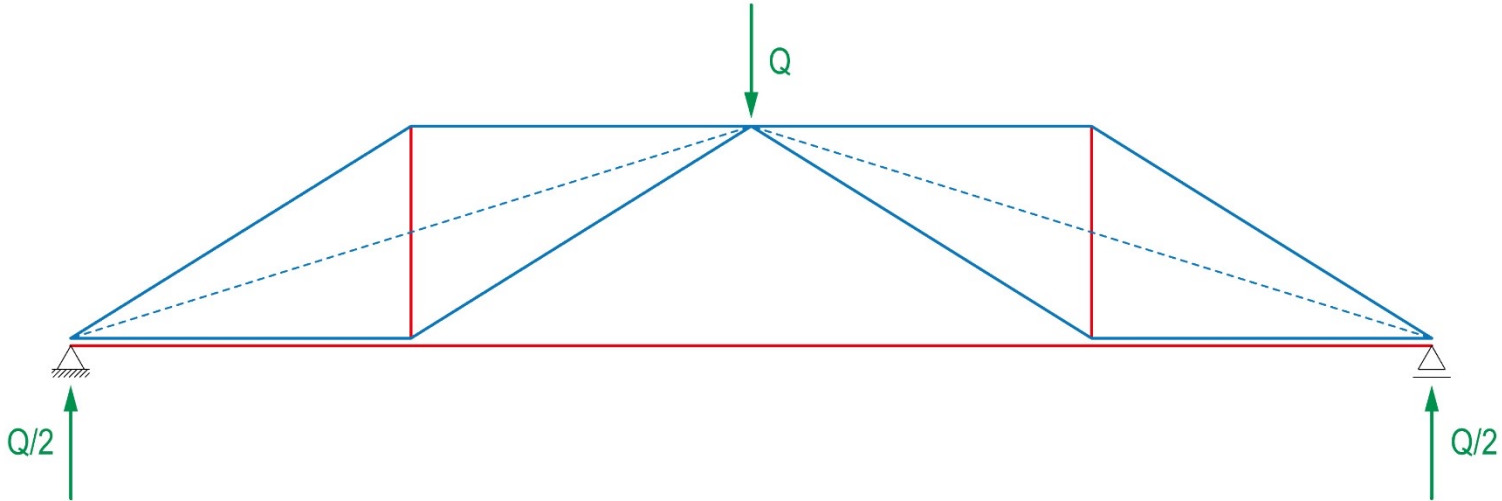
R. Piano, R. Rogers, P. Rice: Centre Georges Pompidou, Paris, 1977



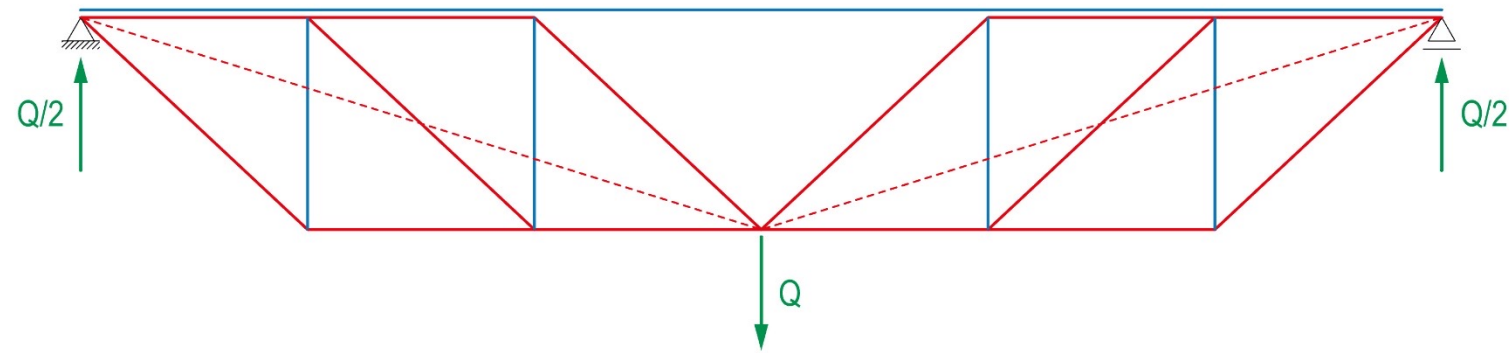
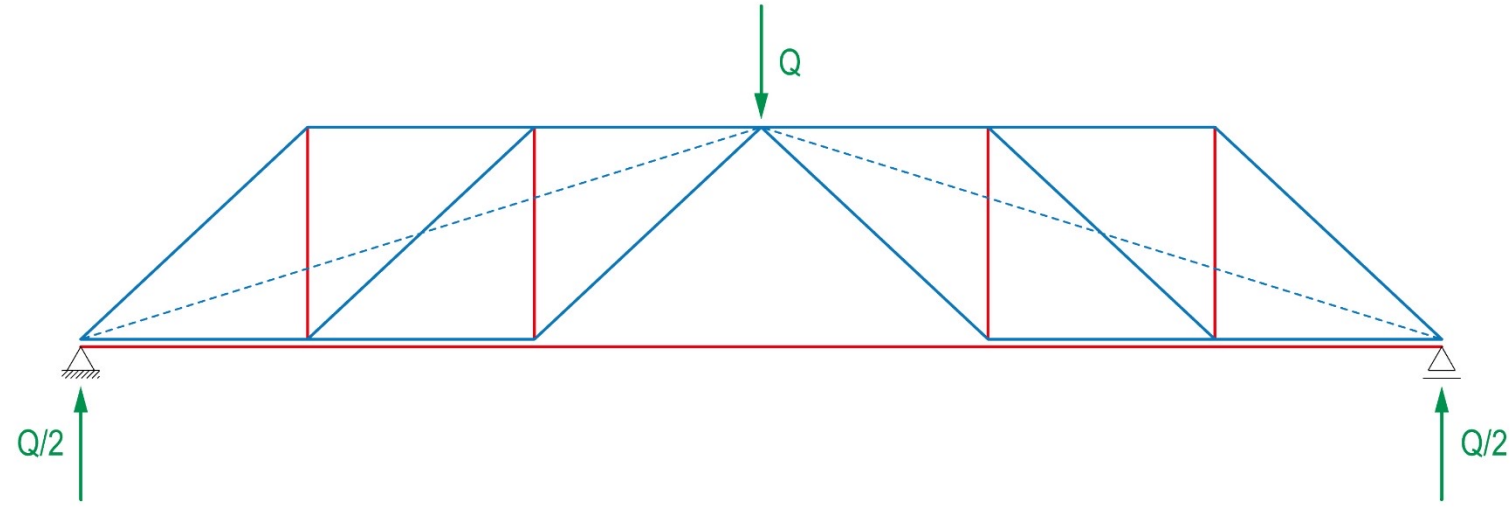
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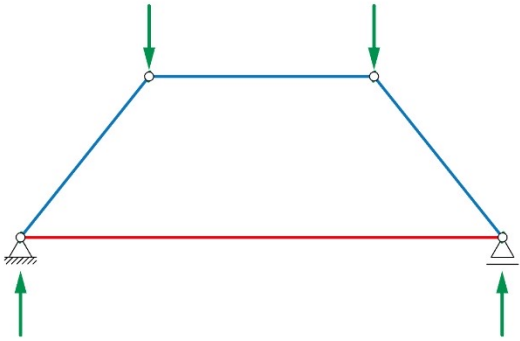
*The truss as a combination of arch-cables*





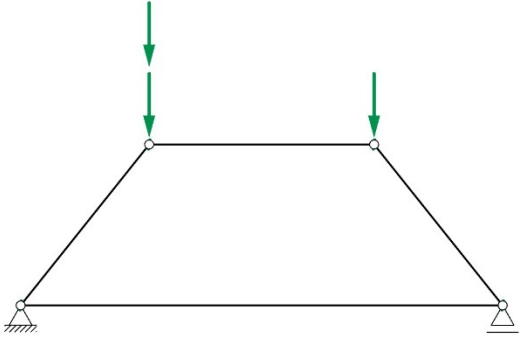
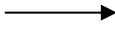
*The truss as a combination of arch-cables*

Bogen-Seil  
*Arch-cable*



Nur für den gegebenen Belastungsfall stabil  
*Only stable for the given loading case*

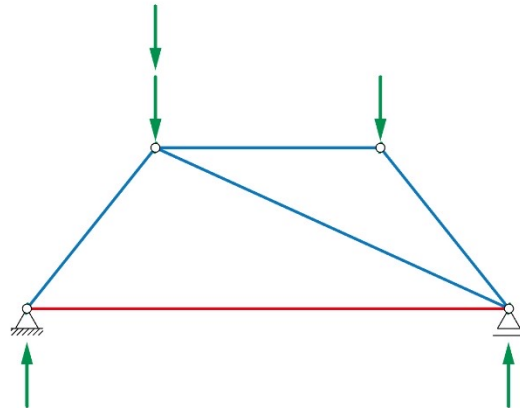
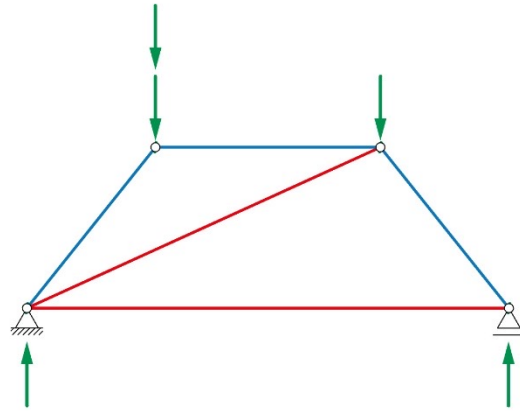
Formfindung  
*Form-finding*



Instabil!  
*Unstable!*

Zusätzliches Element  
*Additional Element*

Fachwerk  
*Truss*



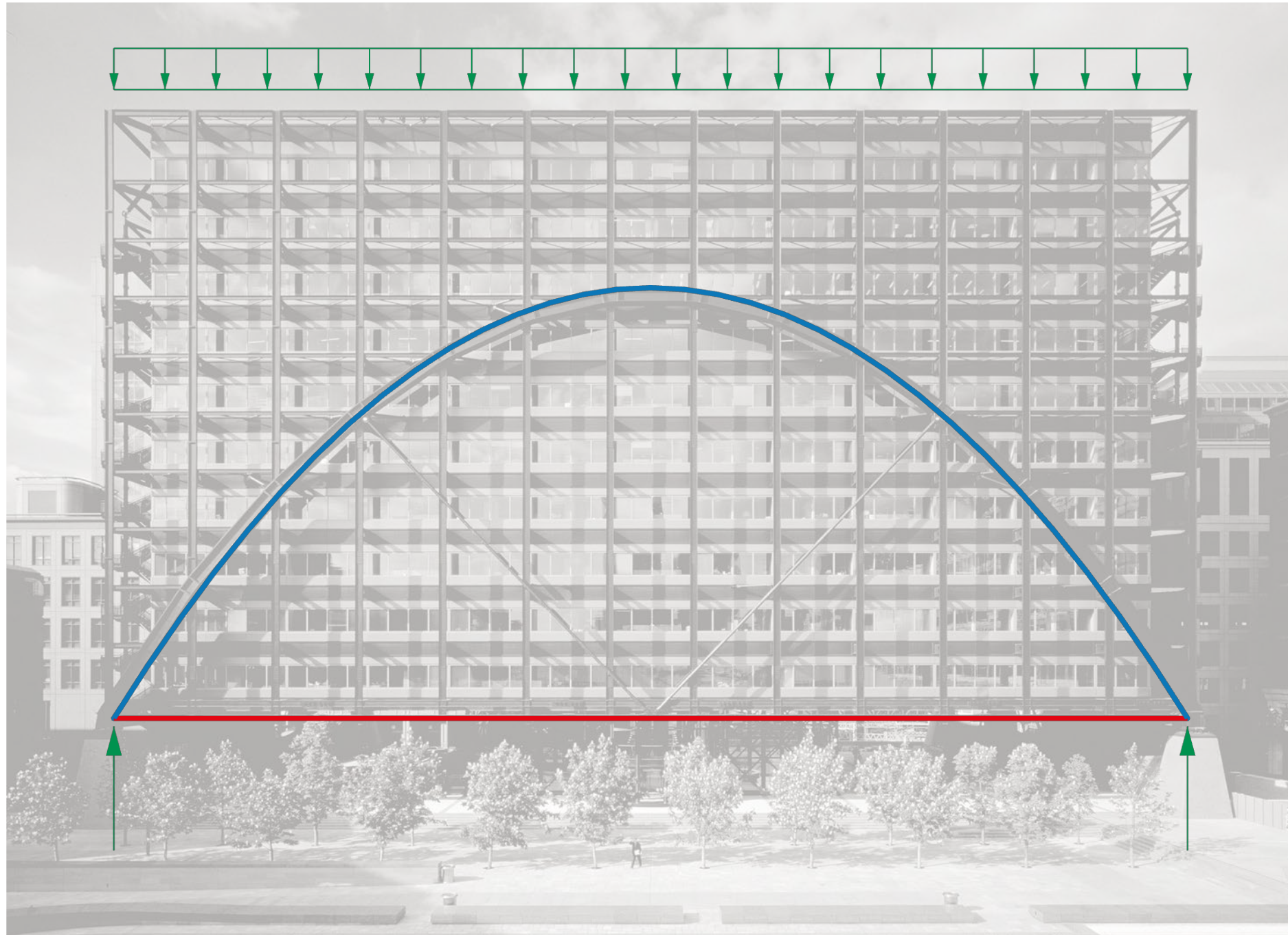
Für beliebige Belastungen stabil  
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Analyse  
*Analysis*

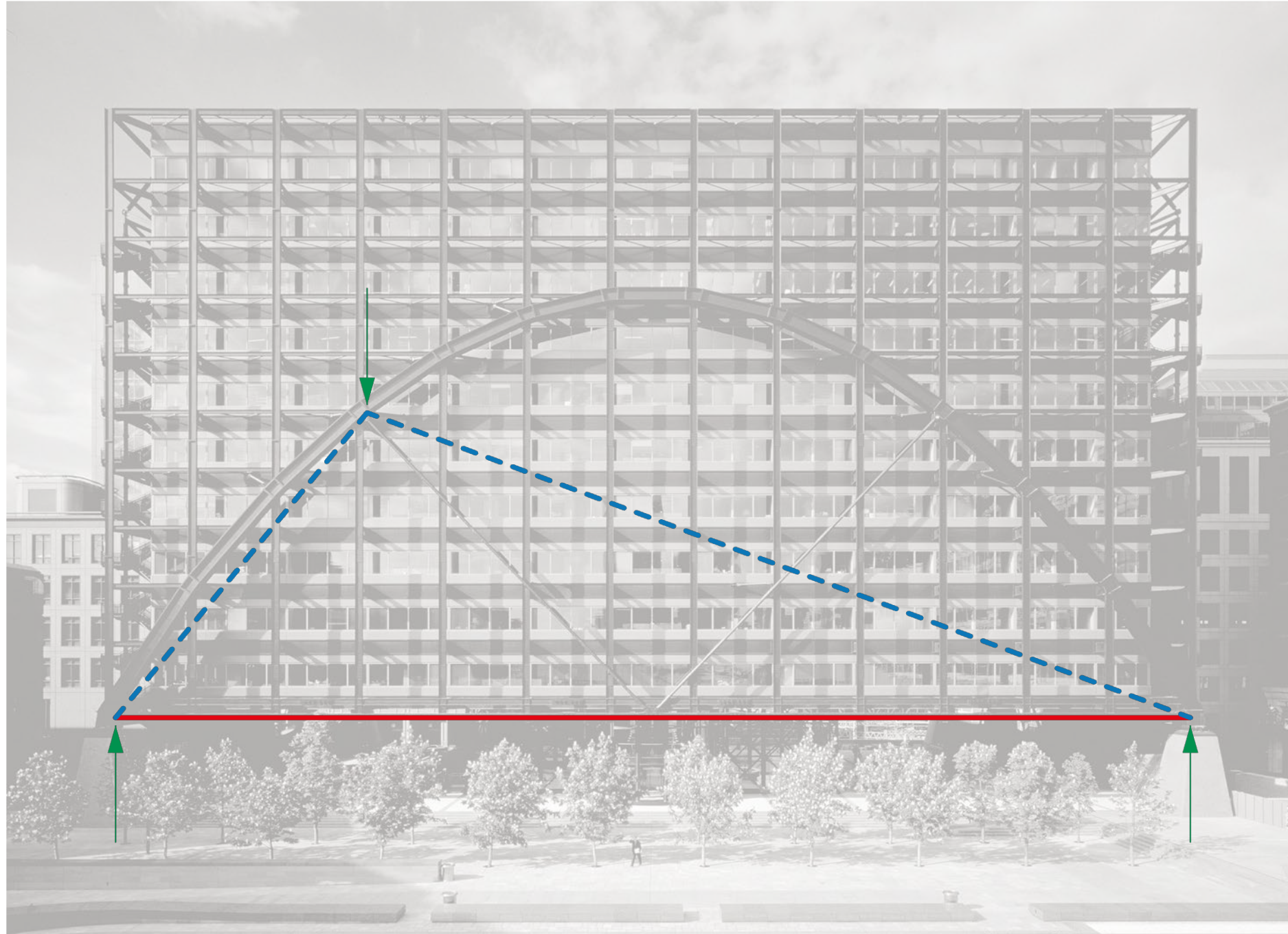


Skidmore, Owings & Merrill (SOM): Exchange House, Broadgate, London, 1990

*The truss as a combination of arch-cables*



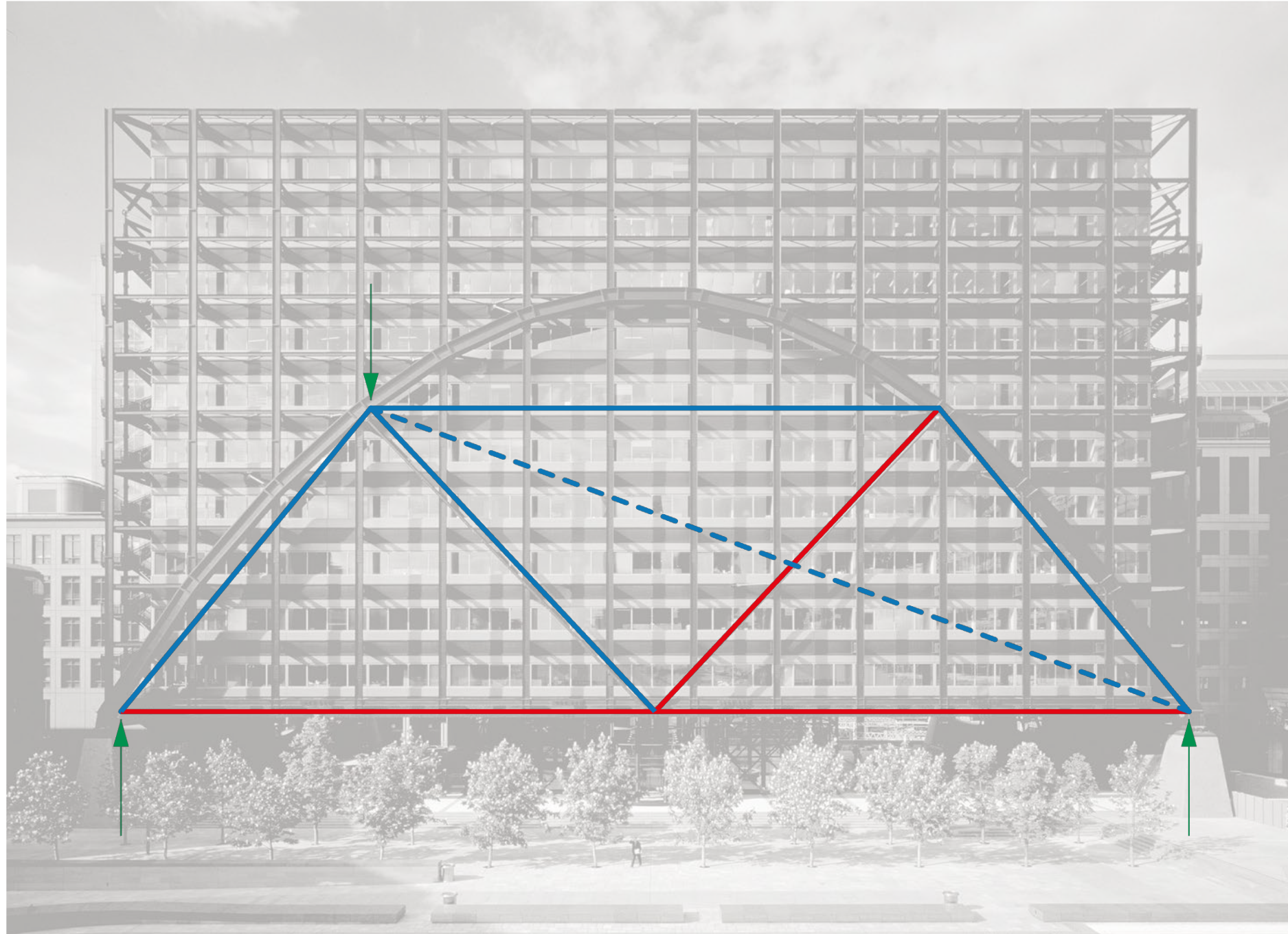
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# Fachwerke

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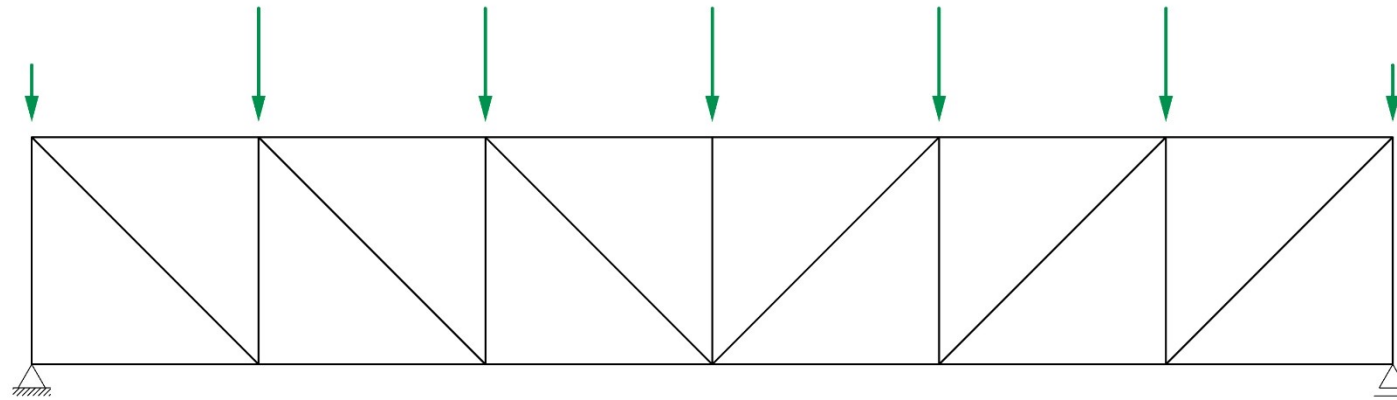
*Slender trusses*

Konstruktion von Fachwerken

*Construction of trusses*

Räumliche Fachwerke

*Spatial trusses*

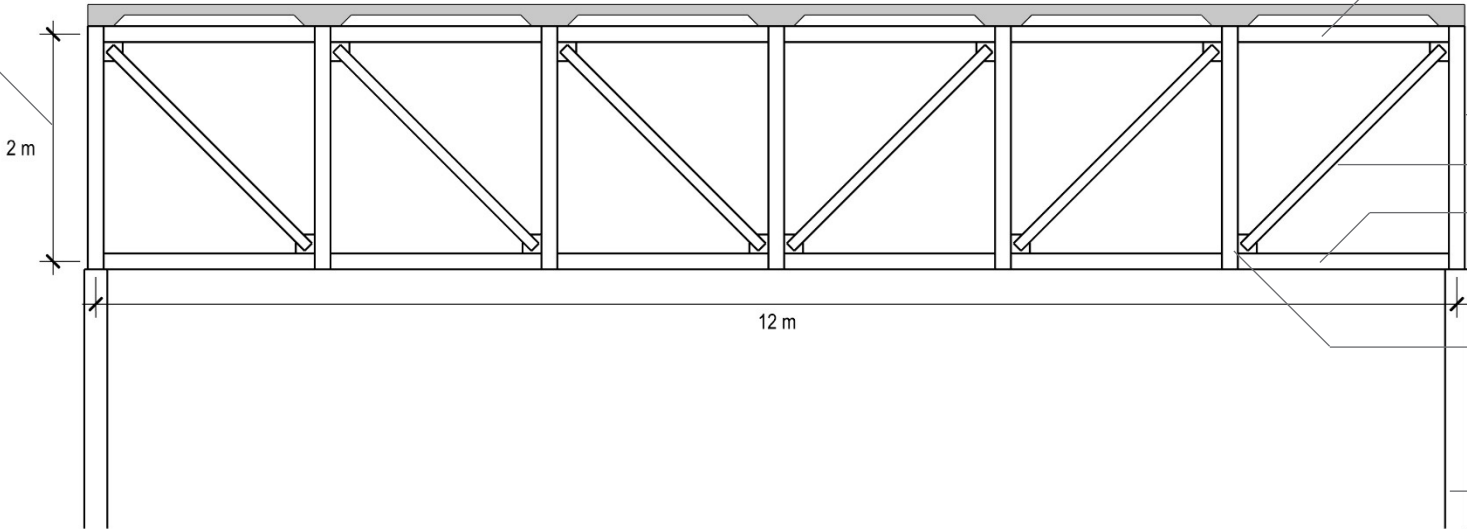


- Alle Verbindungen sind gelenkig
- Alle Elemente sind gerade
- Lasten greifen nur an Knotenpunkten an
- Es treten nur axiale Kräfte auf
- Fachwerke setzen sich aus Dreiecken zusammen, um stabil zu sein

- *All connections are hinged*
- *All elements are straight*
- *Loads only act at nodes*
- *Only axial forces occur*
- *Trusses are composed of triangles in order to be stable*



Statische Höhe  
*Statical depth*



Stäbe:

*Members:*

Obergurt / *Top chord*

Pfosten / *Post*

Strebe / *Strut*

Untergurt / *Bottom chord*

Knoten

*Node*

Stütze

*Column*

Fachwerkbalken

*Beam truss*

Fachwerkrahmen

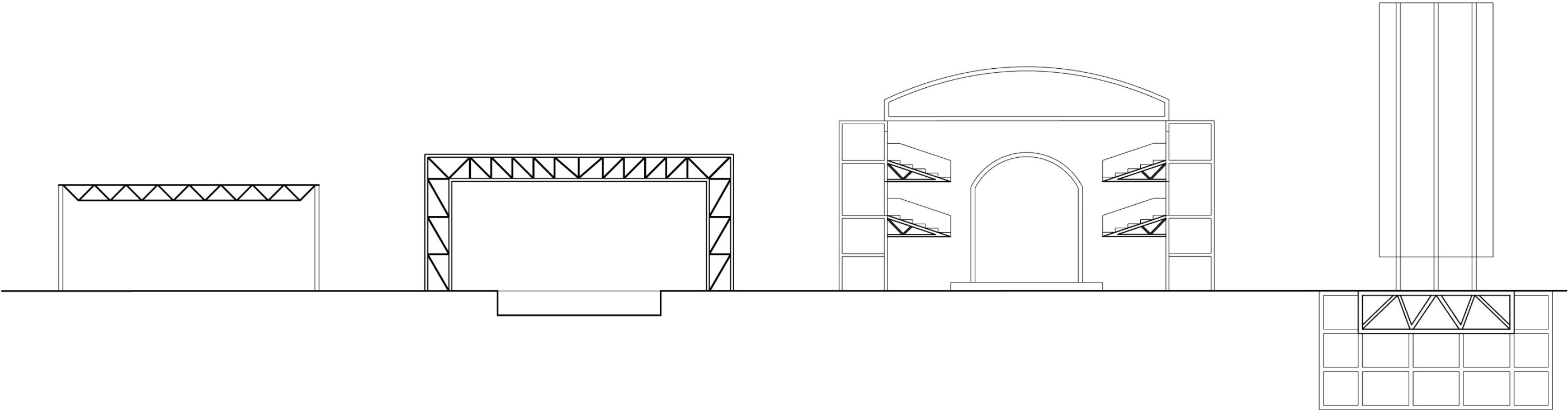
*Frame truss*

Fachwerkkonsole

*Cantilevering truss*

Fachwerkabfangung

*Transfer truss*



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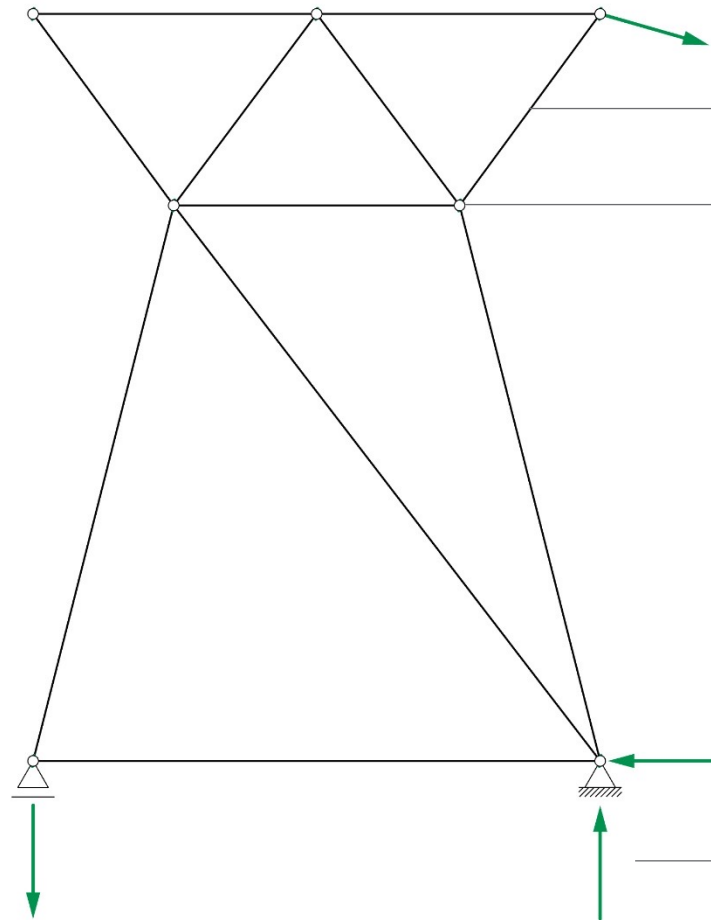
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Räumliche Fachwerke

*Spatial trusses*



S = Anzahl Stäbe / Elemente  
*S = Number of elements / Members*  
 K = Anzahl Knoten  
*K = Number of nodes*

A = Anzahl der Auflagerbedingungen  
*A = Number of reactions*

$$S + A < 2 * K$$

Das System ist labil

*The system is not stable*

$$S + A = 2 * K$$

Das System ist statisch bestimmt

*The system is statically determined*

$$S + A > 2 * K$$

Das System ist statisch unbestimmt

*The system is statically not determined*

$$S = 11$$

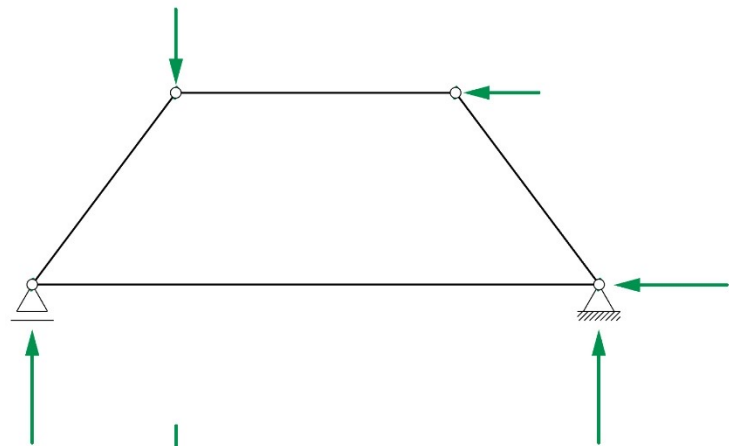
$$S + A = 14 = 2 * K = 14$$

$$A = 3$$

Das System ist statisch bestimmt

*The system is statically determined*

$$K = 7$$



$S = 4$

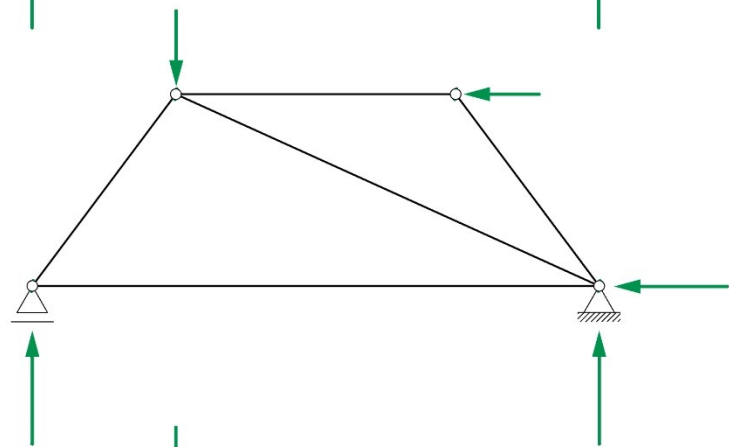
$S + A = 7 < 2 * K = 8$

$A = 3$

Das System ist labil

*The system is not stable*

$K = 4$



$S = 5$

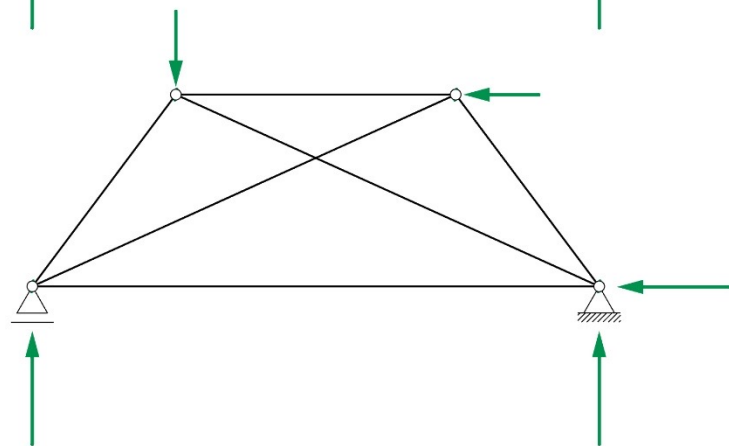
$S + A = 8 = 2 * K = 8$

$A = 3$

Das System ist statisch bestimmt

*The system is statically determined*

$K = 4$



$S = 6$

$S + A = 9 > 2 * K = 8$

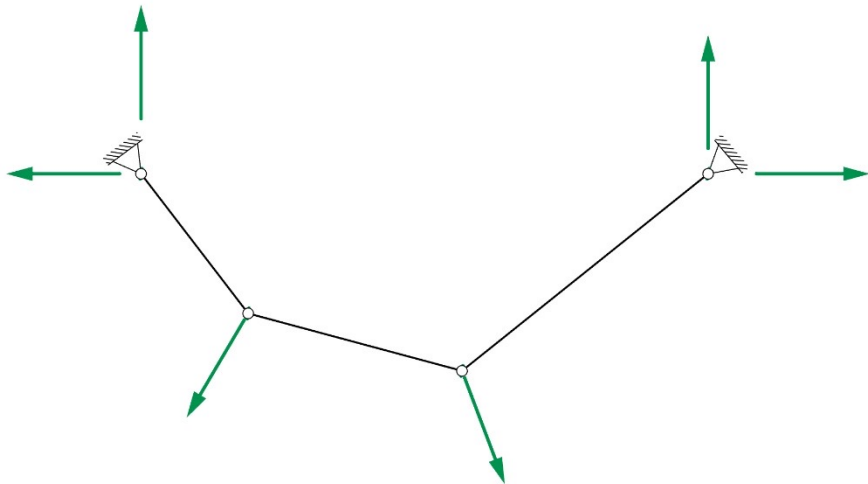
$A = 3$

Das System ist statisch unbestimmt

*The system is statically not determined*

$K = 4$

*Statical Determinacy*



$S = 3$

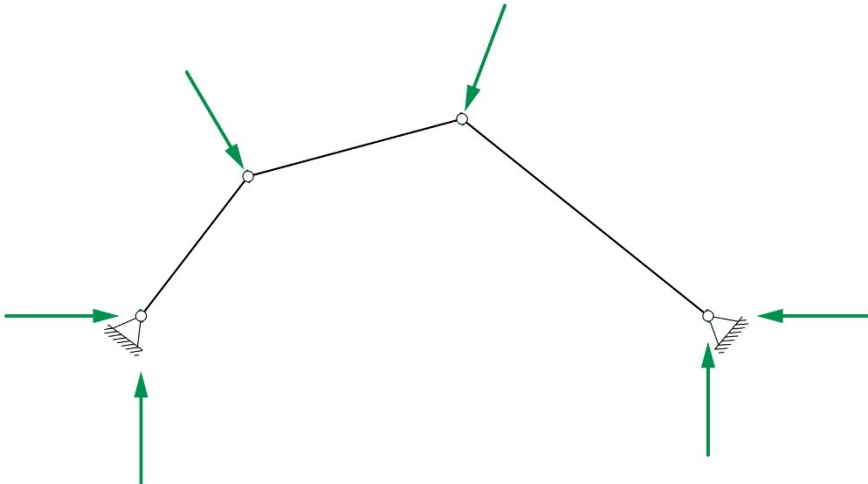
$A = 4$

$K = 4$

$S + A = 7 < 2 * K = 8$

Das System ist labil

*The system is not stable*



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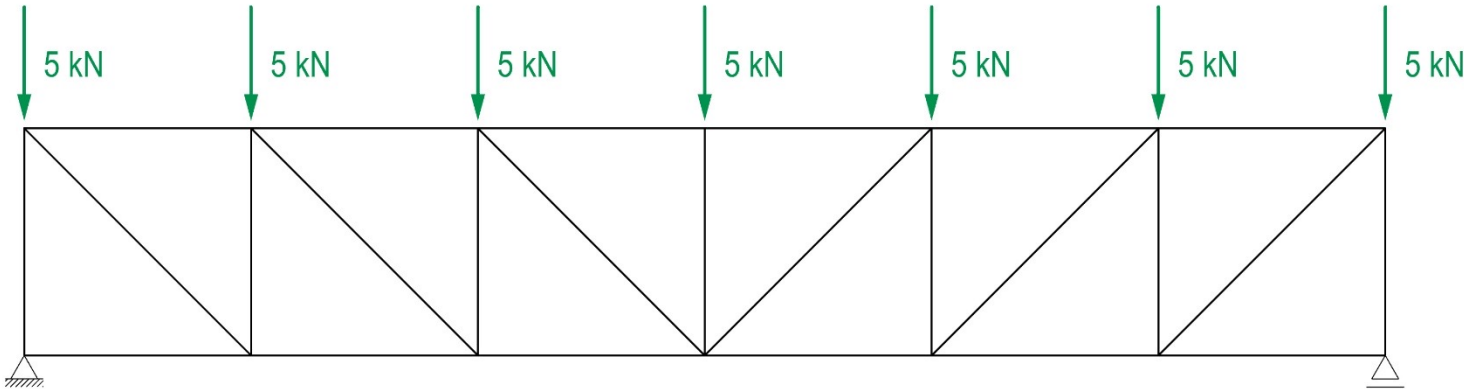
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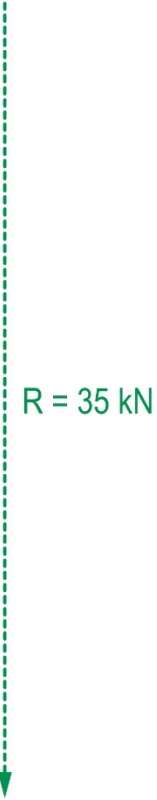
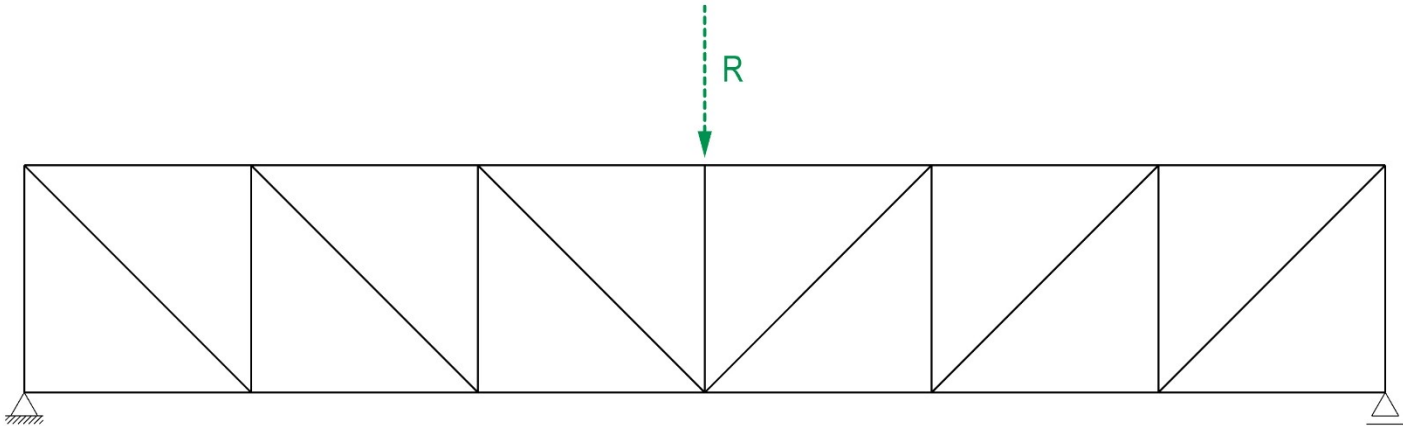


Lageplan 1:100  
Form diagram 1:100

Kräfteplan 1 cm  $\cong$  1 kN  
Force diagram 1 cm  $\cong$  1 kN

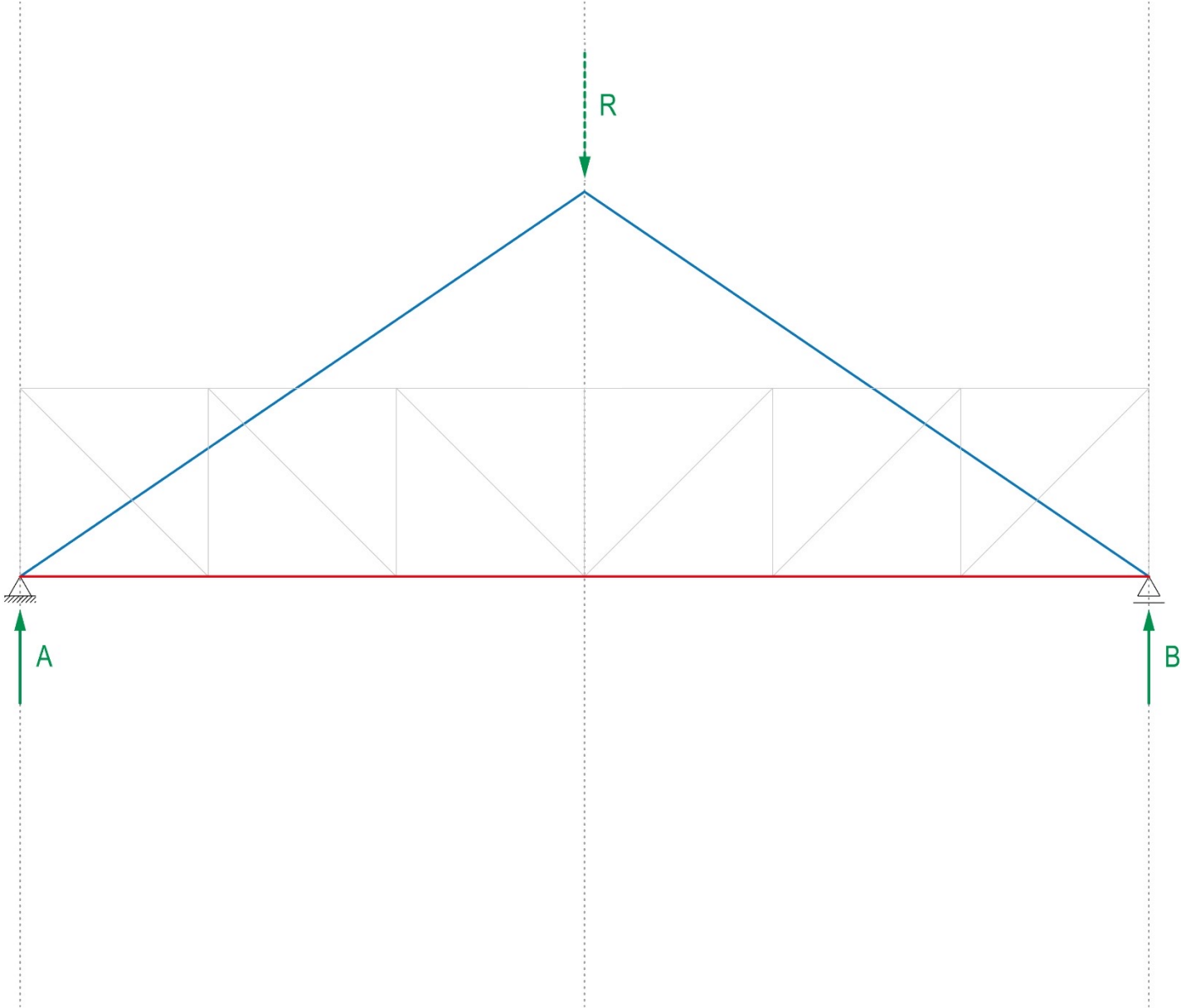


*Calculation of inner forces*

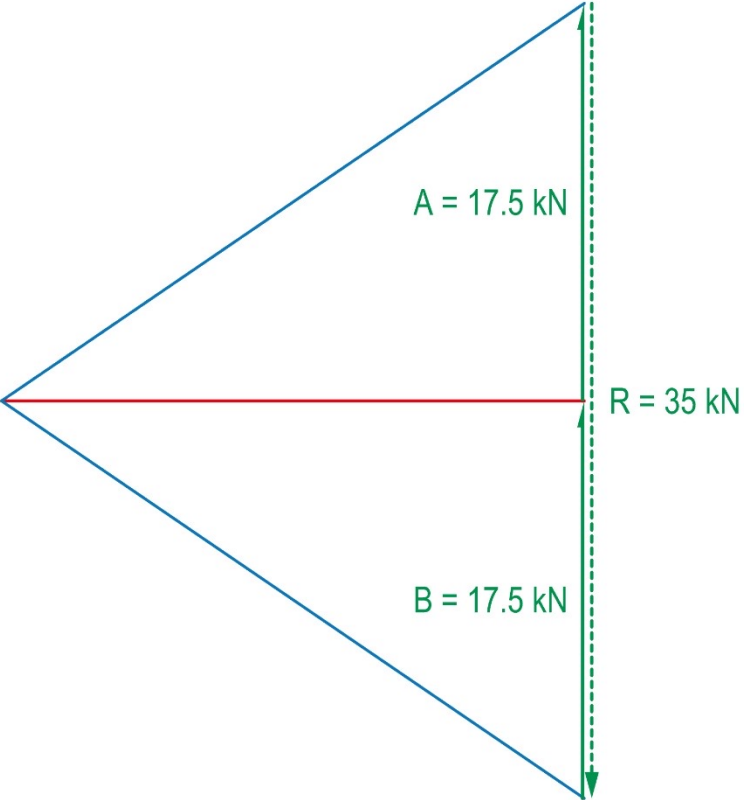


Lageplan 1:100  
*Form diagram 1:100*

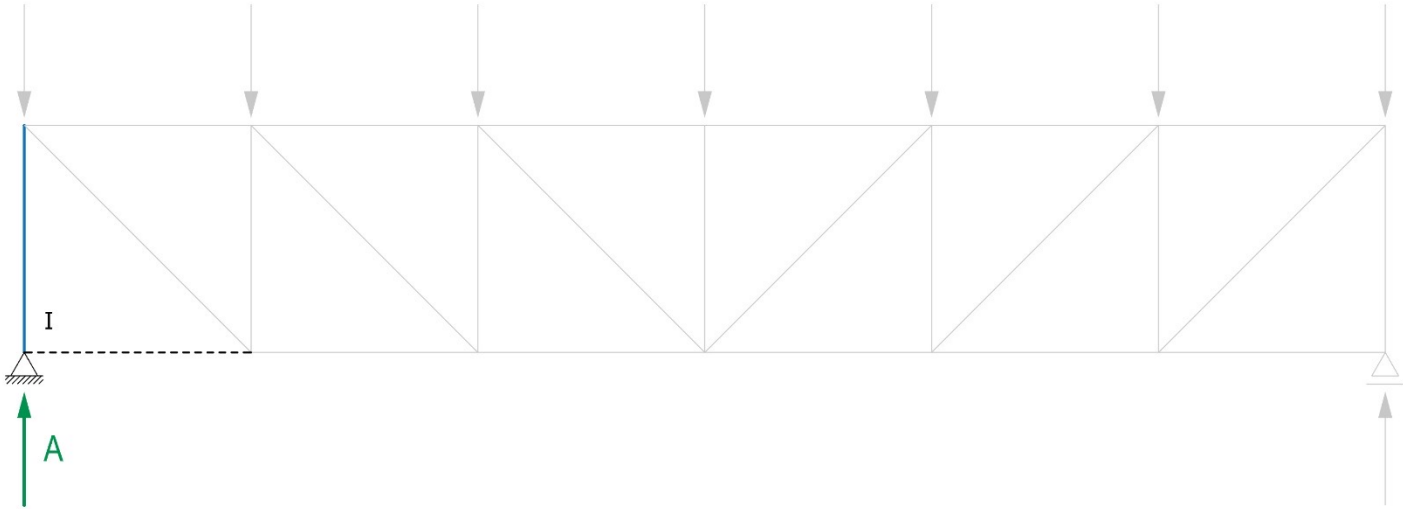
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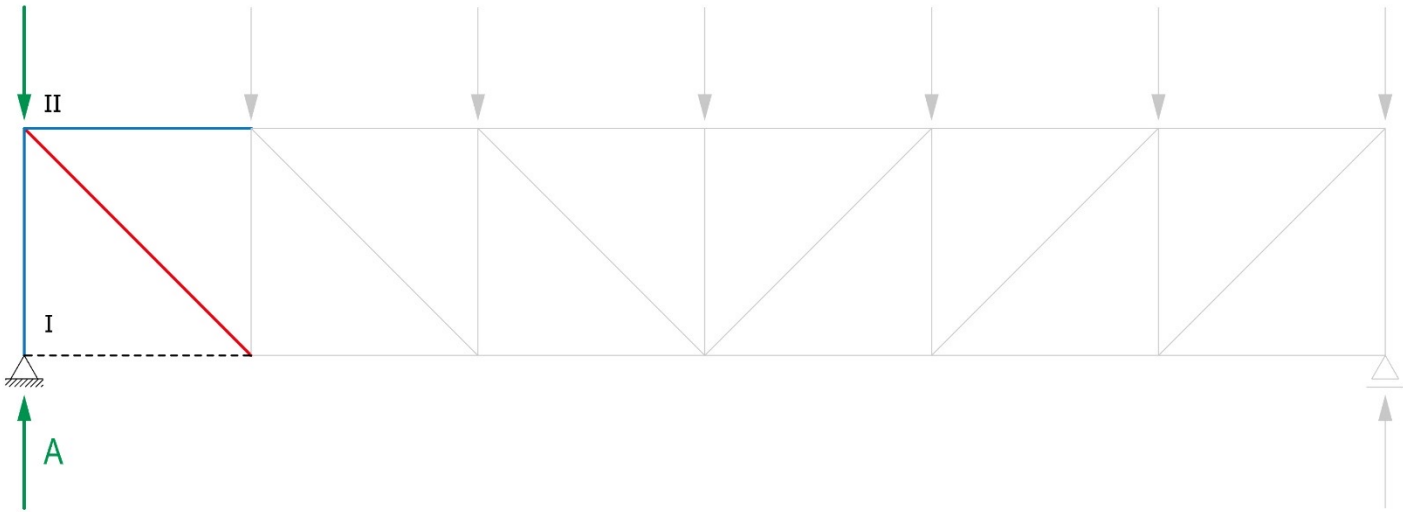


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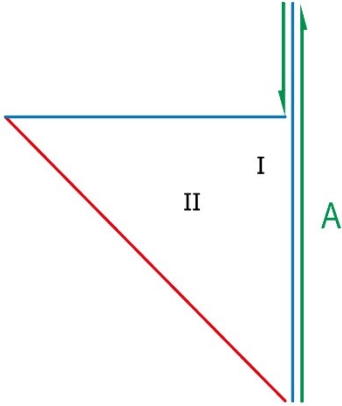


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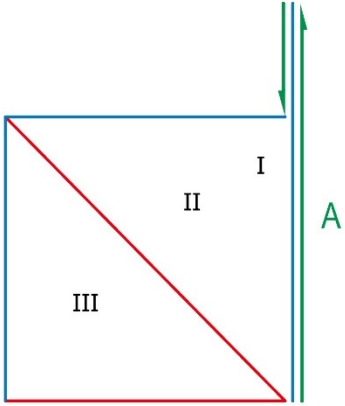
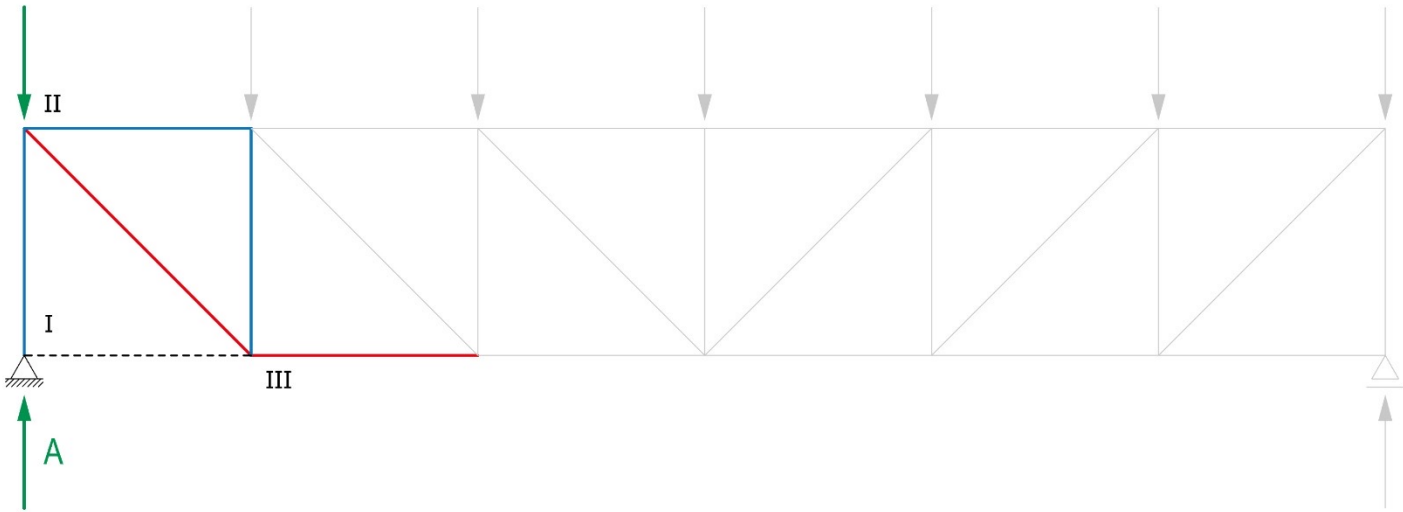
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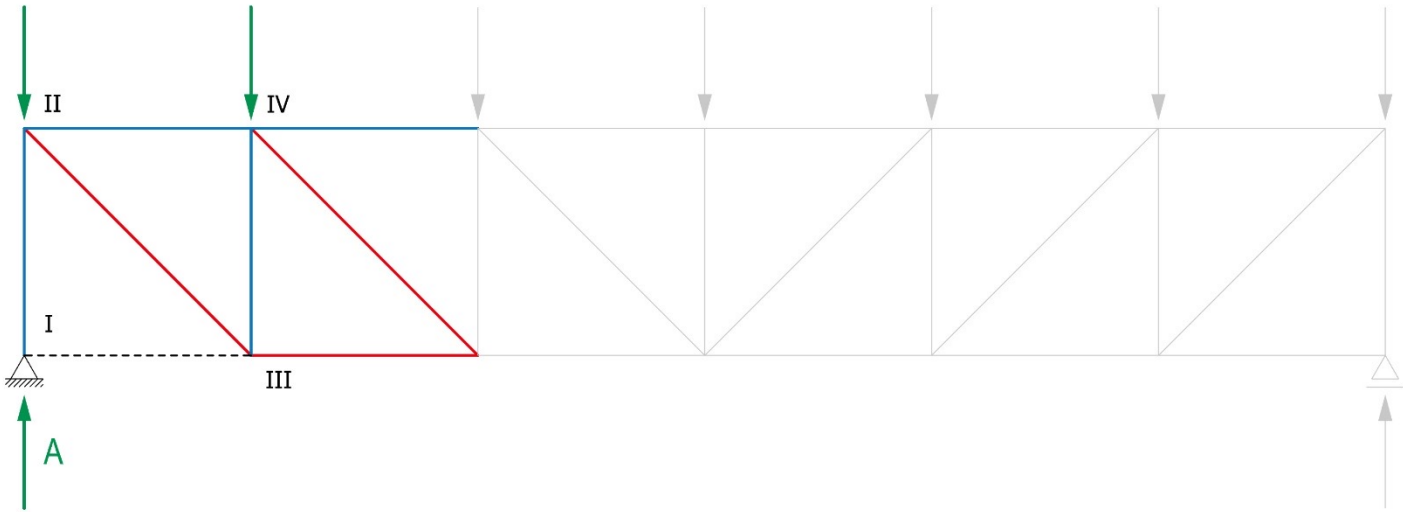


Kräfteplan 1 cm ≙ 1 kN  
 Force diagram 1 cm ≙ 1 kN

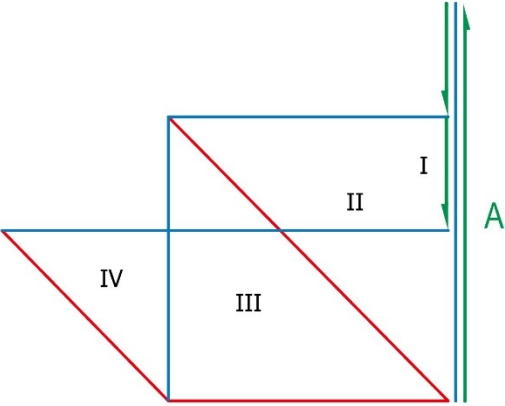


Lageplan 1:100  
Form diagram 1:100

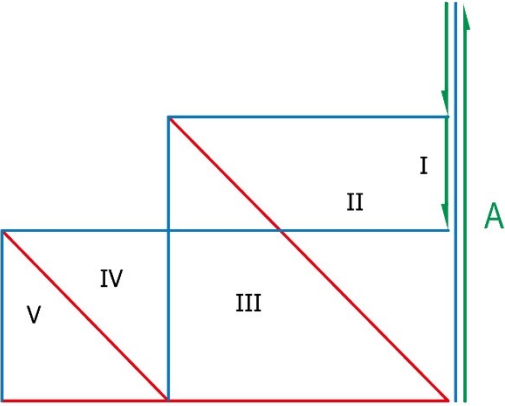
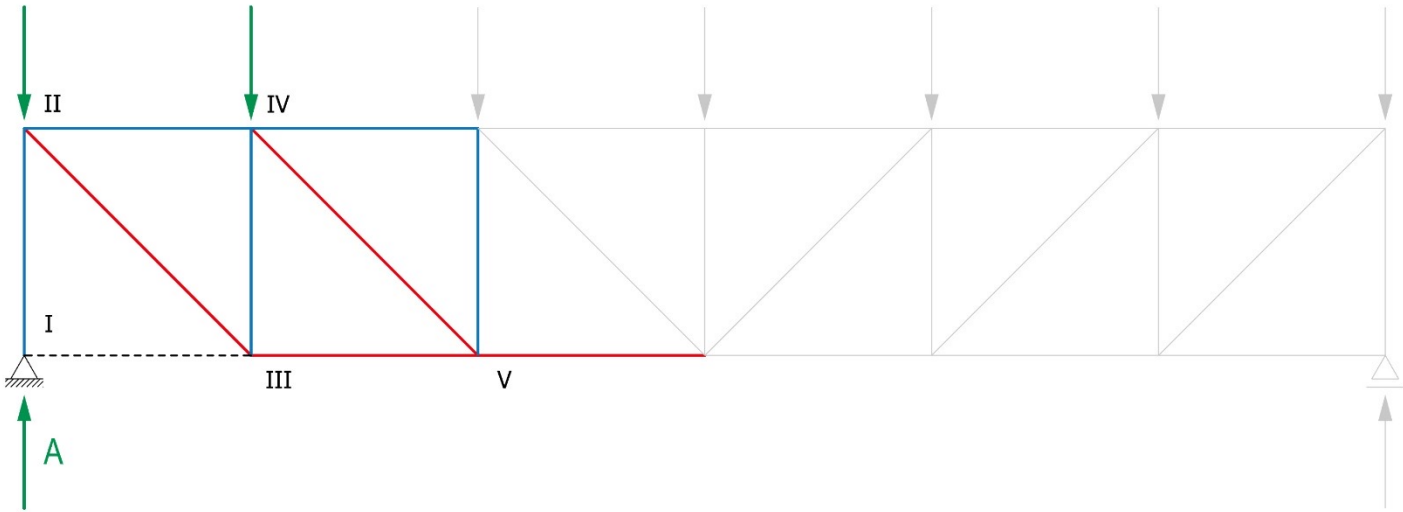
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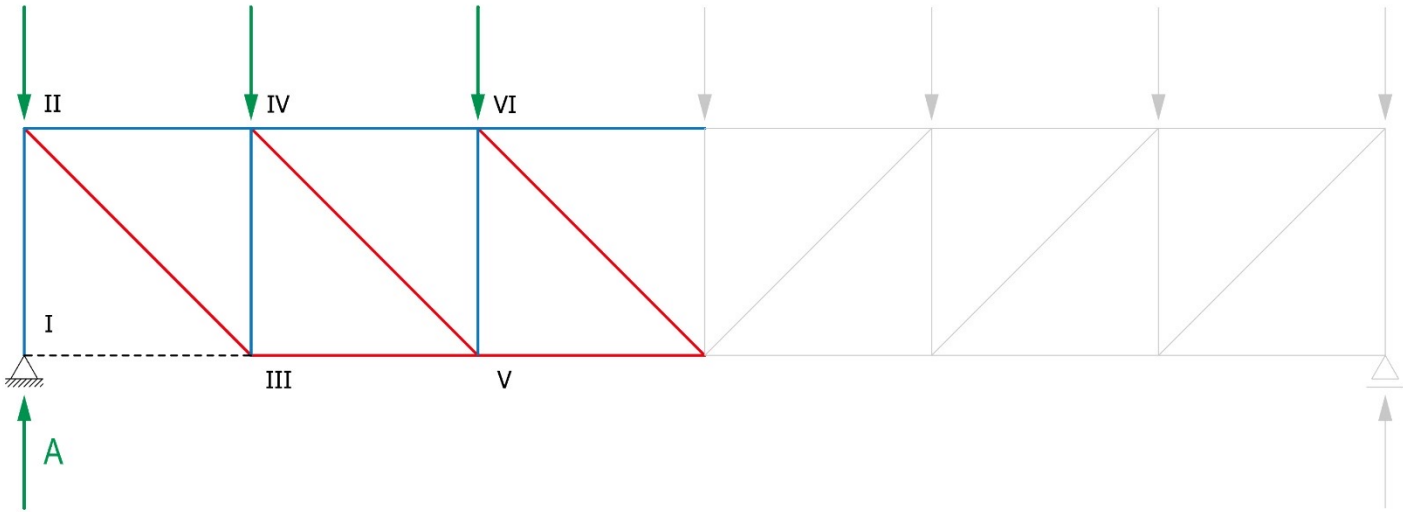


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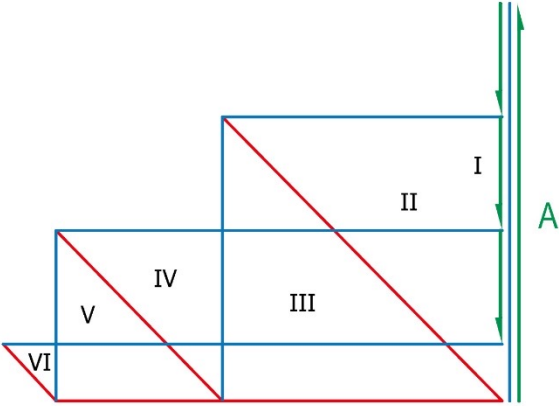


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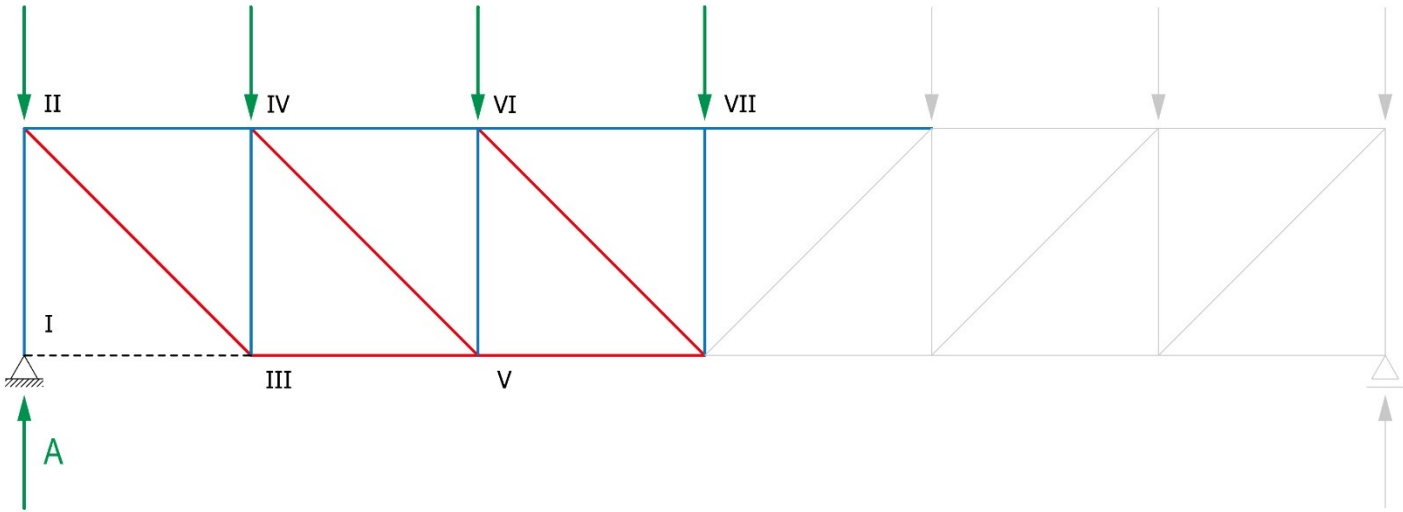


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Form diagram 1:100

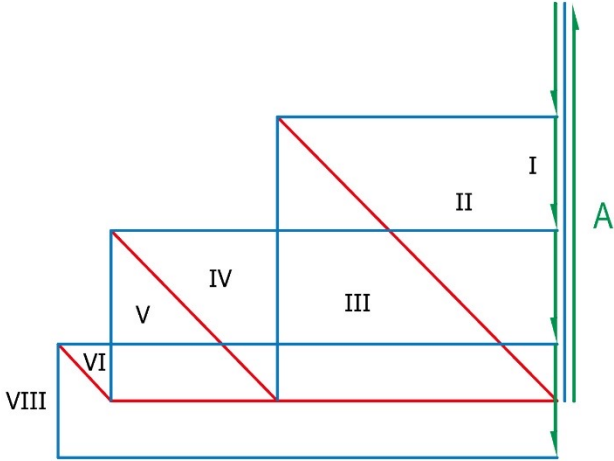


Kräfteplan 1 cm ≙ 1 kN  
Force diagram 1 cm ≙ 1 kN

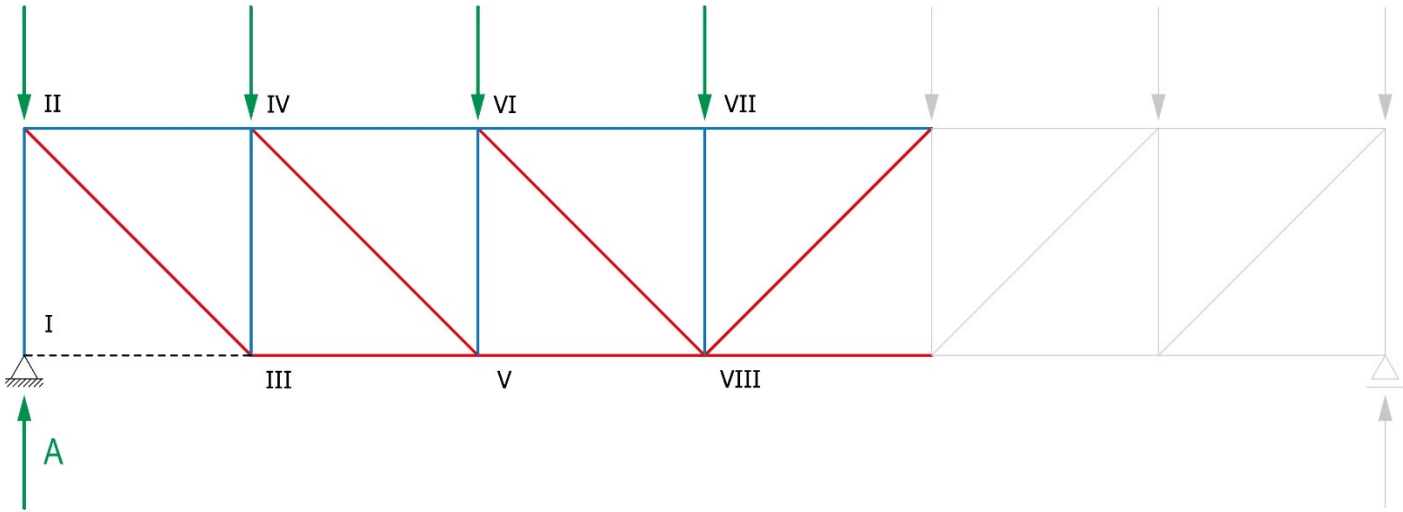




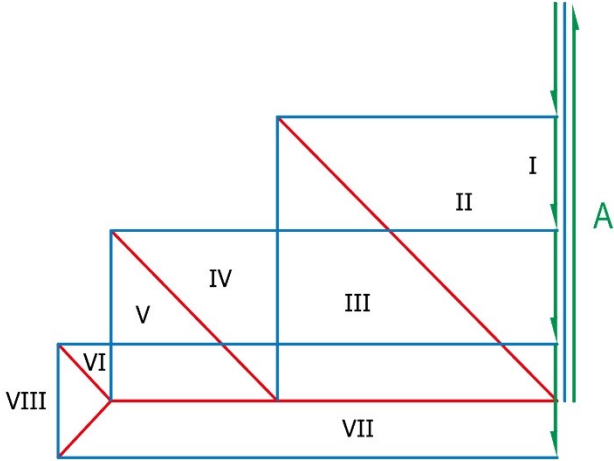
Lageplan 1:100  
Form diagram 1:100



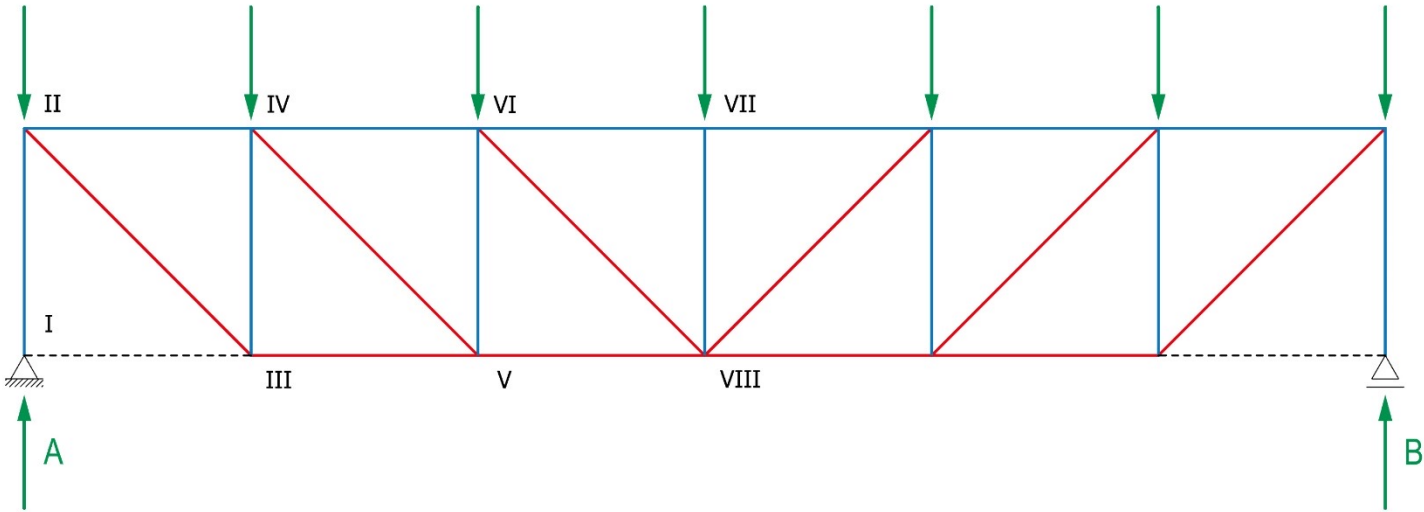
Kräfteplan 1 cm ≙ 1 kN  
Force diagram 1 cm ≙ 1 kN



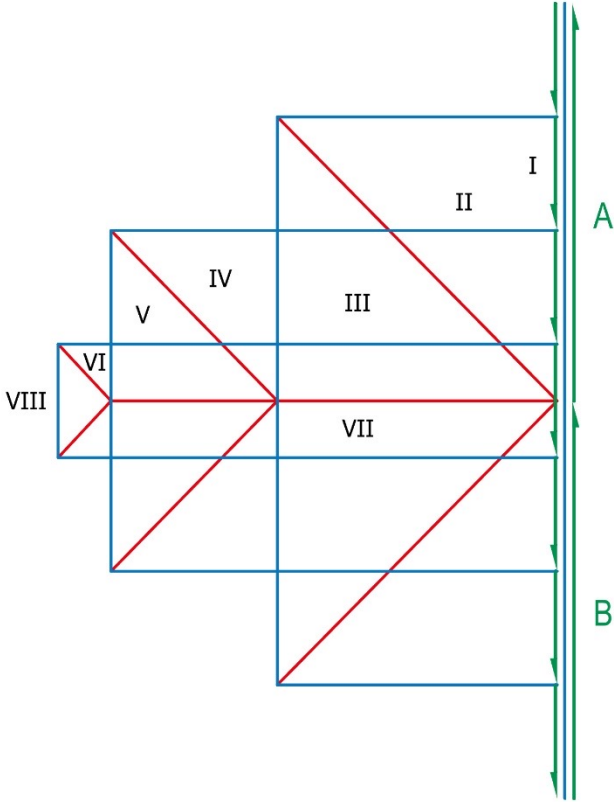
Lageplan 1:100  
Form diagram 1:100



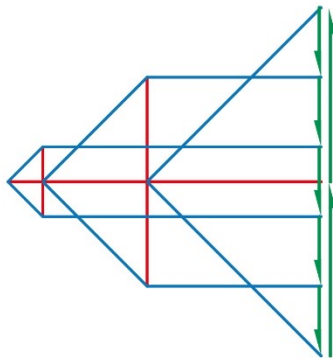
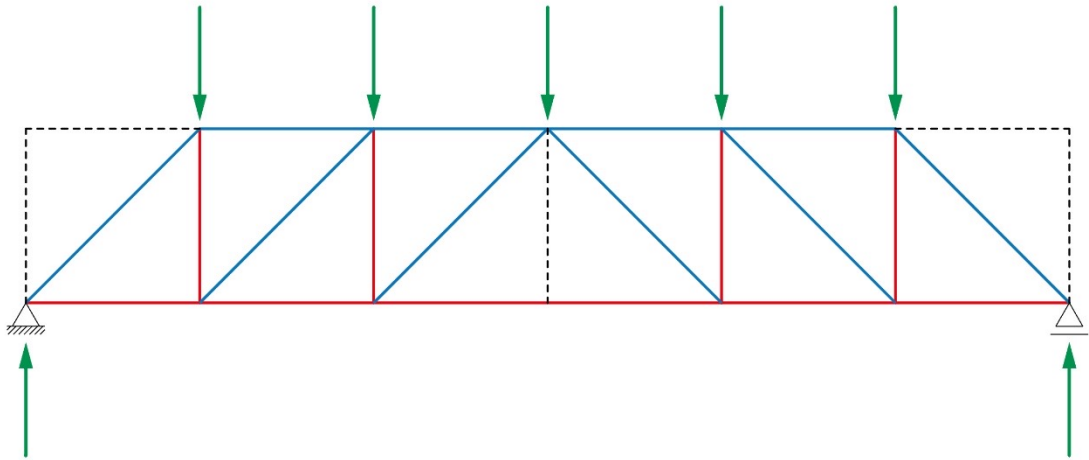
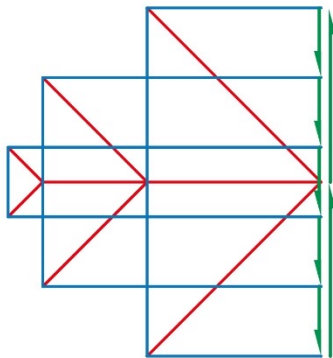
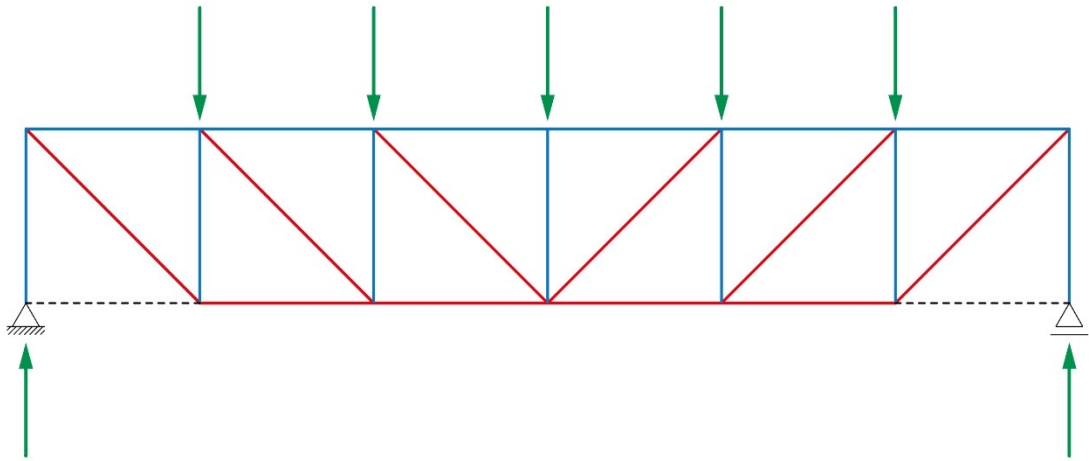
Kräfteplan 1 cm ≙ 1 kN  
Force diagram 1 cm ≙ 1 kN



Lageplan 1:100  
Form diagram 1:100



Kräfteplan 1 cm ≙ 1 kN  
Force diagram 1 cm ≙ 1 kN



Lageplan 1:100  
 Form diagram 1:100

Kräfteplan 1 cm  $\cong$  1 kN  
 Force diagram 1 cm  $\cong$  1 kN

eQ: Pratt / Howe truss

mode = 0

scales forces show/hide

Form Diagram

Force Diagram

Howe / Pratt  offsetLoads = 0  offsetReactionForces = 0.6

<http://www.block.arch.ethz.ch/eq/drawing/view/37>

# Fachwerke

## *Trusses*

Von Bogen-Seiltragwerken zu Fachwerken

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*Geometric variation*

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Variation der Randbedingungen

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Schlankheit von Fachwerken

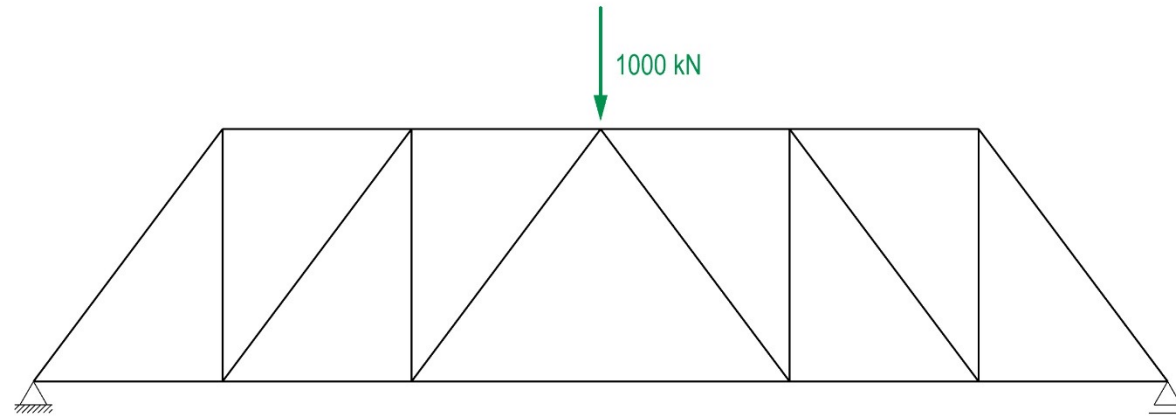
*Slender trusses*

Konstruktion von Fachwerken

*Construction of trusses*

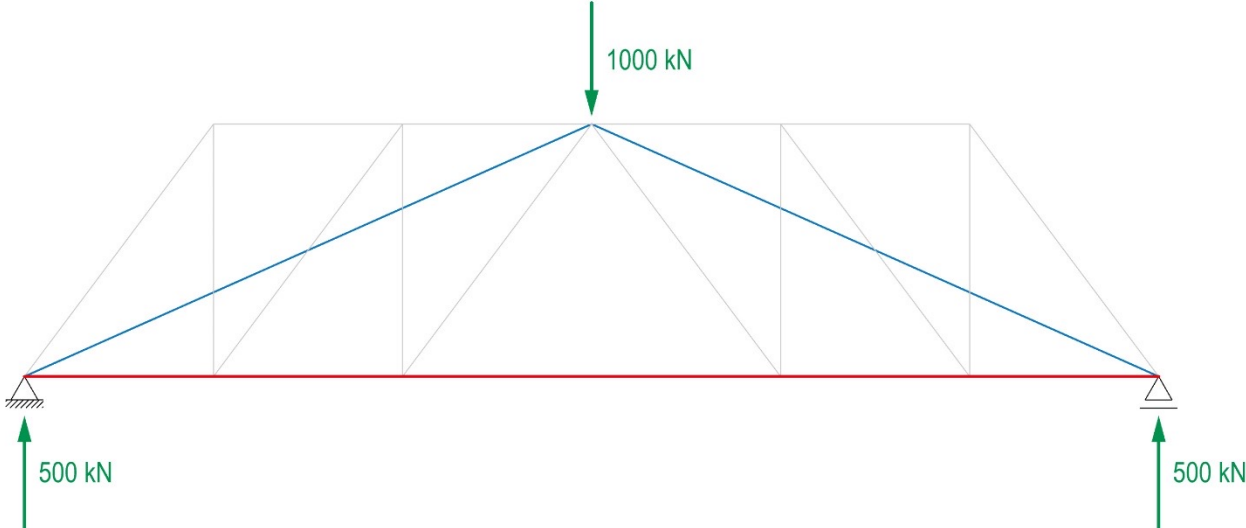
Räumliche Fachwerke

*Spatial trusses*

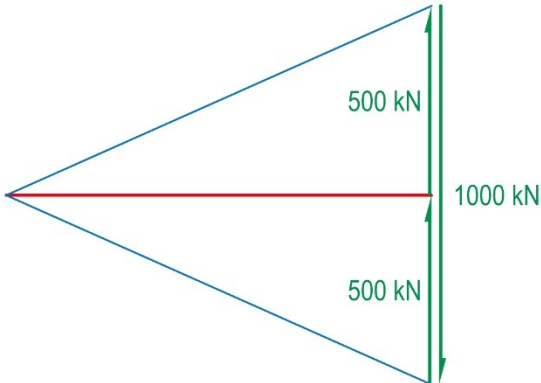


Lageplan 1:100  
*Form diagram 1:100*

Kräfteplan 1 cm  $\cong$  1 kN  
*Force diagram 1 cm  $\cong$  1 kN*

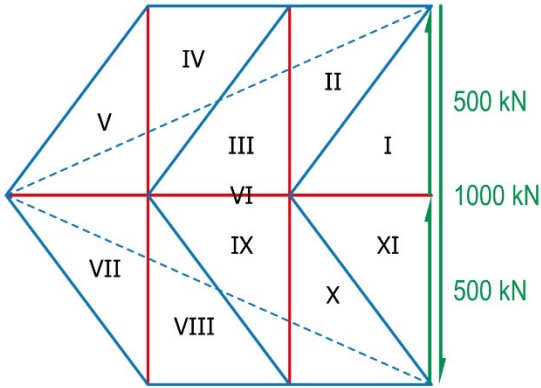
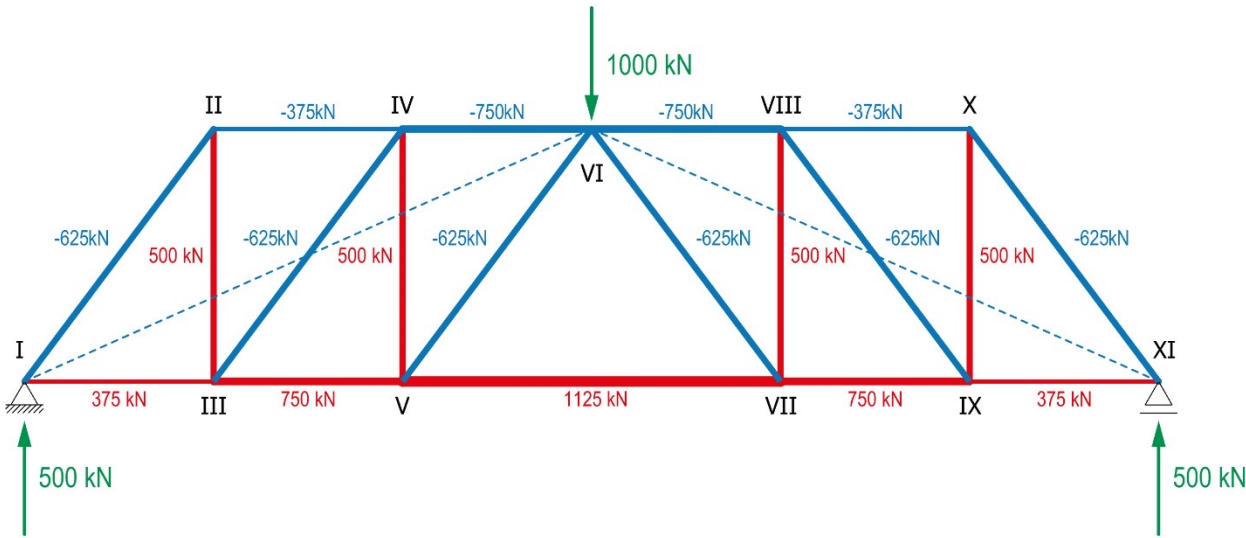


Lageplan 1:100  
*Form diagram 1:100*



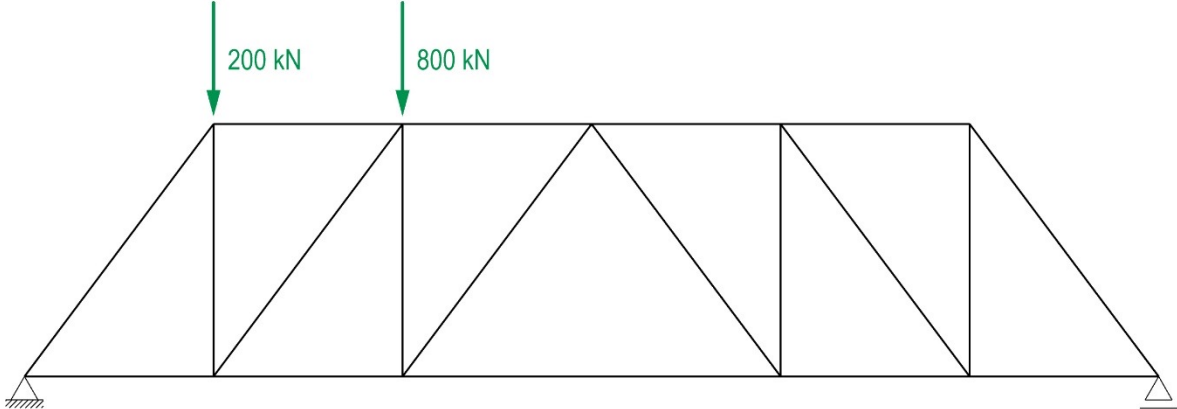
Kräfteplan 1 cm ≙ 1 kN  
*Force diagram 1 cm ≙ 1 kN*





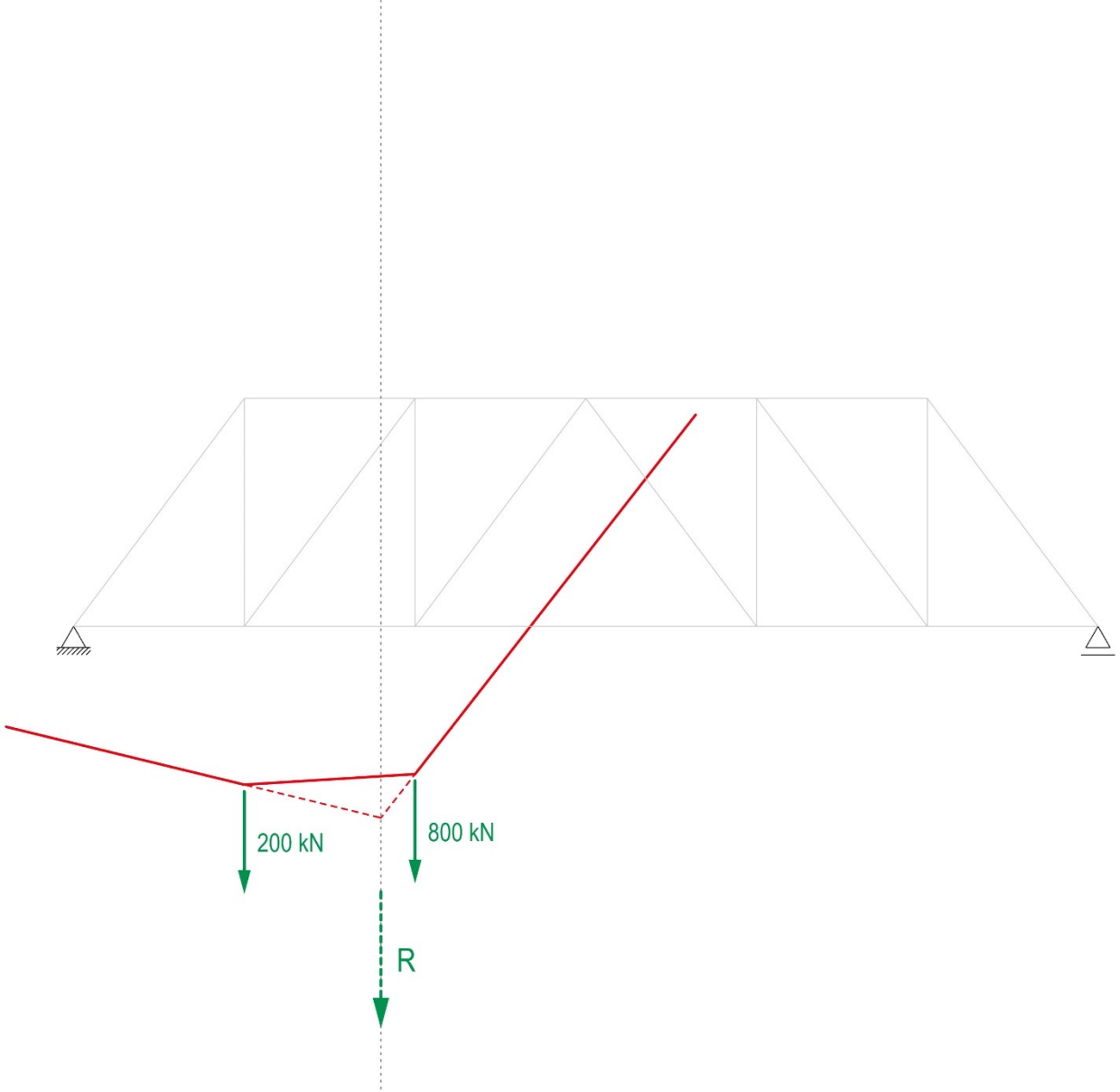
Lageplan 1:100  
*Form diagram 1:100*

Kräfteplan 1 cm  $\cong$  1 kN  
*Force diagram 1 cm  $\cong$  1 kN*

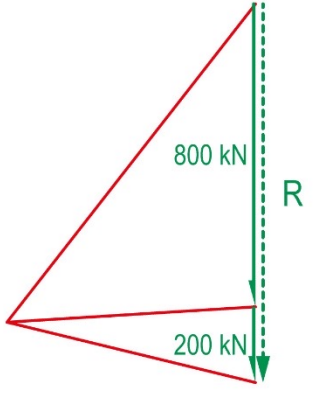


Lageplan 1:100  
*Form diagram 1:100*

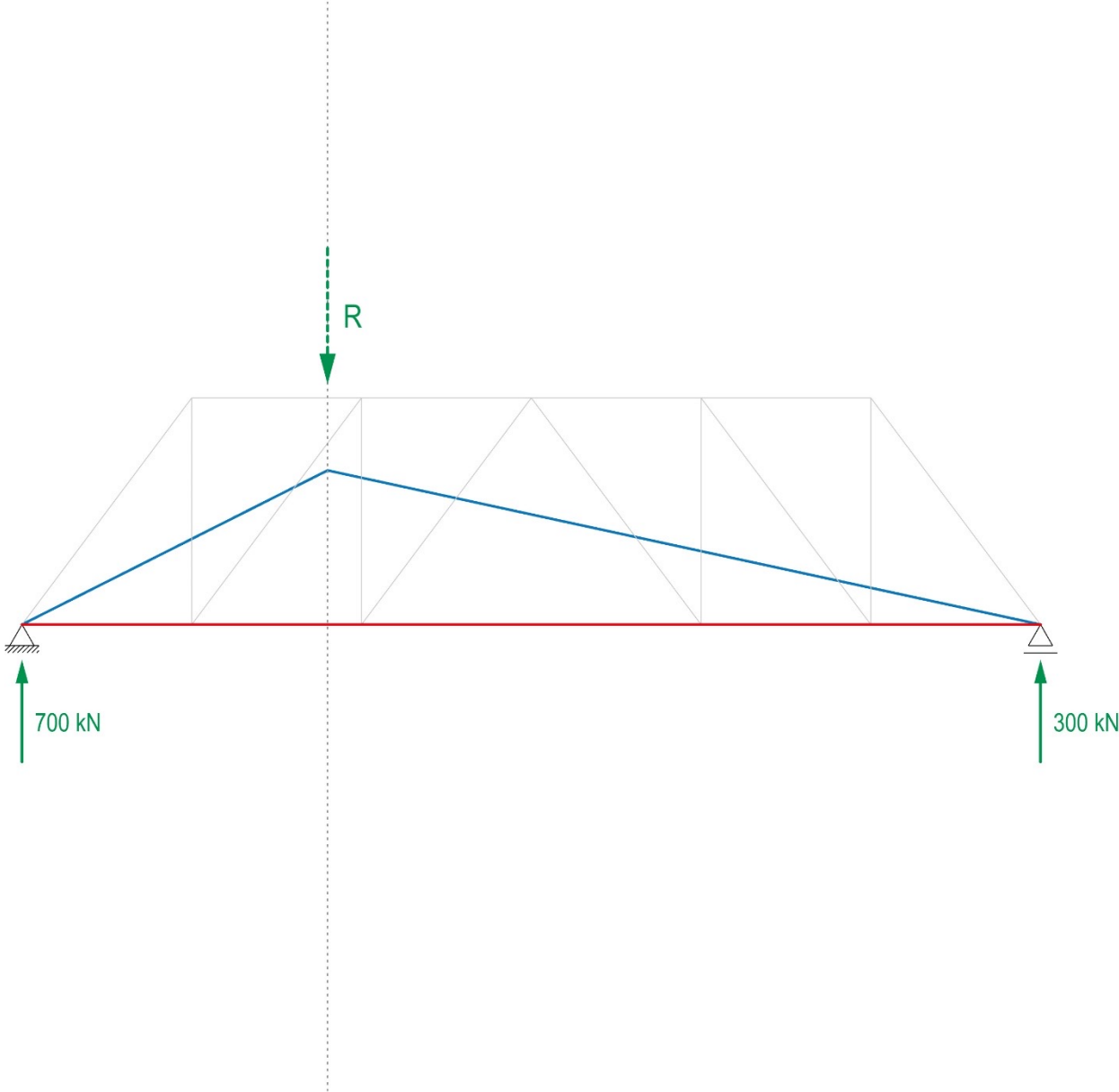
Kräfteplan 1 cm  $\cong$  1 kN  
*Force diagram 1 cm  $\cong$  1 kN*



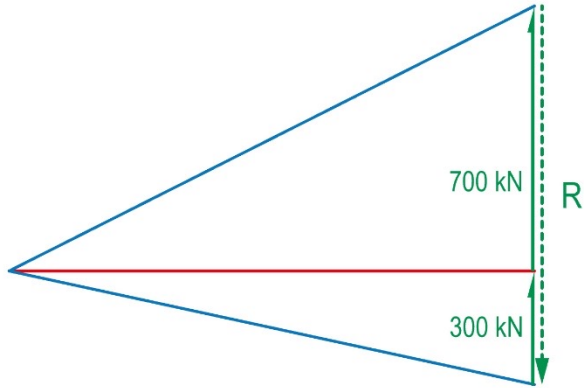
Lageplan 1:100  
*Form diagram 1:100*



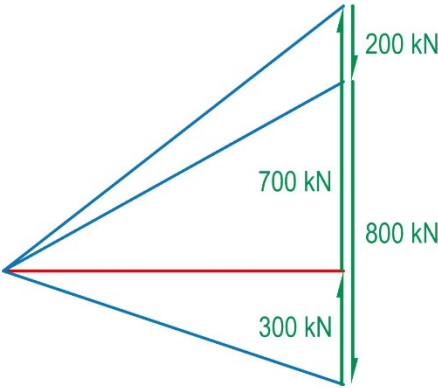
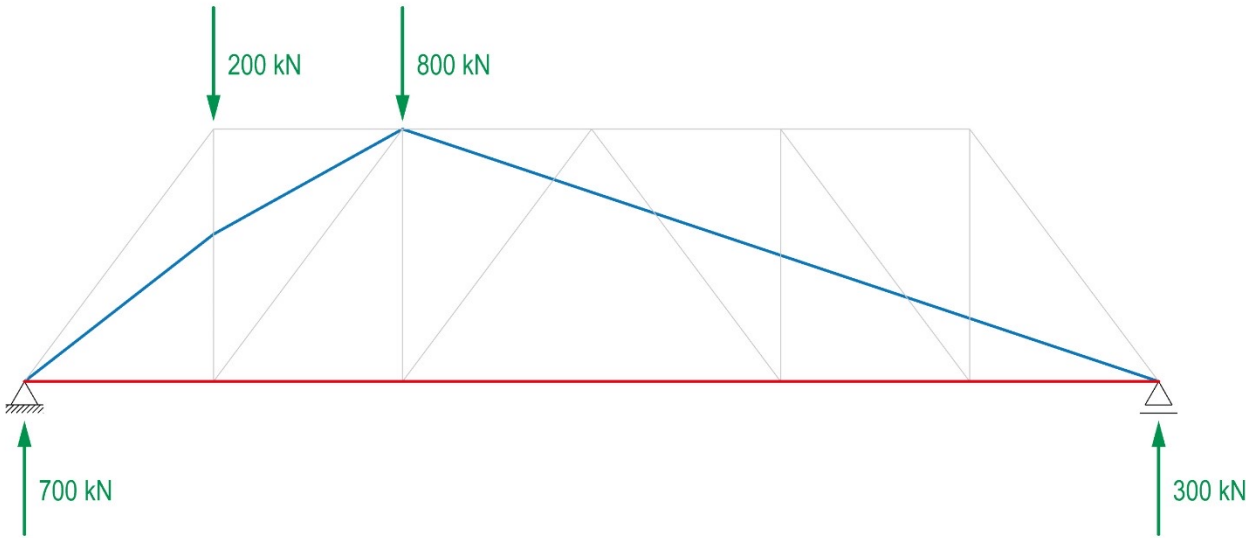
Kräfteplan 1 cm ≙ 1 kN  
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Lageplan 1:100  
*Form diagram 1:100*

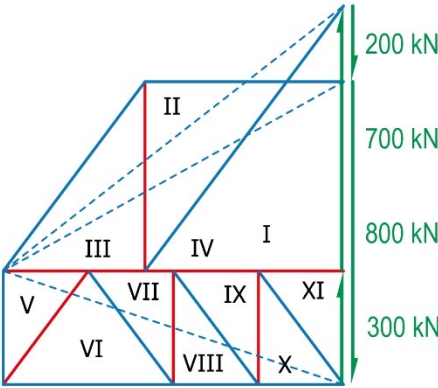
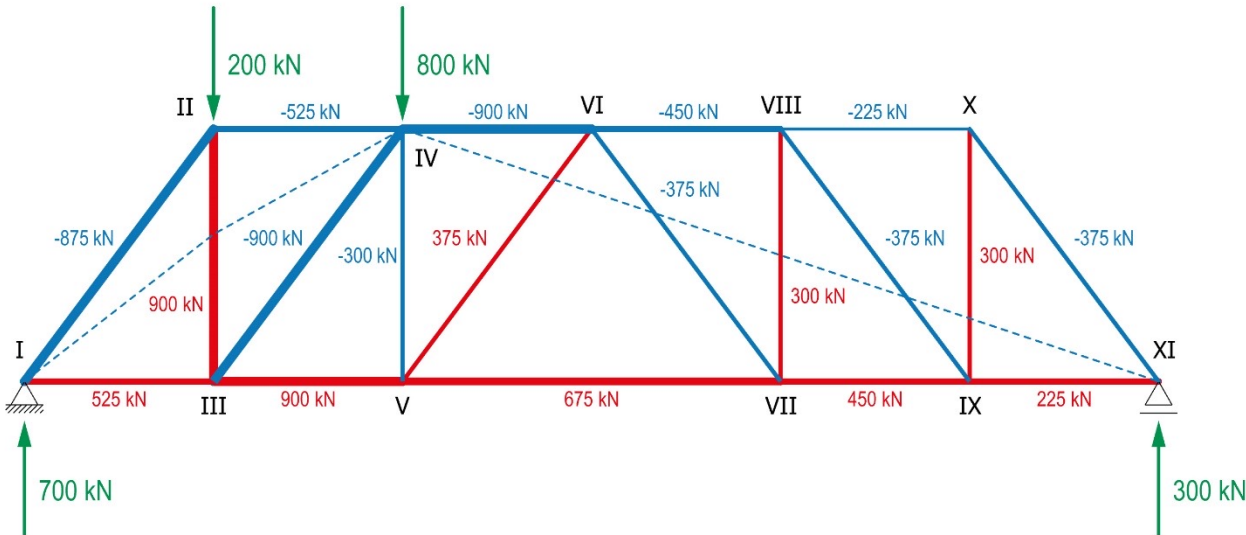


Kräfteplan 1 cm  $\cong$  1 kN  
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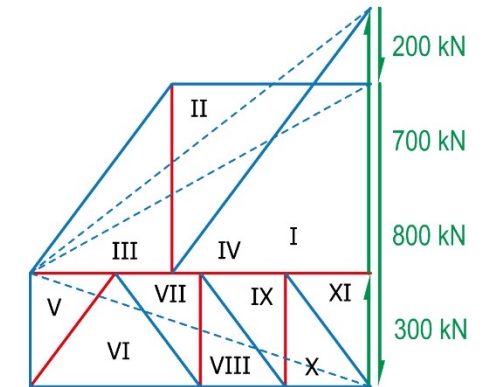
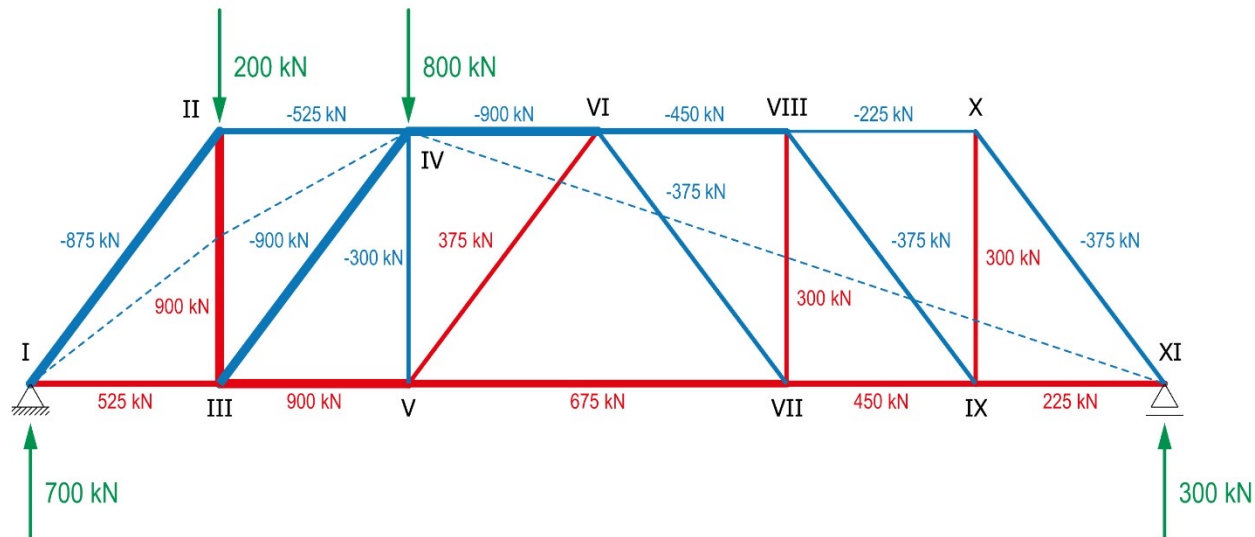
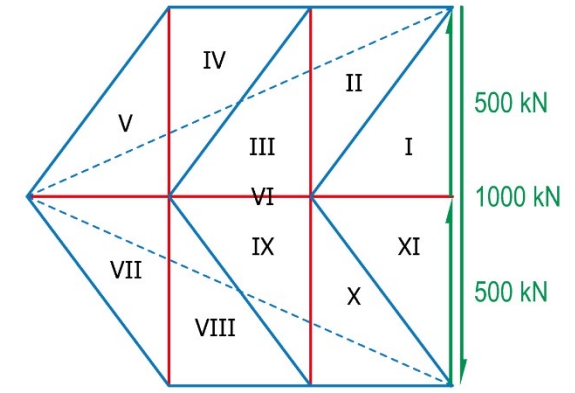
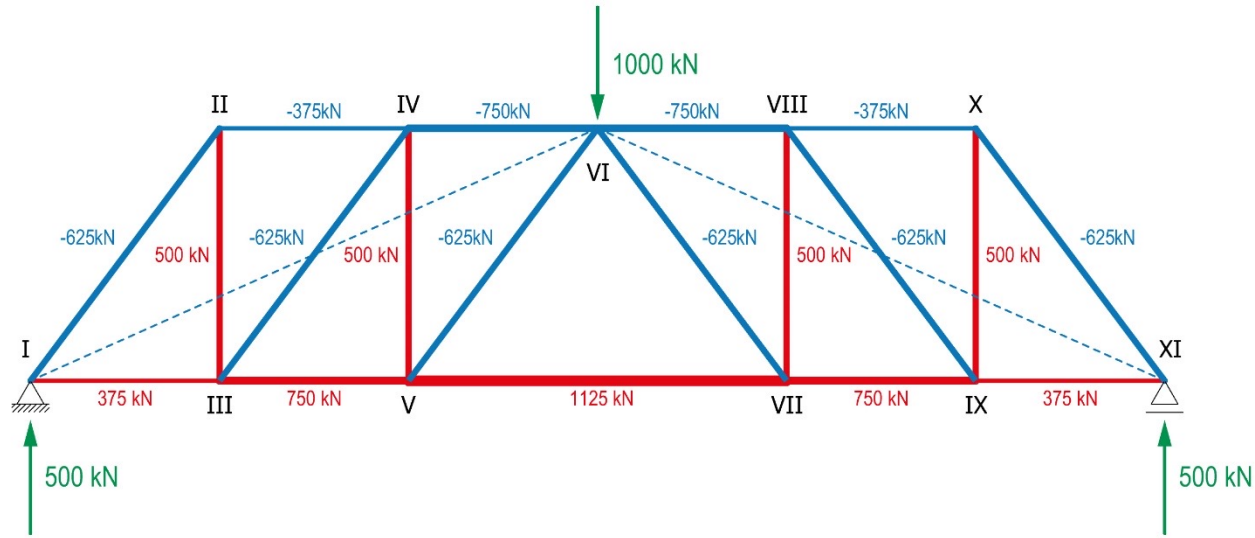
Lageplan 1:100  
*Form diagram 1:100*

Kräfteplan 1 cm  $\cong$  1 kN  
*Force diagram 1 cm  $\cong$  1 kN*



Lageplan 1:100  
*Form diagram 1:100*

Kräfteplan 1 cm ≅ 1 kN  
*Force diagram 1 cm ≅ 1 kN*



Lageplan 1:100  
Form diagram 1:100

Kräfteplan 1 cm  $\cong$  1 kN  
Force diagram 1 cm  $\cong$  1 kN

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*Geometric variation*

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Variation der Randbedingungen

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Schlankheit von Fachwerken

*Slender trusses*

Konstruktion von Fachwerken

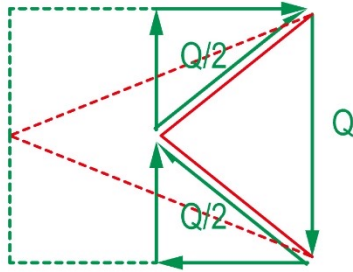
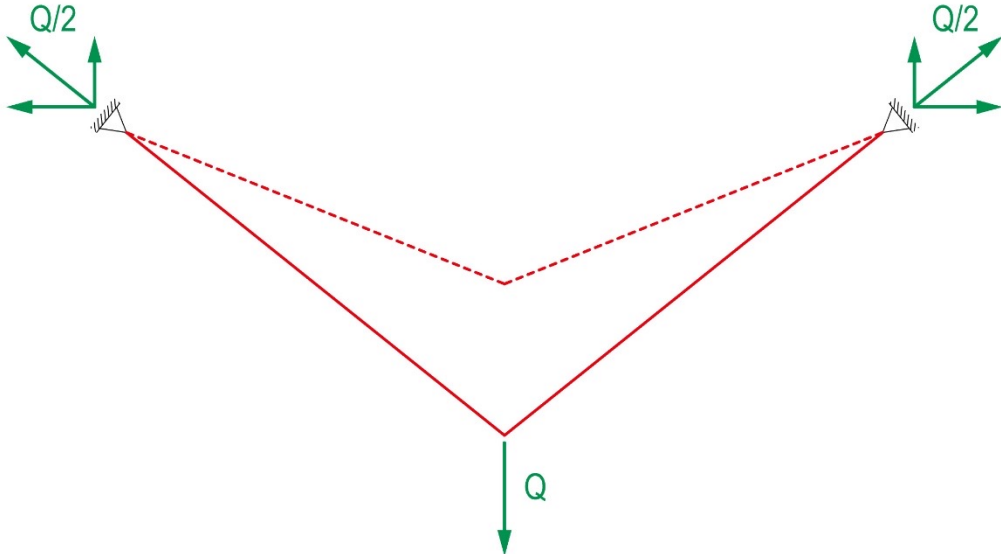
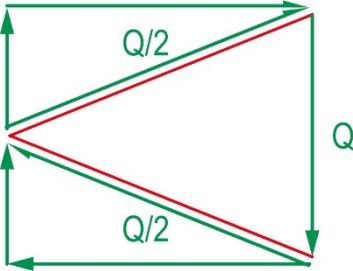
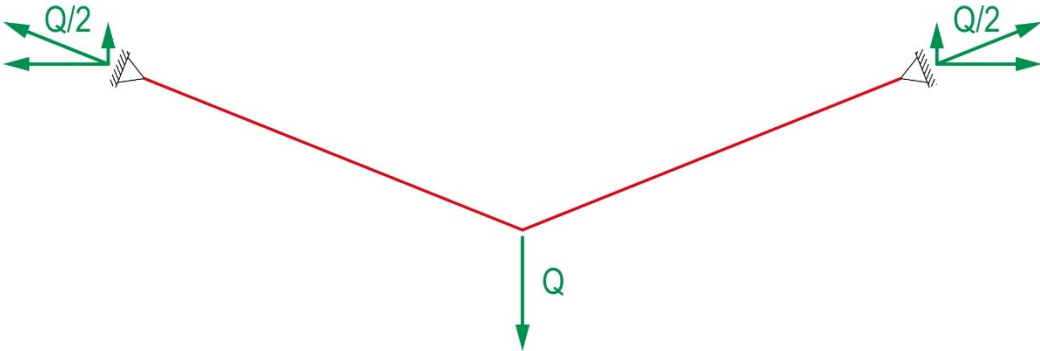
*Construction of trusses*

Räumliche Fachwerke

*Spatial trusses*



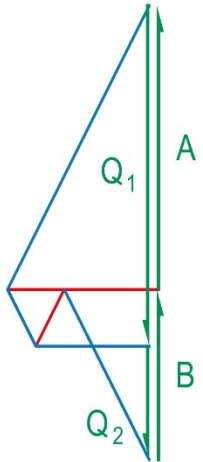
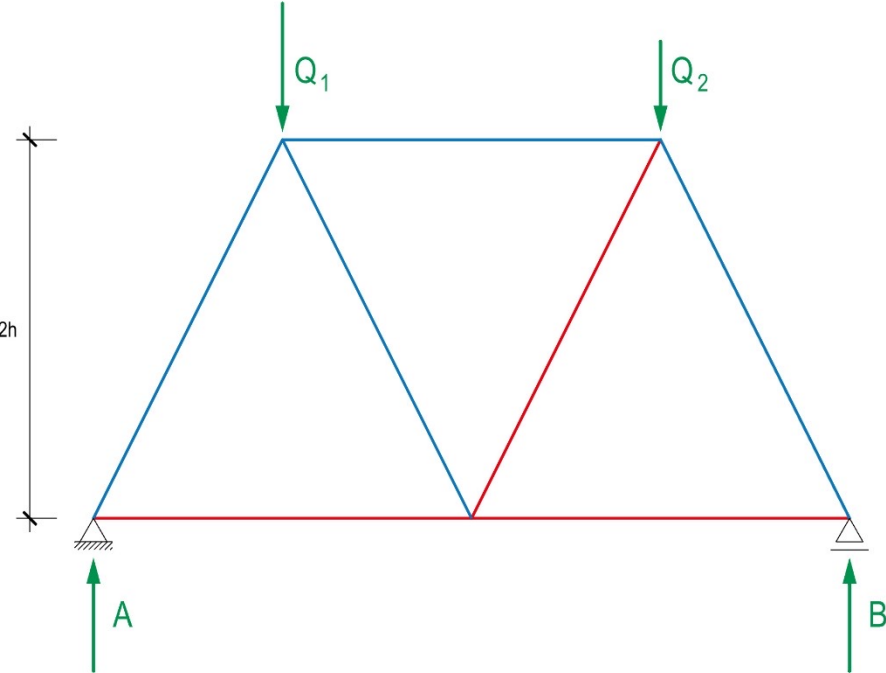
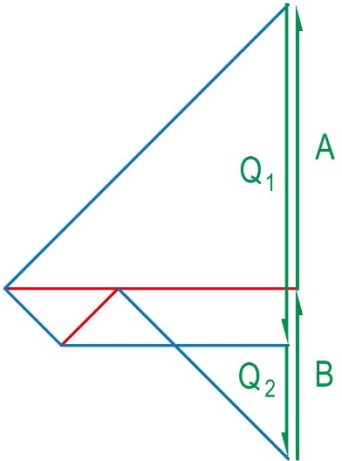
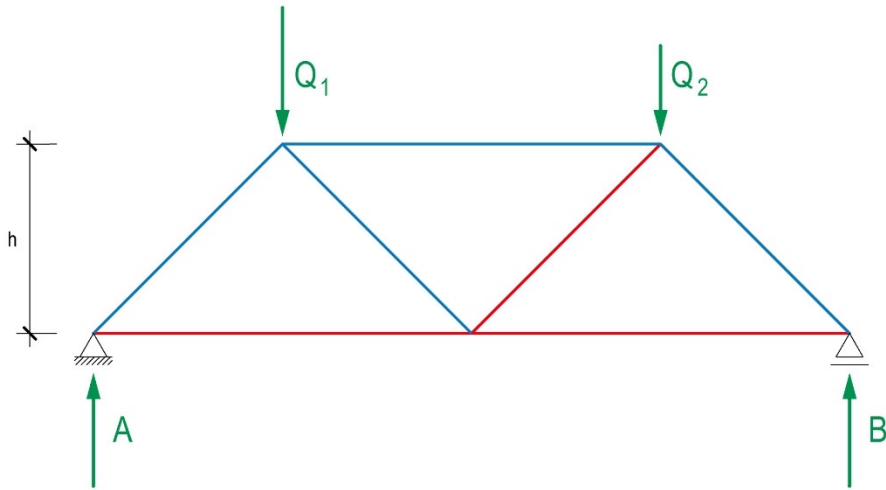
*Geometric variation*



Lageplan 1:100  
*Form diagram 1:100*

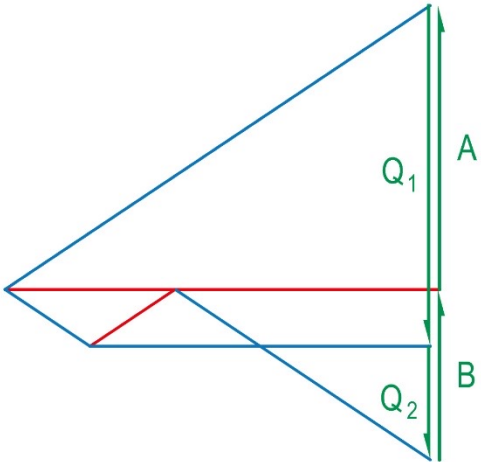
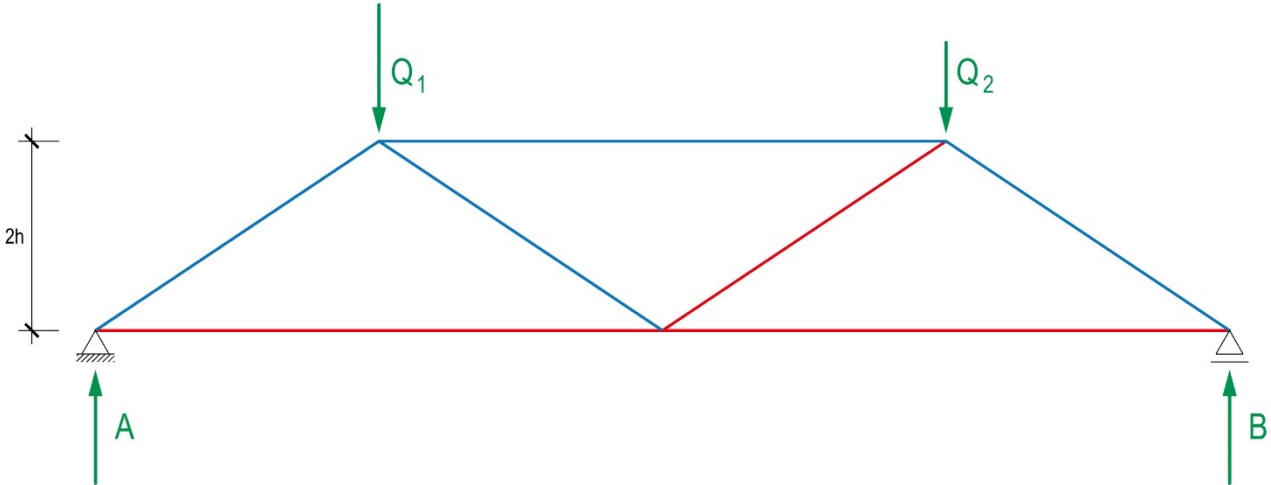
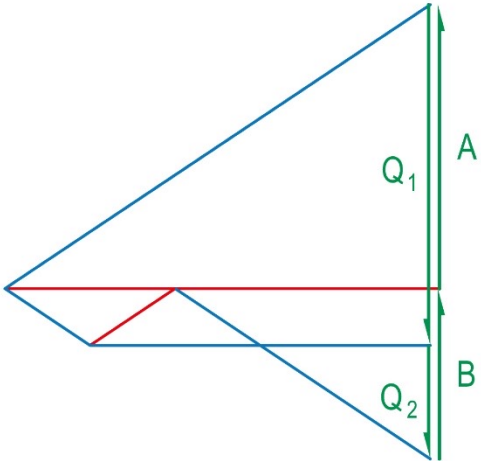
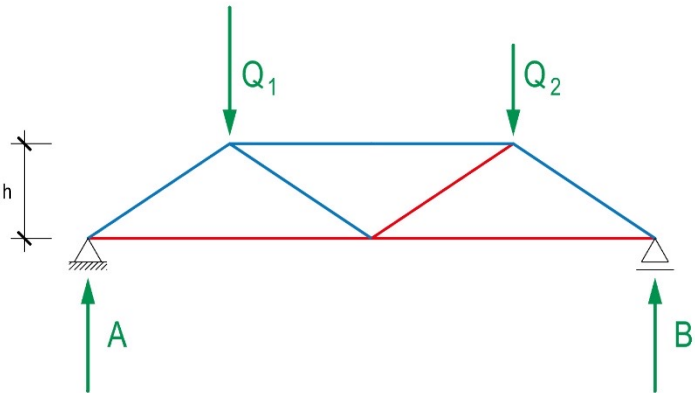
Kräfteplan 1 cm  $\cong$  1 kN  
*Force diagram 1 cm  $\cong$  1 kN*

*Geometric variation*



Lageplan 1:100  
*Form diagram 1:100*

Kräfteplan 1 cm ≅ 1 kN  
*Force diagram 1 cm ≅ 1 kN*



Lageplan 1:100  
*Form diagram 1:100*

Kräfteplan 1 cm ≙ 1 kN  
*Force diagram 1 cm ≙ 1 kN*

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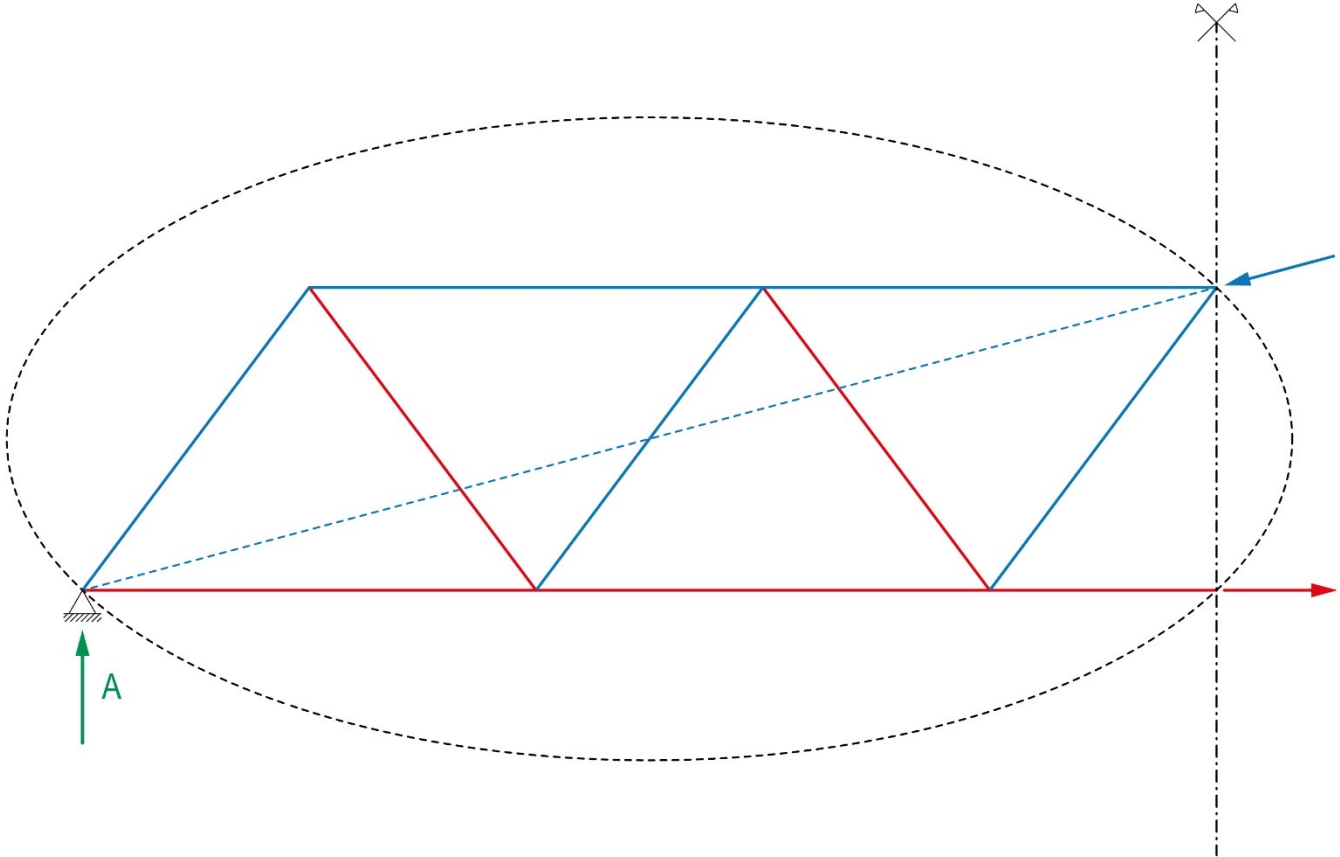
*Slender trusses*

Konstruktion von Fachwerken

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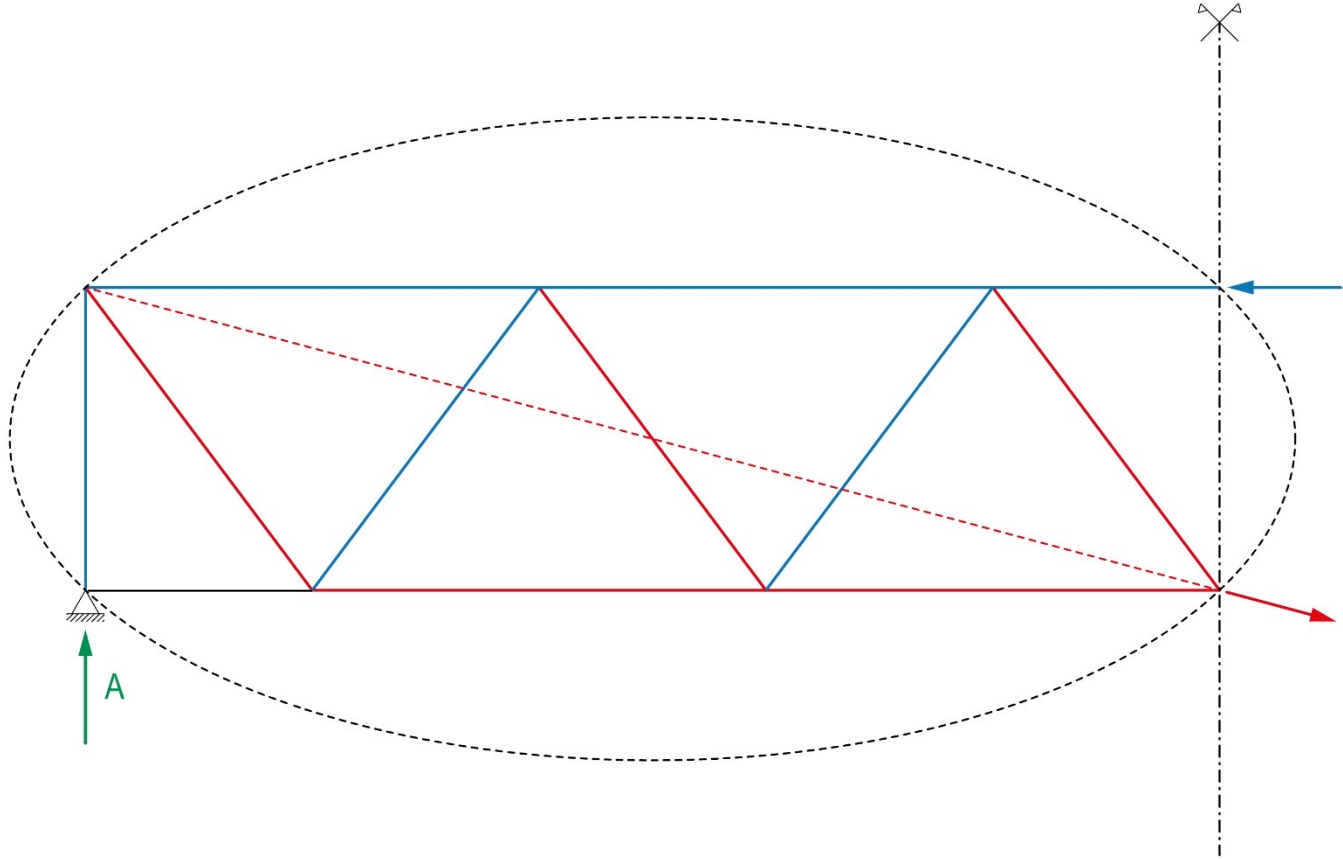
Räumliche Fachwerke

*Spatial trusses*



Fachwerk mit V-förmigen Diagonalen: System Warren

*Truss with V-shaped diagonals: System Warren*

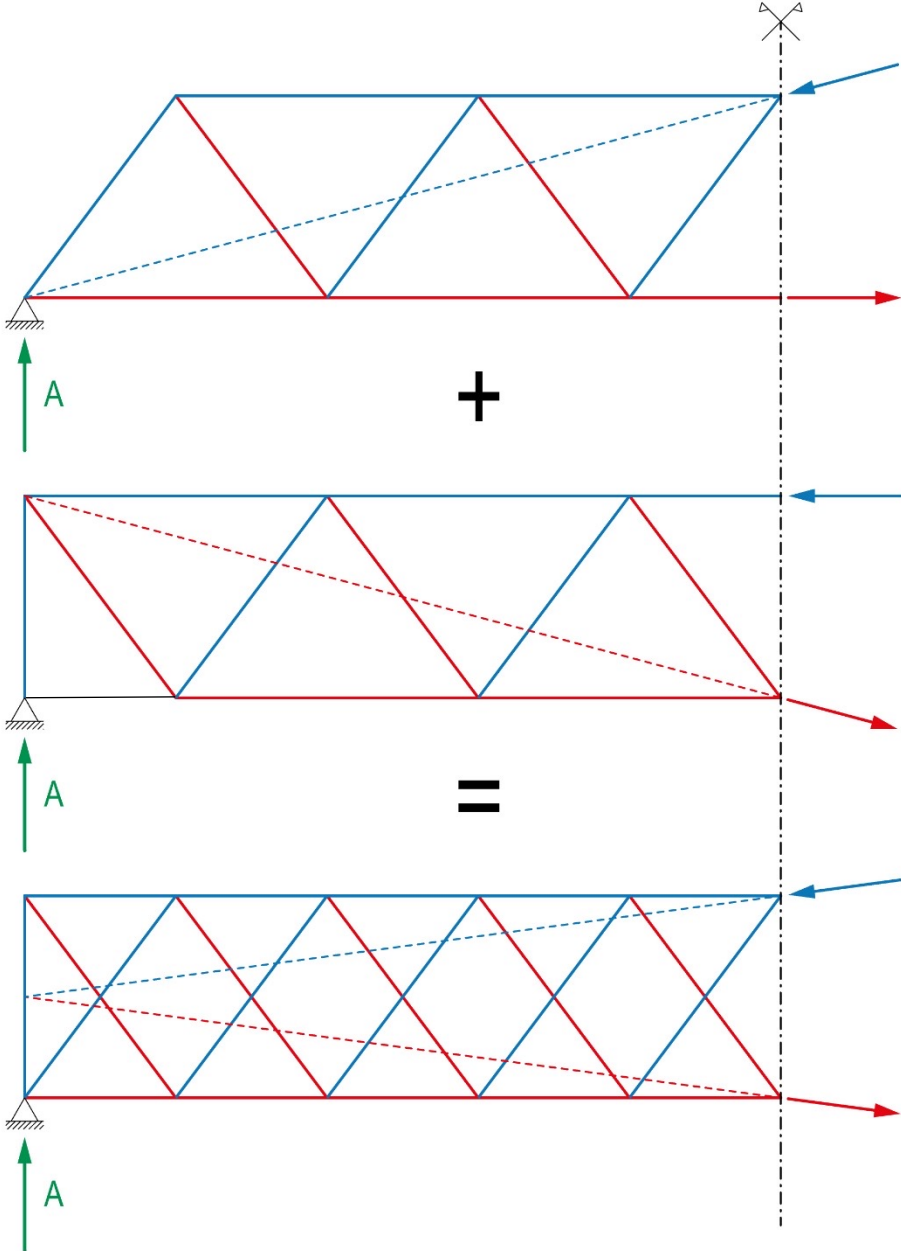


Fachwerk mit V-förmigen Diagonalen: System Warren

*Truss with V-shaped diagonals: System Warren*



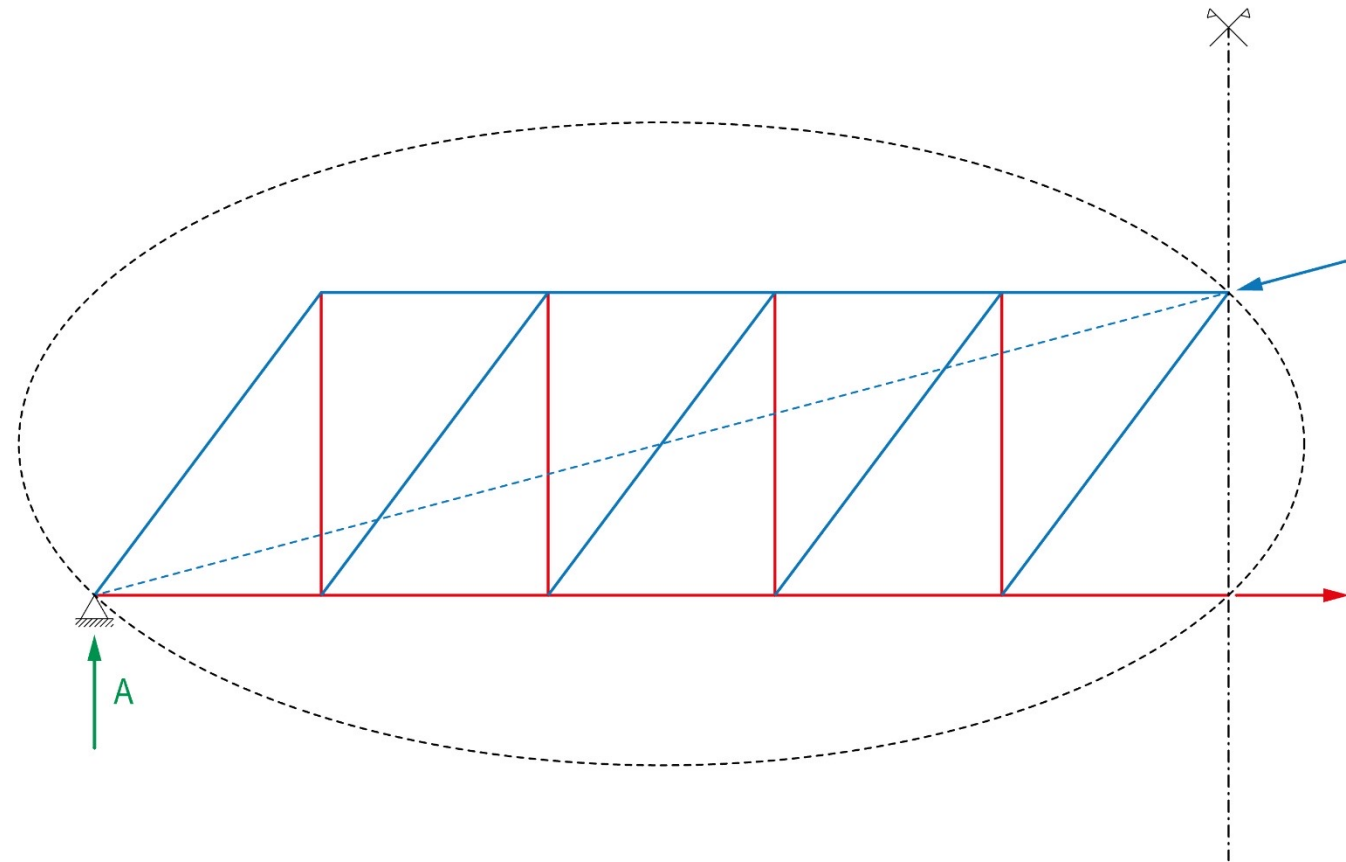
R. Piano, R. Rogers, P. Rice: Centre Georges Pompidou, Paris, 1977





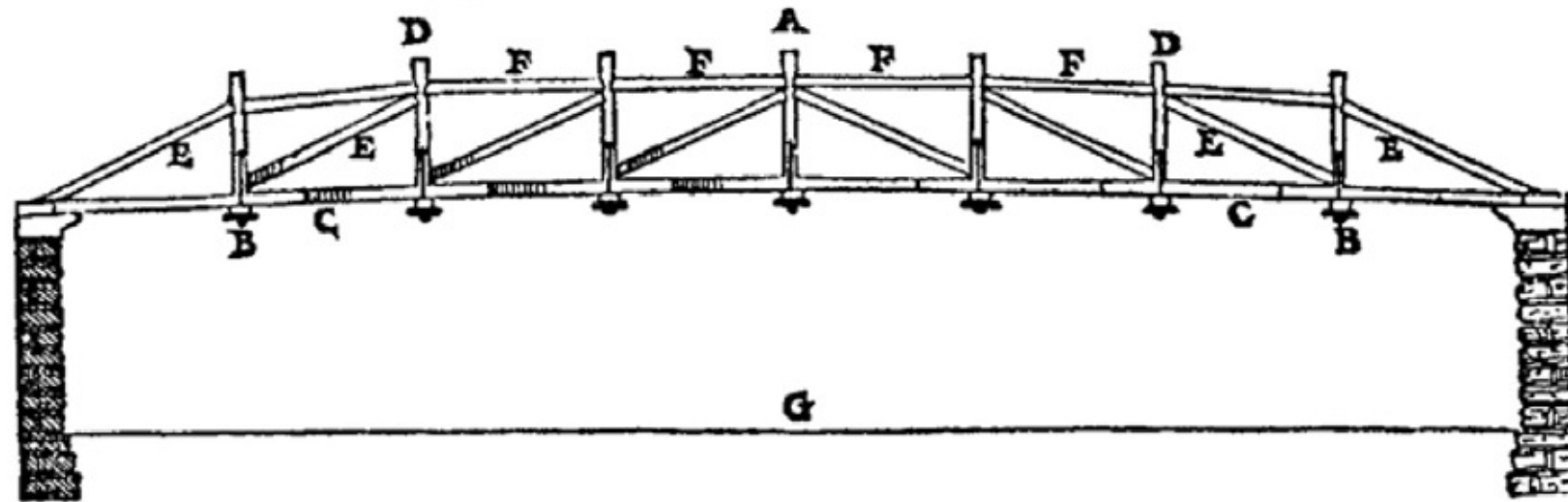


Joseph Paxton, Fox Henderson: Crystal palace, London, 1851



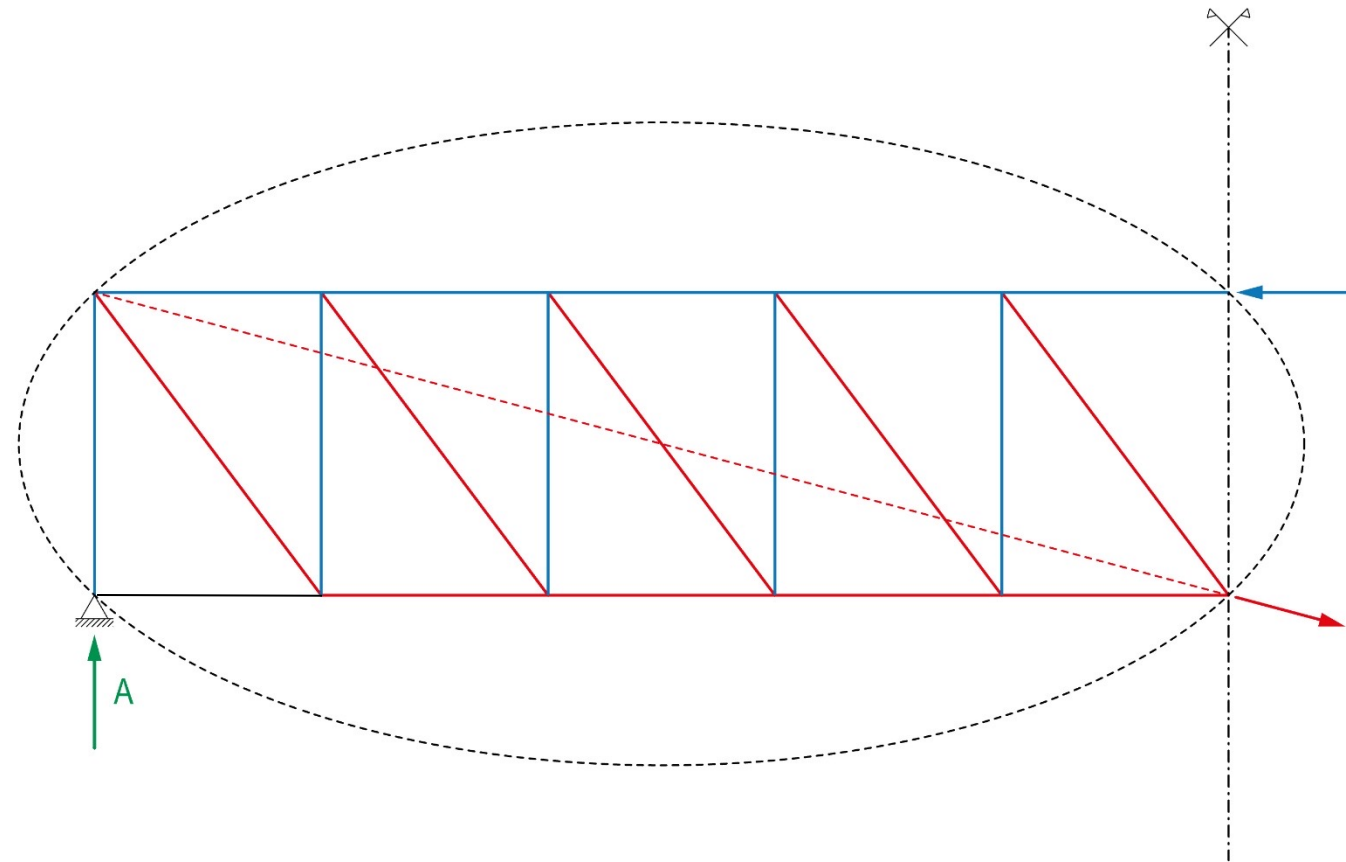
Fachwerk mit N-Förmigen Diagonalen: System Howe, Patent 1840

*Truss with N-shaped diagonals: System Howe, patent 1840*



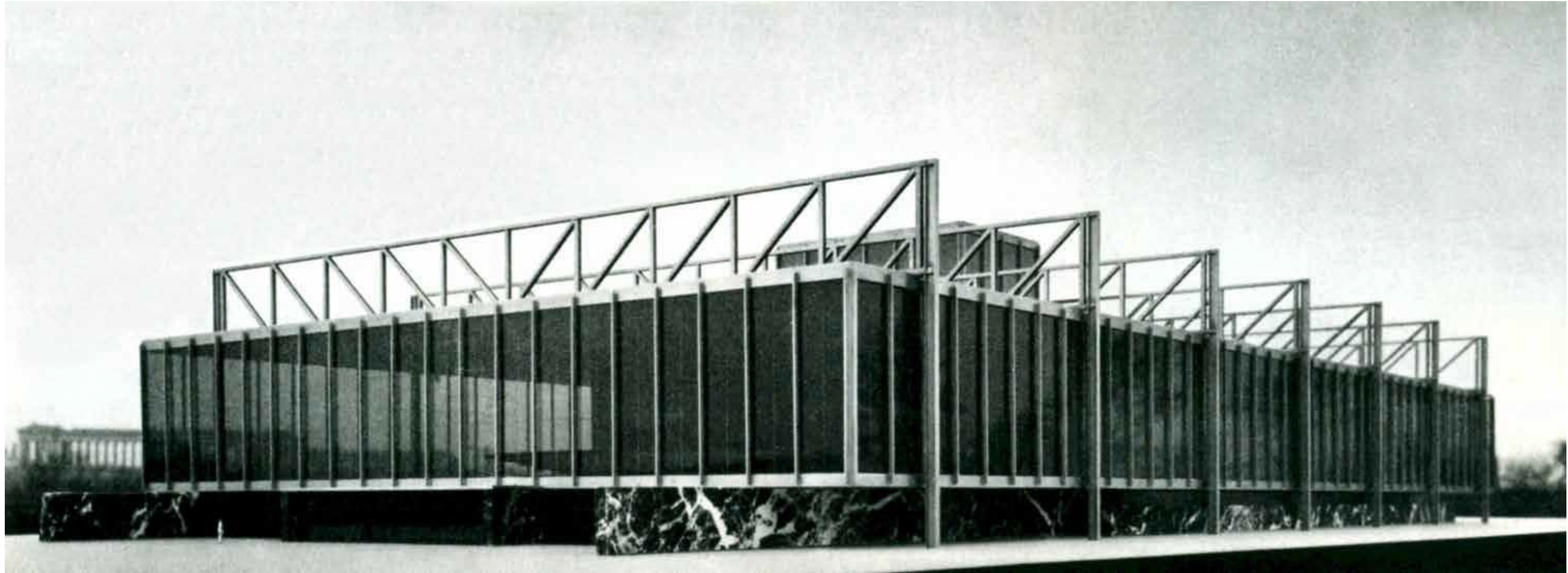
Von A. Palladio vorgeschlagenes Tragwerk, 1570 (in: "Die vier Bücher der Architektur", 3. Buch, Kapitel VIII)

*Truss as proposed by A. Palladio, 1570 (in: "The four Books of Architecture", 3. Book, chapter VIII)*

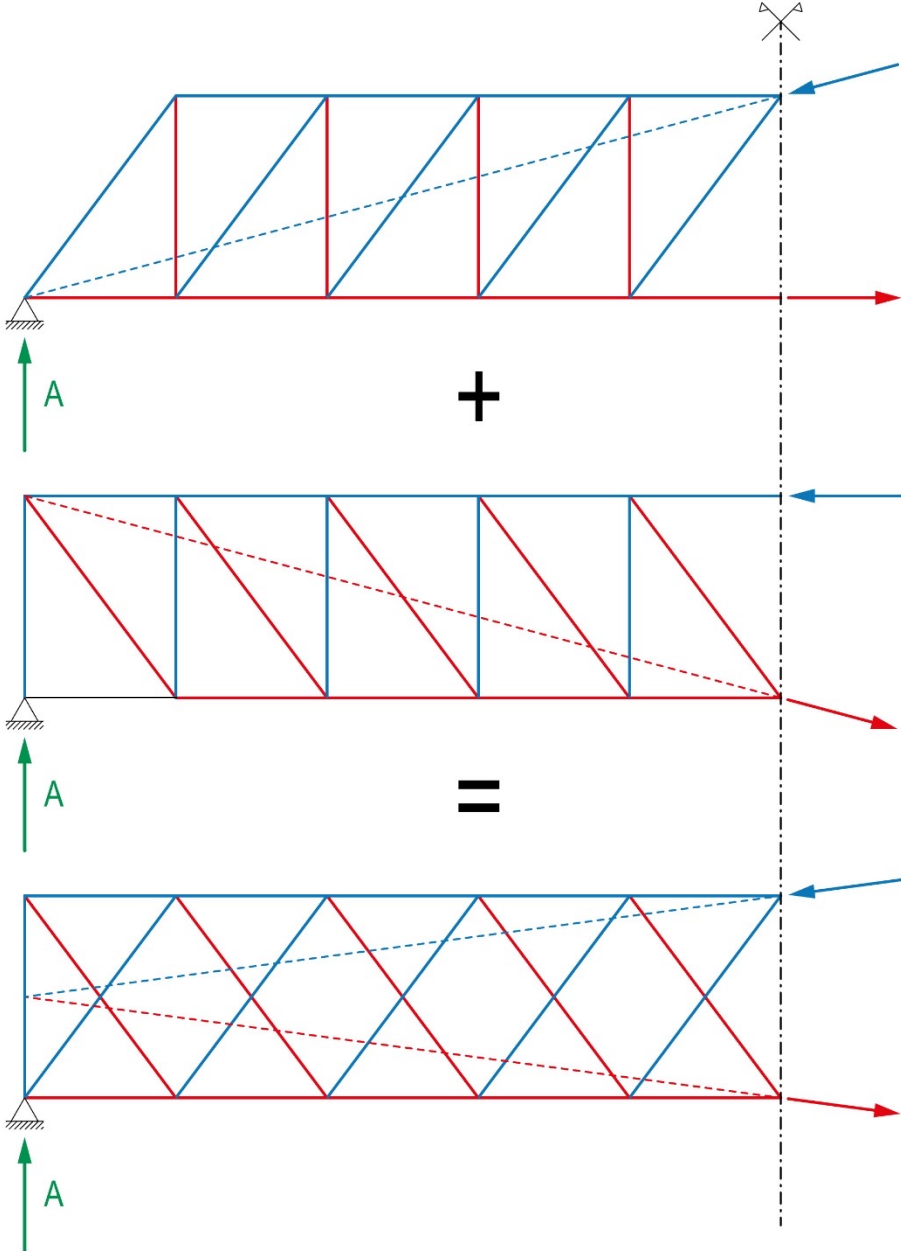


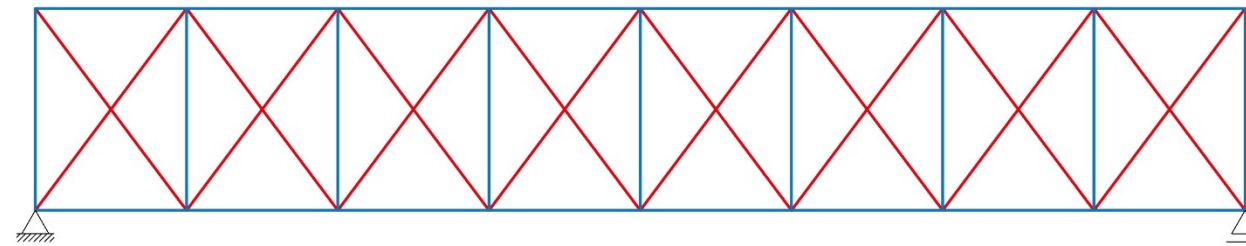
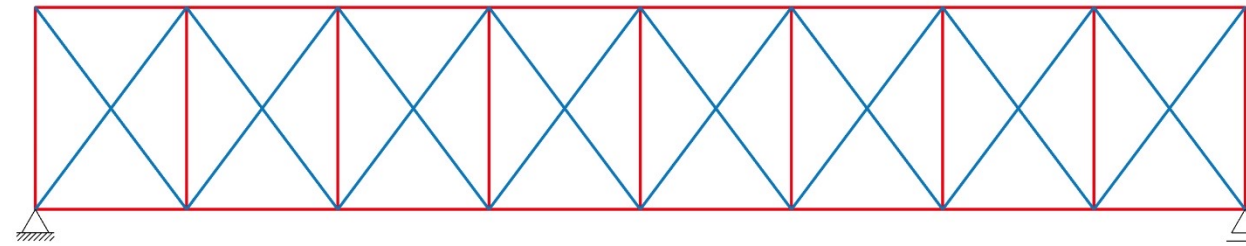
Fachwerk mit N-Förmigen Diagonalen: System Pratt, Patent 1844

*Truss with N-shaped diagonals: System Pratt, patent 1844*



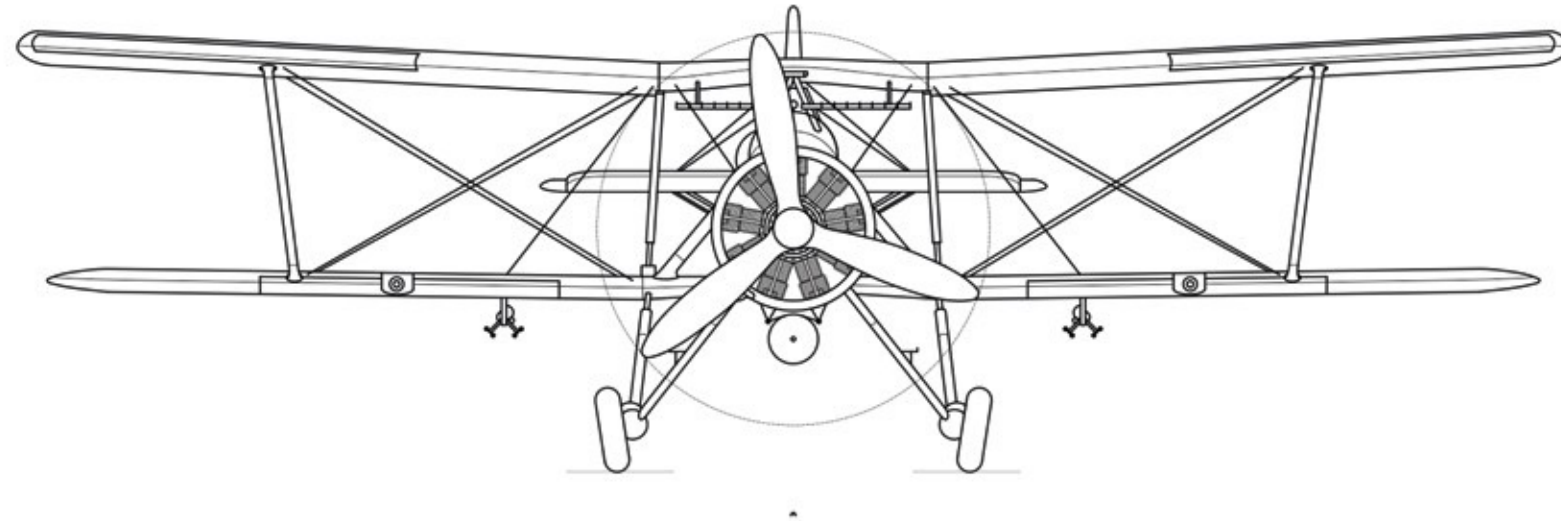
Ludwig Mies van der Rohe: Projekt, Nationaltheater, Mannheim, 1953





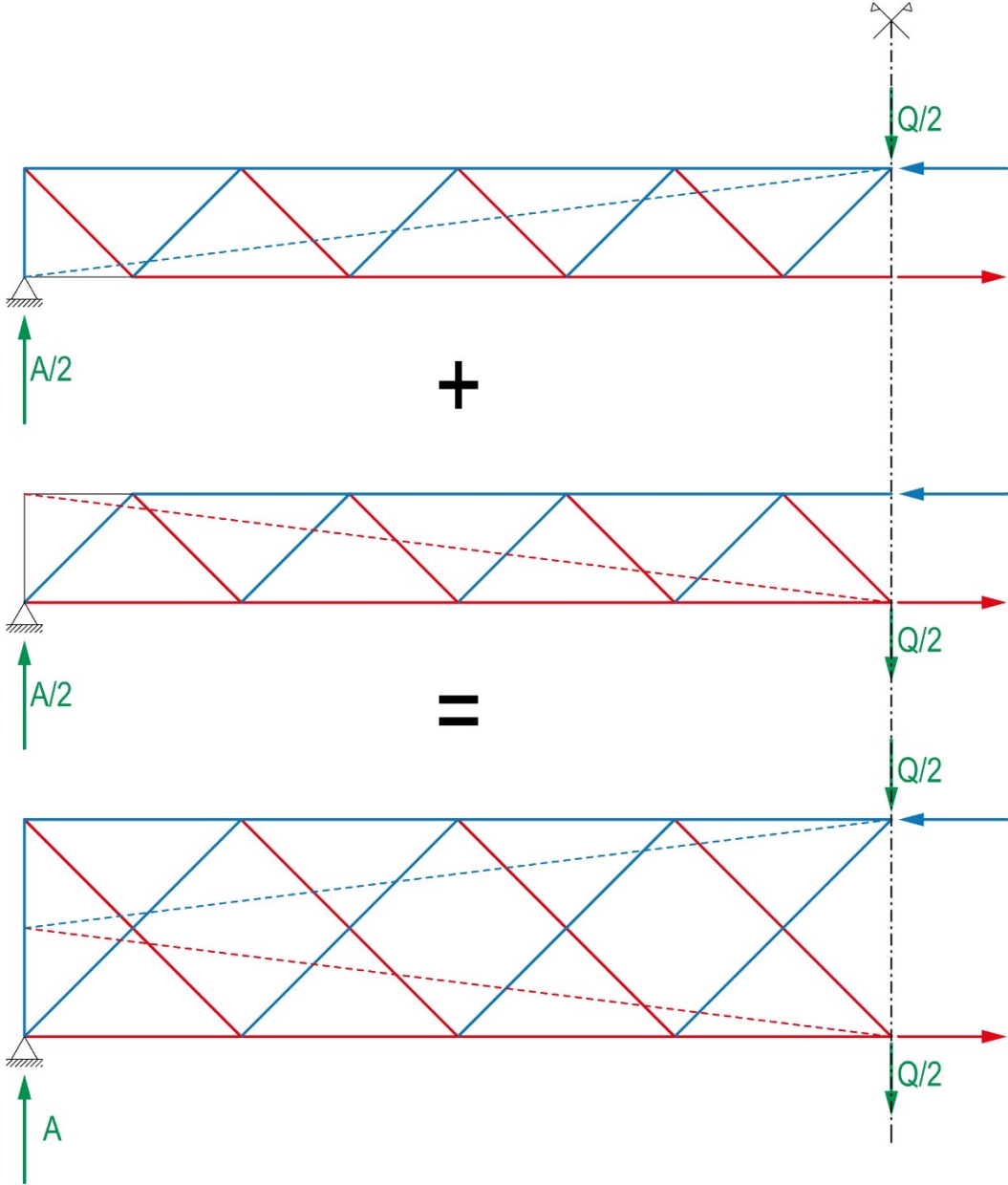
Fachwerk mit X-Förmigen Diagonalen: System Long, Patente 1830 & 1839

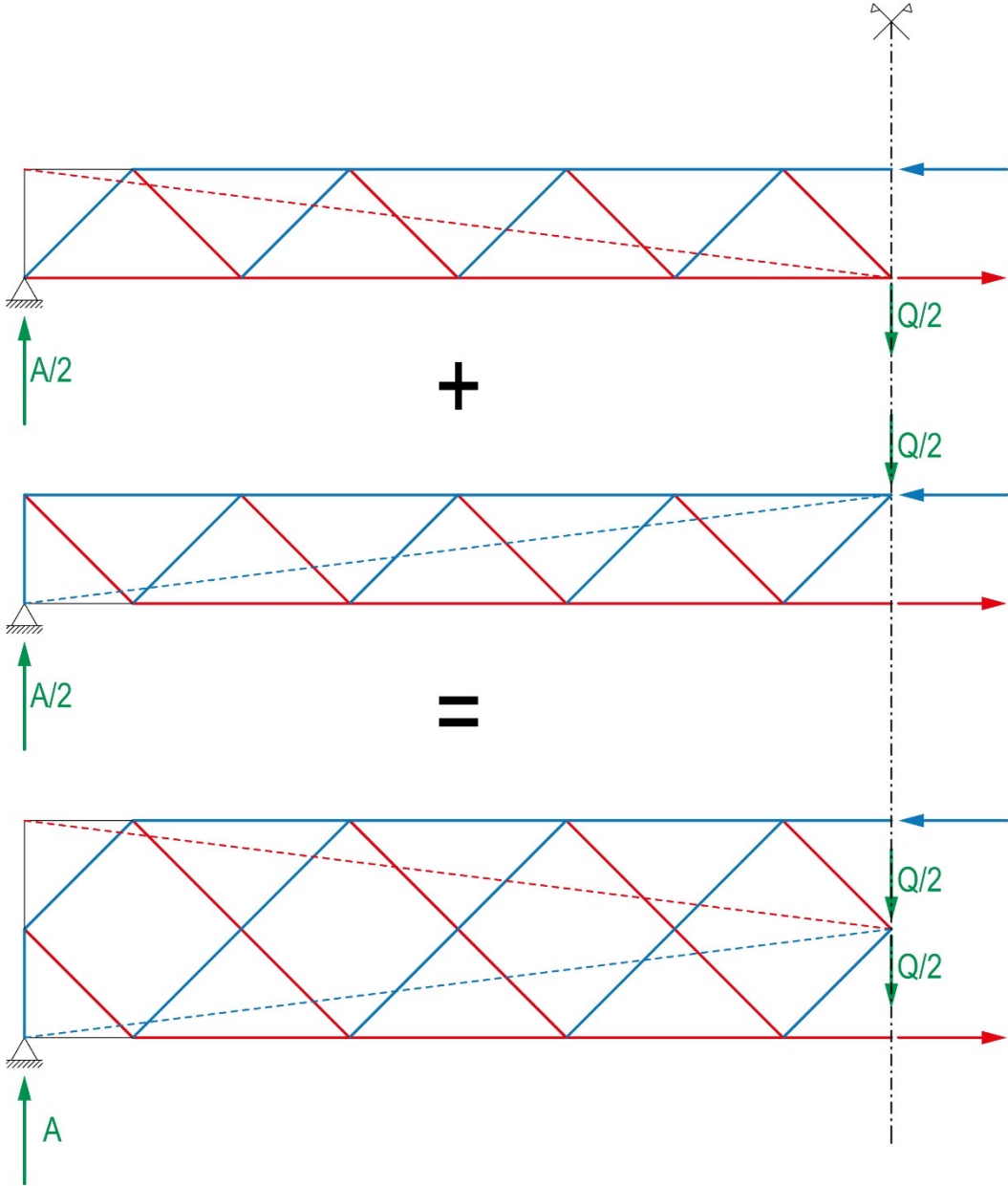
*Truss with X-shaped diagonals: System Long, patents 1830 & 1839*

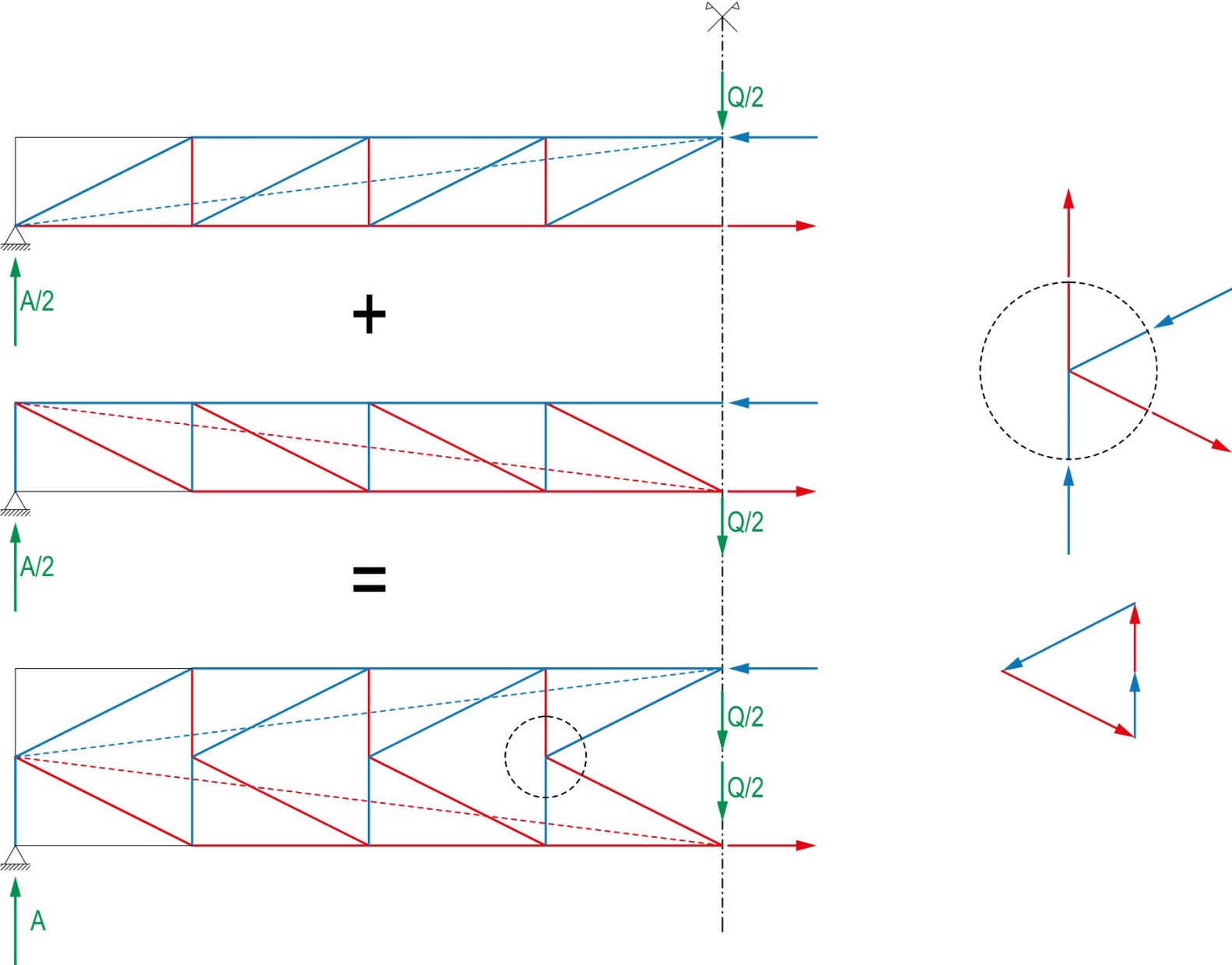


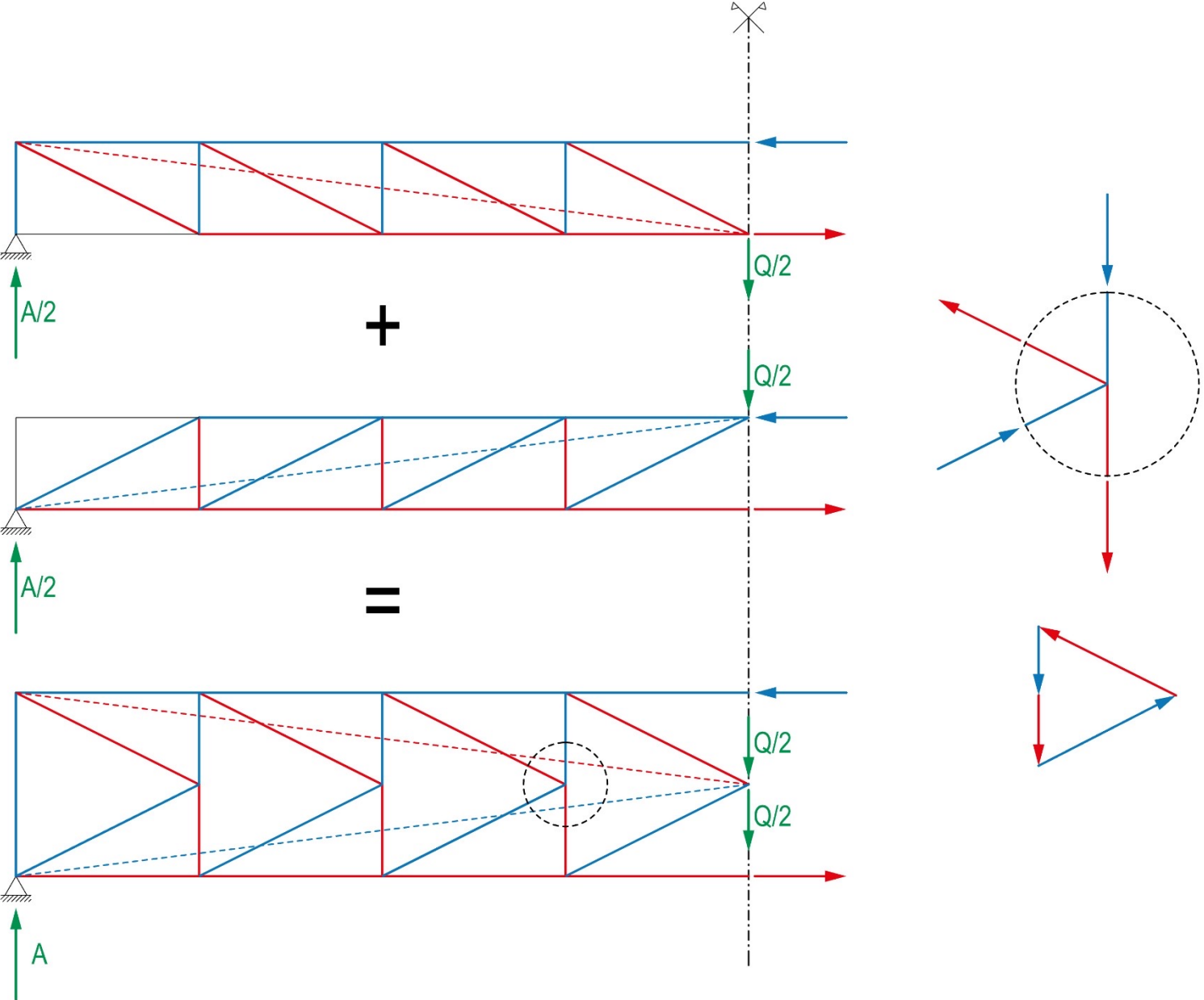
Doppeldecker Fairey Swordfish I, GB, 1934

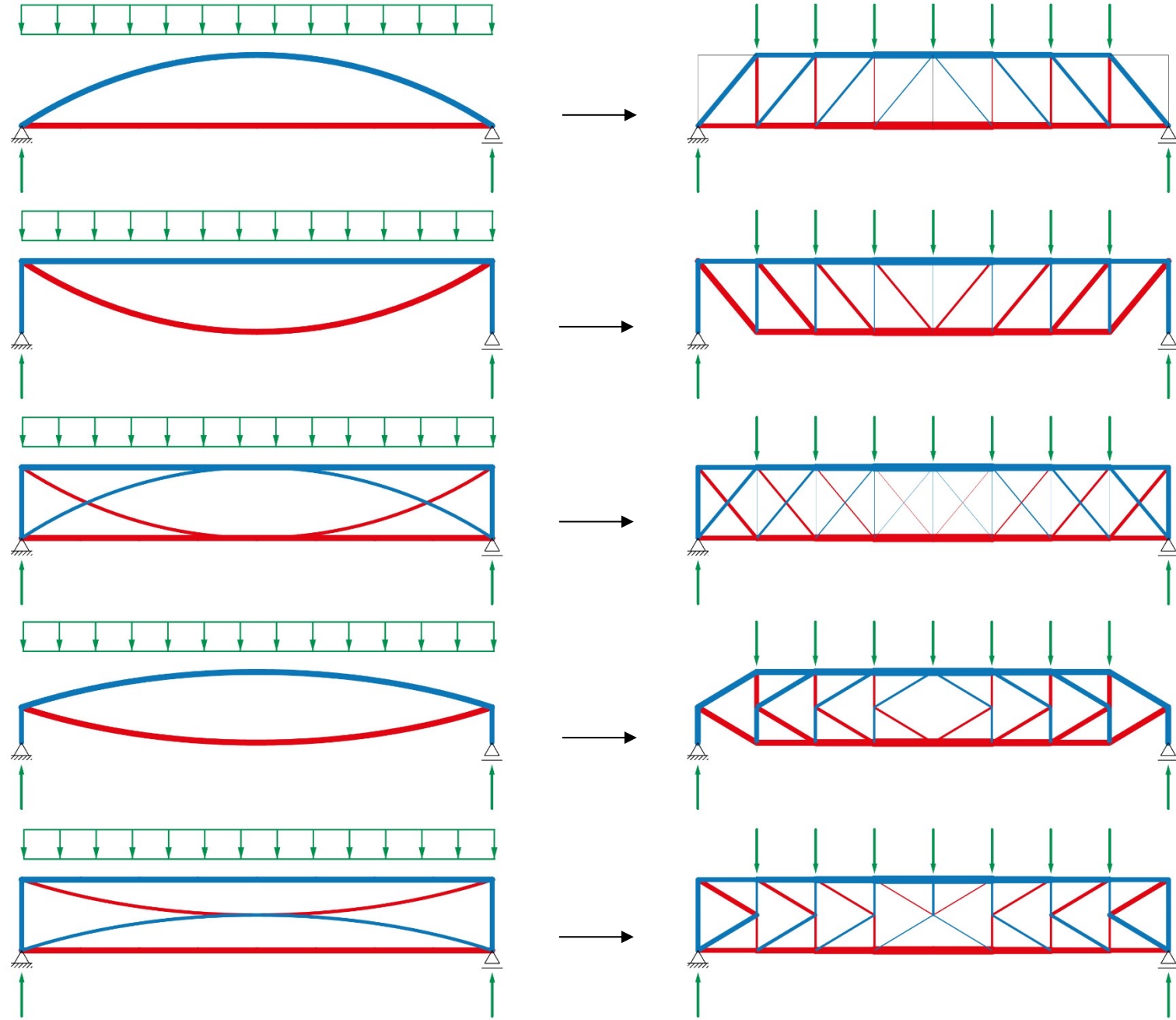


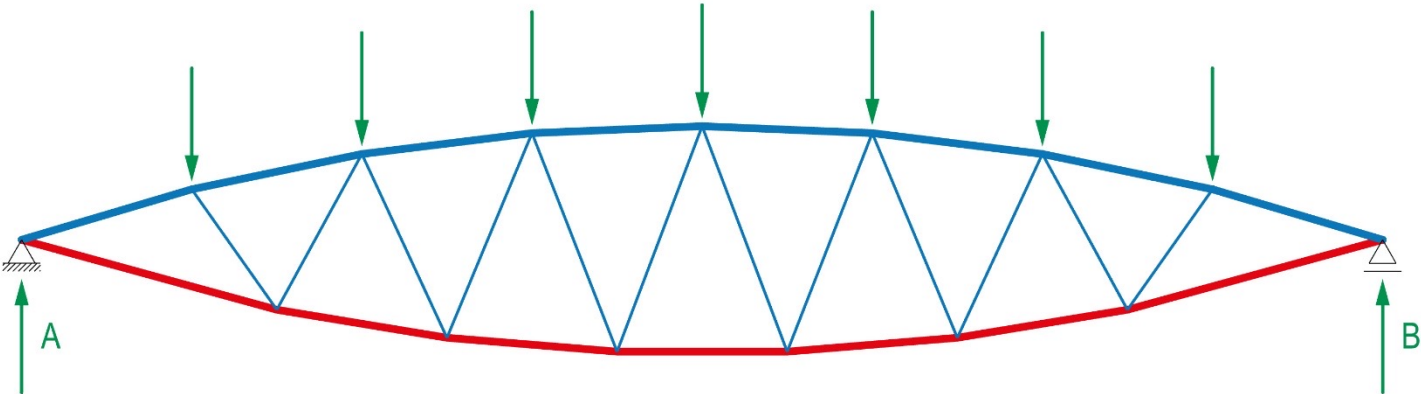
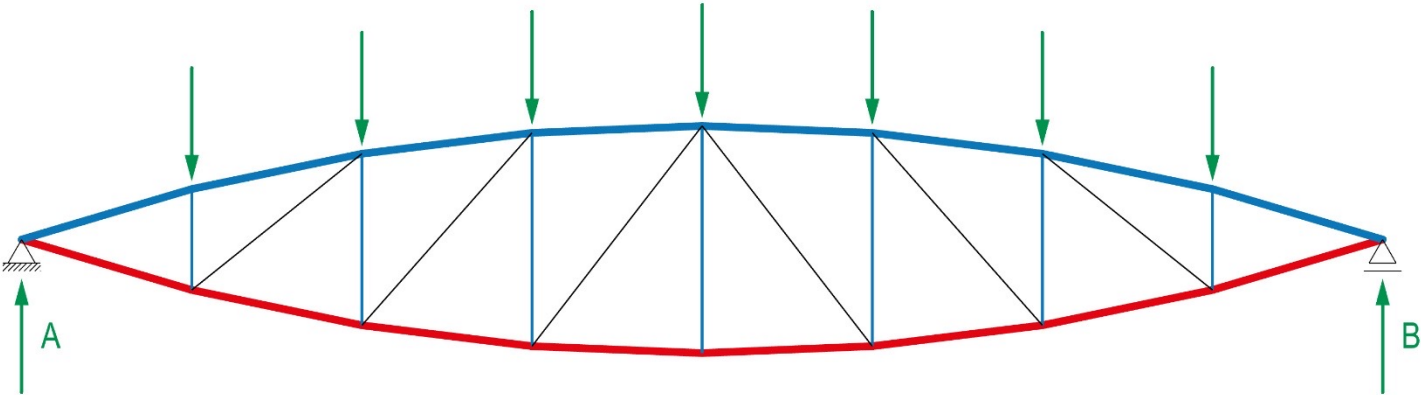


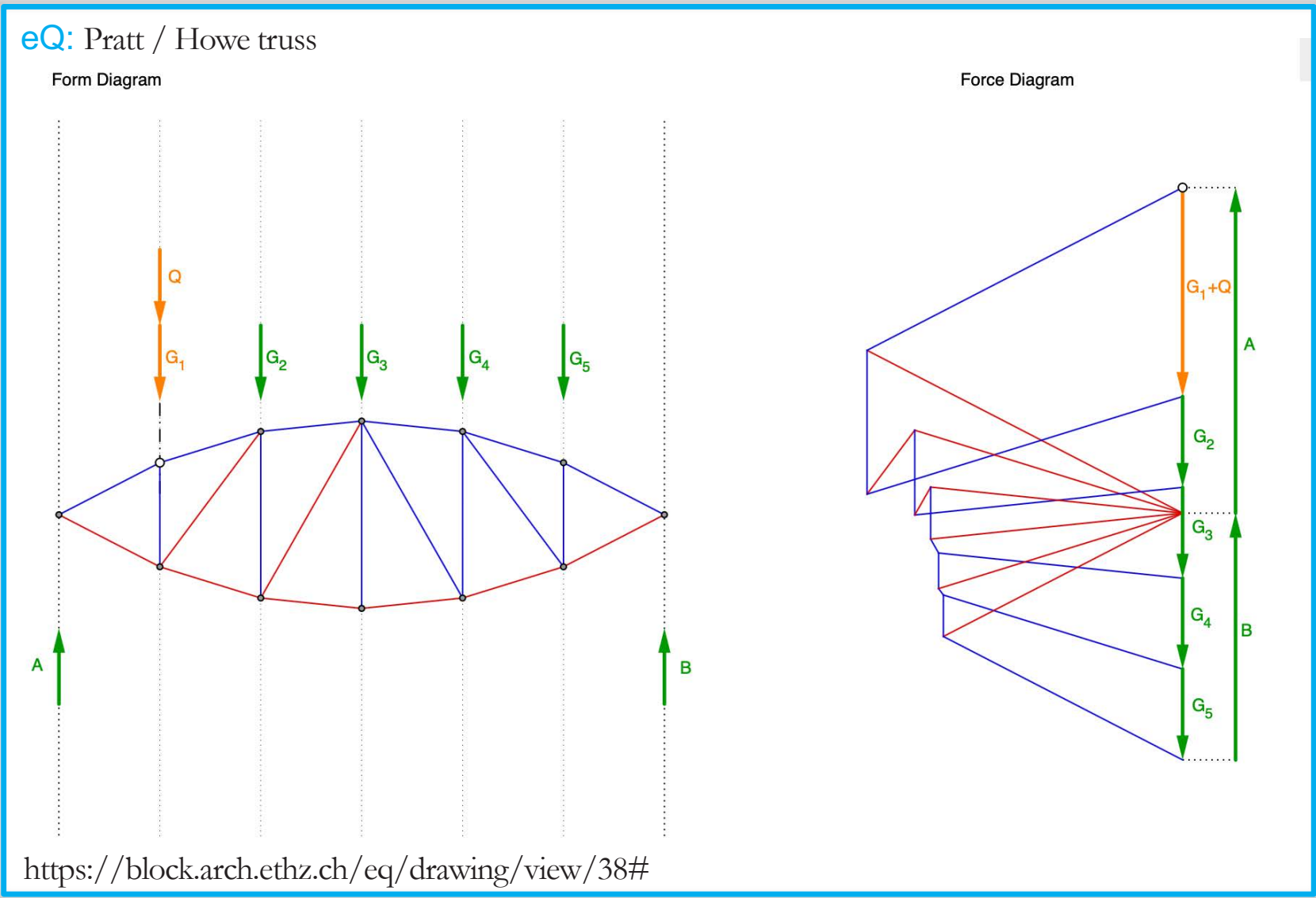








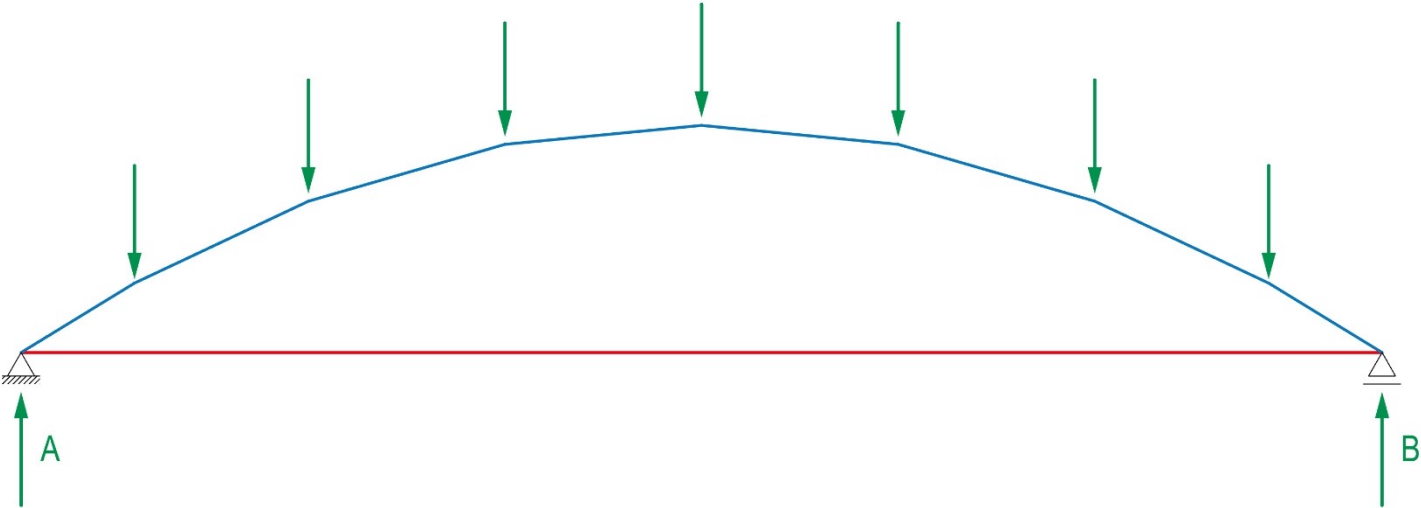


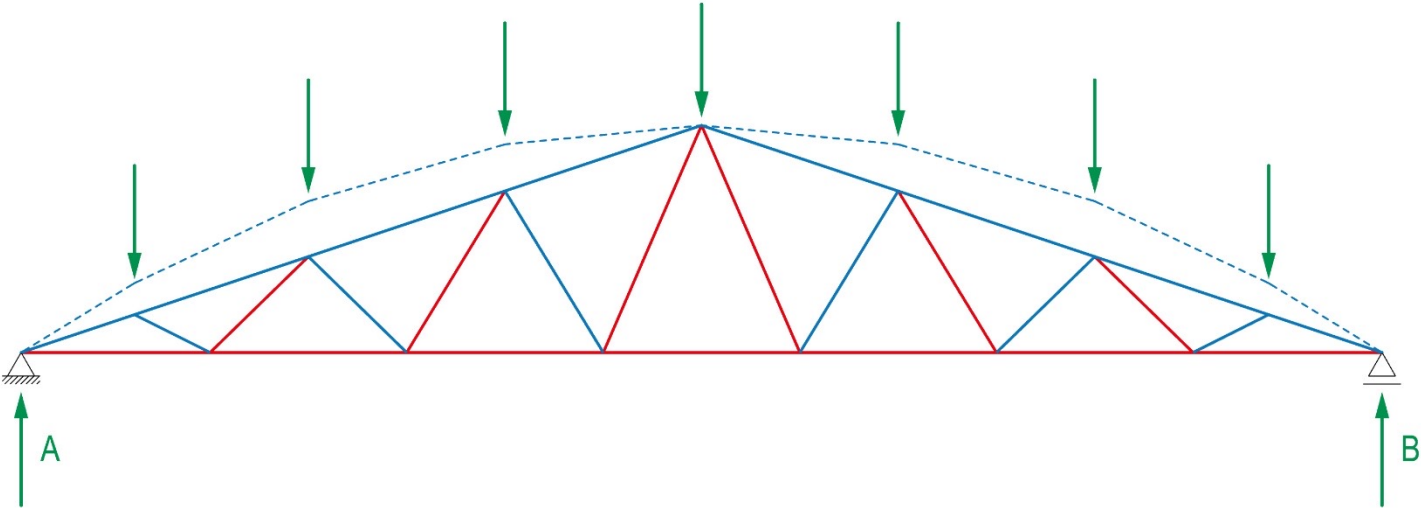




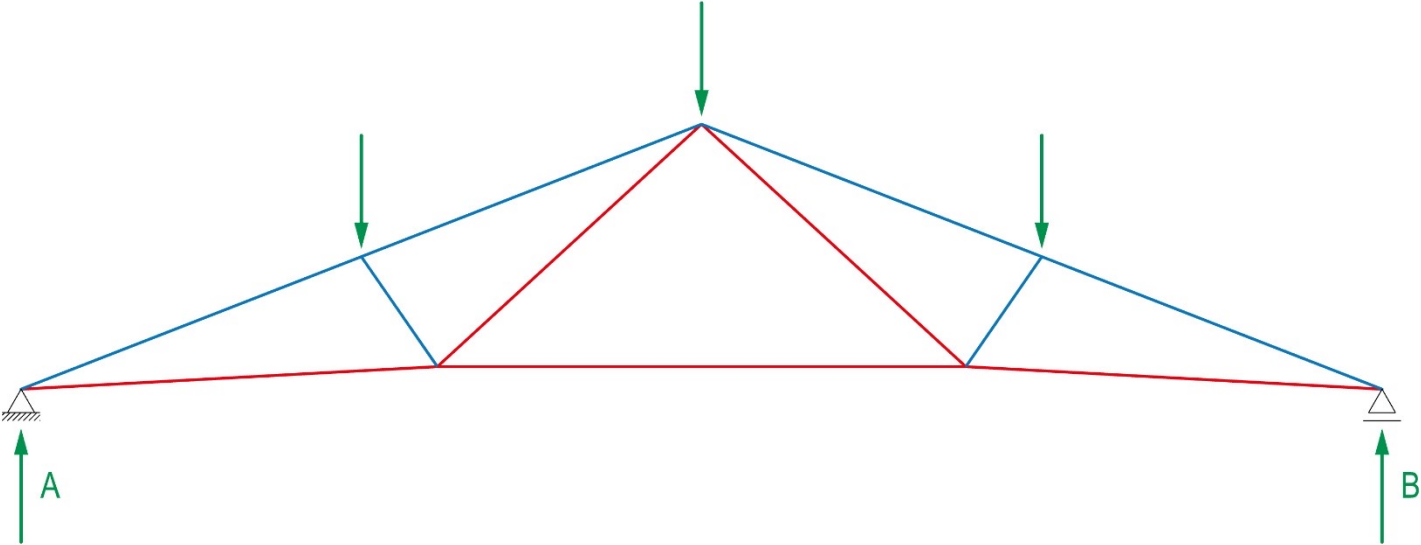
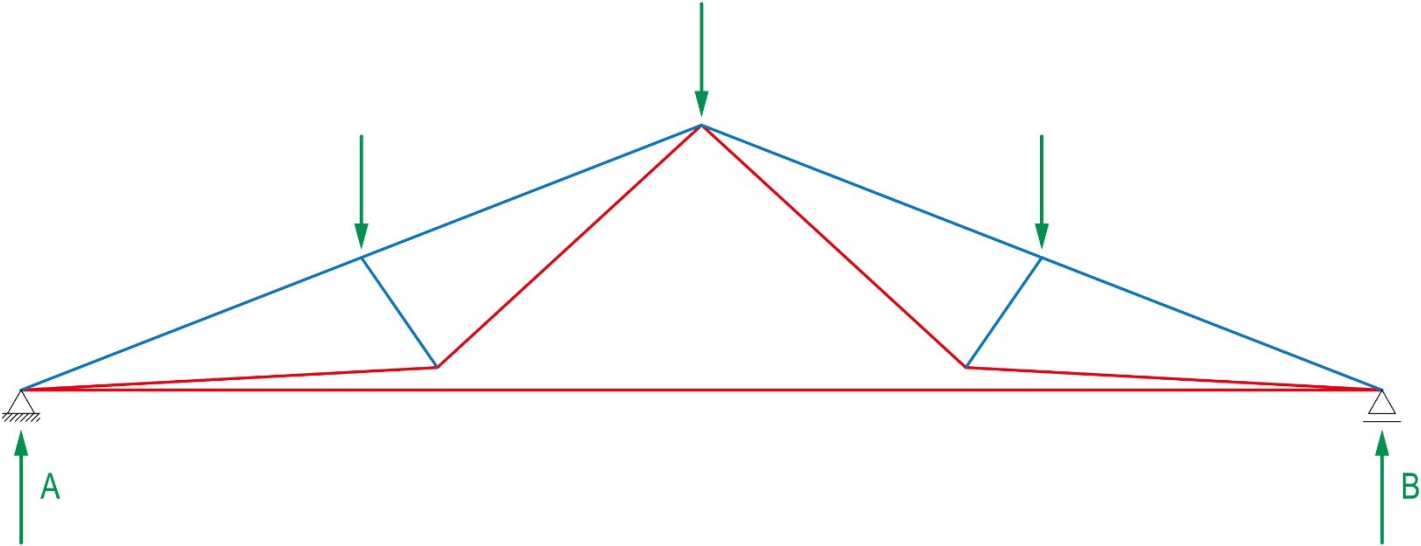
Friedrich August von Pauli, Heinrich Gerber, Ludwig Werder: Isarbrücke, Grosshesselohe, D, 1857







*Types of trusses*





Jakob Ignatz Hittorf: Gare du Nord, Paris, 1865

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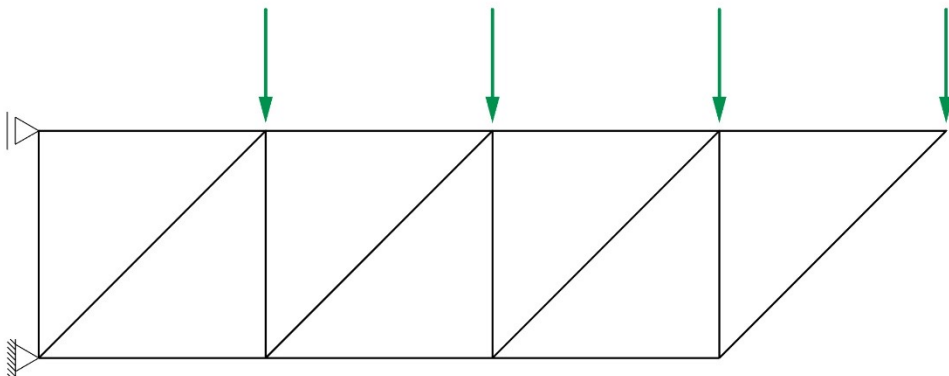
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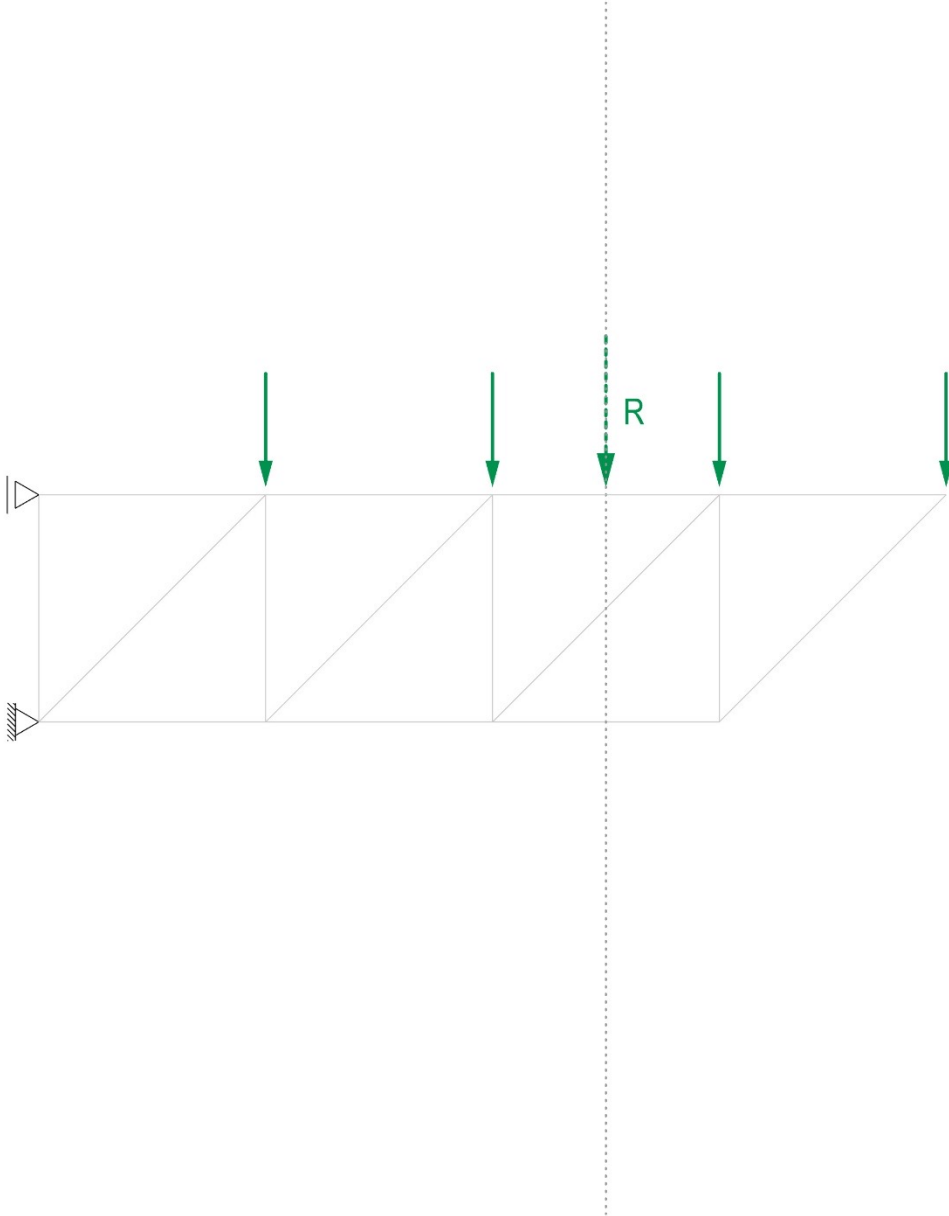
Räumliche Fachwerke

*Spatial trusses*



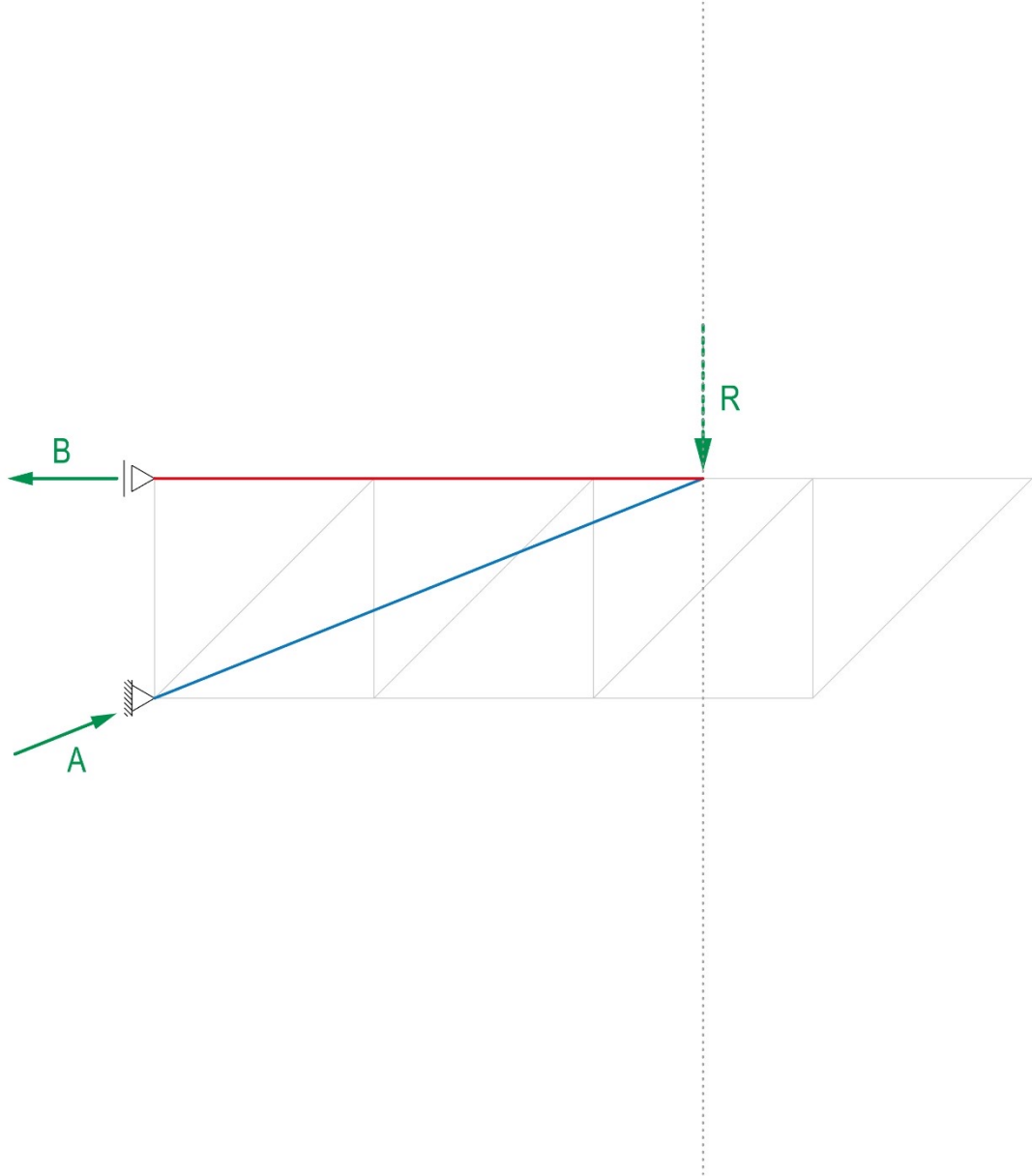
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*Form diagram 1:100*

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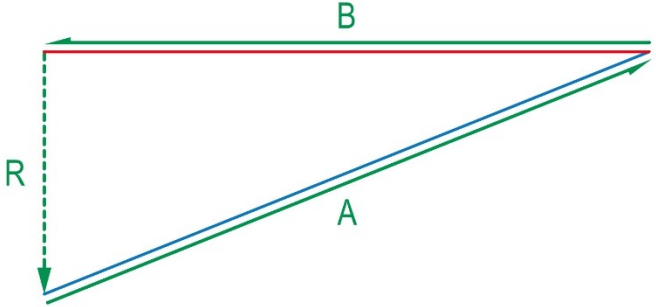


Lageplan 1:100  
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*Force diagram 1 cm  $\cong$  1 kN*

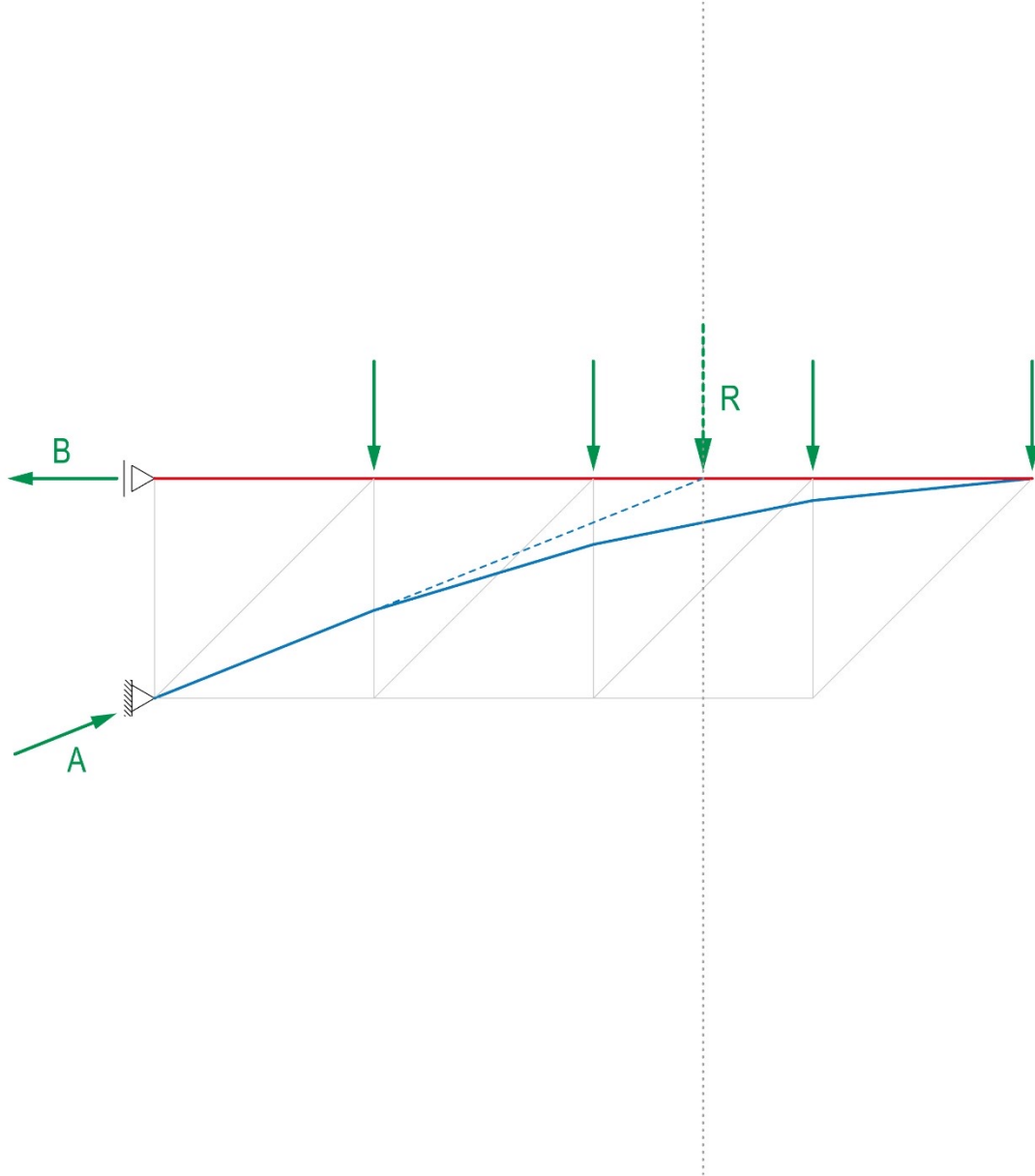


Lageplan 1:100  
*Form diagram 1:100*

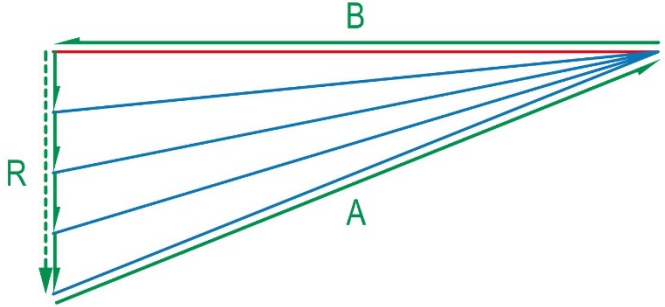


Kräfteplan 1 cm  $\cong$  1 kN  
*Force diagram 1 cm  $\cong$  1 kN*

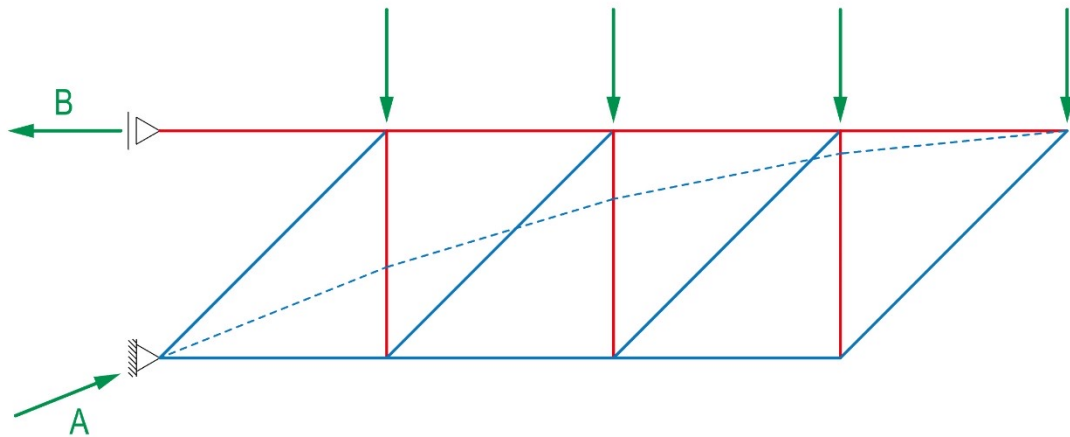




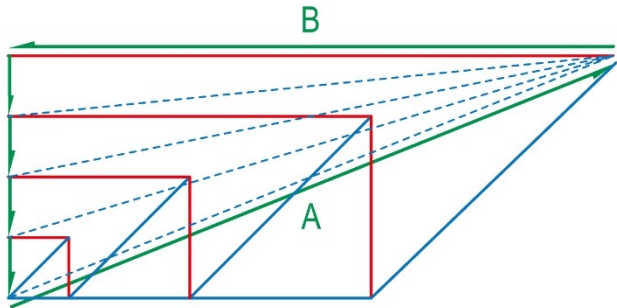
Lageplan 1:100  
*Form diagram 1:100*



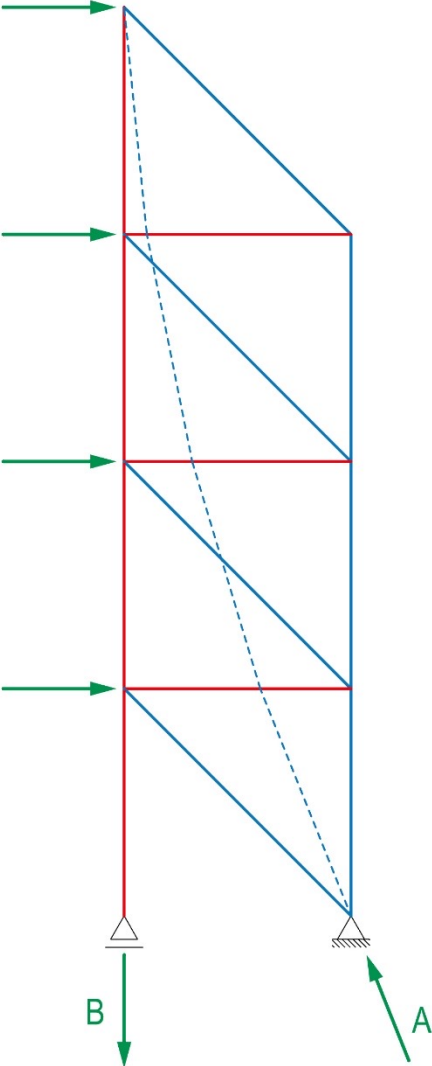
Kräfteplan 1 cm ≅ 1 kN  
*Force diagram 1 cm ≅ 1 kN*



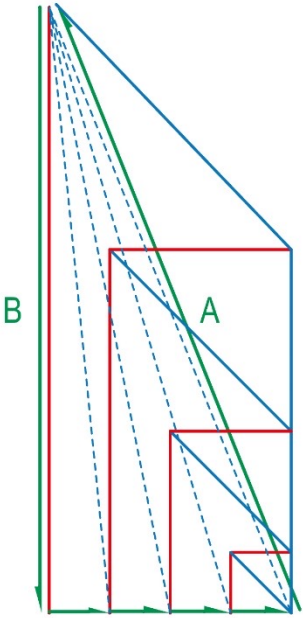
Lageplan 1:100  
*Form diagram 1:100*



Kräfteplan 1 cm  $\cong$  1 kN  
*Force diagram 1 cm  $\cong$  1 kN*



Lageplan 1:100  
*Form diagram 1:100*



Kräfteplan 1 cm ≅ 1 kN  
*Force diagram 1 cm ≅ 1 kN*



SOM, F. Kahn: John Hancock Center, Chicago, 1969

# Fachwerke

## *Trusses*

Von Bogen-Seiltragwerken zu Fachwerken

*From arch-cable-structures to trusses*

Das Fachwerk als Kombination von Bogen-Seilen

*The truss as a combination of arch-cables*

Terminologie

*Terminology*

Statische Bestimmtheit

*Statical determinacy*

Ermittlung der inneren Kräfte

*Calculation of inner forces*

Einfluss der Lage der äusseren Kräfte

*Influence of the position of external forces*

Variation der Geometrie

*Geometric variation*

Arten von Fachwerken

*Types of trusses*

Variation der Randbedingungen

*Variation of boundary conditions*

>>

Schlankheit von Fachwerken

*Slender trusses*

Konstruktion von Fachwerken

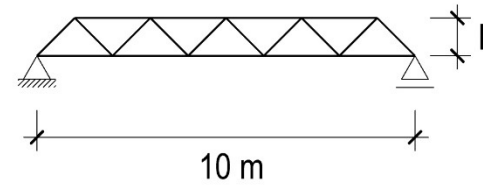
*Construction of trusses*

Räumliche Fachwerke

*Spatial trusses*

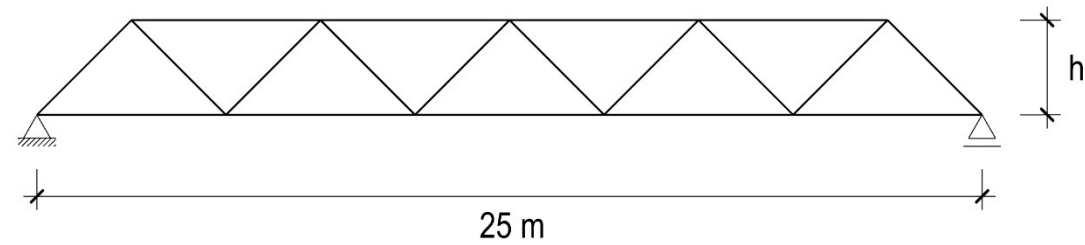
Material	Tragwerk	wirtschaftliche Schlankheit $l/b$ für einfache Balken *
Stahl	Vierendeelträger	7 – 10
	Fachwerkträger	10 - 15
	Raumfachwerk	12 - 18
	Balken	15 - 20
Stahlbeton	Balken	12 – 18
	Platten	20 – 25
Spannbeton	Balken	18 – 25
	Platten	28 – 35
Holz	Balken	15 - 20

\* Bei Konsolen entspricht  $l$  der zweifachen Spannweite der Konsole, bei Balken mit Konsolen bzw. Durchlaufträgern entspricht  $l$  dem Abstand der beiden zwischen den Auflagern liegenden Gelenken.



$$h = 10 \text{ m} / 10 = 1 \text{ m}$$

$$h = 10 \text{ m} / 15 = 0.66 \text{ m}$$



$$h = 25 \text{ m} / 10 = 2.5 \text{ m}$$

$$h = 25 \text{ m} / 15 = 1.66 \text{ m}$$

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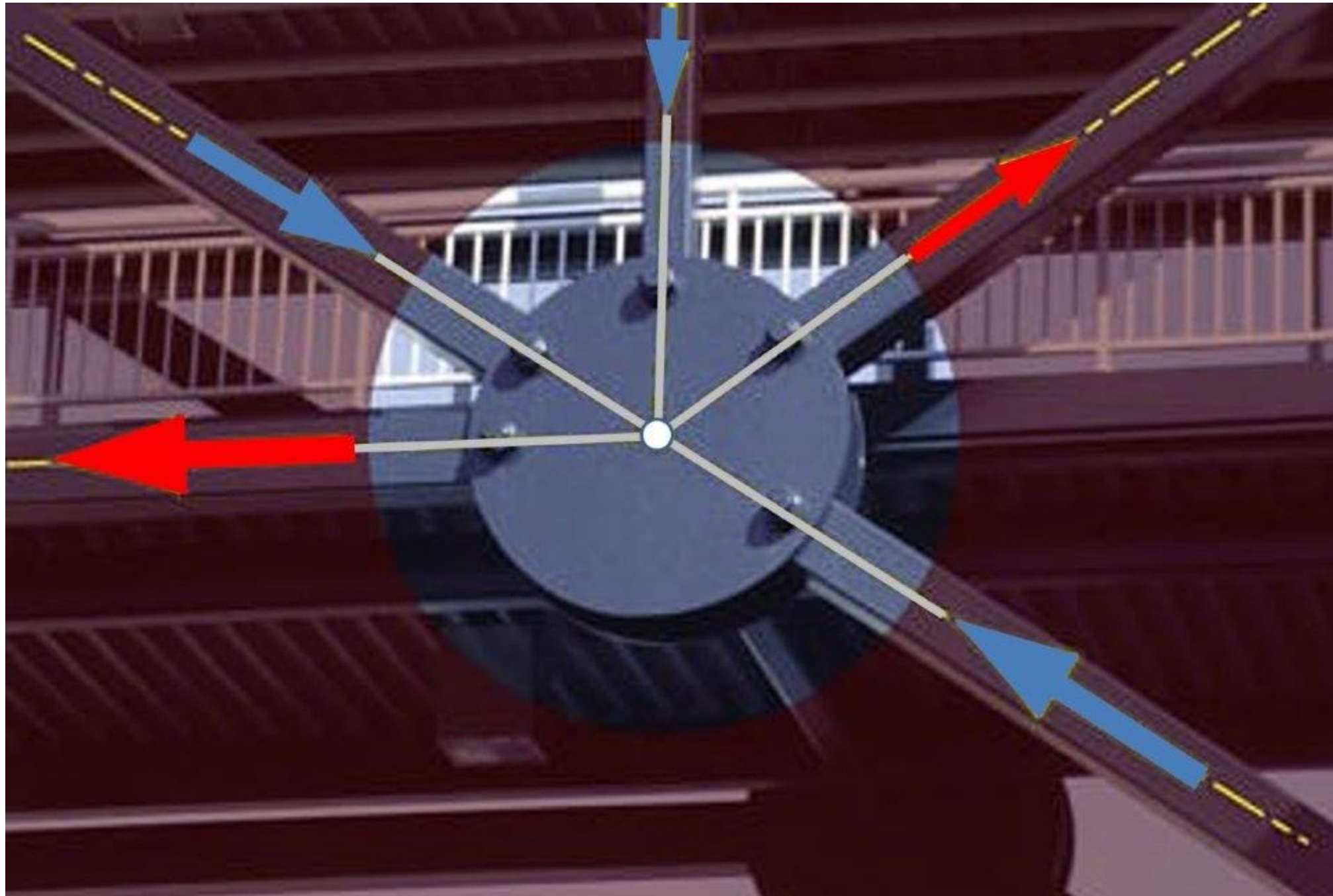


Gustav Eiffel, Theophile Seyring: Maria Pia Brücke, Porto, 1877





Gustav Eiffel, Theophile Seyring: Maria Pia Brücke, Porto, 1877



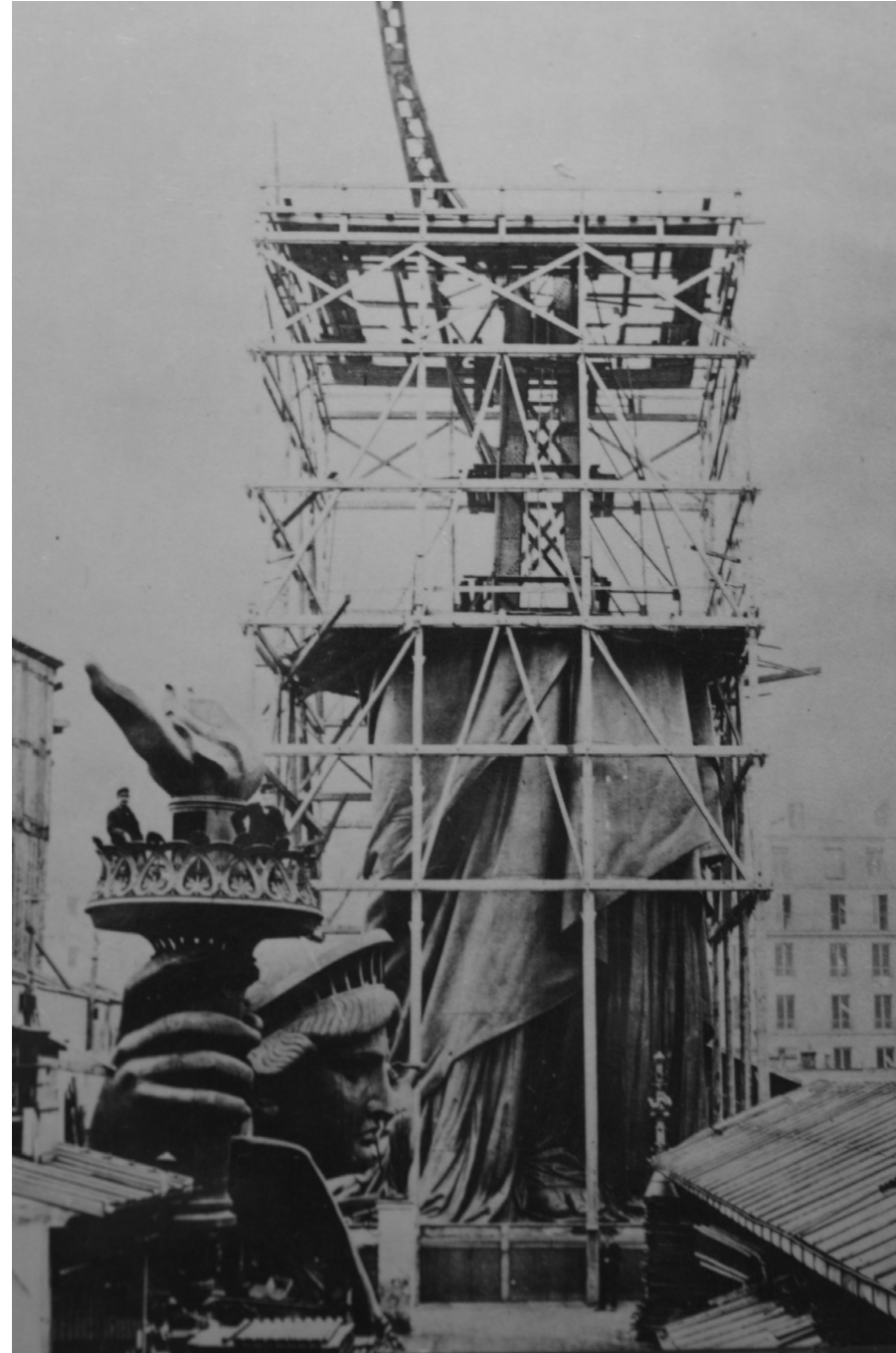
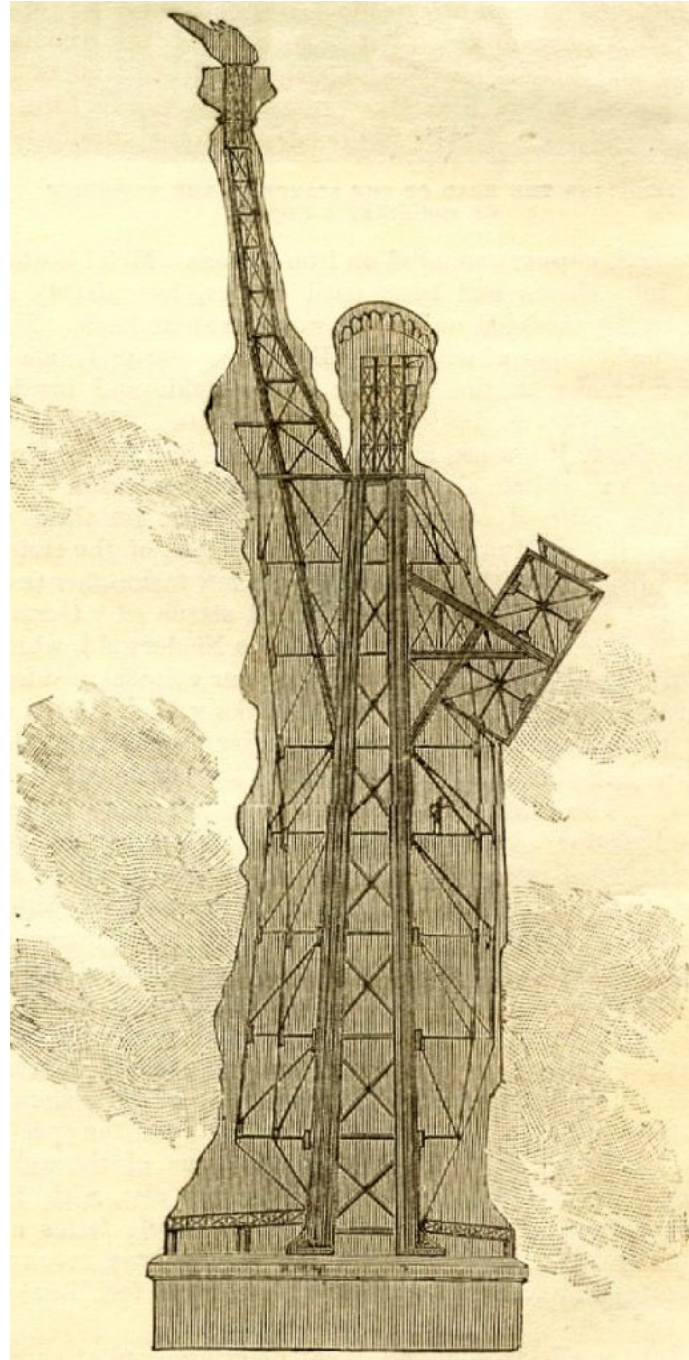
Squire Whipple, Cairo Rail Bridge, Illinois, USA, 1899



Squire Whipple, Cairo Rail Bridge, Illinois, USA, 1899



Office Eiffel, Maurice Koechlin: Eiffelturm, Paris, 1889



Frederic-Auguste Bartholdi, Gustave Eiffel: Statue of Liberty, New York, 1886

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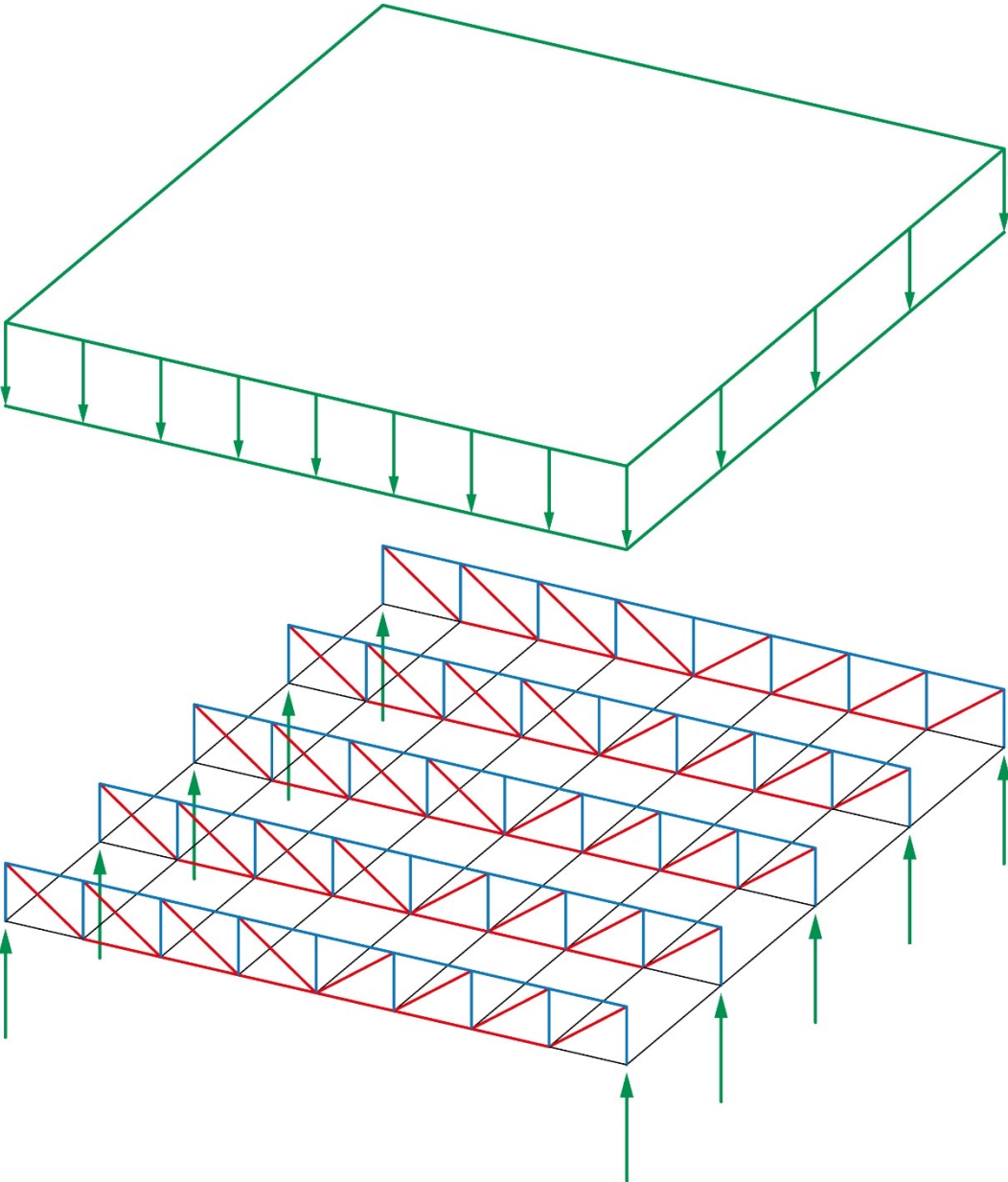
*Slender trusses*

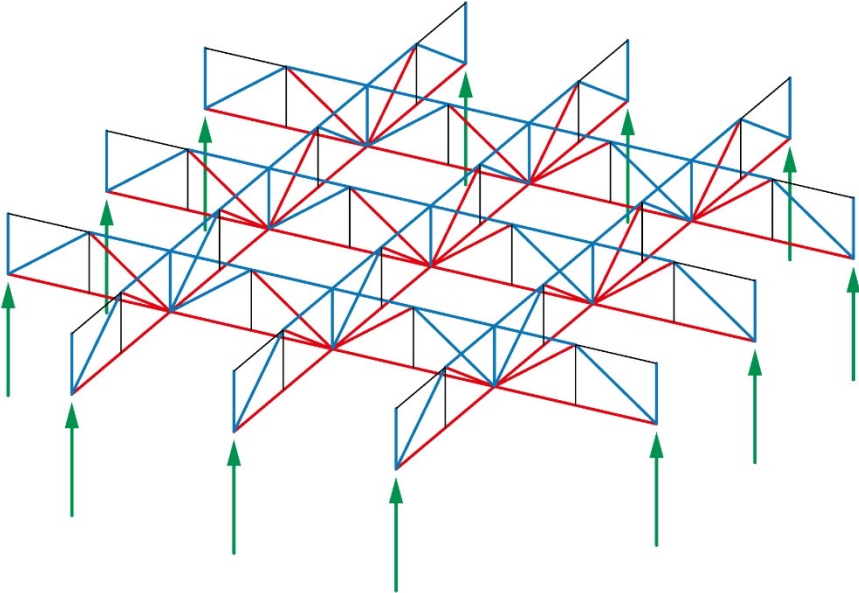
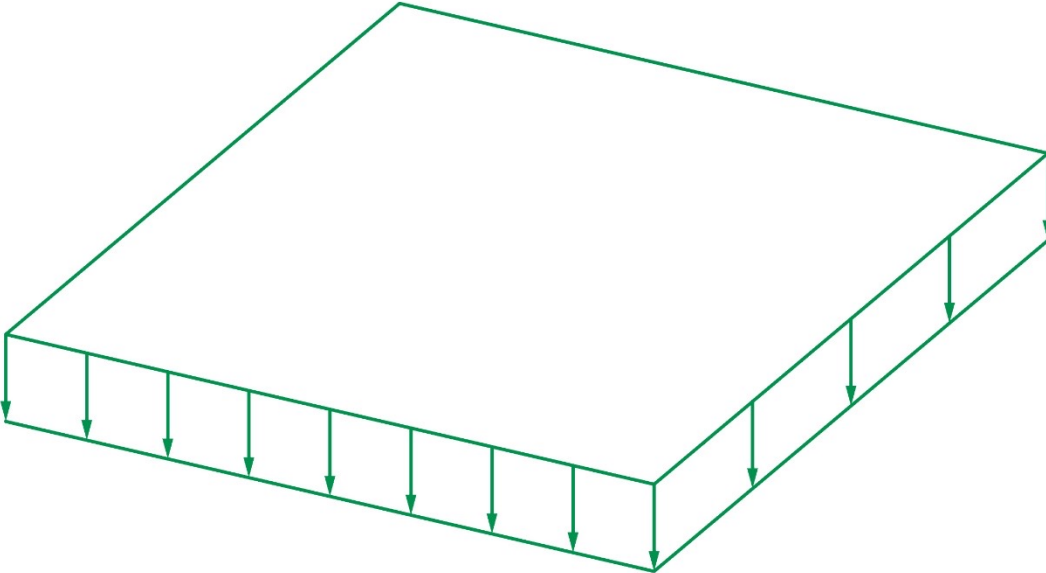
Konstruktion von Fachwerken

*Construction of trusses*

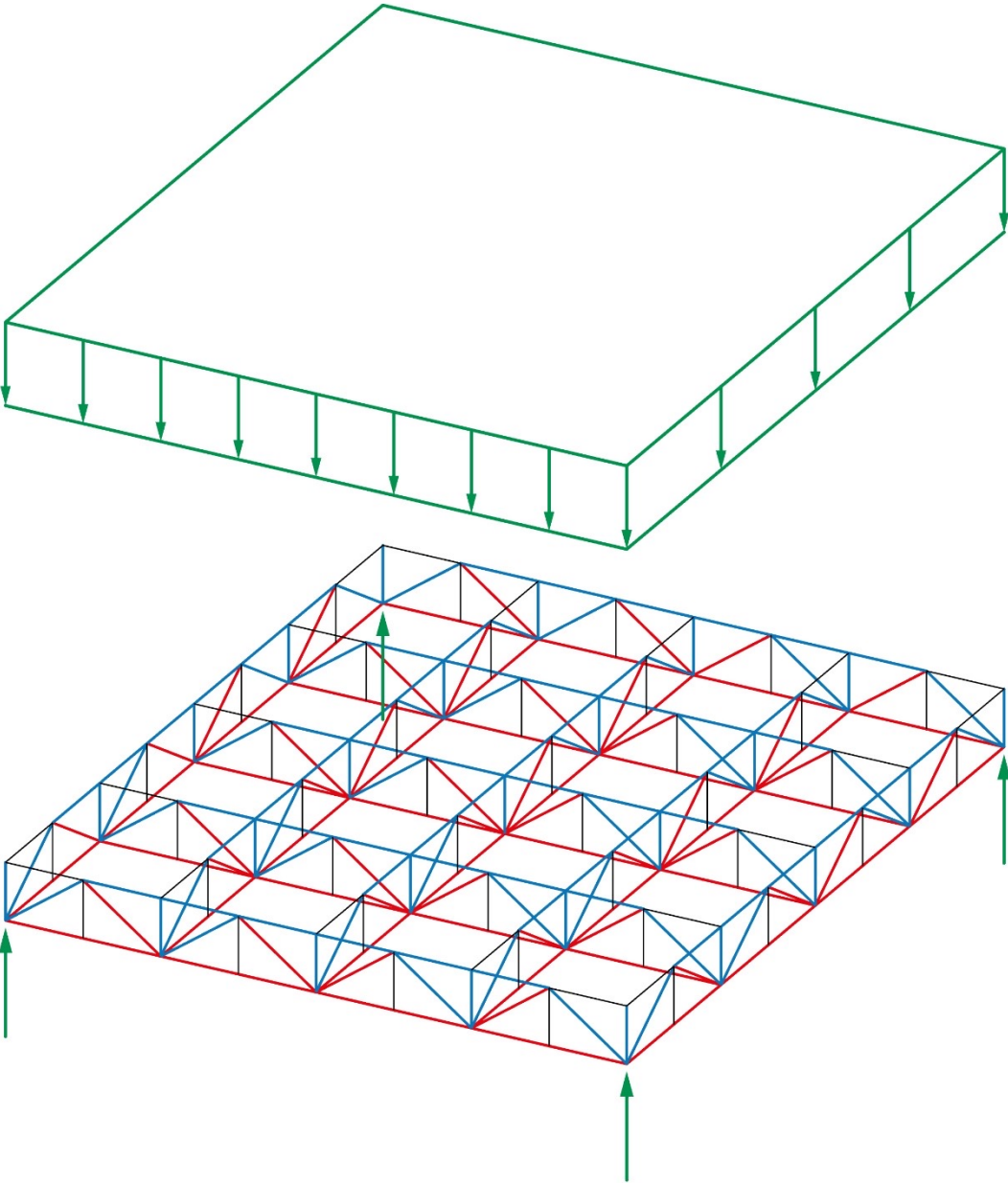
>> Räumliche Fachwerke

*Spatial trusses*







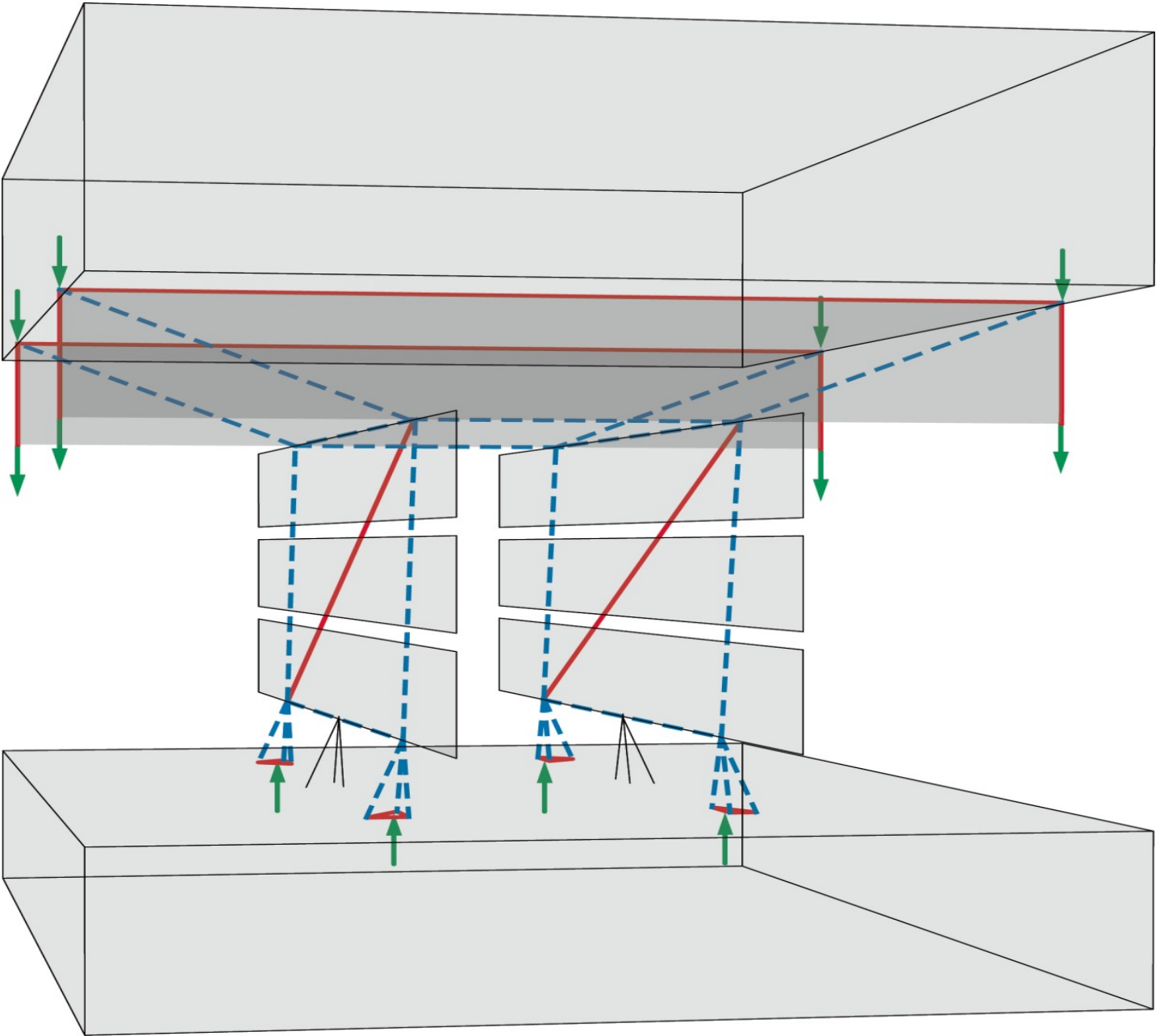




Bruno und Fritz Haller, Emch & Berger: USM-Fabrik, Münsingen, 1964



Christian Kerez, Joseph Schwartz: Schulhaus Leutschenbach, Zürich, 2009



Christian Kerez, Joseph Schwartz: Schulhaus Leutschenbach, Zürich, 2009



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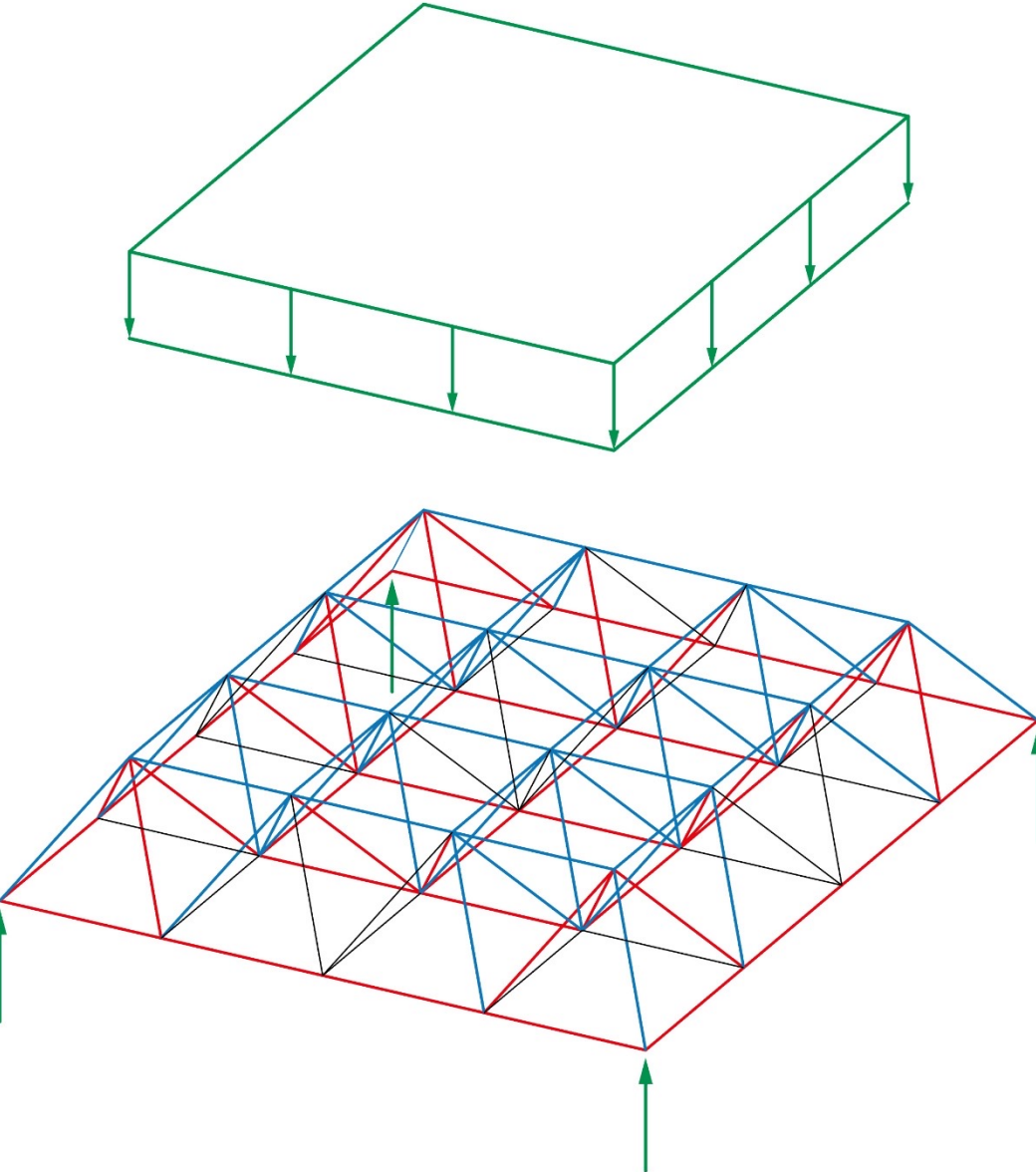
Christian Kerez, Joseph Schwartz: Schulhaus Leutschenbach, Zürich, 2009

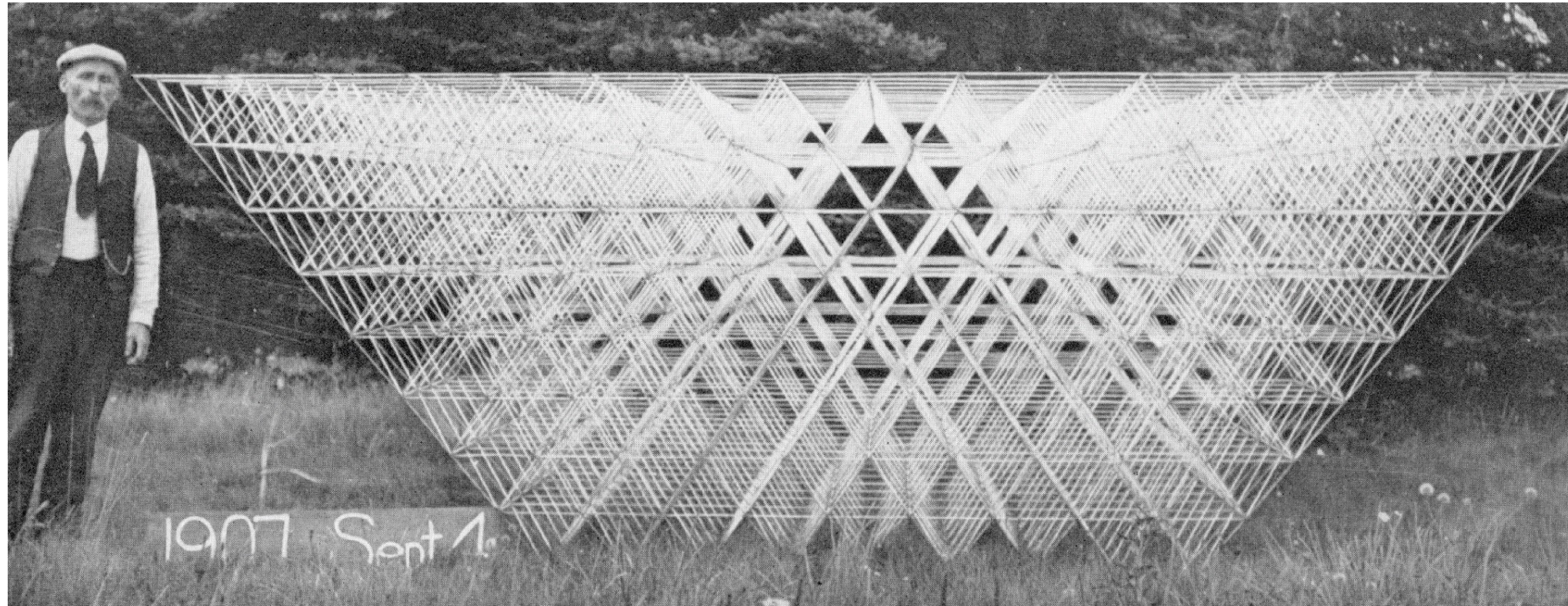


Christian Kerez, Joseph Schwartz: Schulhaus Leutschenbach, Zürich, 2009

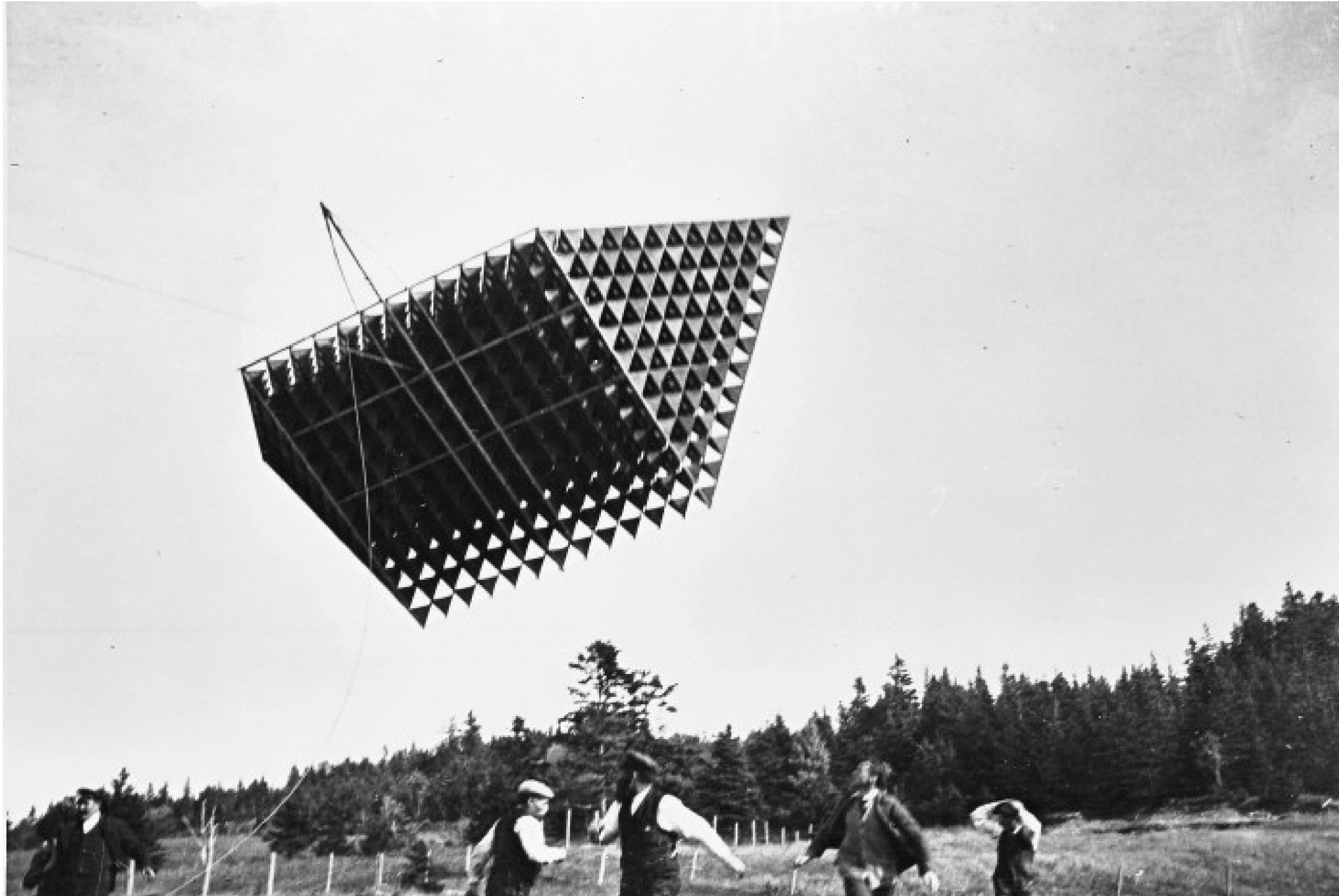


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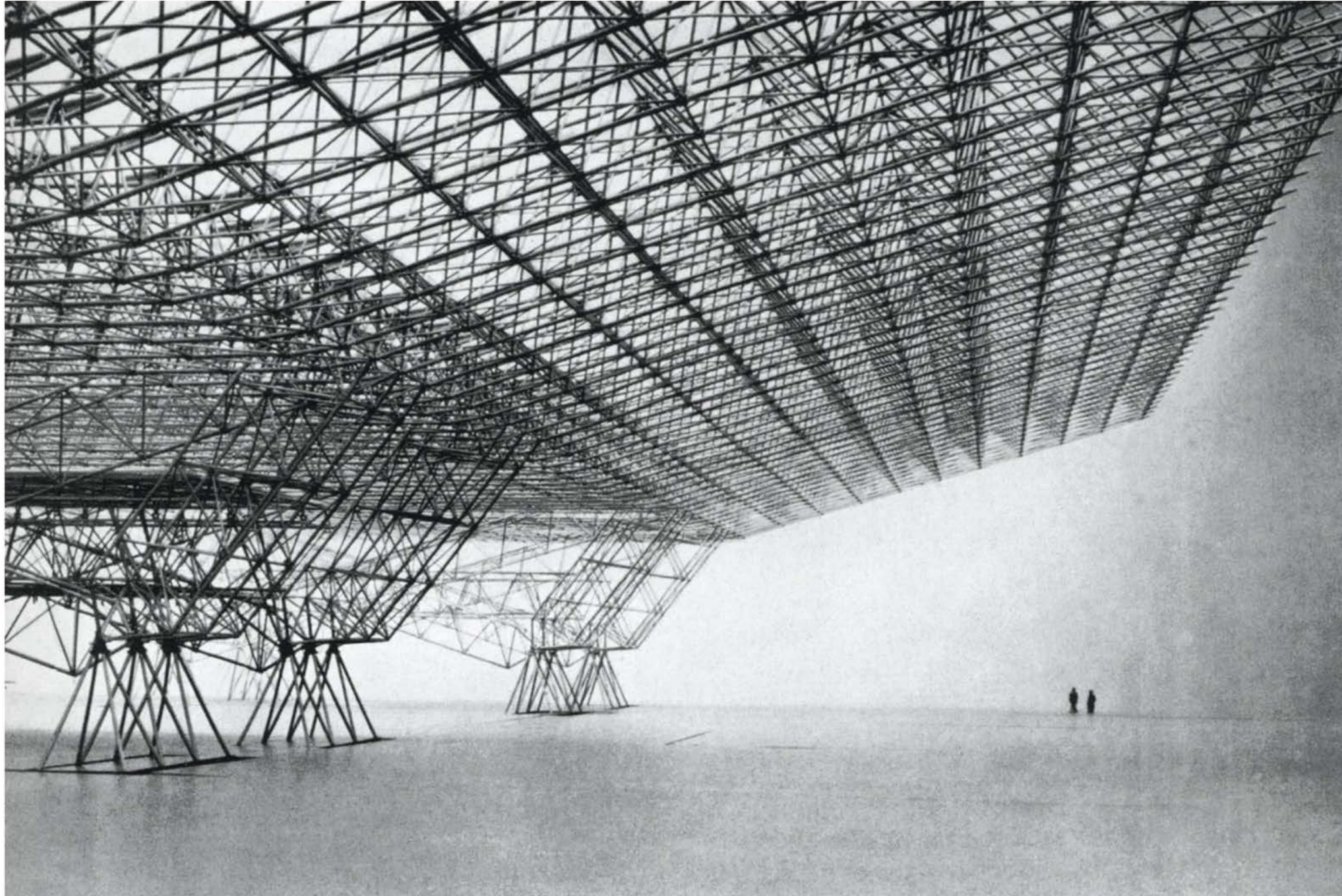




Alexander Graham Bell: Verbunddrachen als Raumfachwerk aus vorfabrizierten Tetraedern, 1907



Alexander Graham Bell: Verbunddrachen als Raumfachwerk aus vorfabrizierten Tetraedern, 1907



Konrad Wachsmann: US Air Force Hangar Project, 1951



Richard Buckminster Fuller, Shoji Sado: US Expo-Pavillion, Montreal, 1967





Richard Buckminster Fuller, Shoji Sado: US Expo-Pavillion, Montreal, 1967