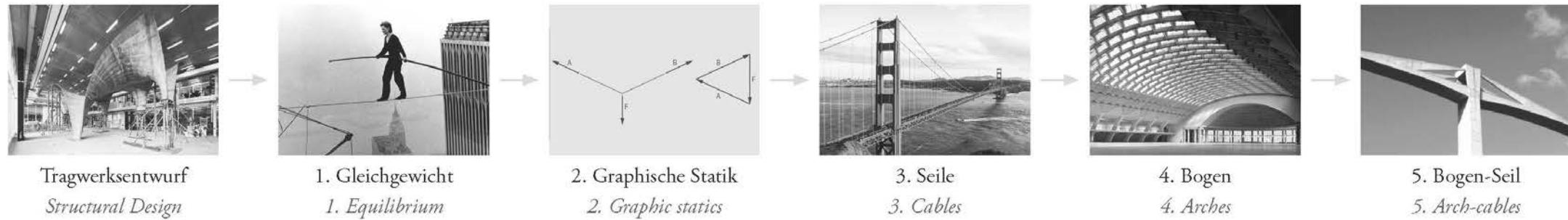


# Tragwerksentwurf II

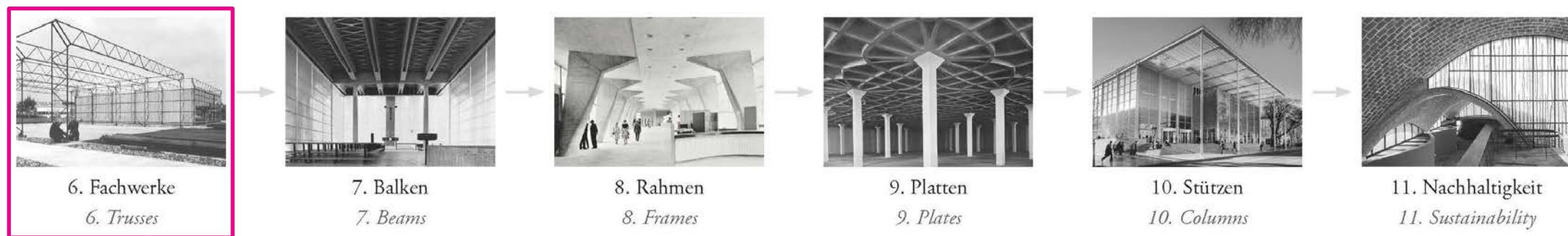
*Structural Design II*

Philippe Block · Joseph Schwartz



## Tragwerksentwurf I *Structural Design I*

## Tragwerksentwurf II *Structural Design II*



# 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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*Calculation of maximum inner forces*

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*Geometric variation*

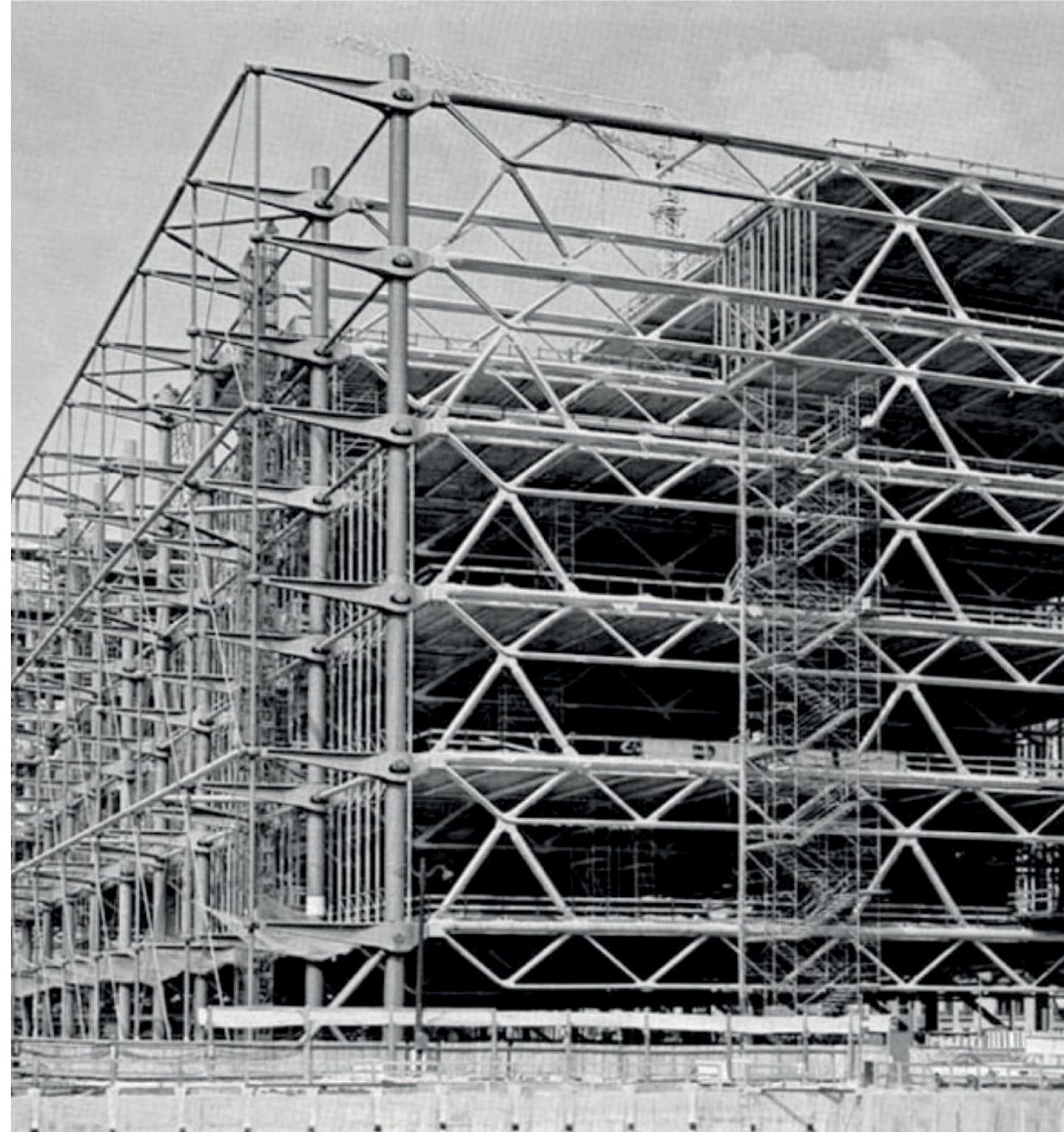
Arten von Fachwerken  
*Types of trusses*

Variation der Randbedingungen  
*Variation of boundary conditions*

Schlankheit von Fachwerken  
*Slender trusses*

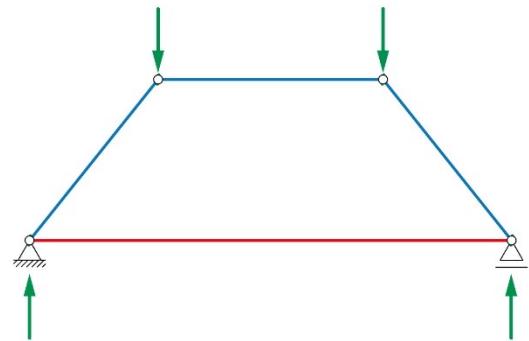
Konstruktion von Fachwerken  
*Construction of trusses*

Räumliche Fachwerke  
*Spatial trusses*



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

Bogen-Seil  
*Arch-cable*



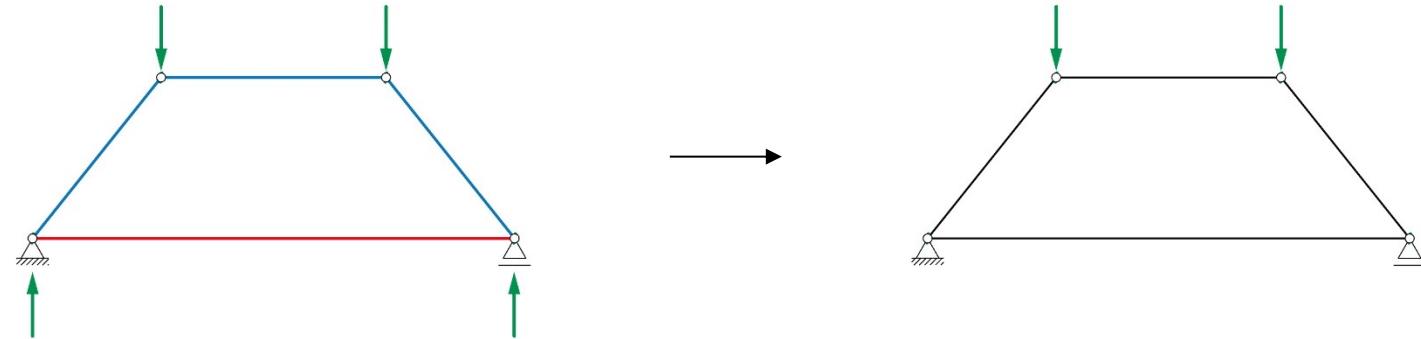
Nur für den gegebenen Belastungsfall stabil

*Only stable for the given loading case*



Formfindung  
*Form-finding*

Bogen-Seil  
*Arch-cable*

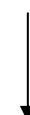


Nur für den gegebenen Belastungsfall stabil

*Only stable for the given loading case*

Instabil!

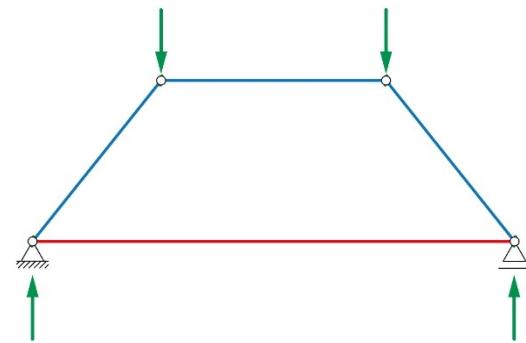
*Unstable!*



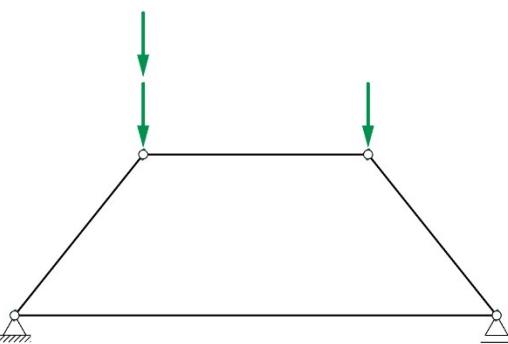
Formfindung

*Form-finding*

Bogen-Seil  
*Arch-cable*

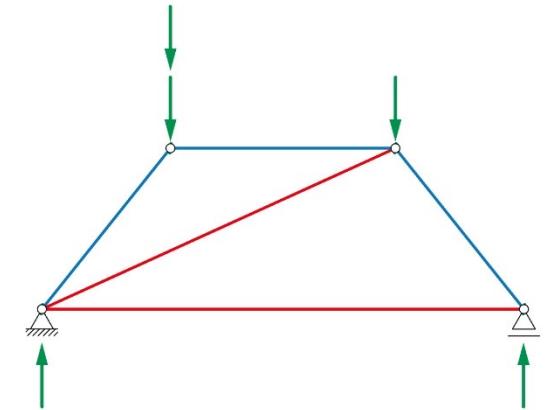


Nur für den gegebenen Belastungsfall stabil  
Only stable for the given loading case

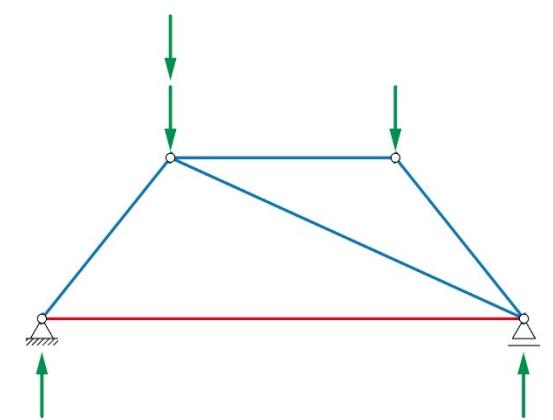


Instabil!  
*Unstable!*

Fachwerk  
*Truss*

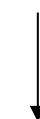


Zusätzliches Element  
*Additional Element*



Für beliebige Belastungen stabil  
Stable for any loading case

Formfindung  
*Form-finding*



Analyse  
*Analysis*

# Fachwerke

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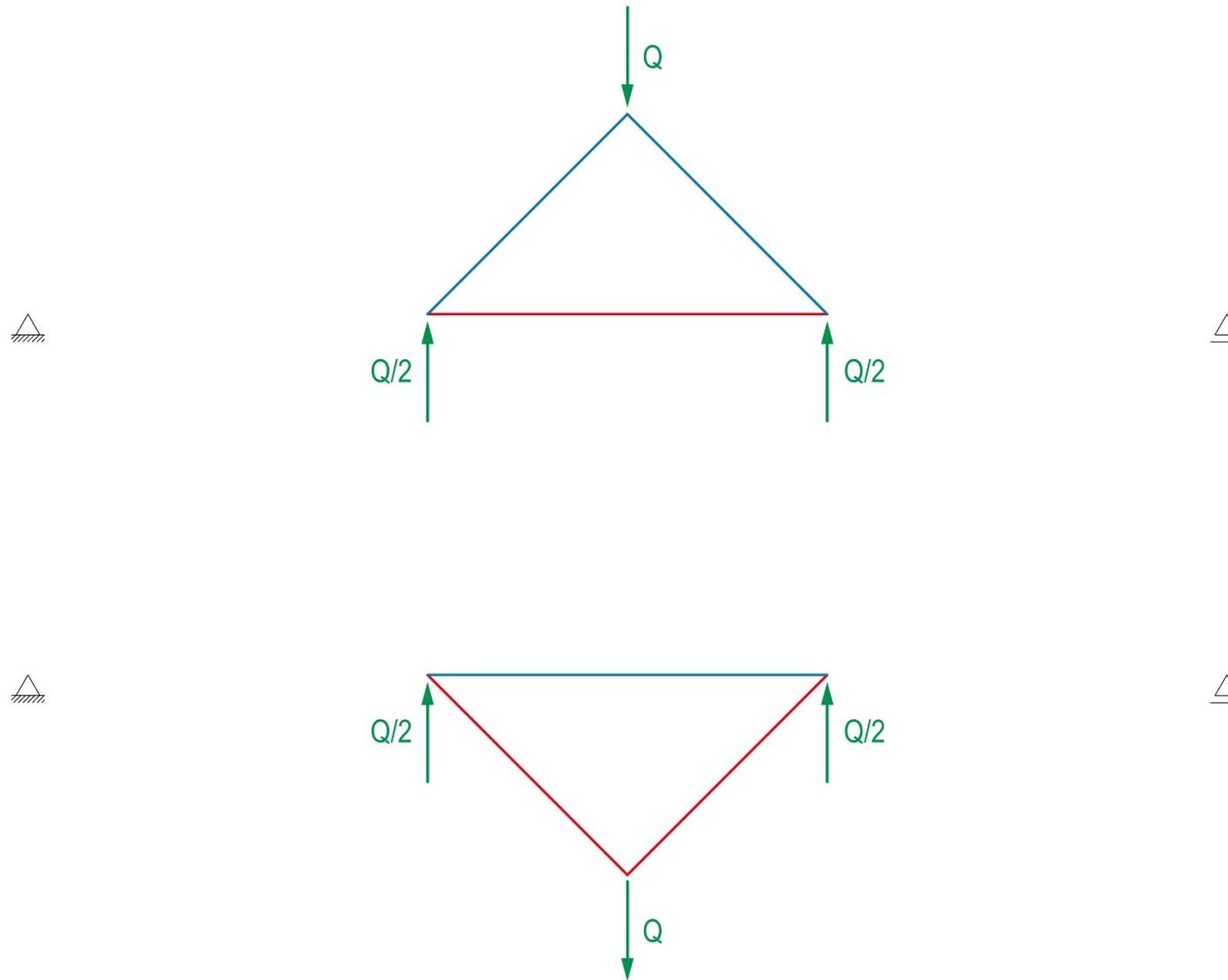
*Slender trusses*

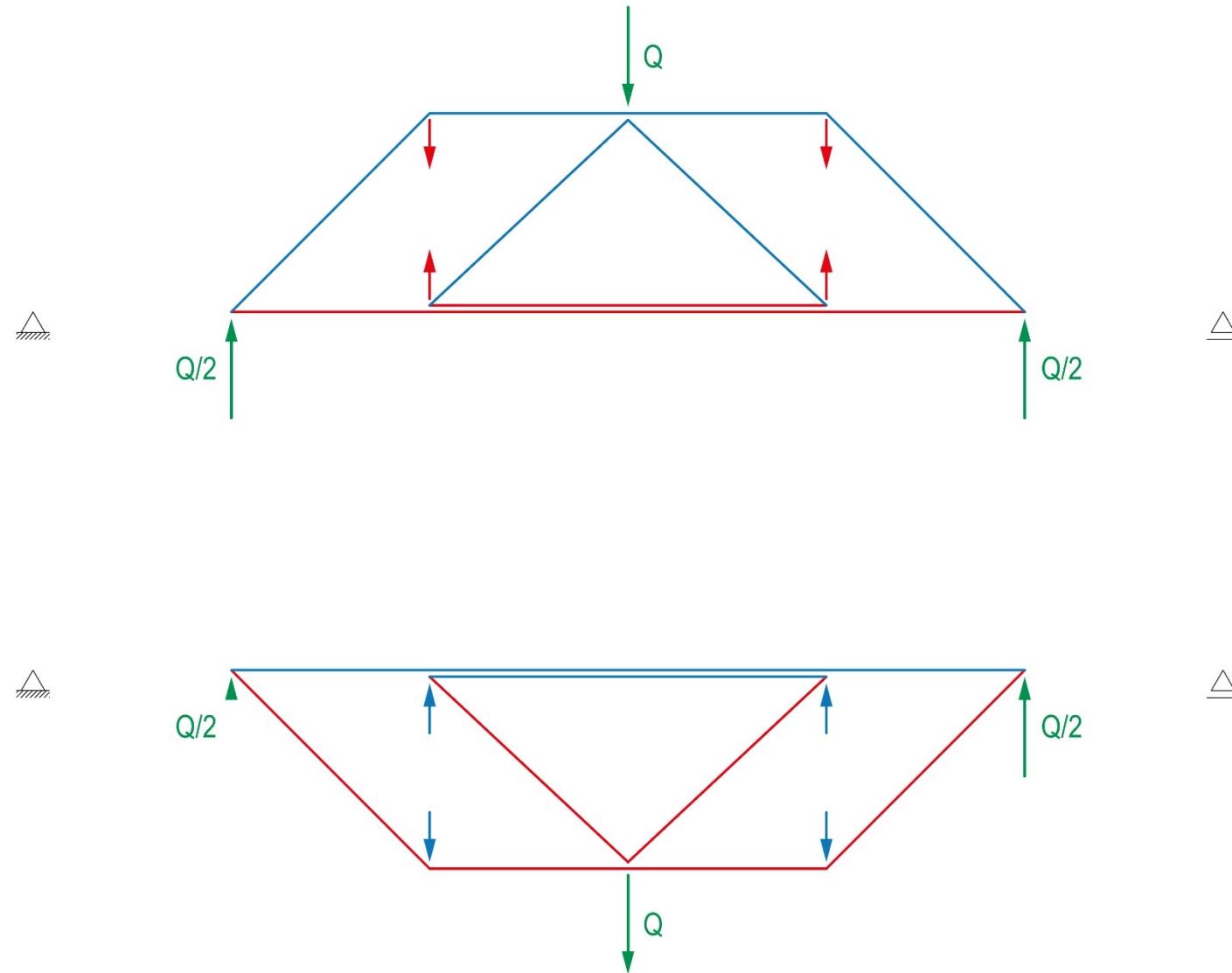
Konstruktion von Fachwerken

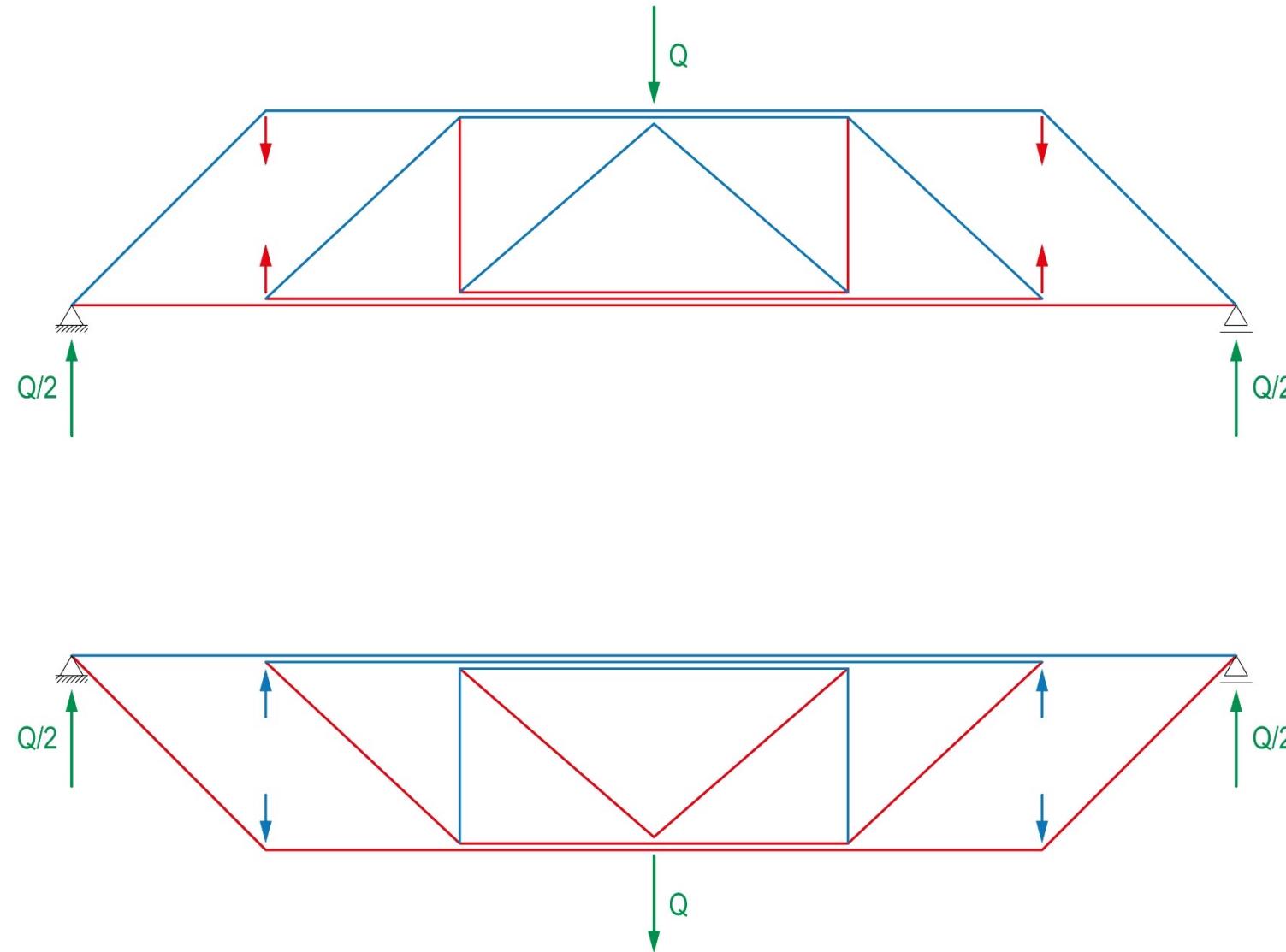
*Construction of trusses*

Räumliche Fachwerke

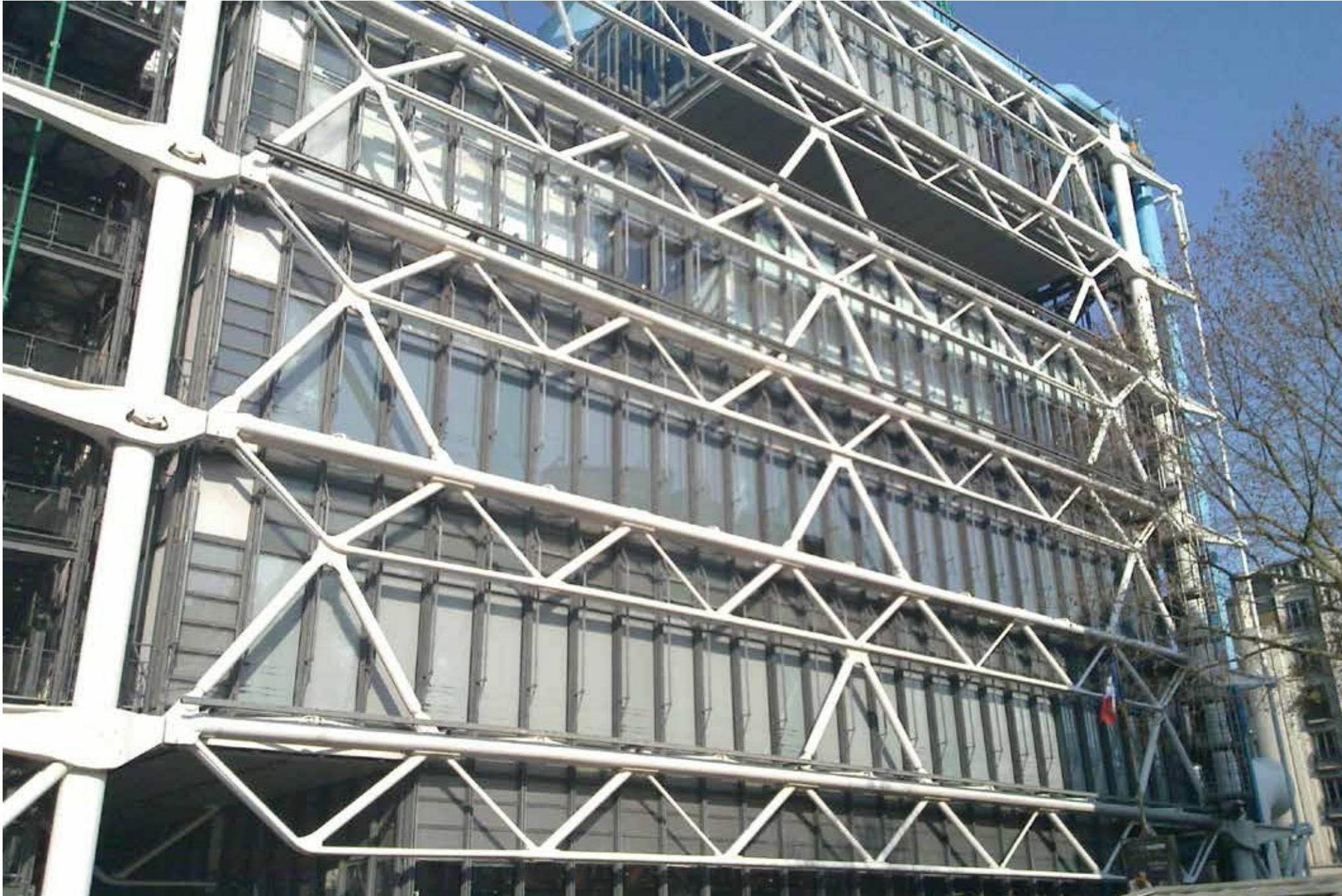
*Spatial trusses*



*The truss as a combination of arch-cables*

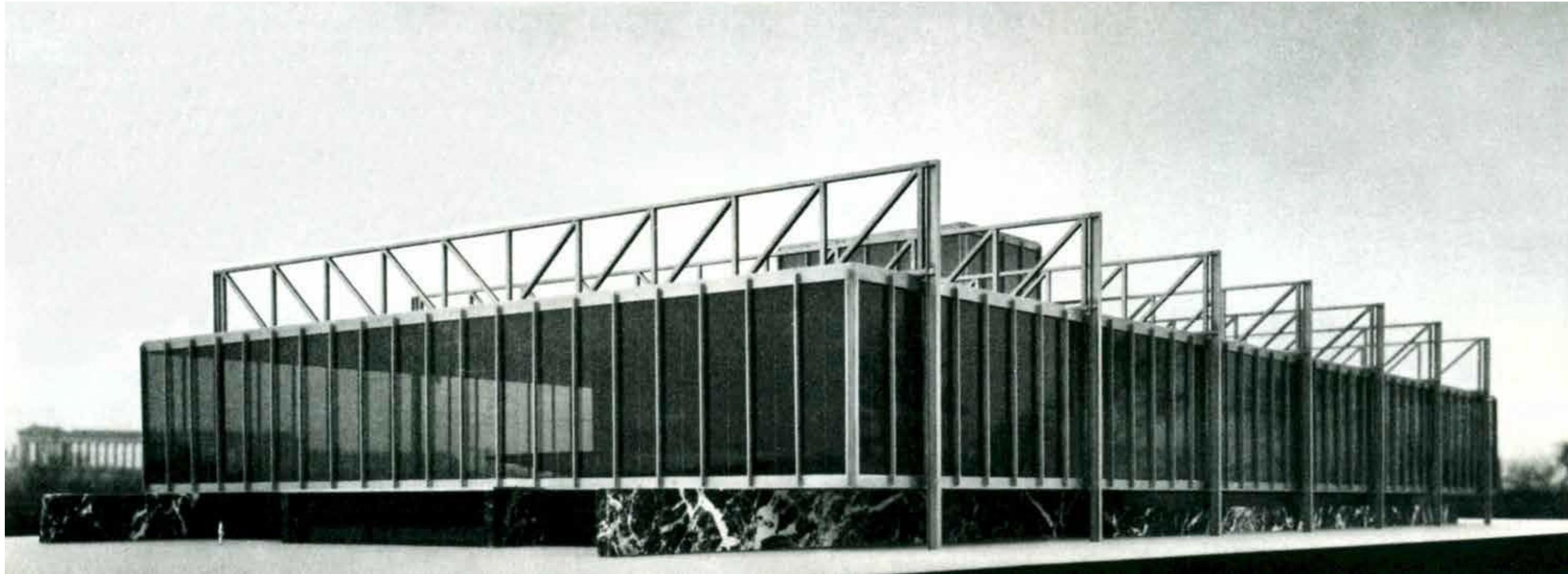
*The truss as a combination of arch-cables*

*The truss as a combination of arch-cables*



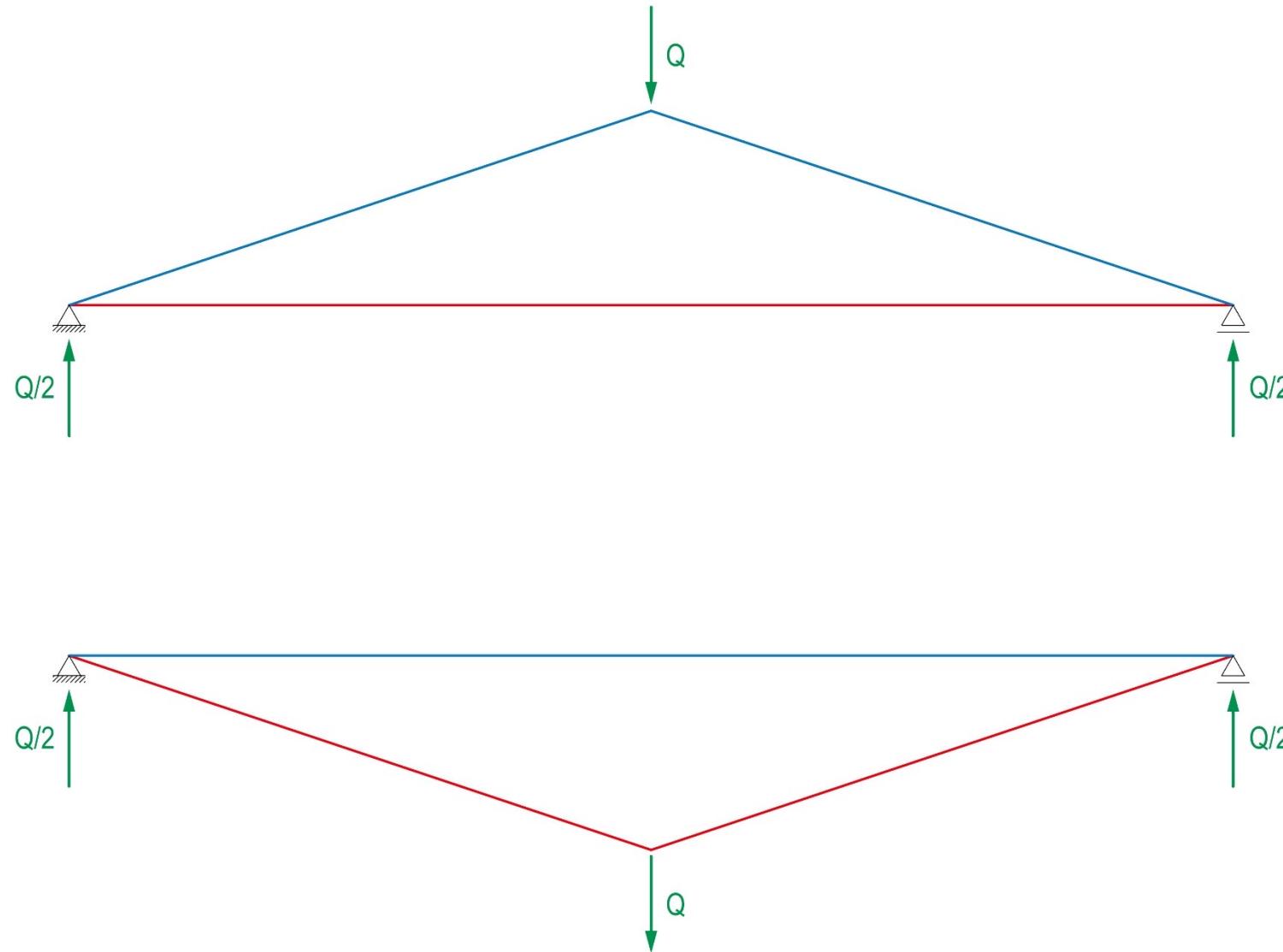
R. Piano, R. Rogers, P. Rice: Centre Georges Pompidou, Paris, 1977

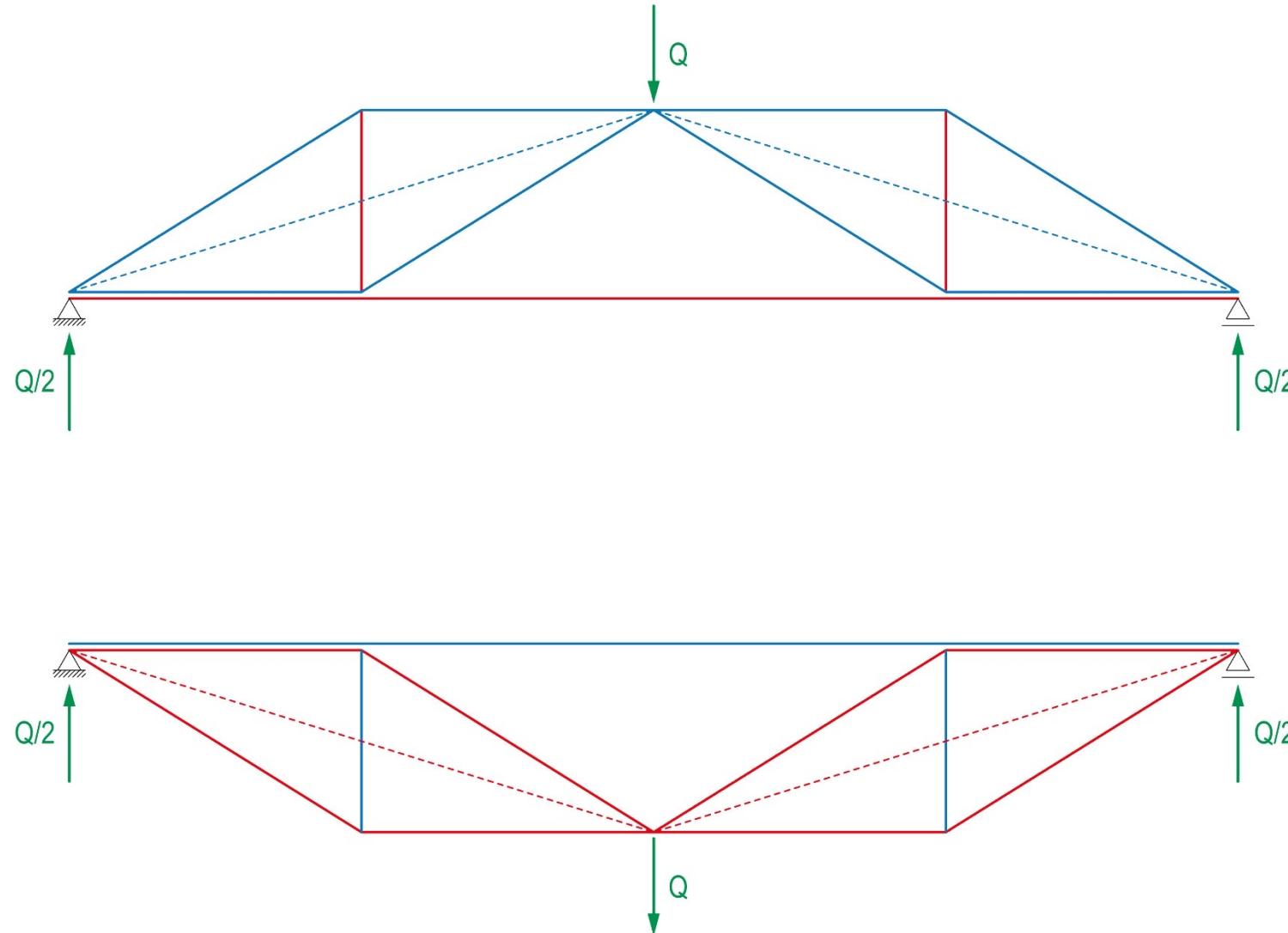
*The truss as a combination of arch-cables*

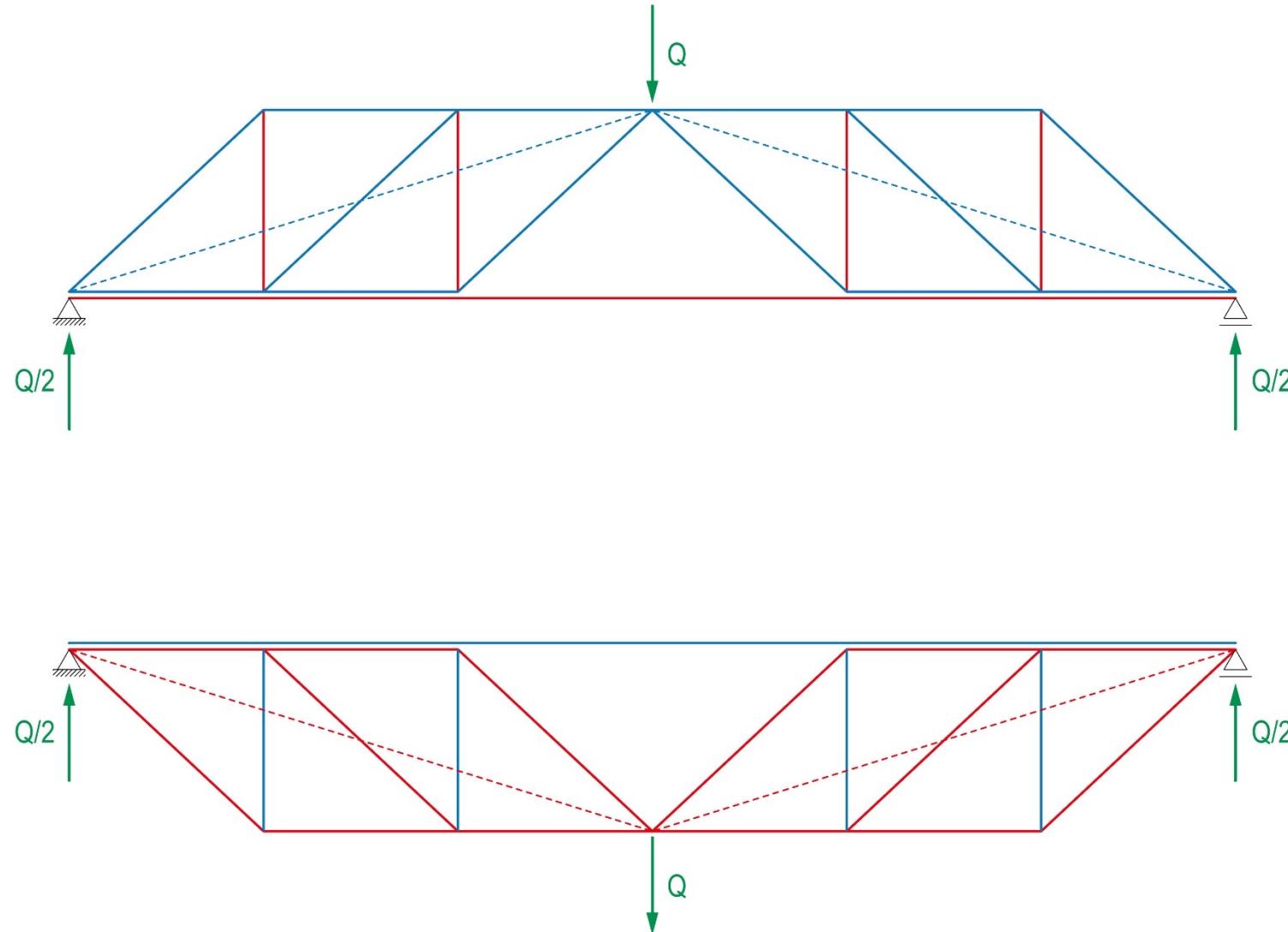


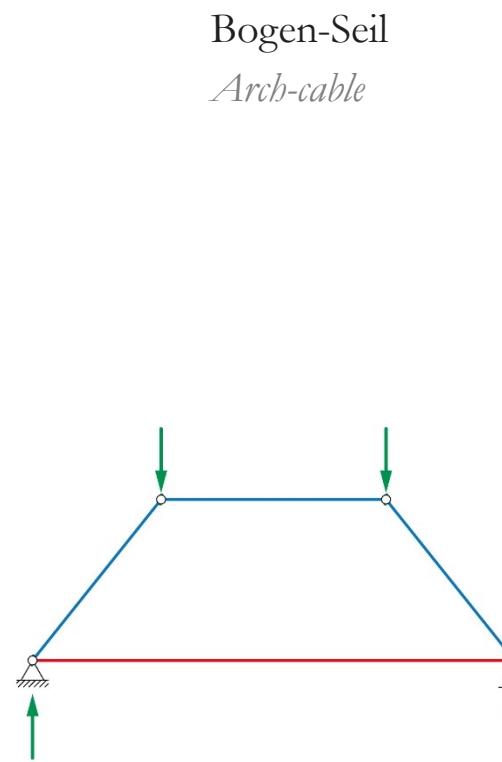
Ludwig Mies van der Rohe: Projekt, Nationaltheater, Mannheim, 1953

The truss as a combination of arch-cables

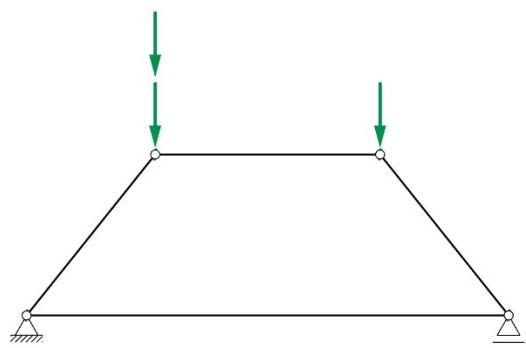


*The truss as a combination of arch-cables*

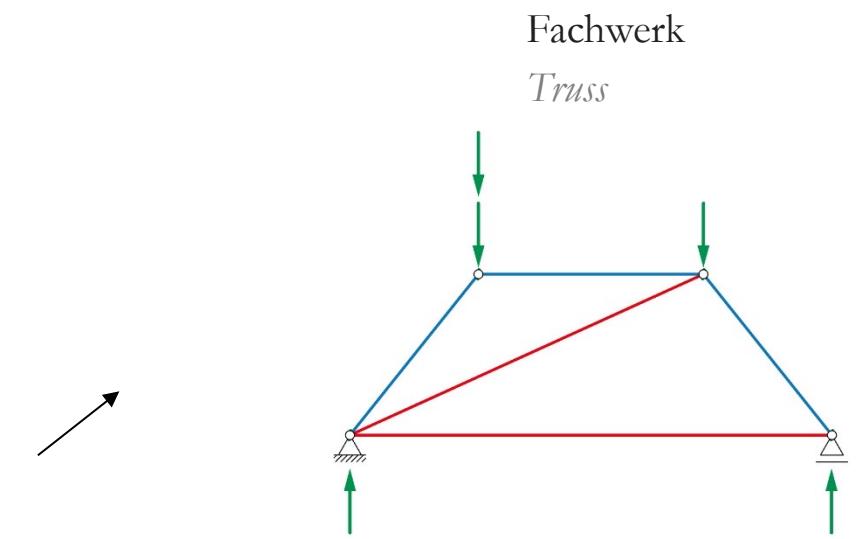
*The truss as a combination of arch-cables*



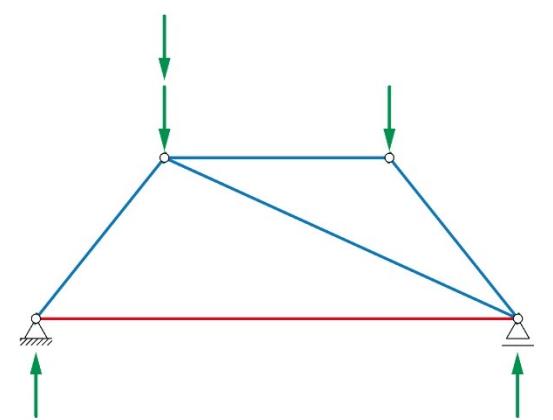
Nur für den gegebenen Belastungsfall stabil  
 Only stable for the given loading case



Instabil!  
*Unstable!*



Zusätzliches Element  
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Für beliebige Belastungen stabil  
 Stable for any loading case

Formfindung  
*Form-finding*

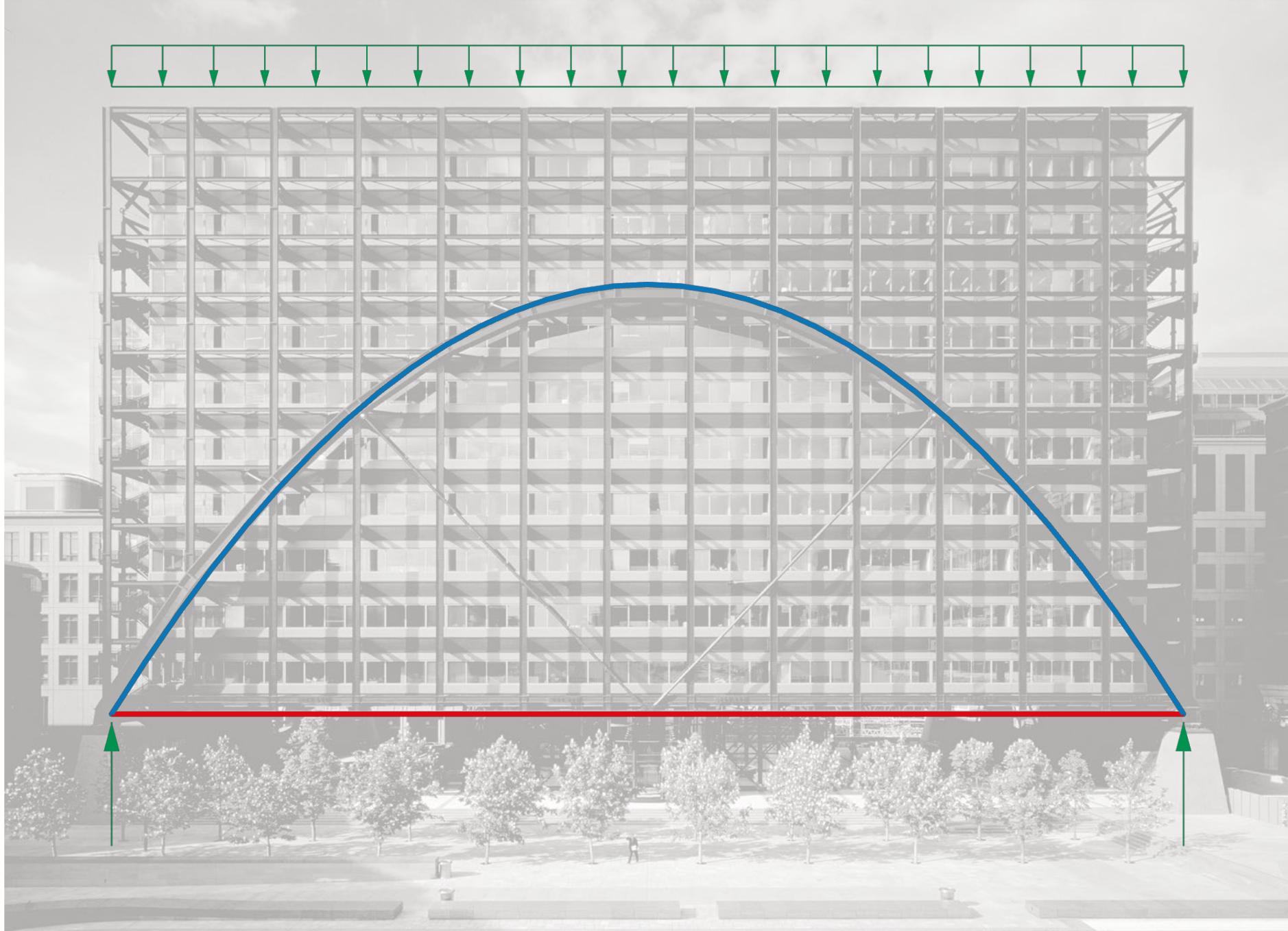
Analyse  
*Analysis*

*The truss as a combination of arch-cables*



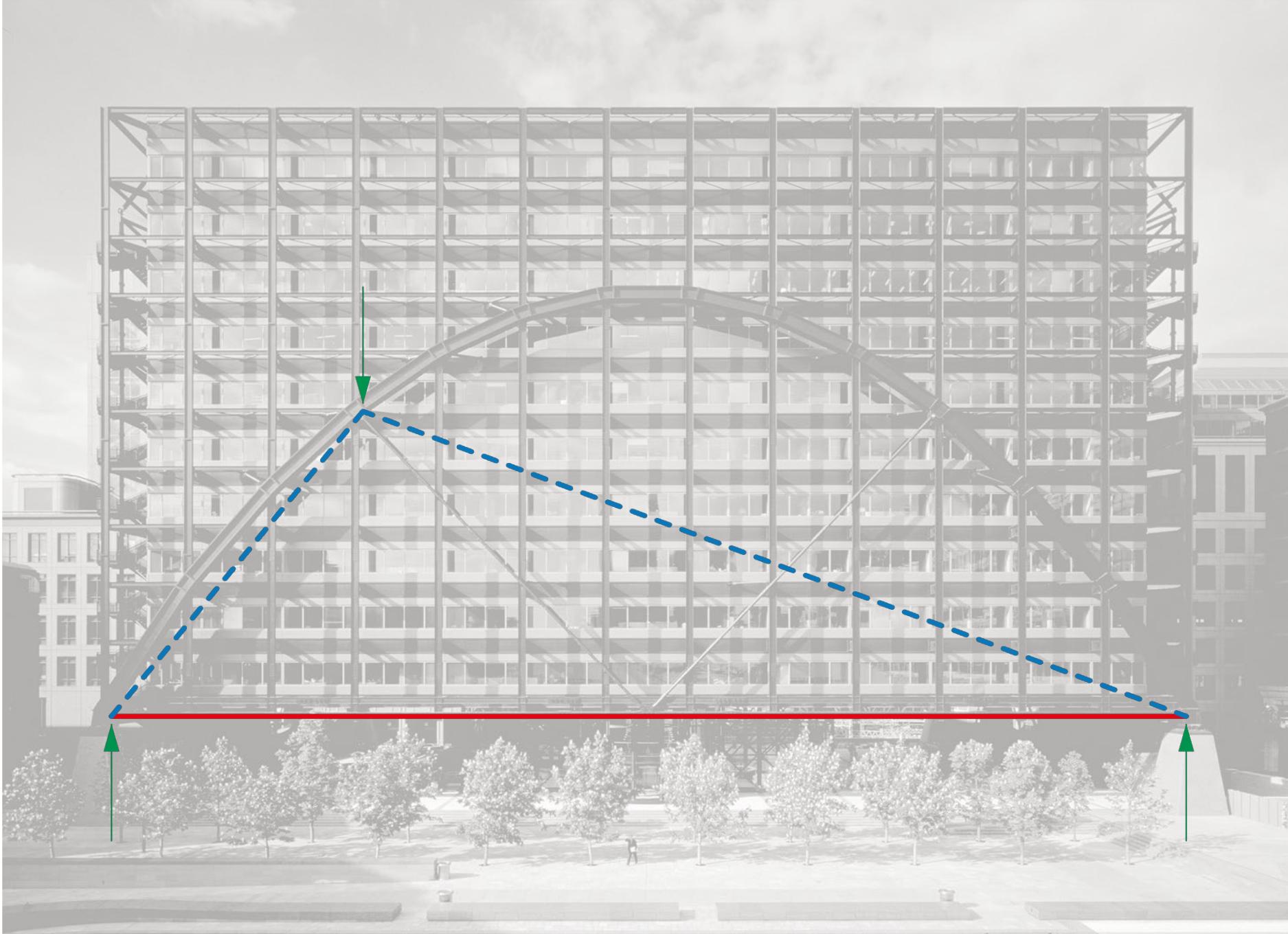
Skidmore, Owings & Merrill (SOM): Exchange House, Broadgate, London, 1990

*The truss as a combination of arch-cables*



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

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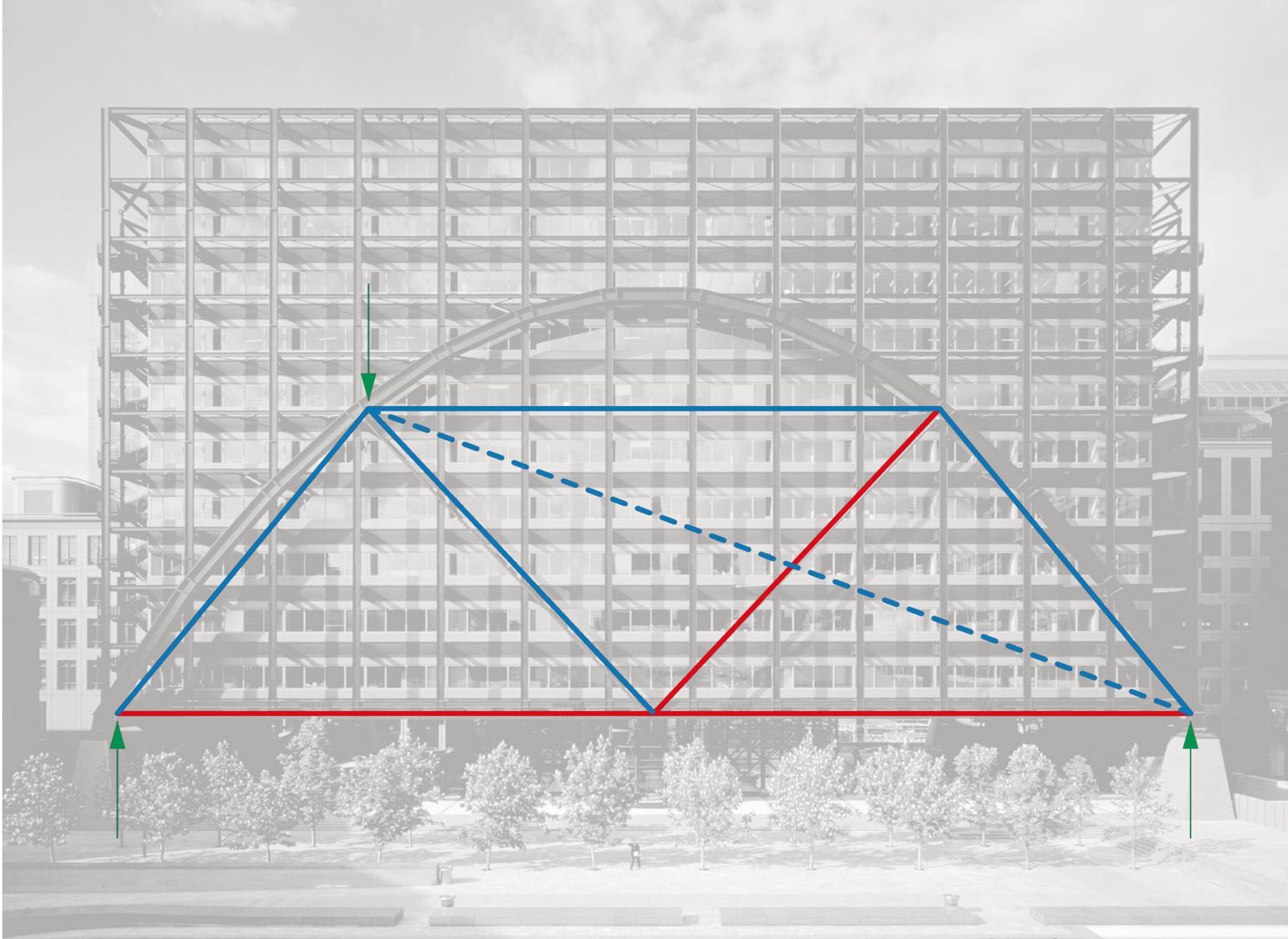
Skidmore, Owings & Merrill (SOM): Exchange House, Broadgate, London, 1990

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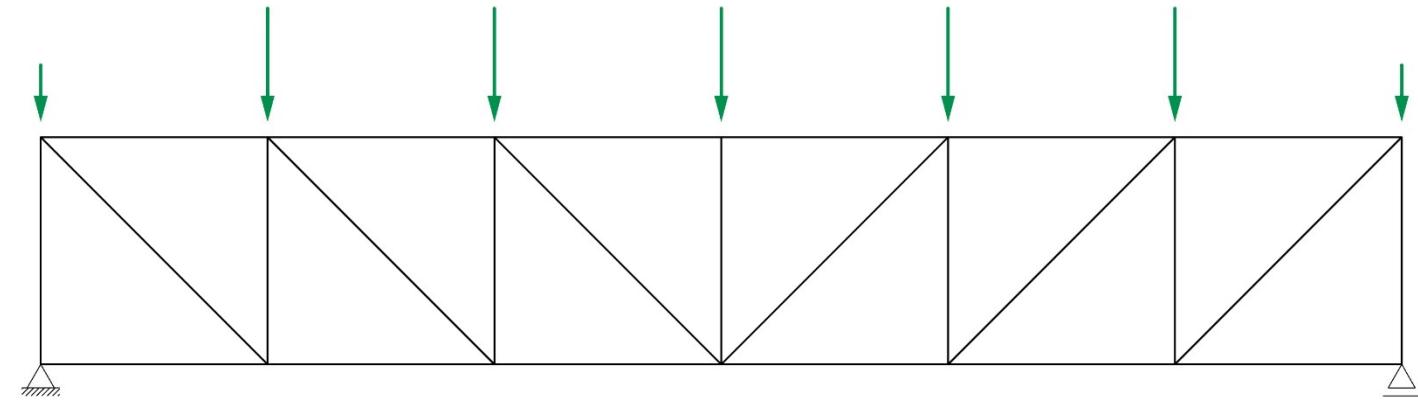
*Slender trusses*

Konstruktion von Fachwerken

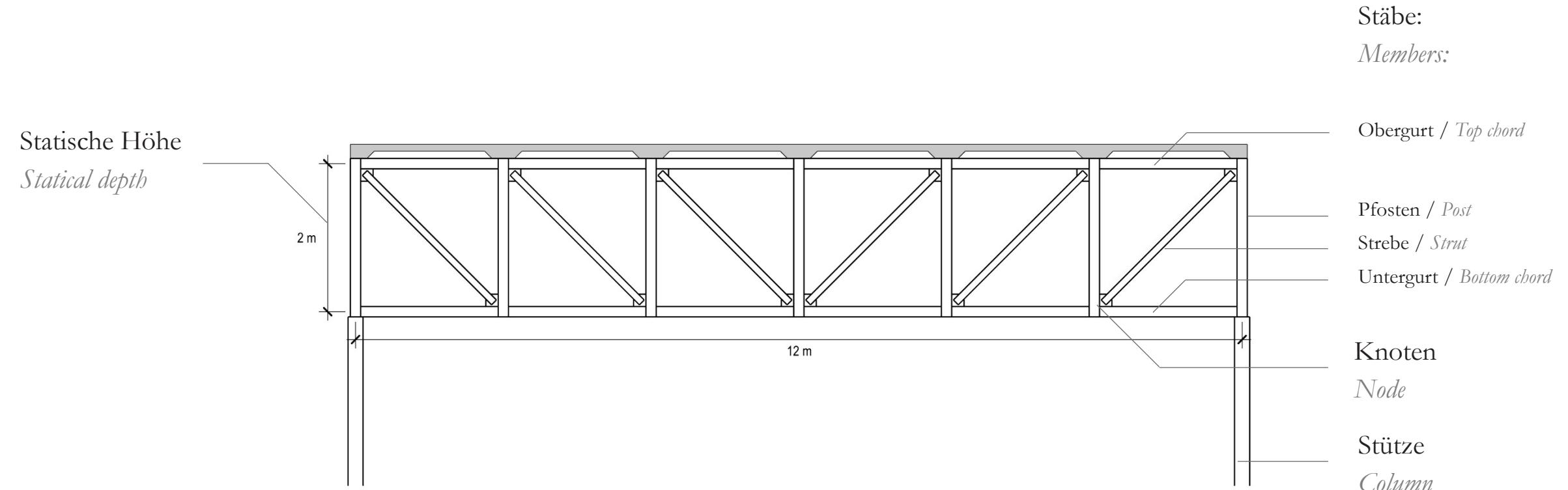
*Construction of trusses*

Räumliche Fachwerke

*Spatial trusses*

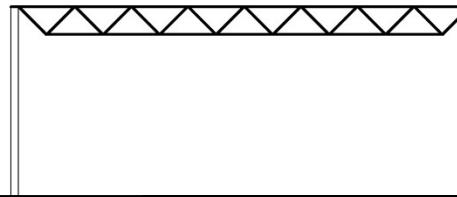


- Alle Verbindungen sind gelenkig
- Alle Elemente sind gerade
- Lasten greifen nur an Knotenpunkten an
- Es treten nur axiale Kräfte auf
- Fachwerke setzen sich aus Dreiecken zusammen, um stabil zu sein
- *All connections are hinged*
- *All elements are straight*
- *Loads only act at nodes*
- *Only axial forces occur*
- *Trusses are composed of triangles in order to be stable*



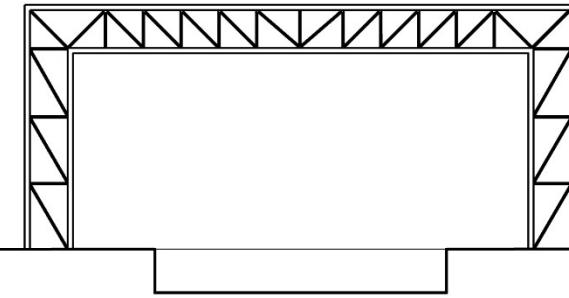
Fachwerk balken

*Beam truss*



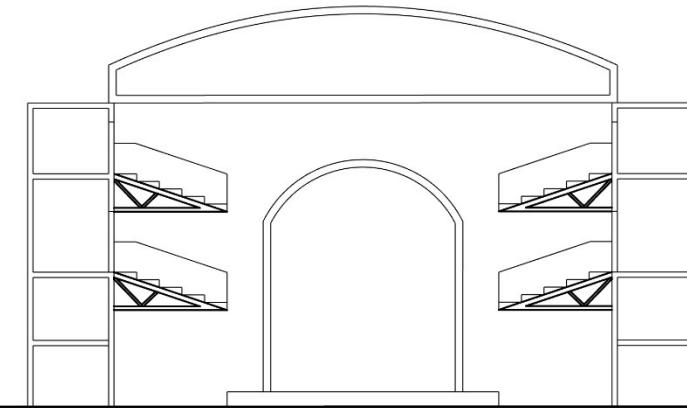
Fachwerkrahmen

*Frame truss*



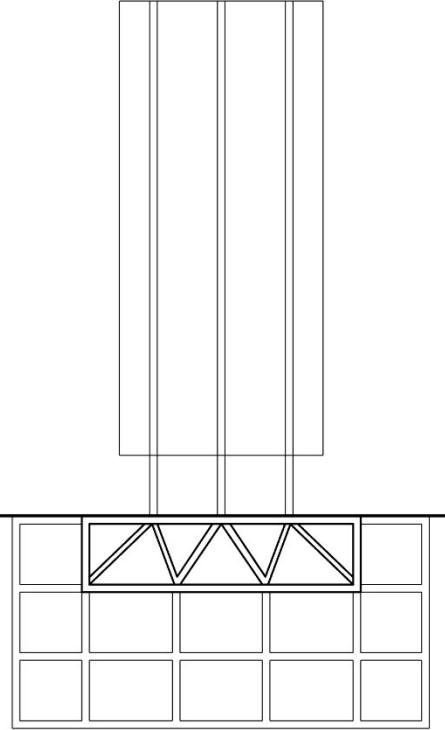
Fachwerkkonsole

*Cantilevering truss*



Fachwerkabfangung

*Transfer truss*



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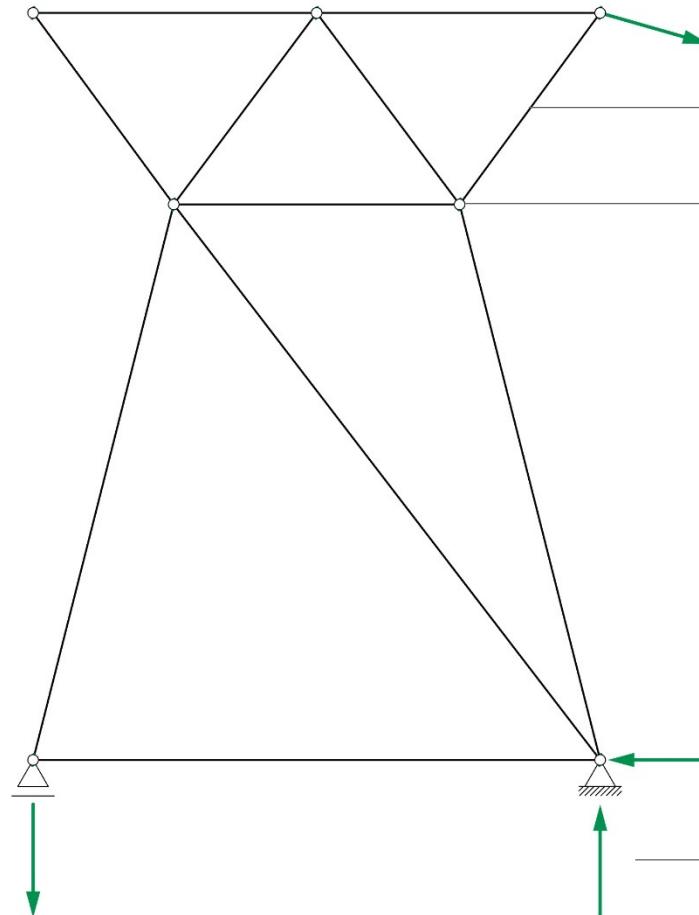
*Slender trusses*

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$S = \text{Anzahl Stäbe / Elemente}$

$S = \text{Number of elements / Members}$

$K = \text{Anzahl Knoten}$

$K = \text{Number of nodes}$

$$S + A < 2 * K$$

$$S + A = 2 * K$$

$$S + A > 2 * K$$

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

Das System ist statisch bestimmt

*The system is statically determined*

$$A = 3$$

$$K = 7$$

$A = \text{Anzahl der Auflagerbedingungen}$

$A = \text{Number of reactions}$

Das System ist labil

*The system is not stable*

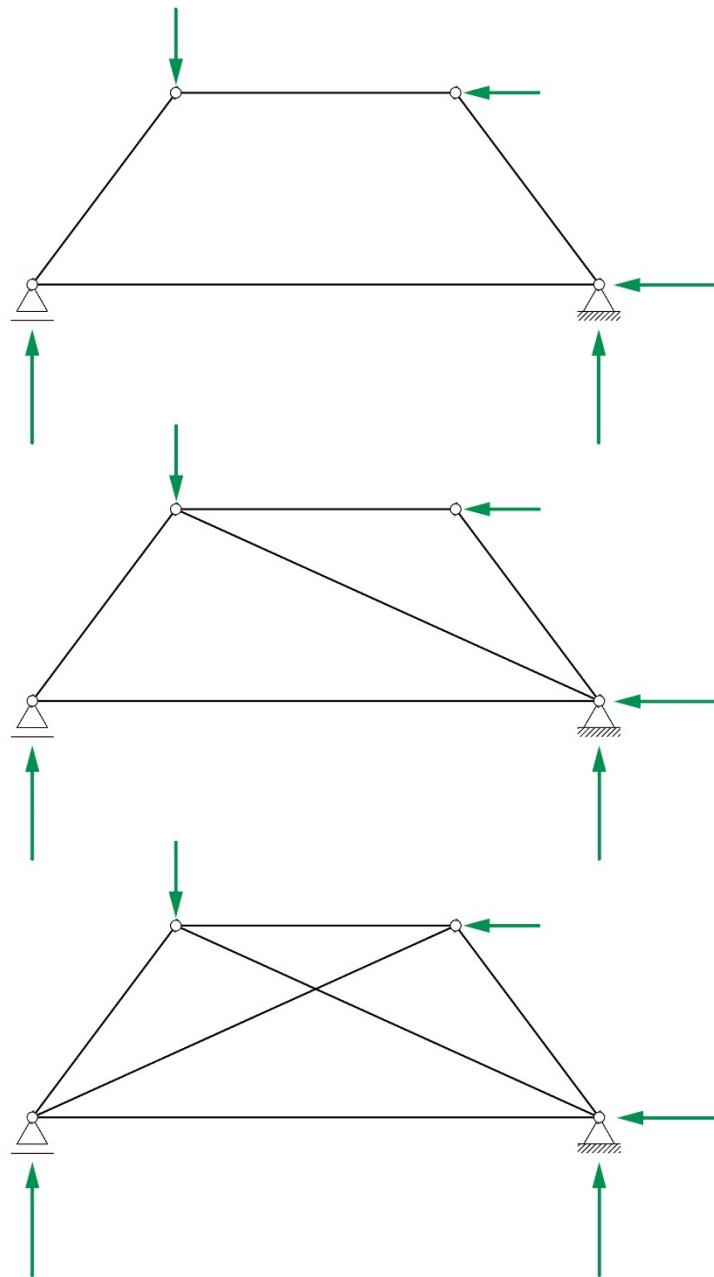
Das System ist statisch bestimmt

*The system is statically determined*

Das System ist statisch unbestimmt

*The system is statically not determined*

## Statical Determinacy



$$S = 4$$

$$A = 3$$

$$K = 4$$

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

Das System ist labil

*The system is not stable*

$$S = 5$$

$$A = 3$$

$$K = 4$$

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

Das System ist statisch bestimmt

*The system is statically determined*

$$S = 6$$

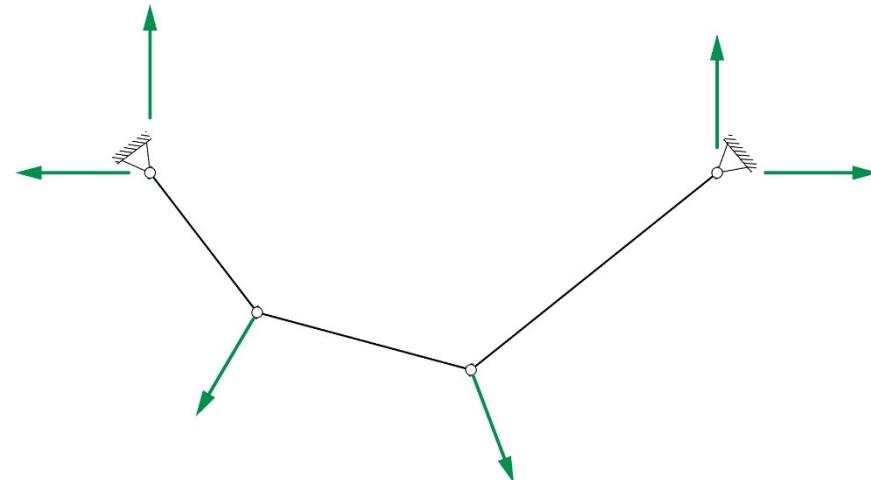
$$A = 3$$

$$K = 4$$

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

Das System ist statisch unbestimmt

*The system is statically not determined*



$$S = 3$$

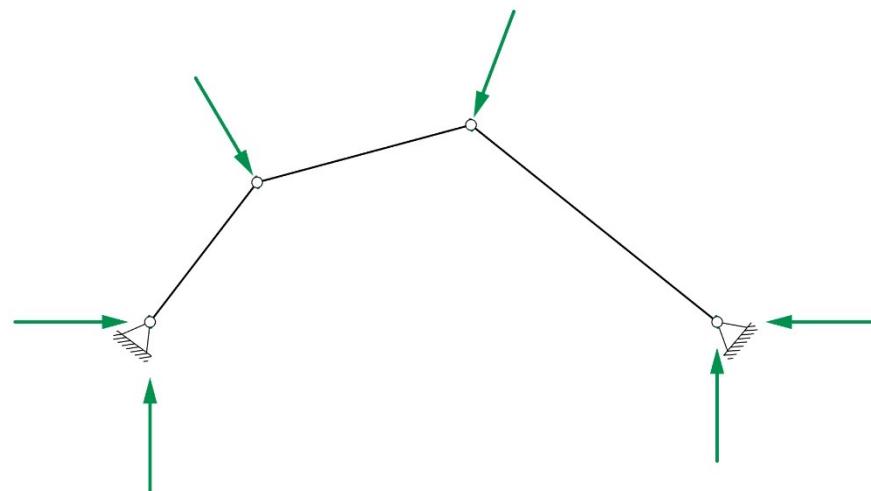
$$A = 4$$

$$K = 4$$

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

Das System ist labil

*The system is not stable*



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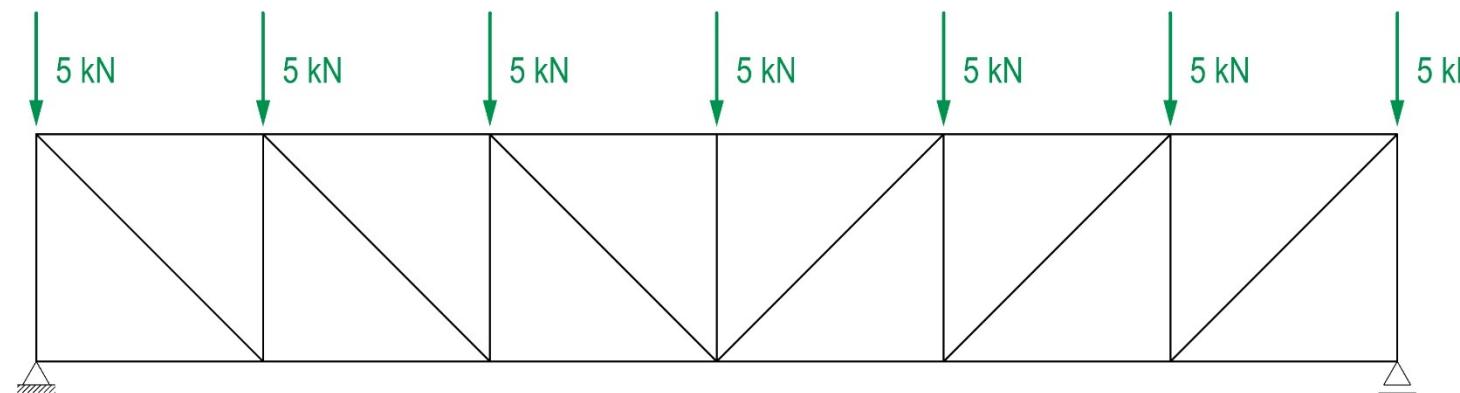
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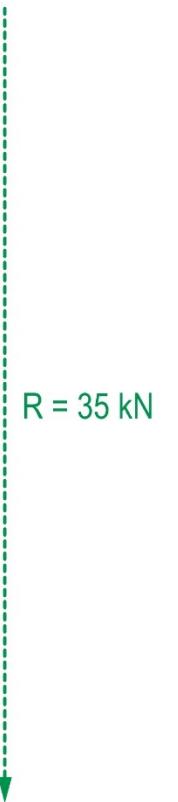
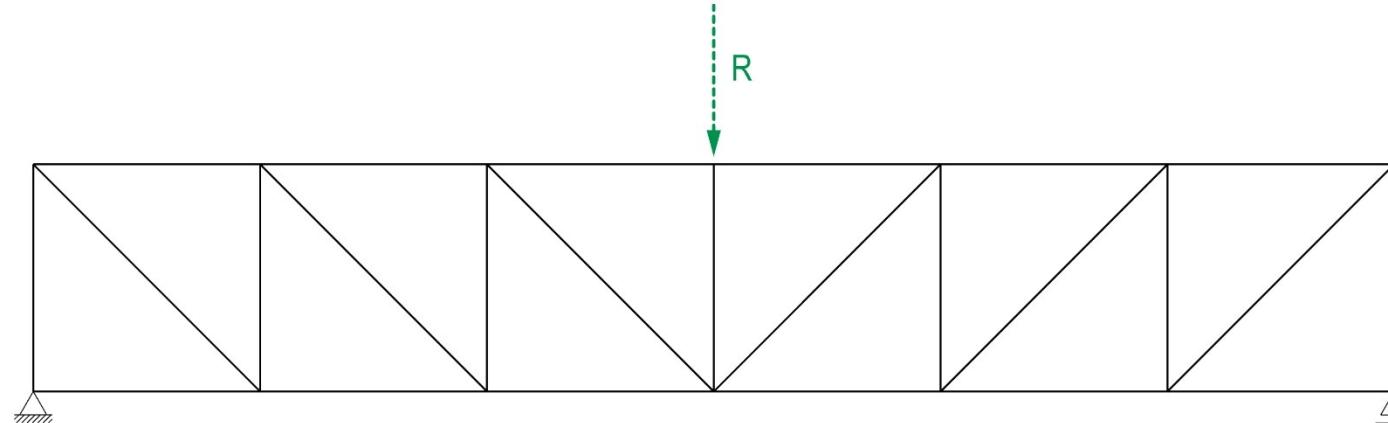
Räumliche Fachwerke

*Spatial trusses*



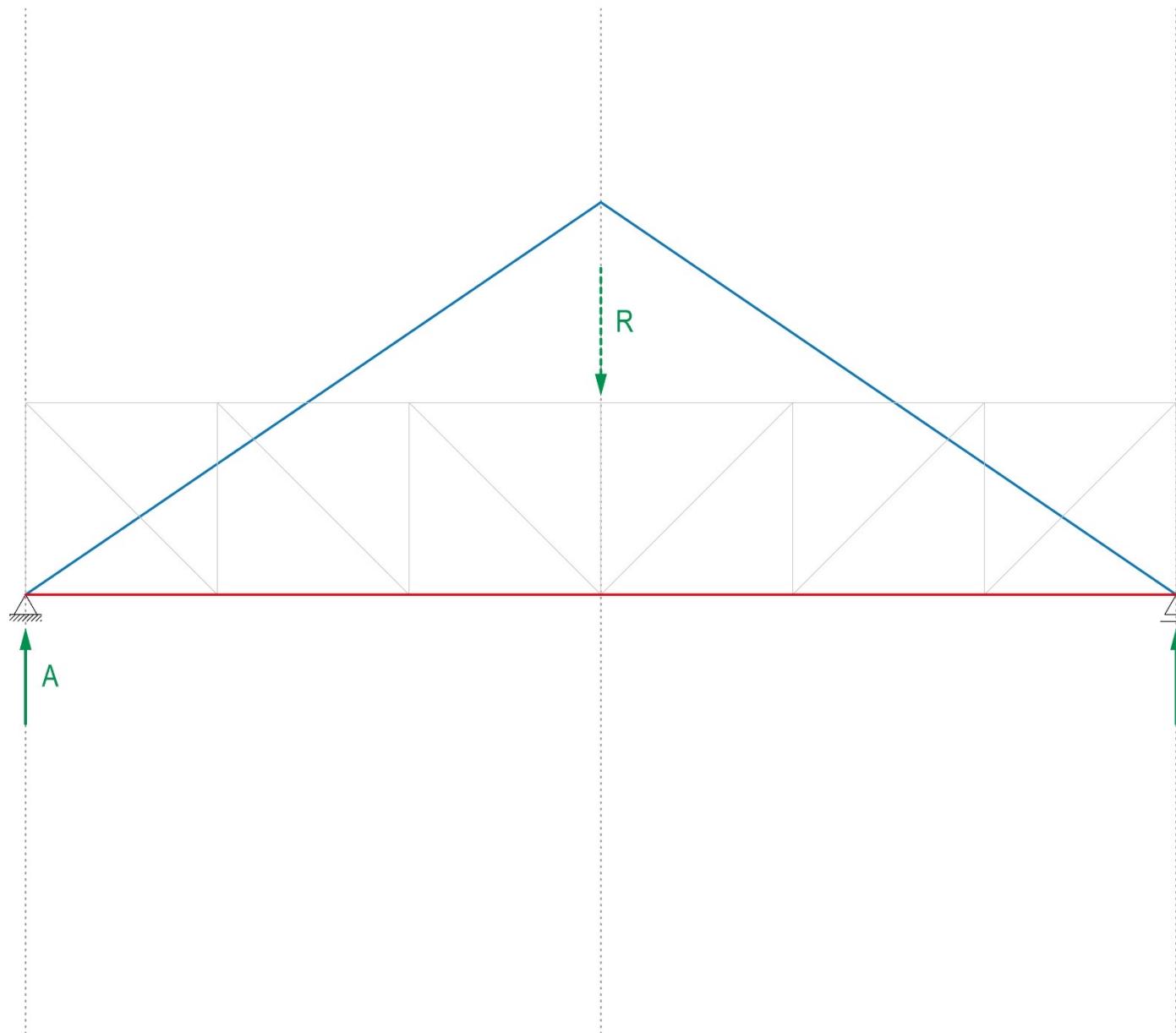
Lageplan 1:100  
*Form diagram 1:100*

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

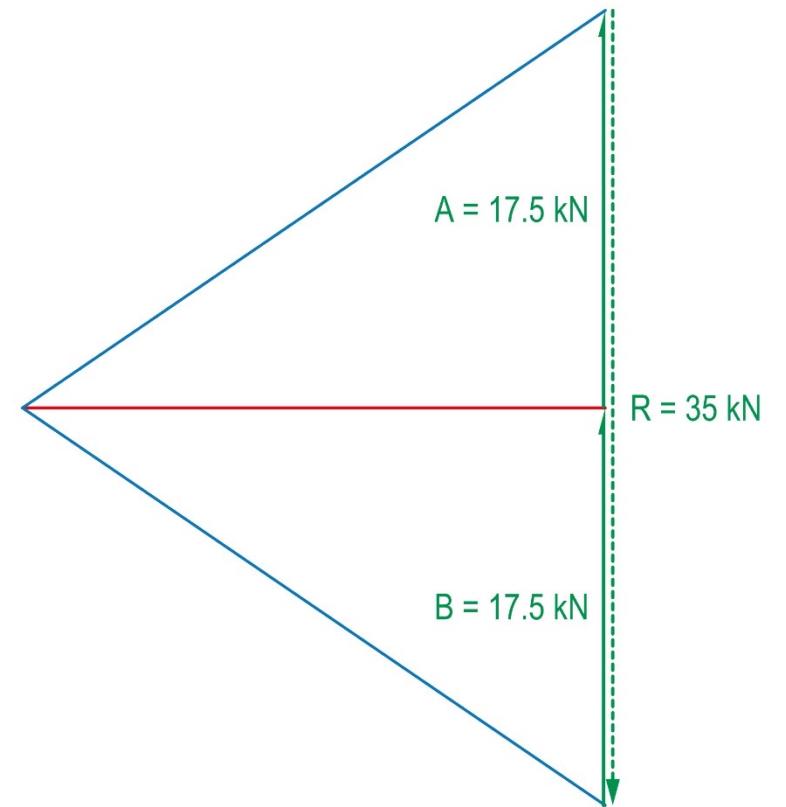


Lageplan 1:100  
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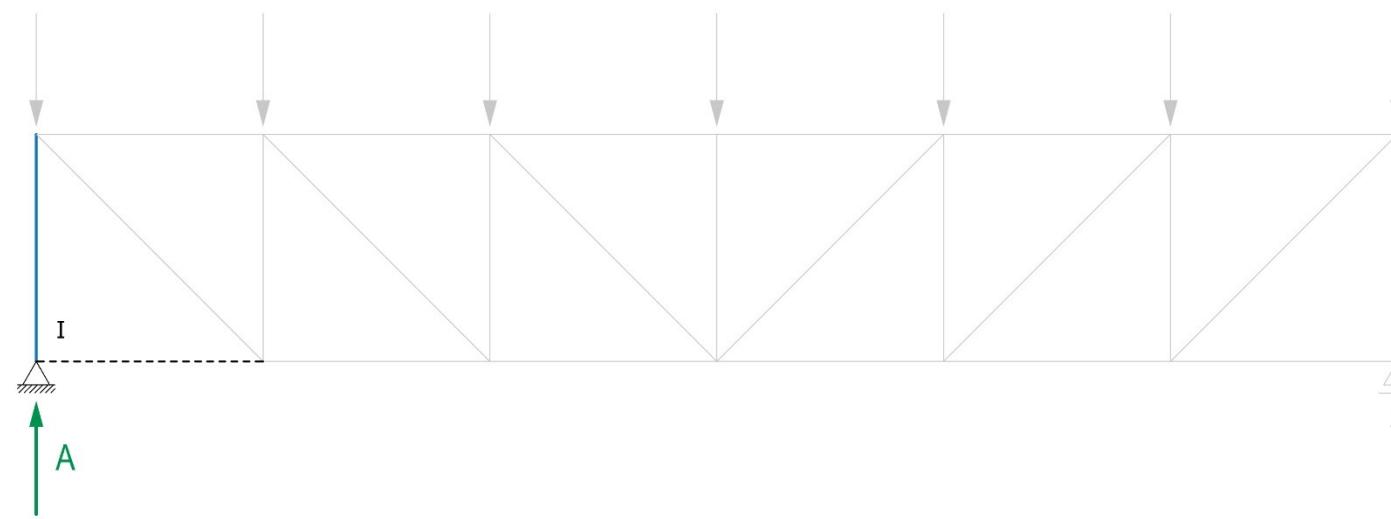
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Lageplan 1:100  
Form diagram 1:100



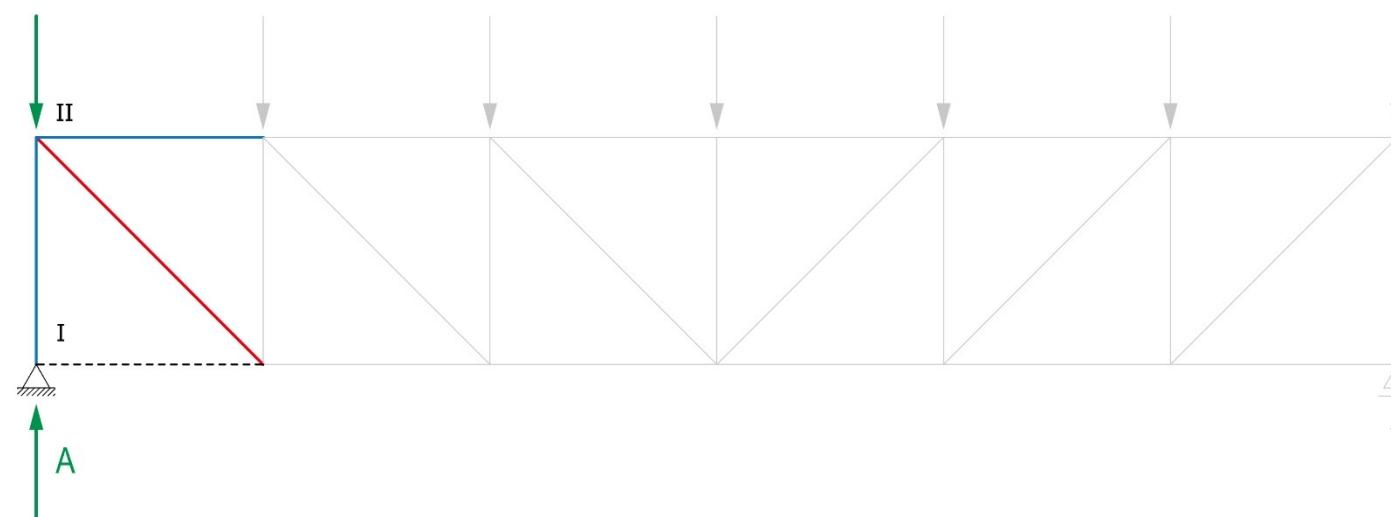
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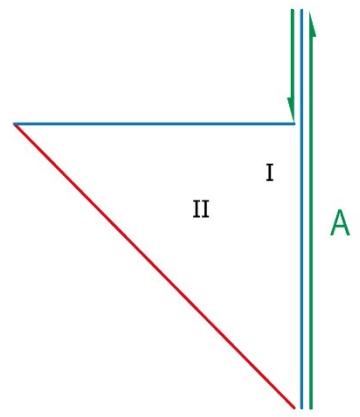
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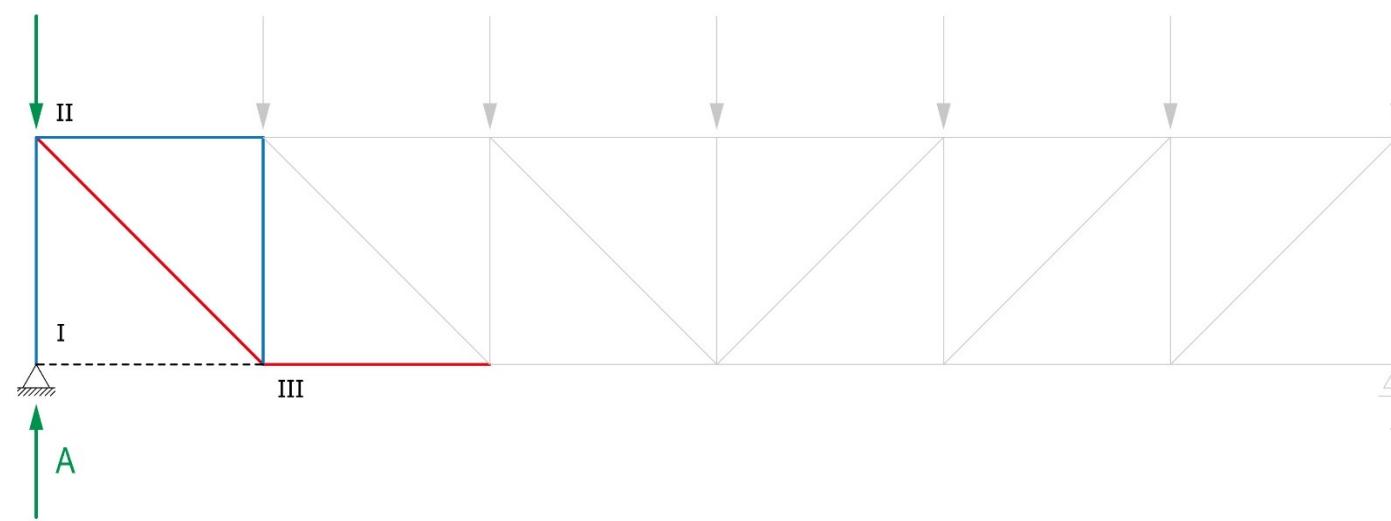




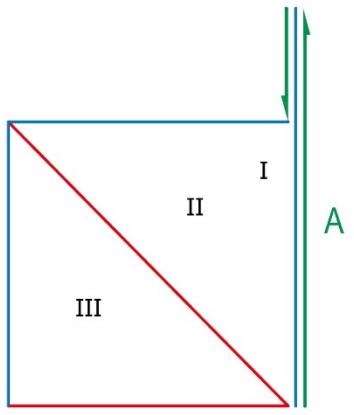
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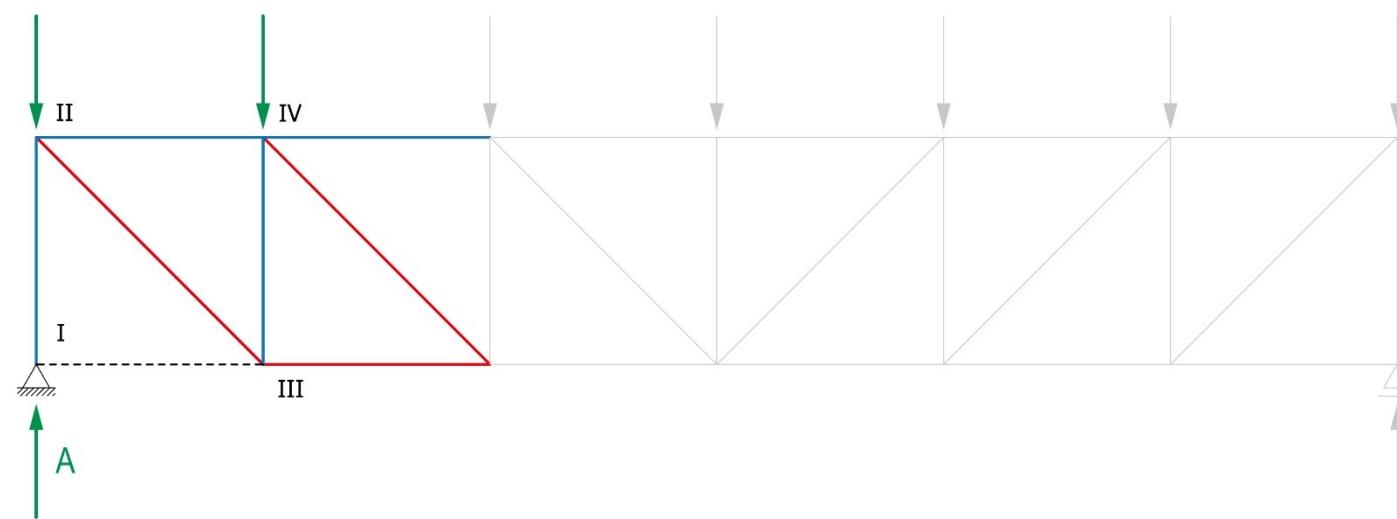
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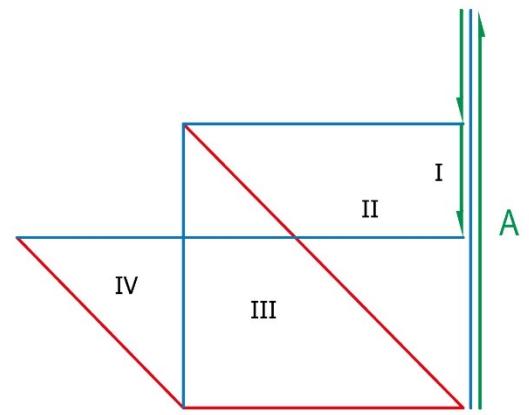
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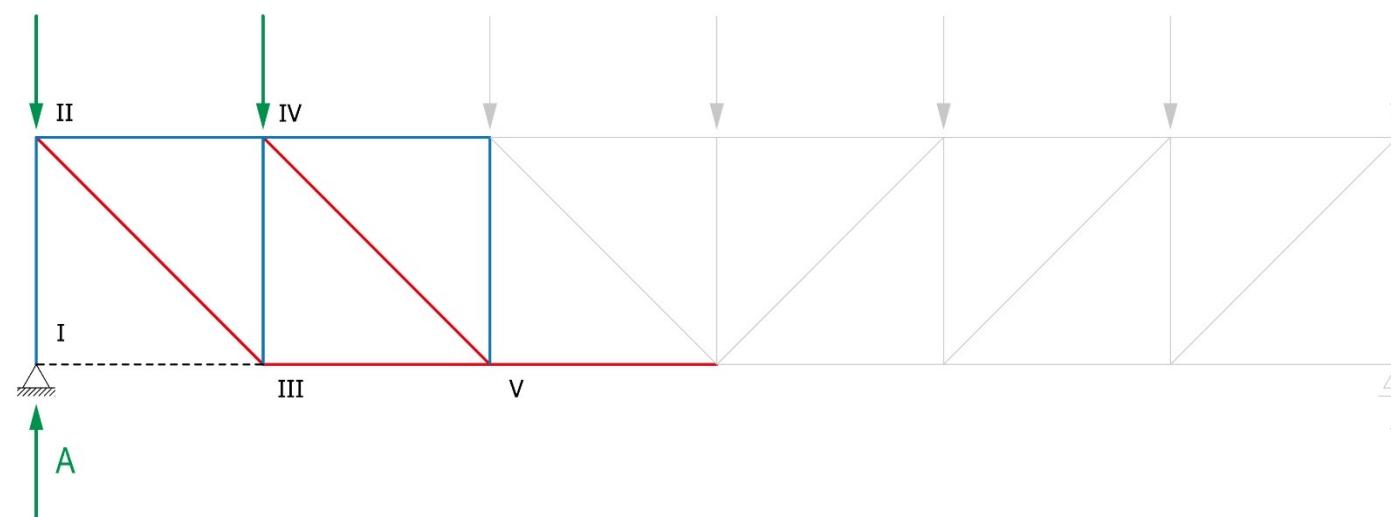
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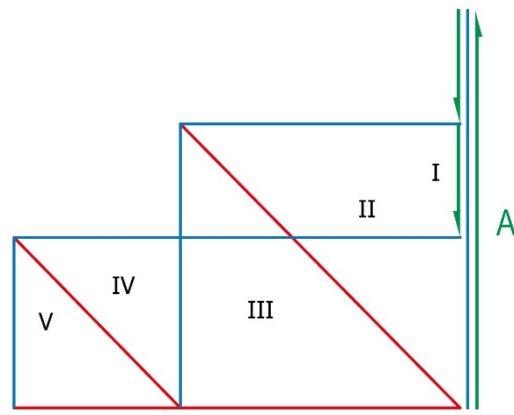
Lageplan 1:100  
*Form diagram 1:100*



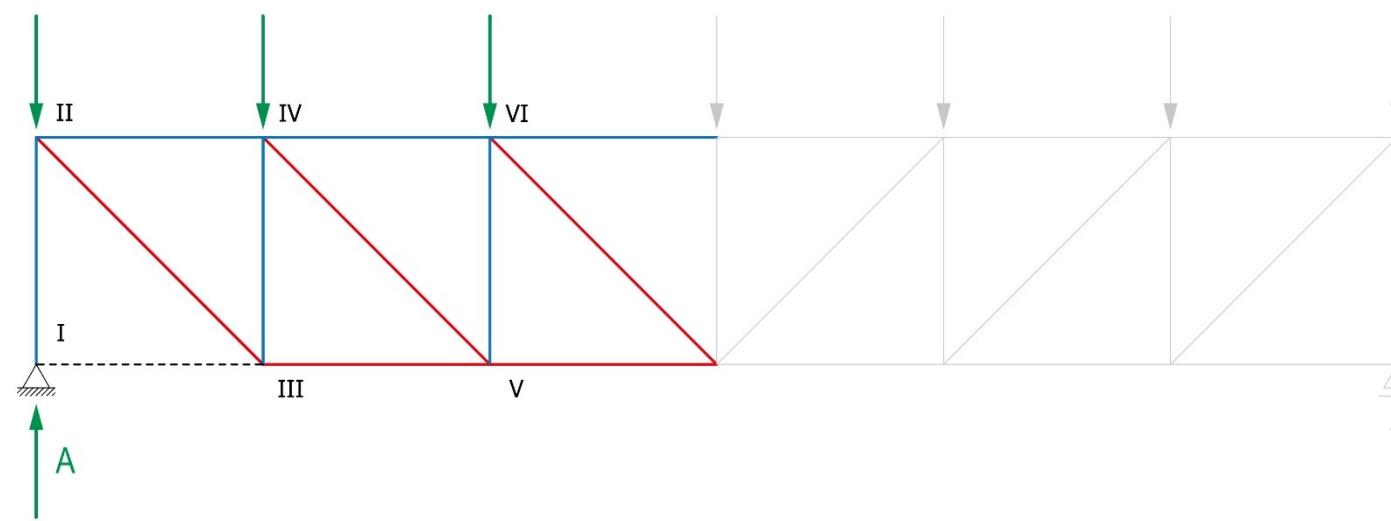
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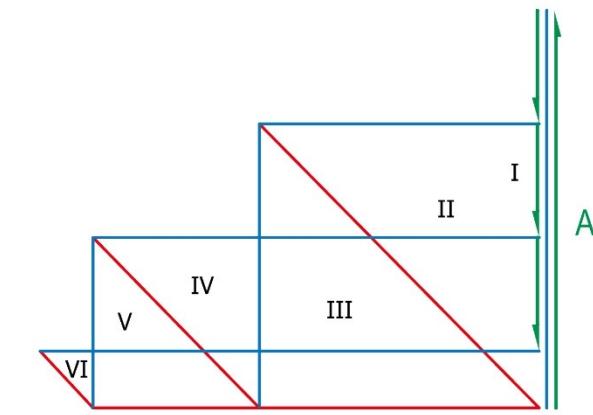
Lageplan 1:100  
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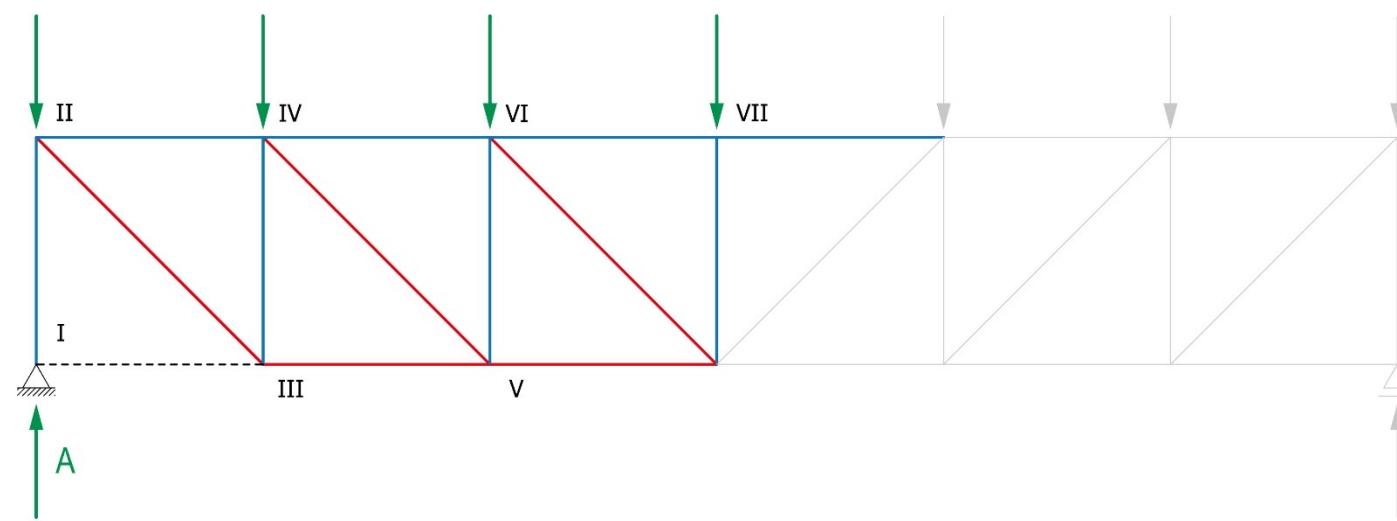
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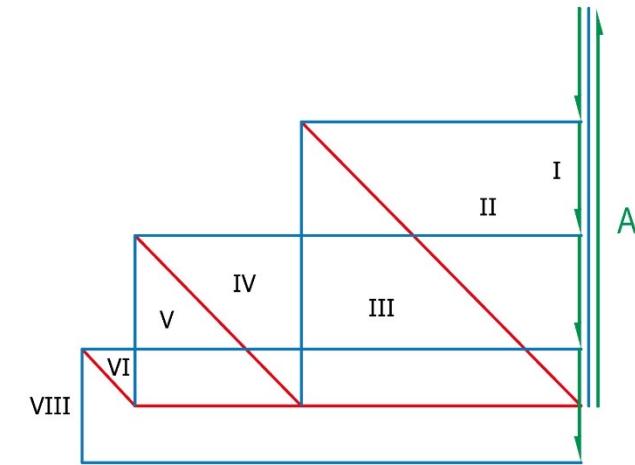
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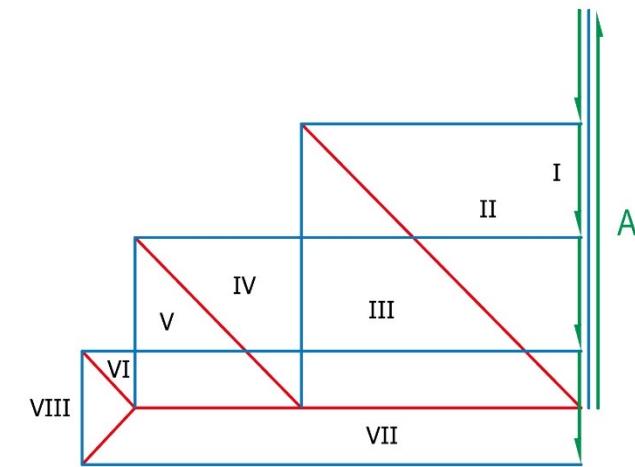
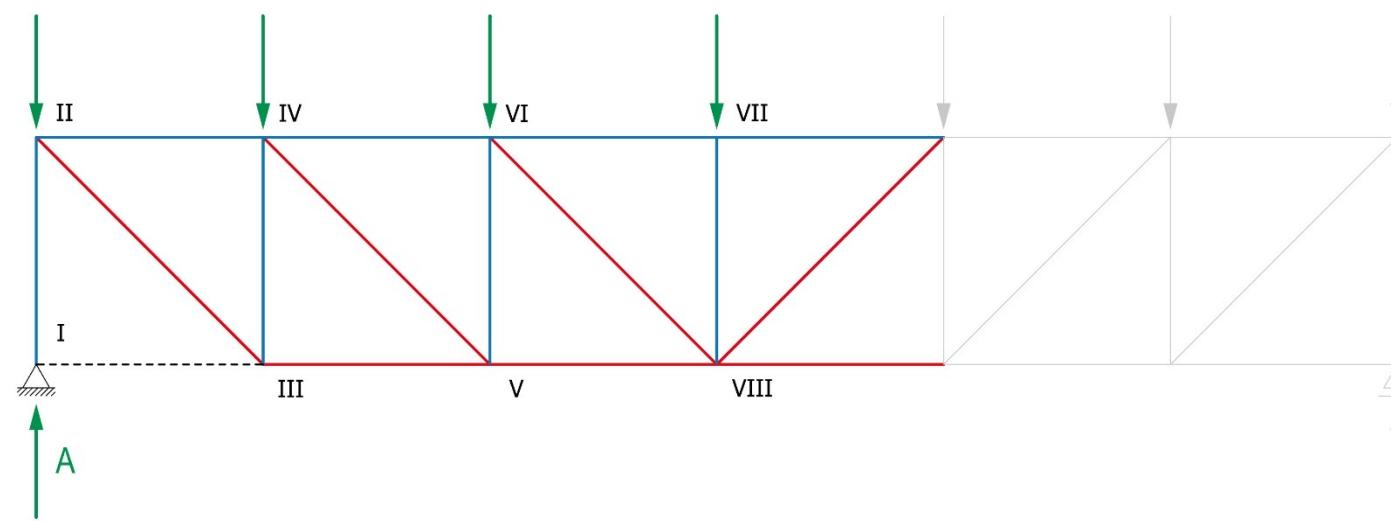
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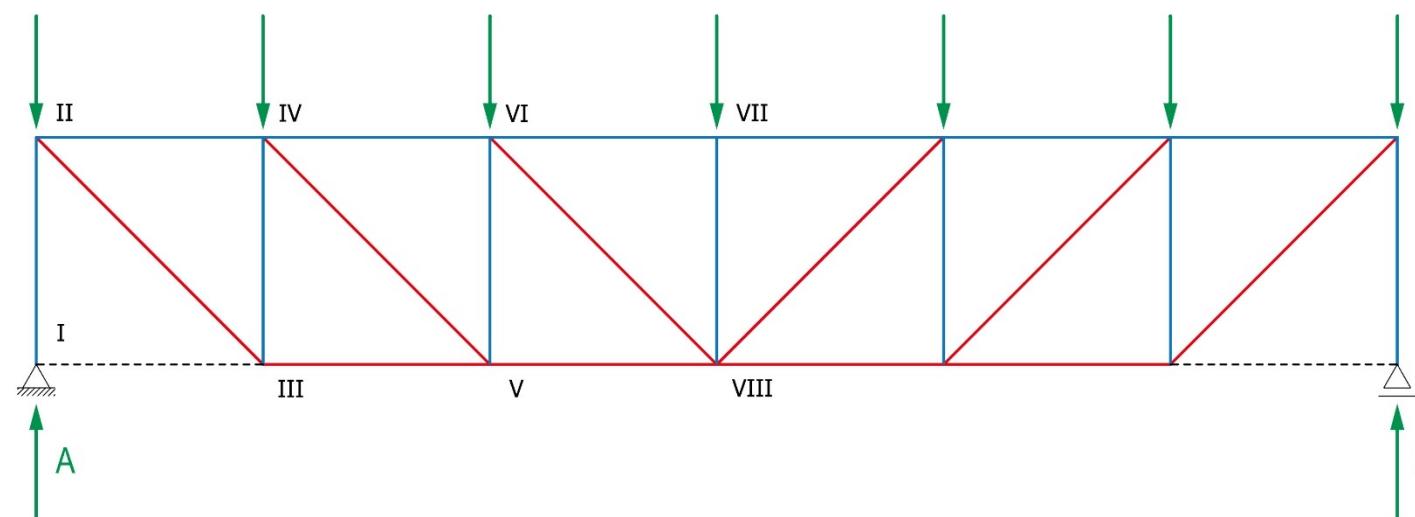


Lageplan 1:100  
*Form diagram 1:100*

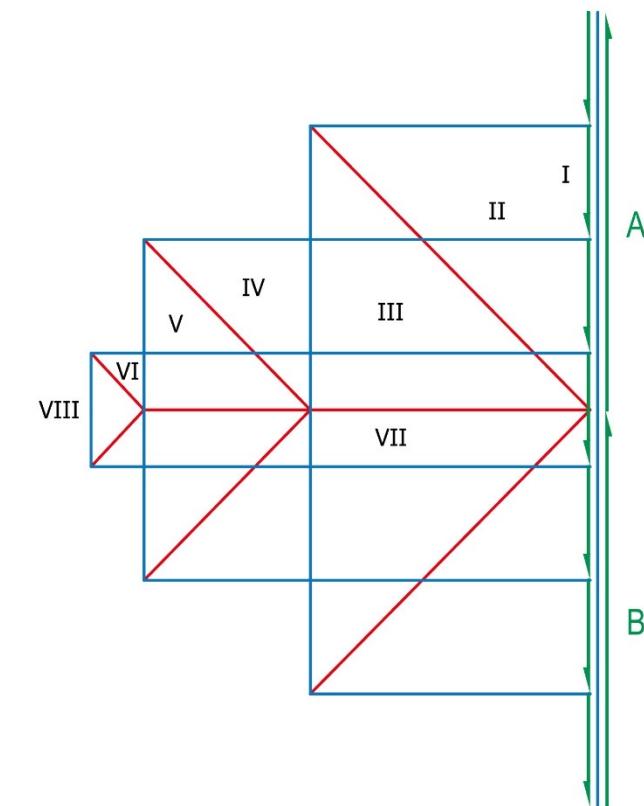


Kräfteplan 1 cm  $\triangleq$  1 kN  
*Force diagram 1 cm  $\triangleq$  1 kN*

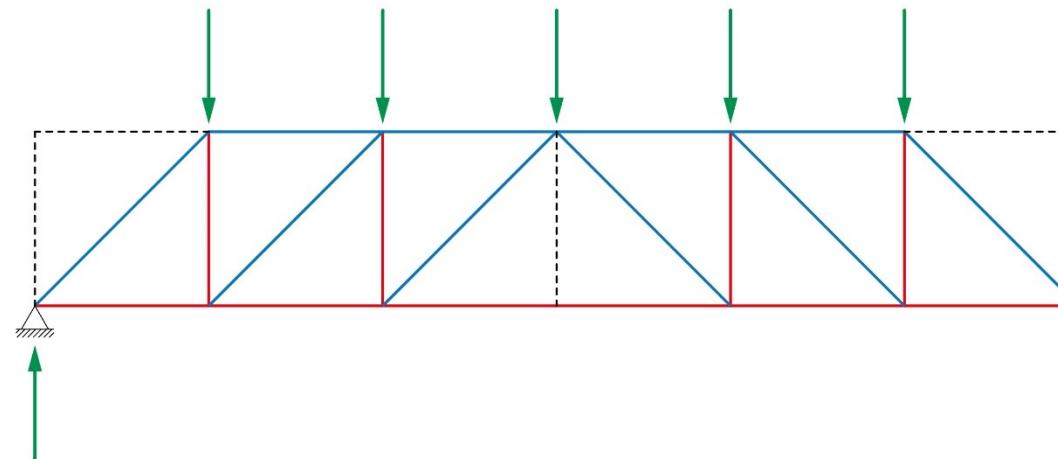
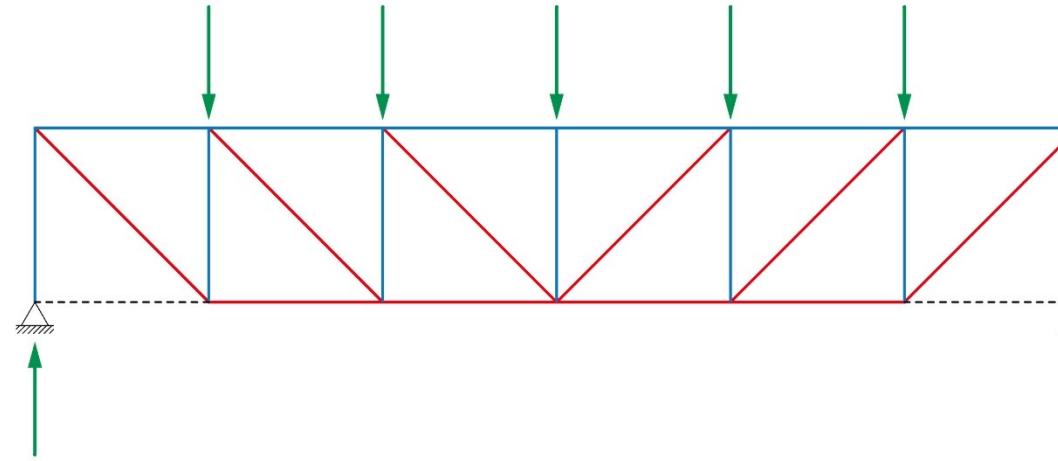




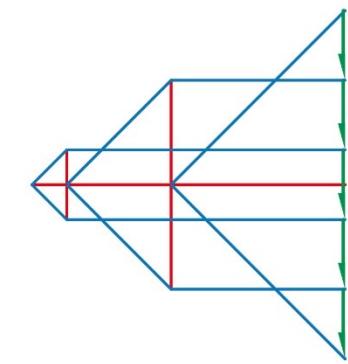
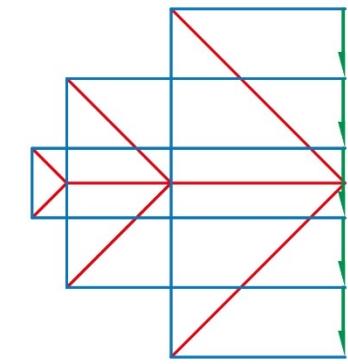
Lageplan 1:100  
*Form diagram 1:100*



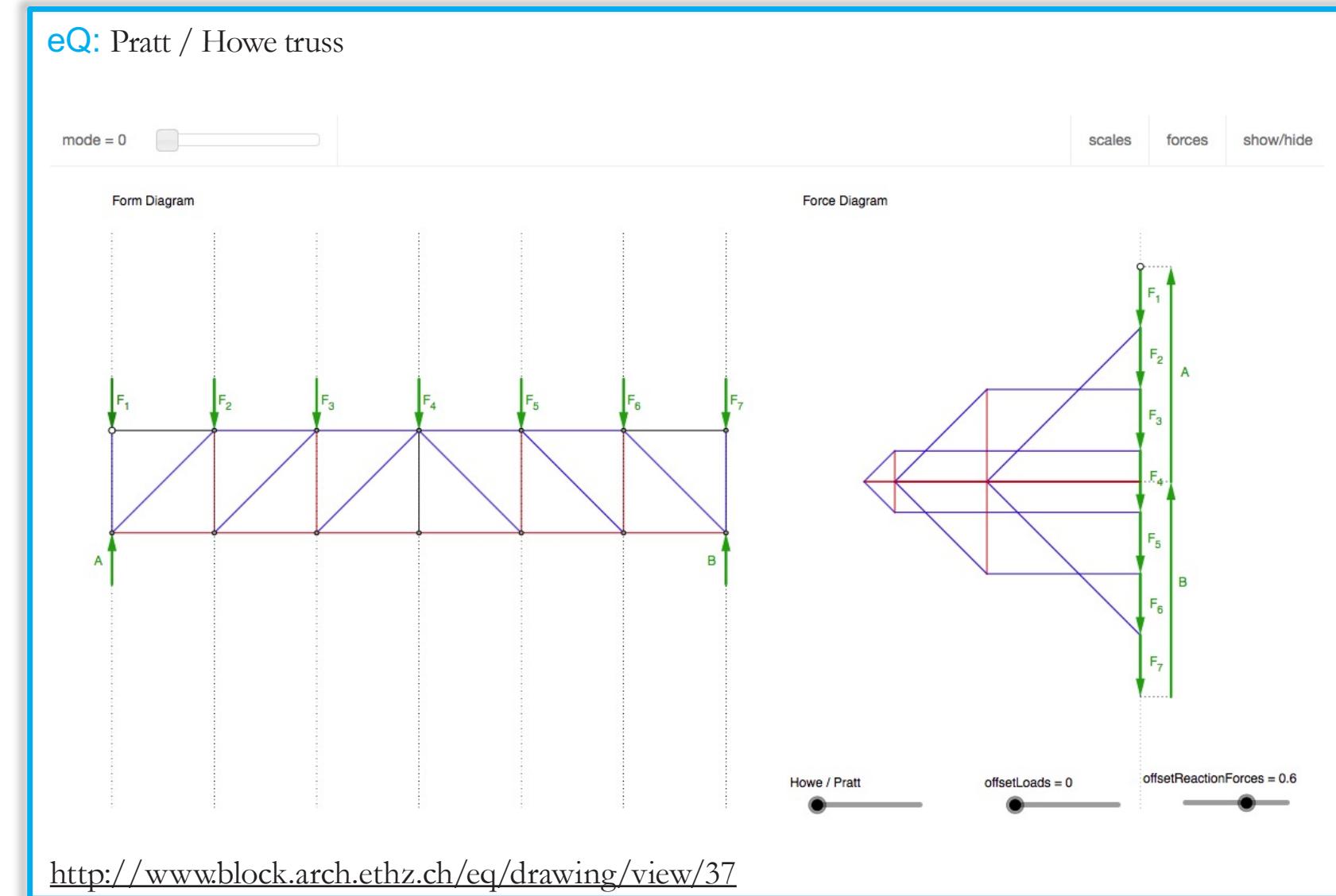
Kräfteplan 1 cm  $\triangleq$  1 kN  
*Force diagram 1 cm  $\triangleq$  1 kN*



Lageplan 1:100  
*Form diagram 1:100*



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



# Fachwerke

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*Variation of boundary conditions*

Schlankheit von Fachwerken

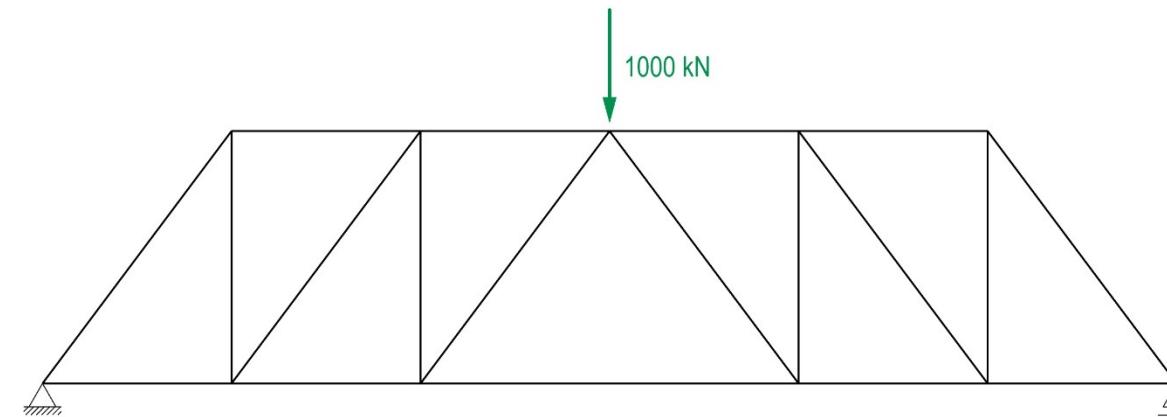
*Slender trusses*

Konstruktion von Fachwerken

*Construction of trusses*

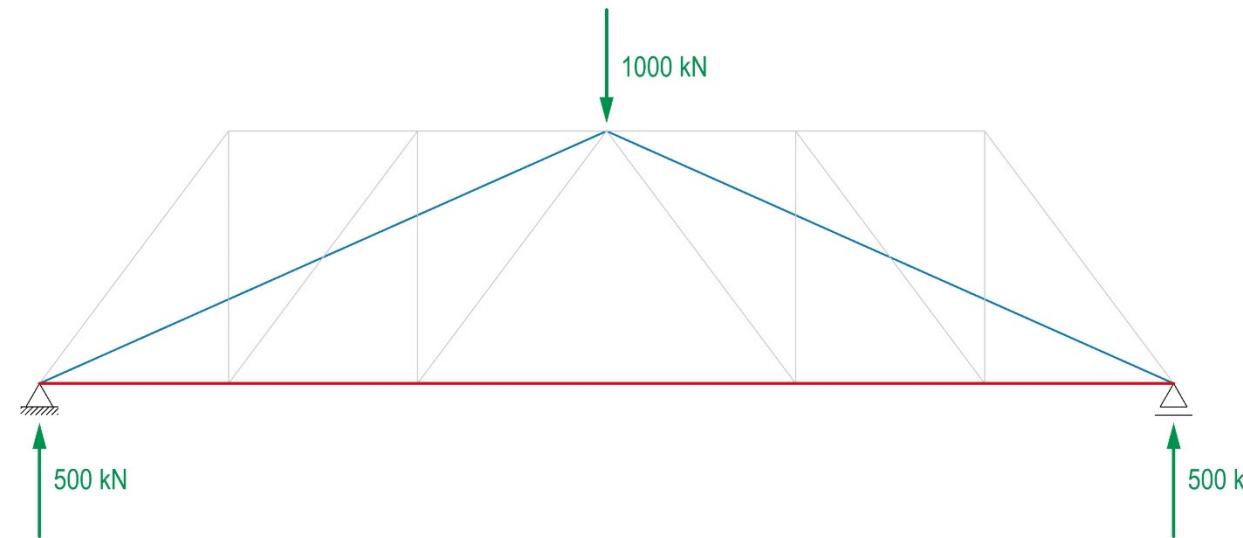
Räumliche Fachwerke

*Spatial trusses*

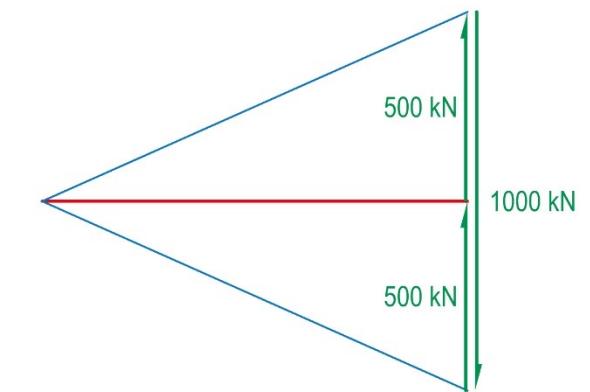


Lageplan 1:100  
Form diagram 1:100

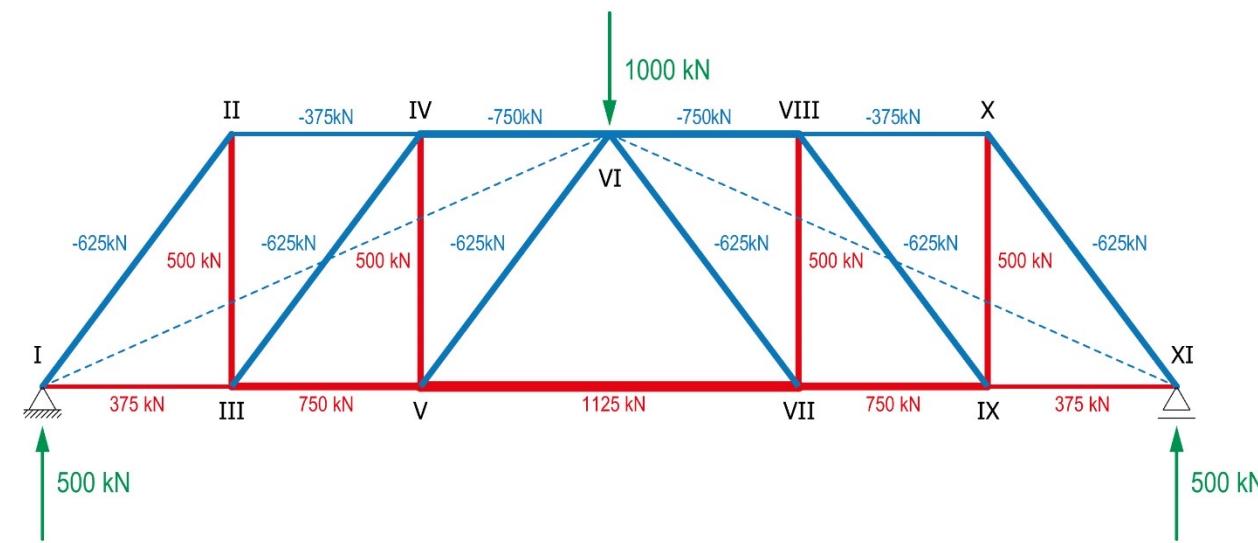
Kräfteplan 1 cm  $\triangleq$  1 kN  
Force diagram 1 cm  $\triangleq$  1 kN



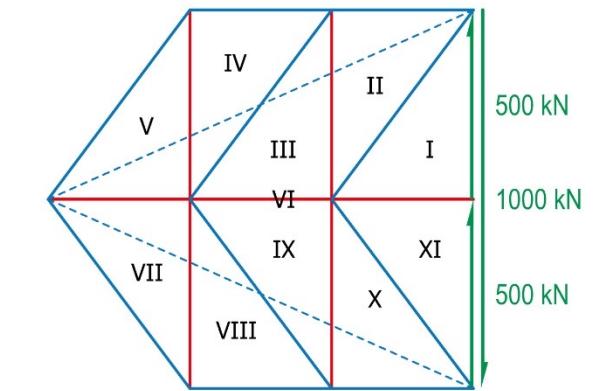
Lageplan 1:100  
Form diagram 1:100



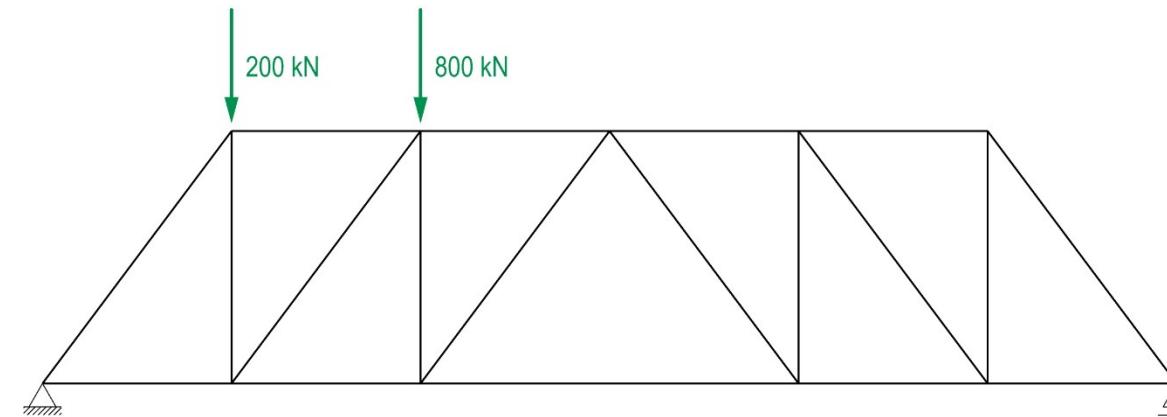
Kräfteplan 1 cm  $\triangleq$  1 kN  
Force diagram 1 cm  $\triangleq$  1 kN



Lageplan 1:100  
Form diagram 1:100



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

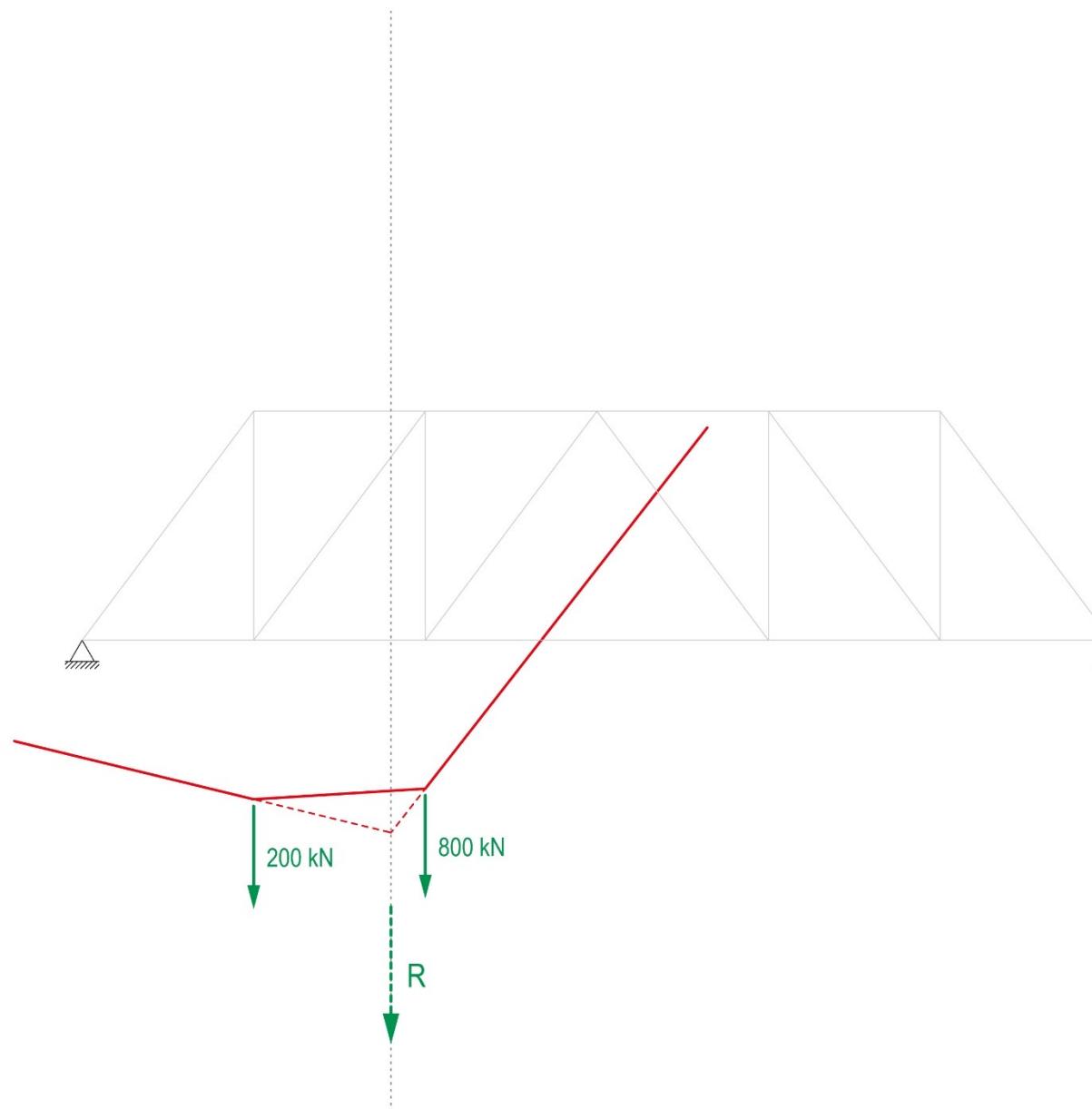


Lageplan 1:100

Form diagram 1:100

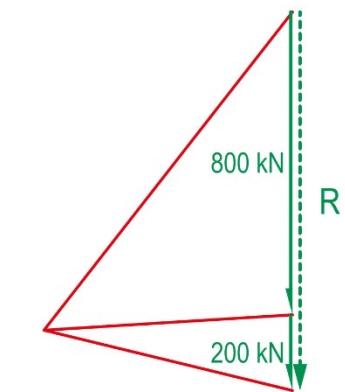
Kräfteplan 1 cm  $\triangleq$  1 kN

Force diagram 1 cm  $\triangleq$  1 kN



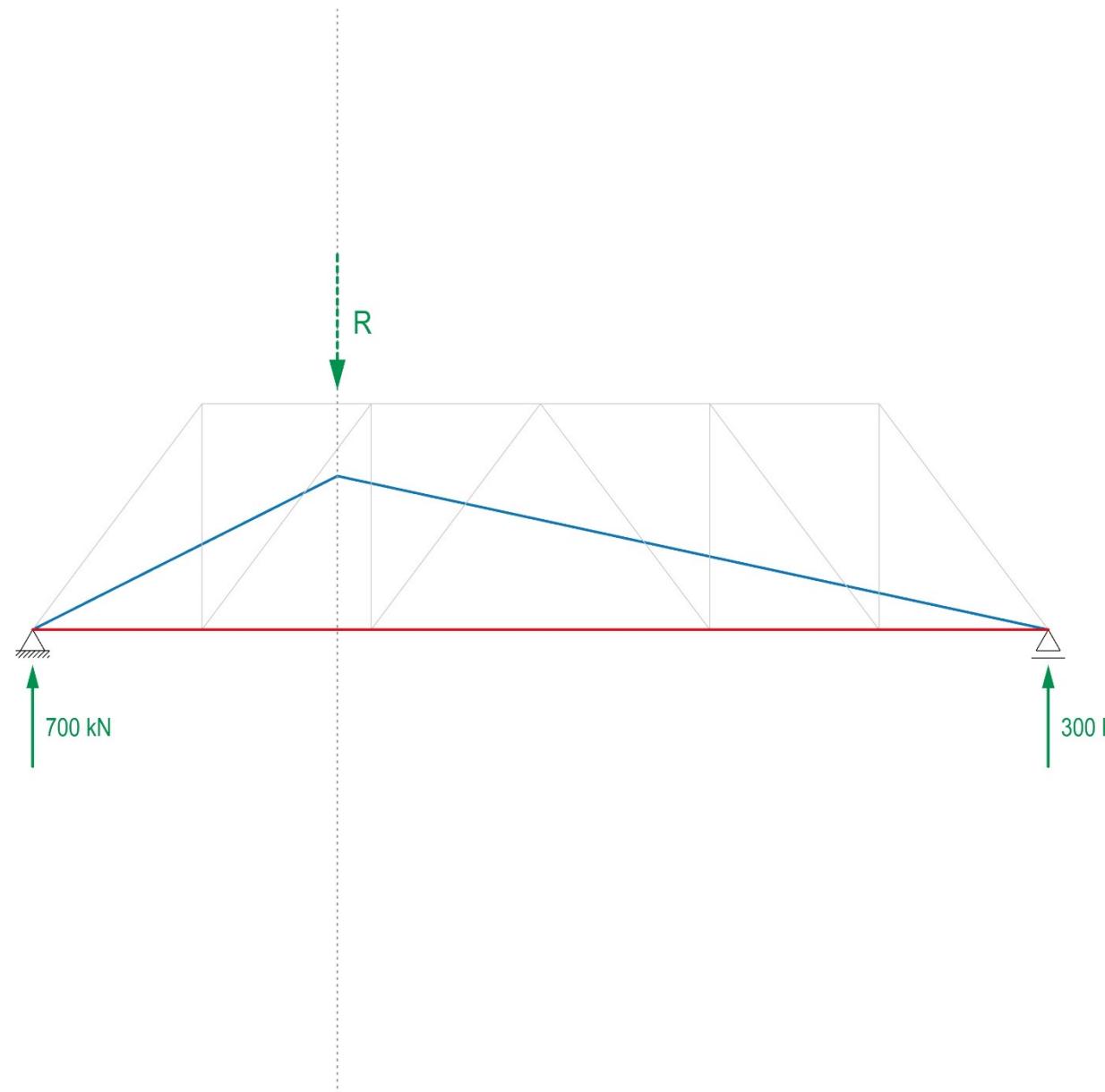
Lageplan 1:100

Form diagram 1:100

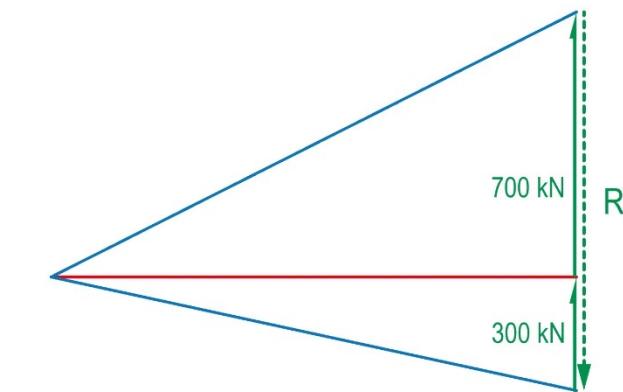


Kräfteplan 1 cm  $\triangleq$  1 kN

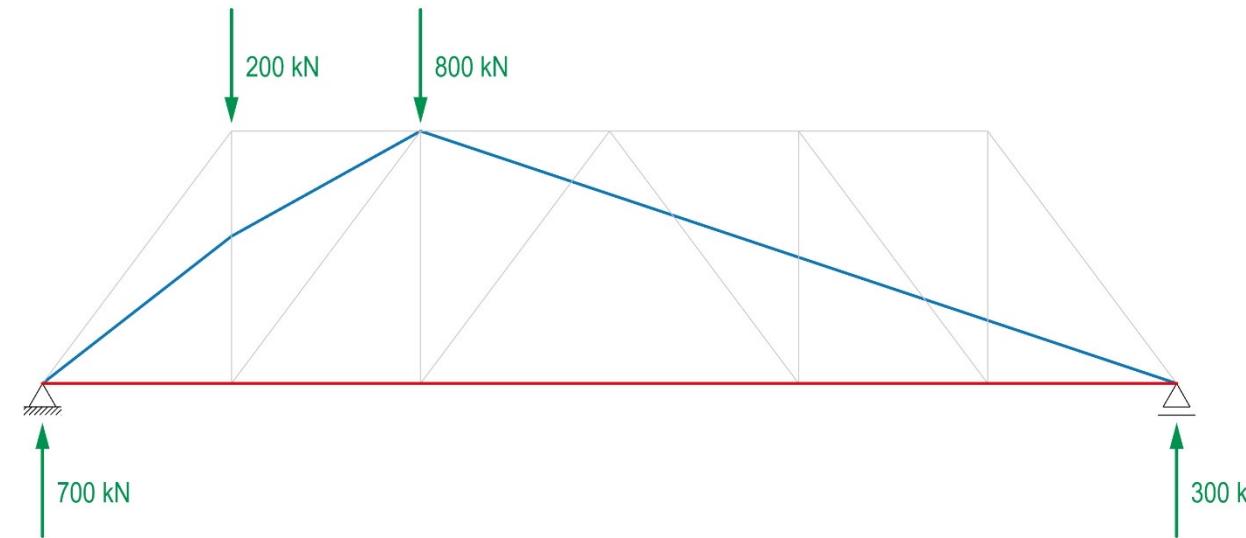
Force diagram 1 cm  $\triangleq$  1 kN



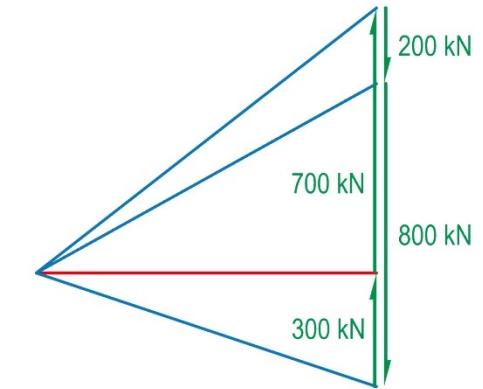
Lageplan 1:100  
Form diagram 1:100



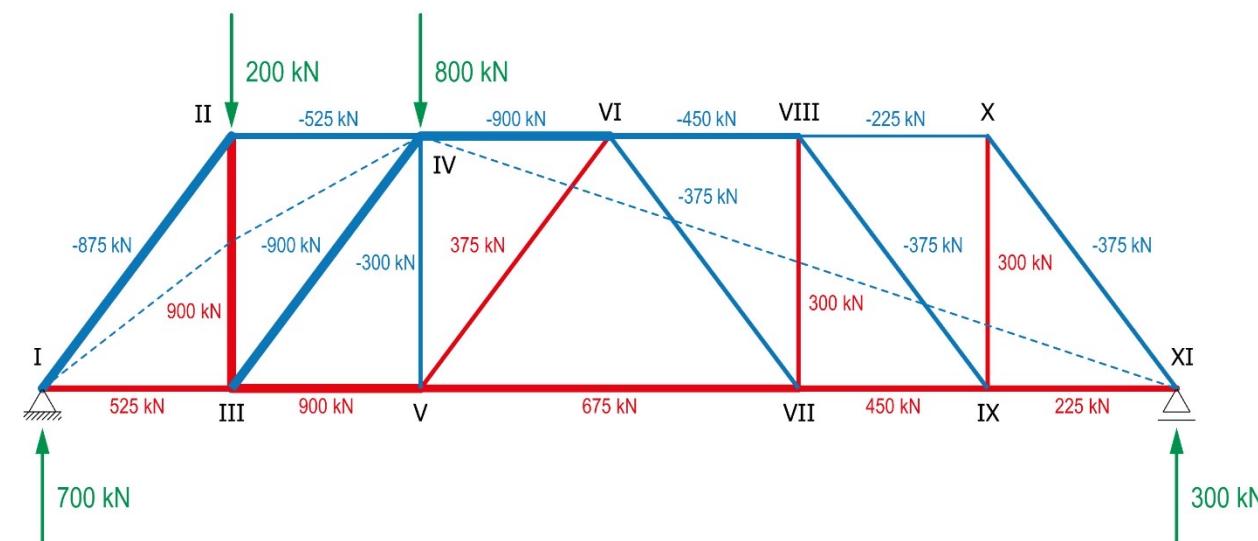
Kräfteplan 1 cm  $\triangleq$  1 kN  
Force diagram 1 cm  $\triangleq$  1 kN



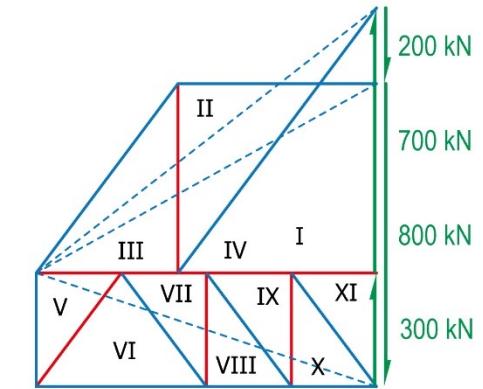
Lageplan 1:100  
Form diagram 1:100



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



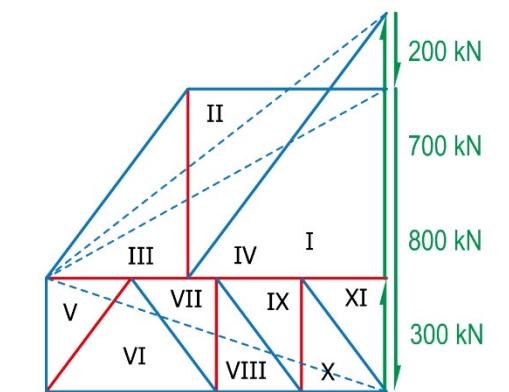
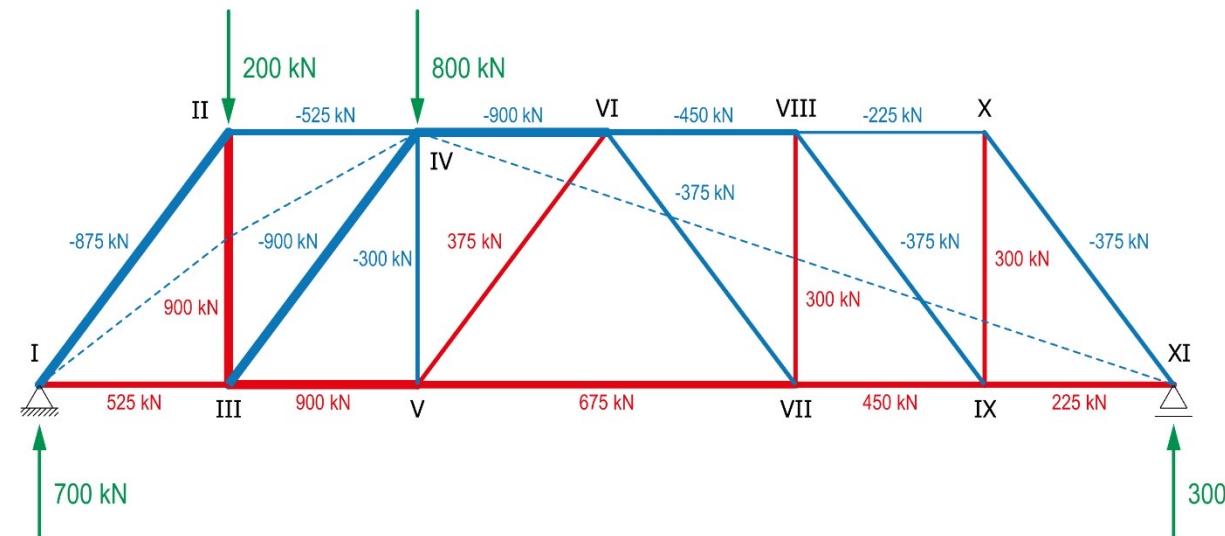
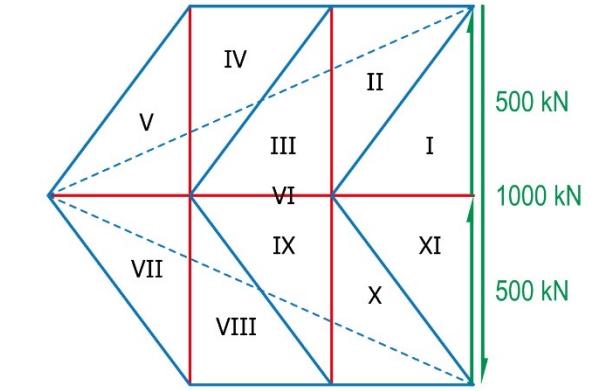
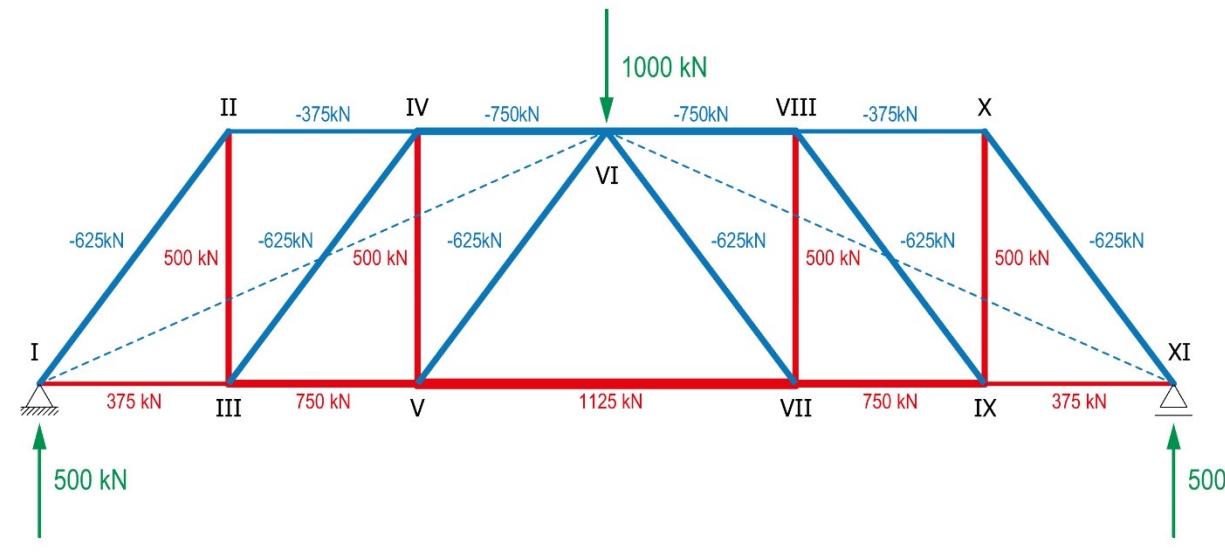
Lageplan 1:100  
Form diagram 1:100



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

# Einfluss der Lage der äusseren Kräfte

Influence of the position of external forces



Lageplan 1:100

Form diagram 1:100

Kräfteplan 1 cm  $\triangleq$  1 kN

Force diagram 1 cm  $\triangleq$  1 kN

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Schlankheit von Fachwerken

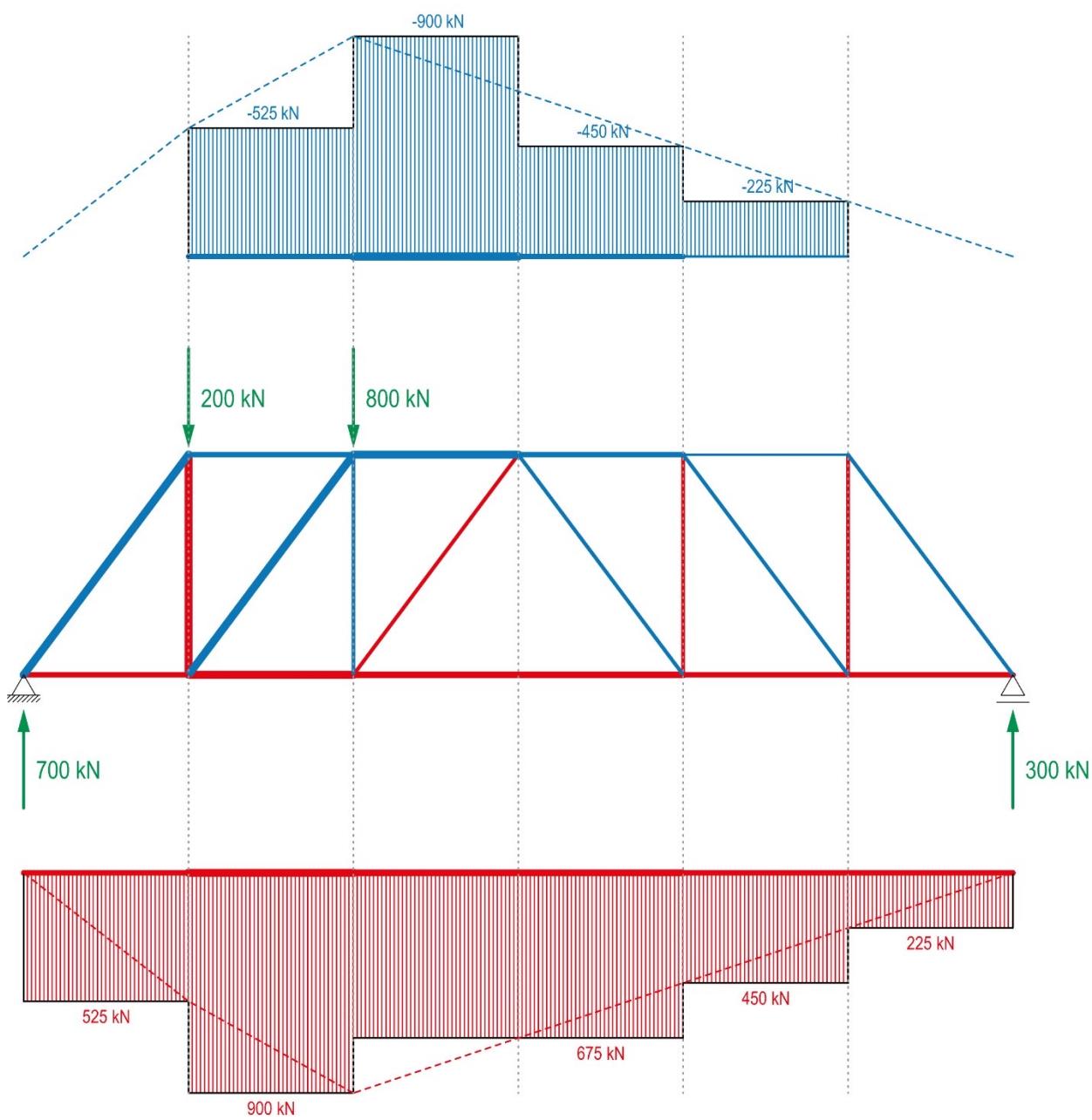
*Slender trusses*

Konstruktion von Fachwerken

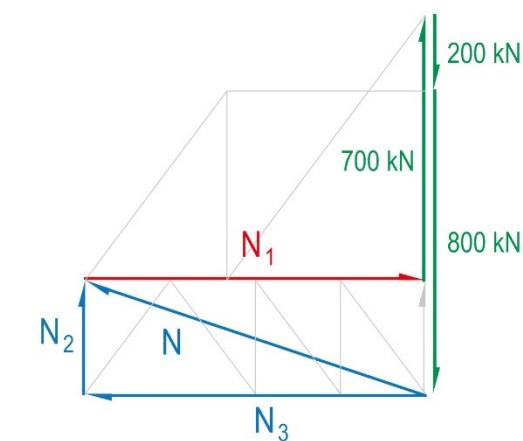
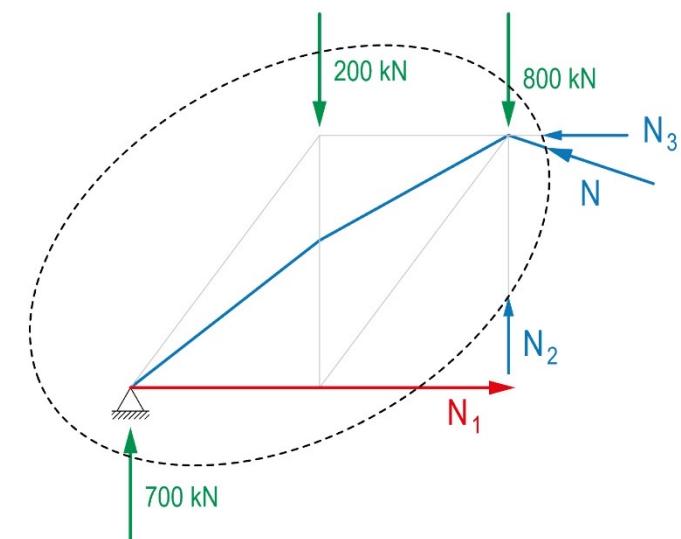
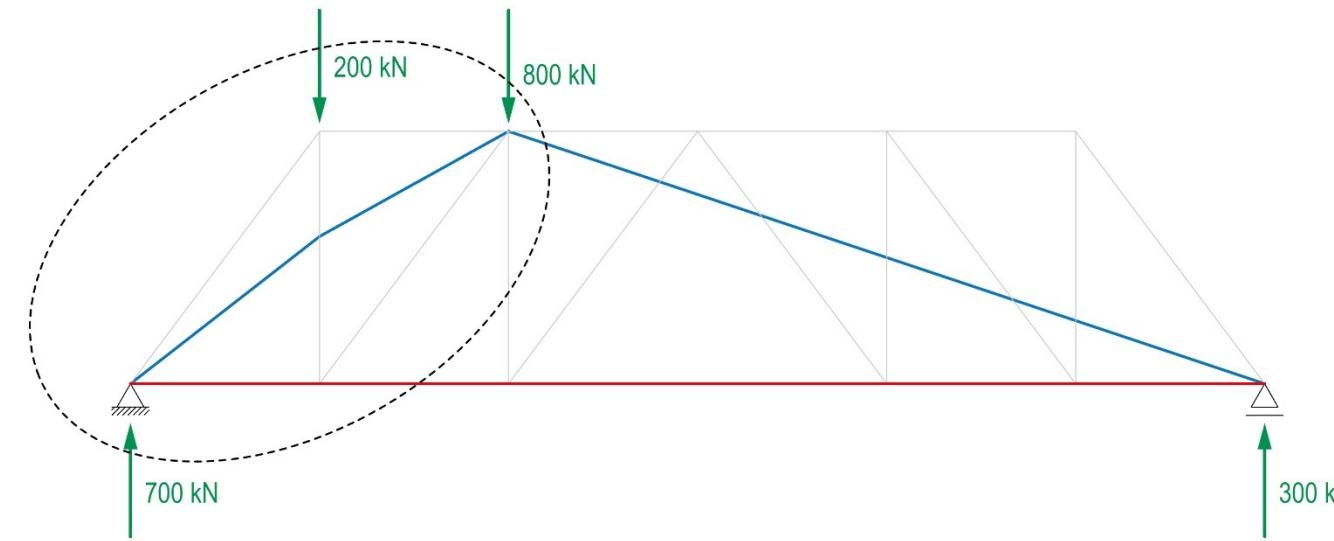
*Construction of trusses*

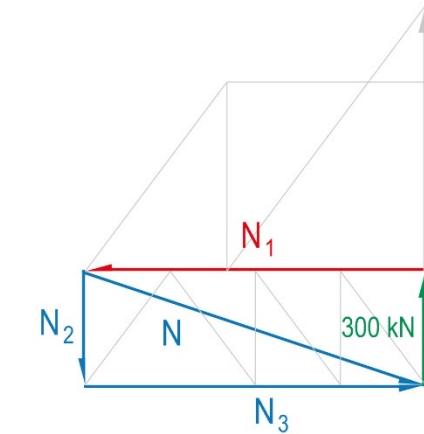
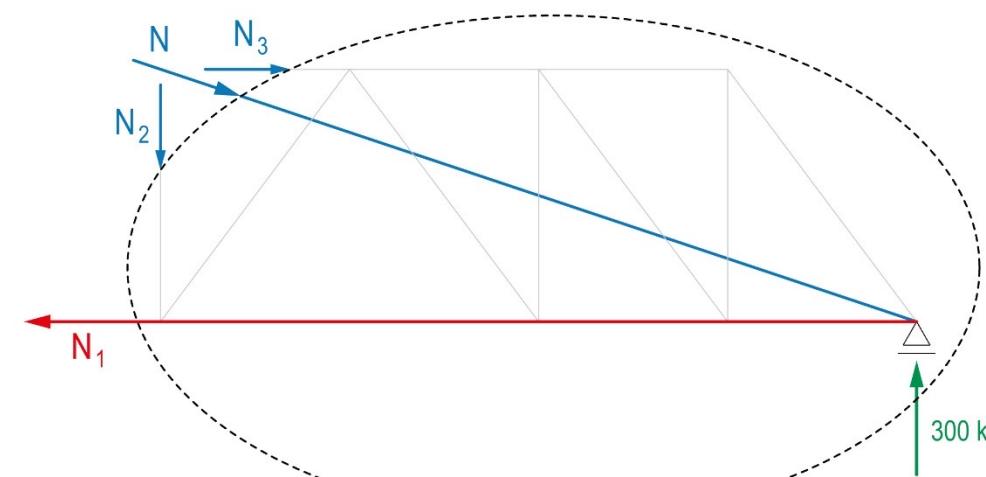
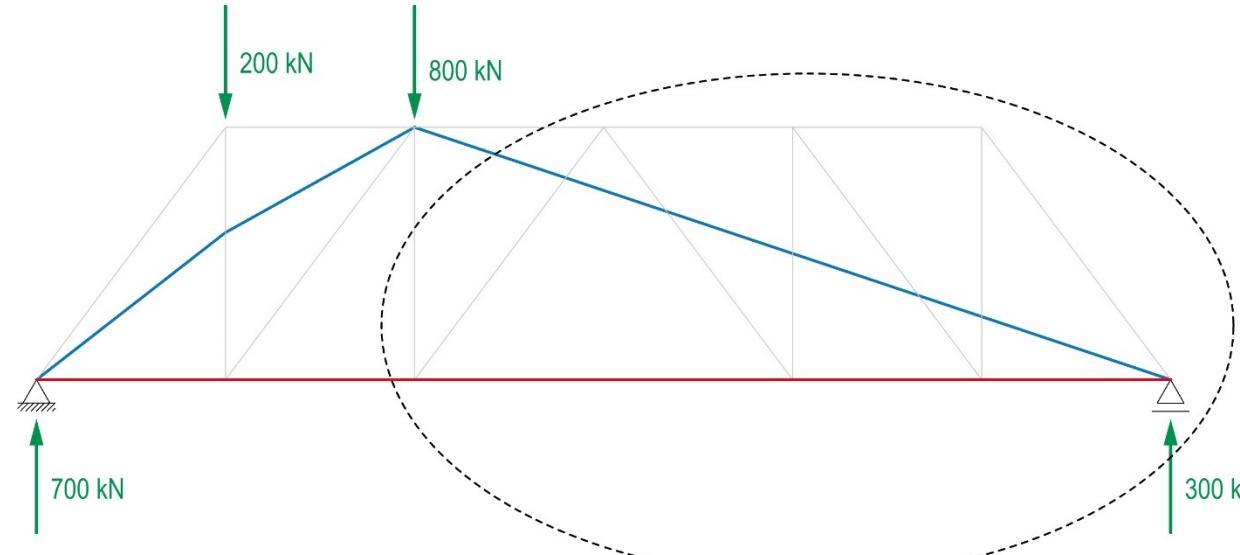
Räumliche Fachwerke

*Spatial trusses*

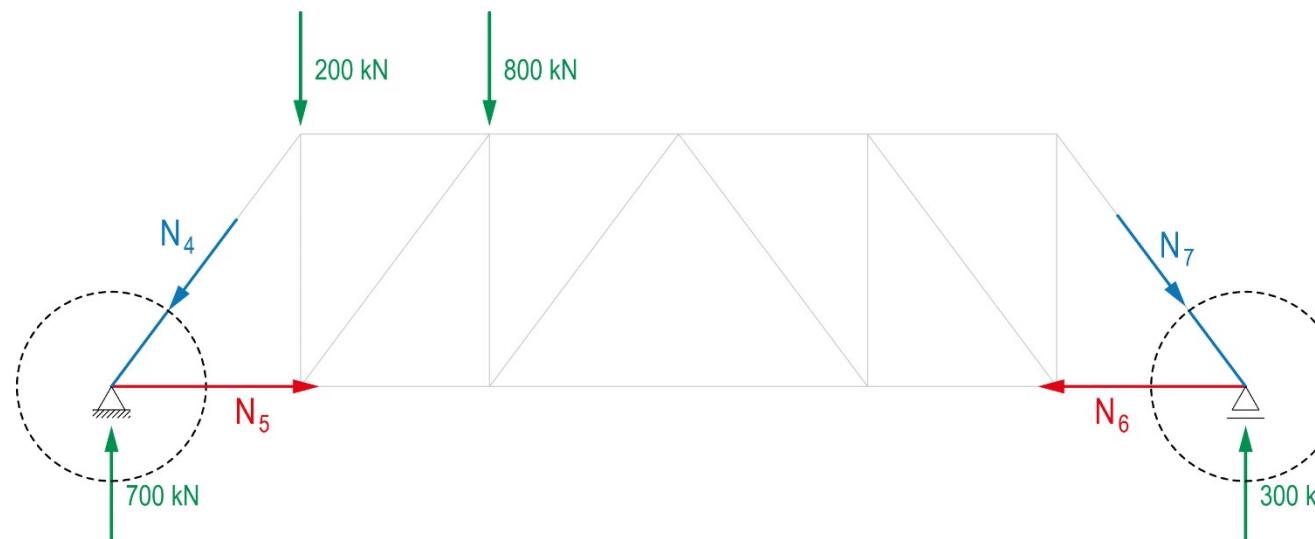
*Calculation of maximum inner forces*

*Calculation of maximum inner forces*

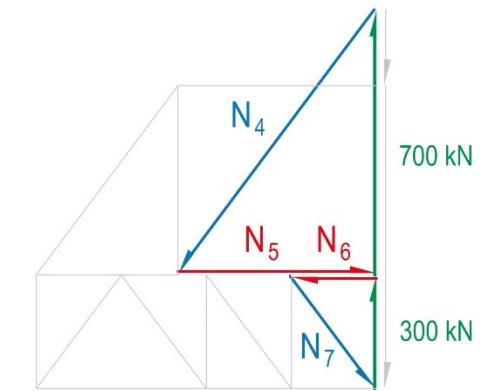


*Calculation of maximum inner forces*

*Calculation of maximum inner forces*



Lageplan 1:100  
*Form diagram 1:100*



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

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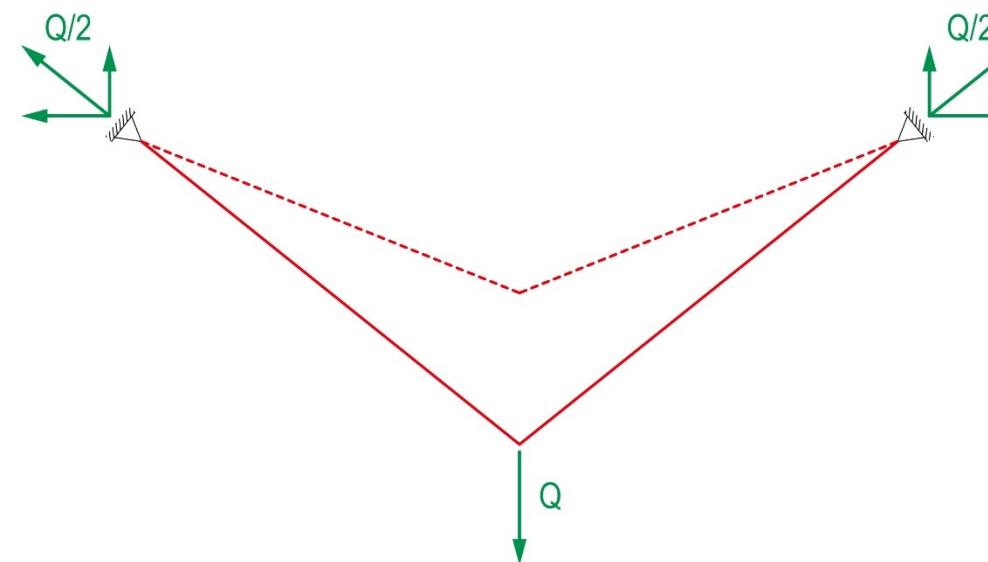
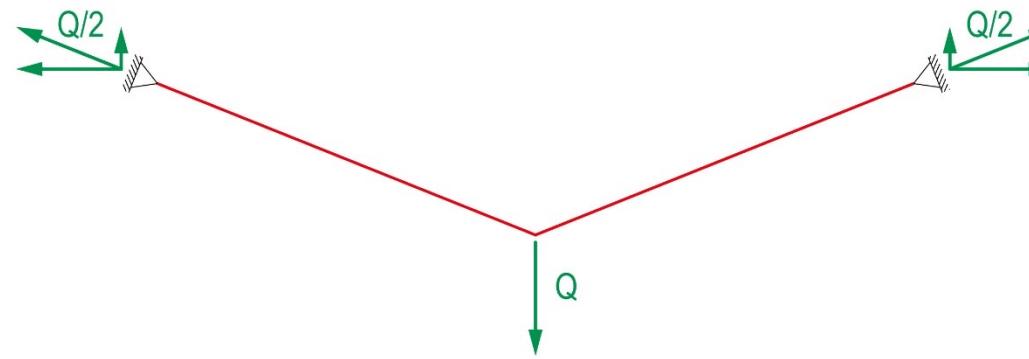
*Slender trusses*

Konstruktion von Fachwerken

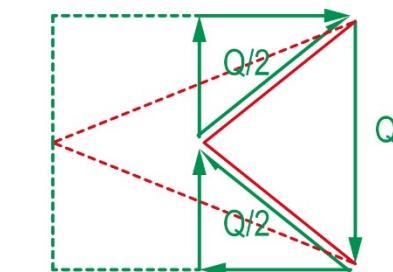
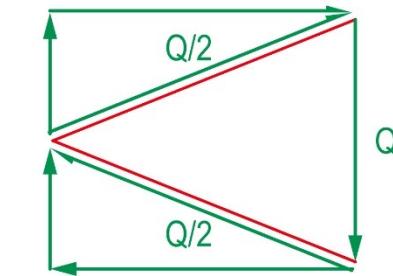
*Construction of trusses*

Räumliche Fachwerke

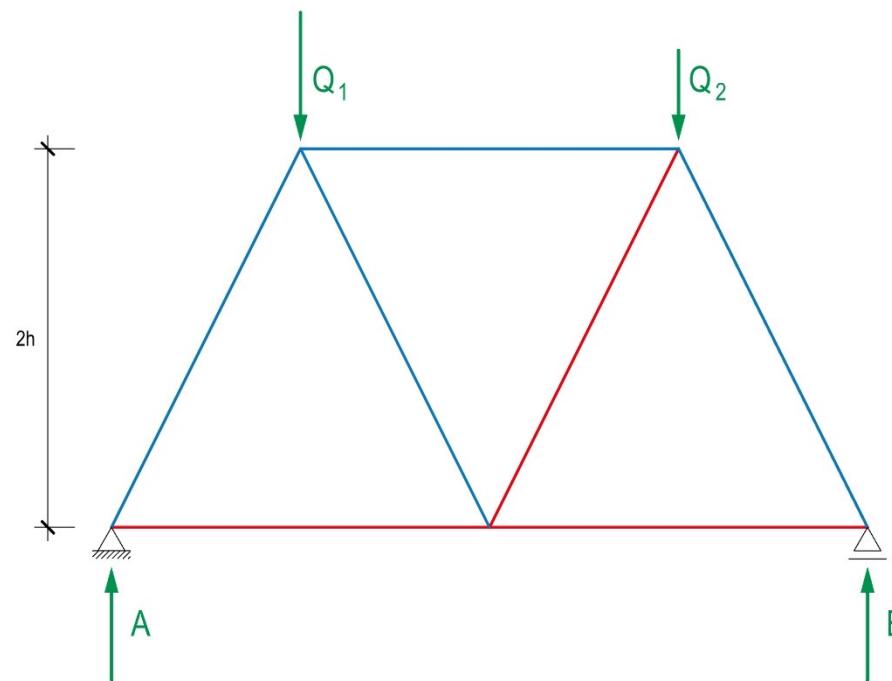
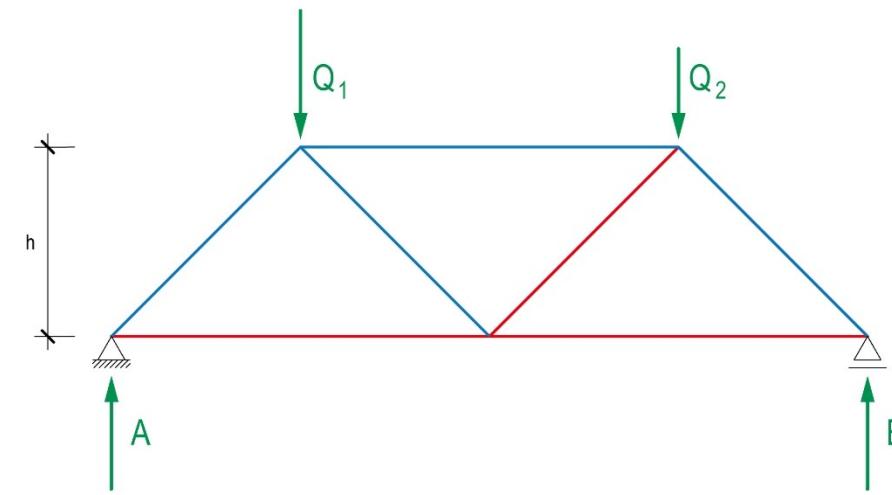
*Spatial trusses*



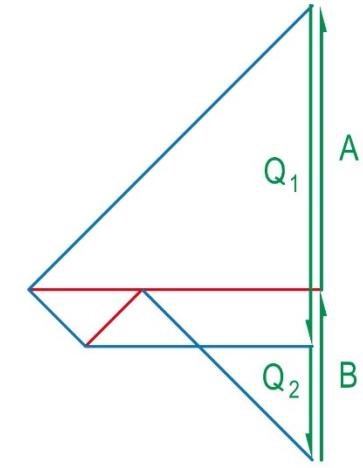
Lageplan 1:100  
Form diagram 1:100



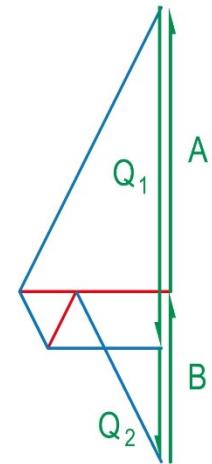
Kräfteplan 1 cm  $\triangleq$  1 kN  
Force diagram 1 cm  $\triangleq$  1 kN

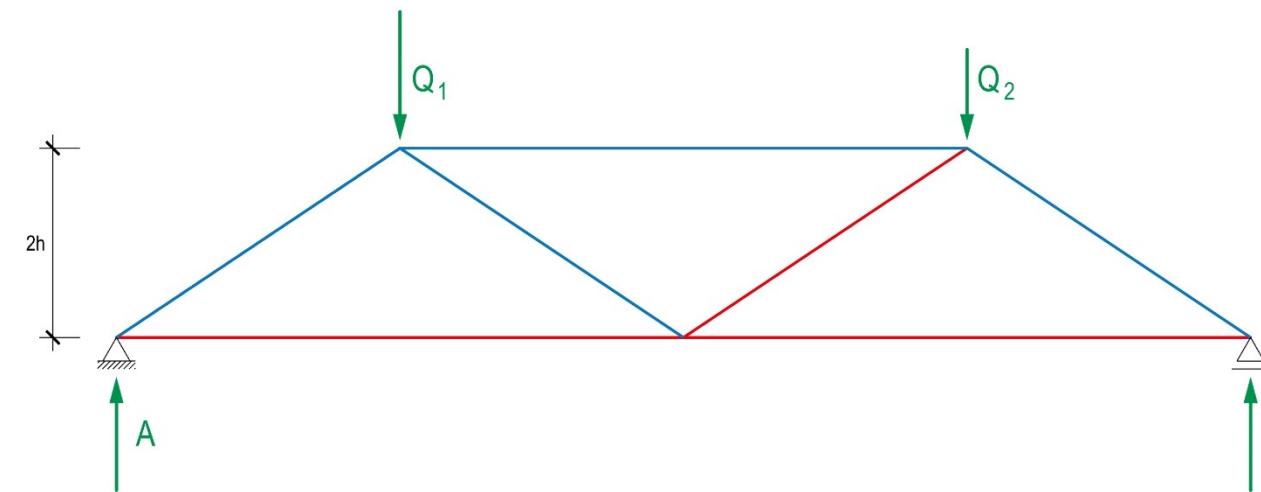
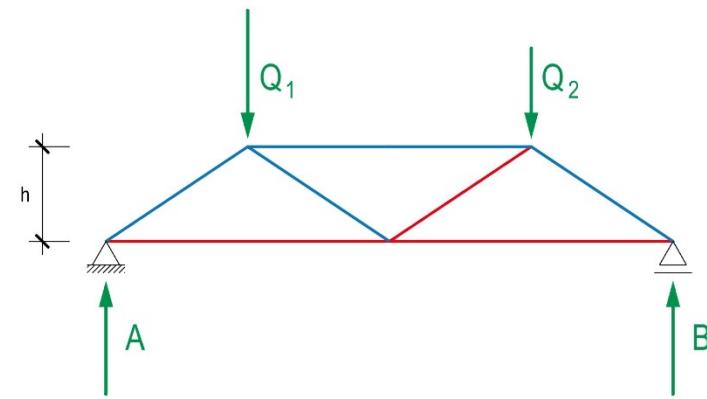


Lageplan 1:100  
Form diagram 1:100

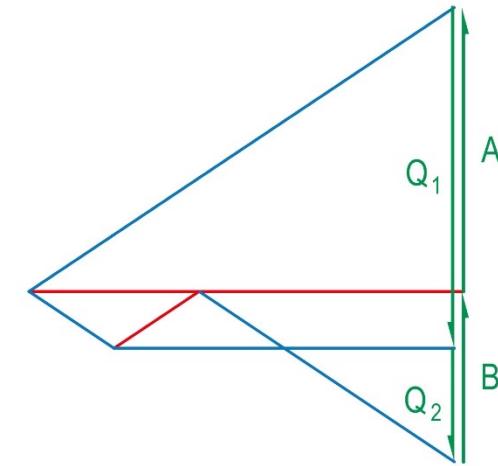
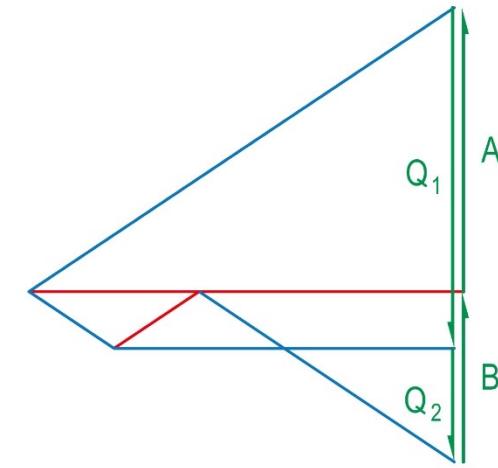


Kräfteplan 1 cm  $\triangleq$  1 kN  
Force diagram 1 cm  $\triangleq$  1 kN





Lageplan 1:100  
Form diagram 1:100



Kräfteplan 1 cm  $\triangleq$  1 kN  
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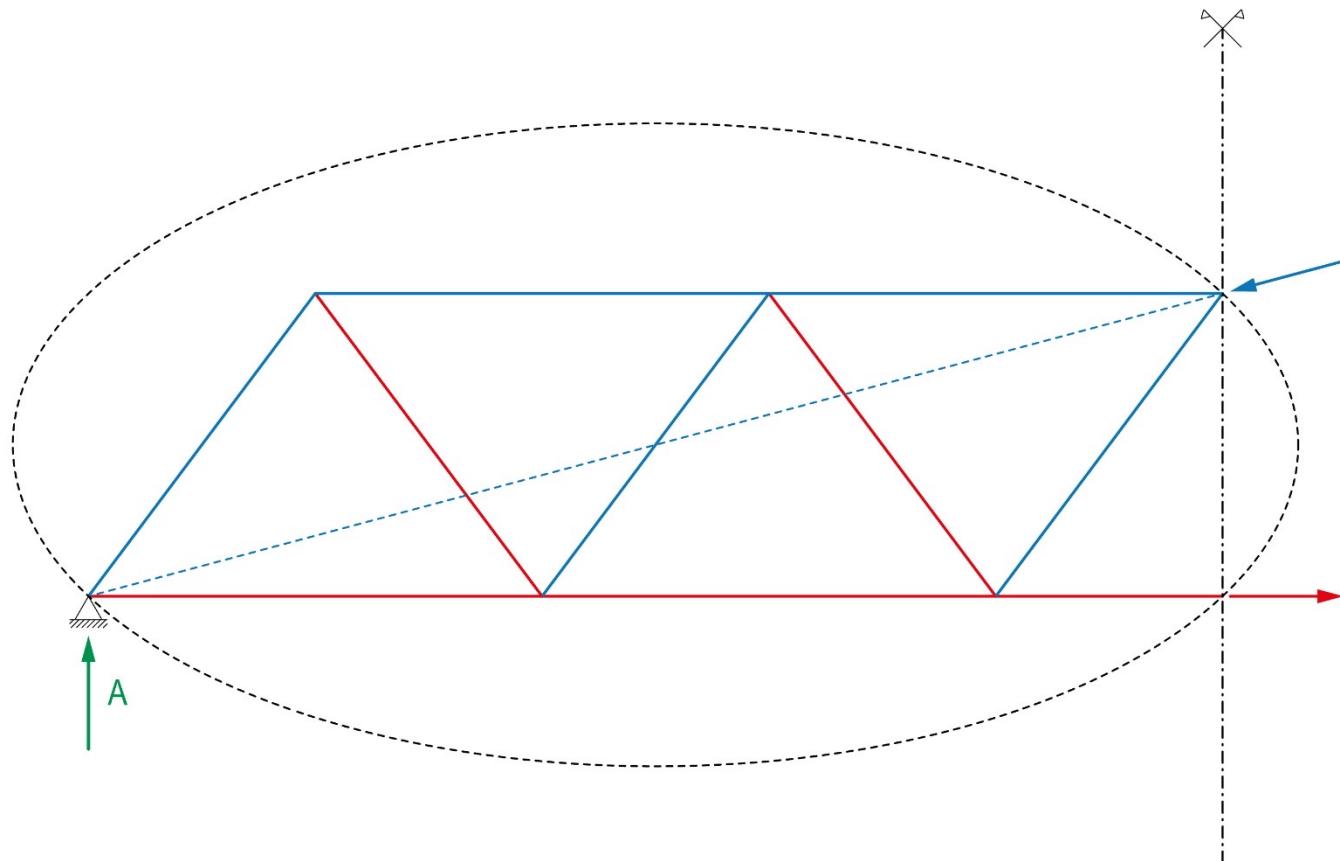
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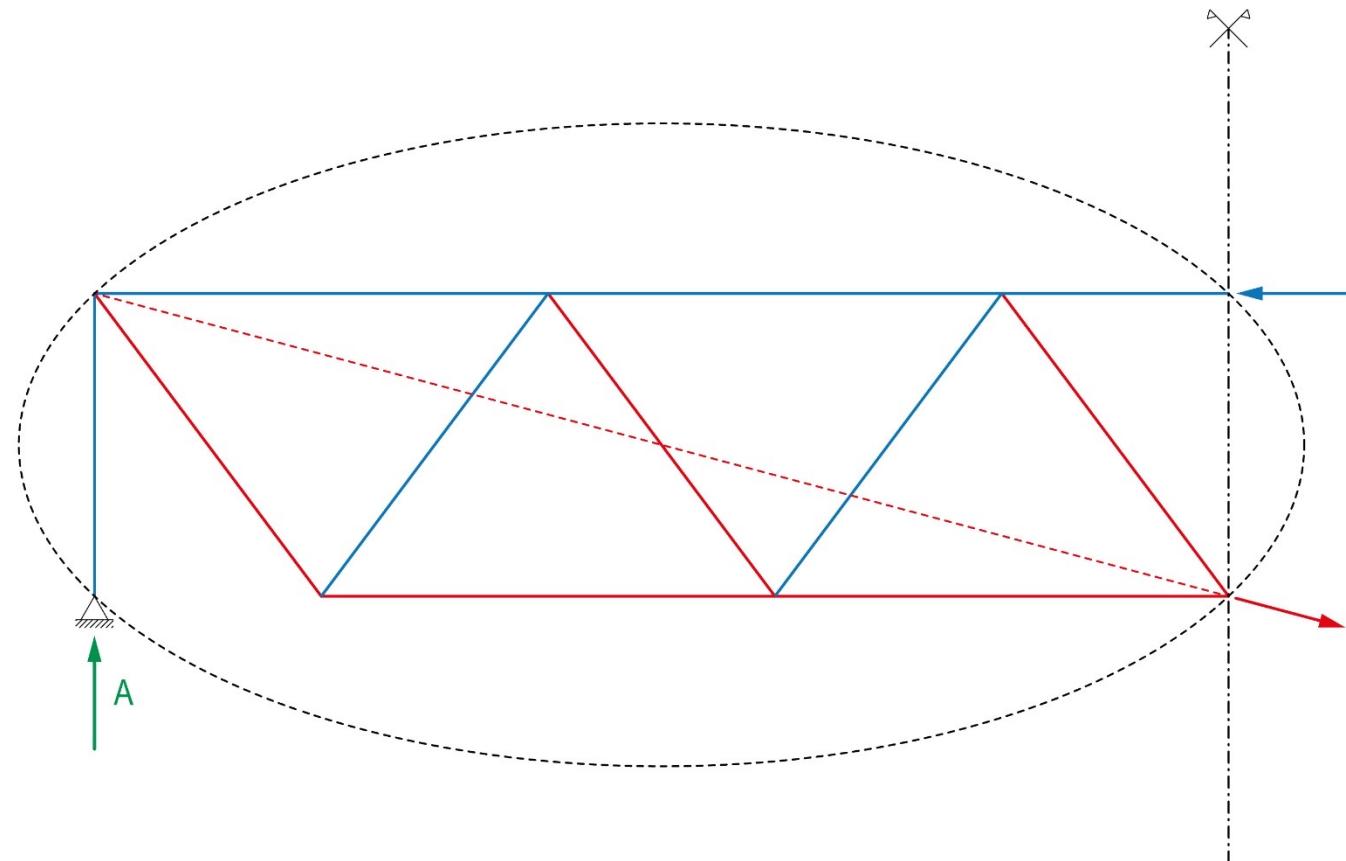
Räumliche Fachwerke

*Spatial trusses*



Fachwerk mit V-förmigen Diagonalen: System Warren

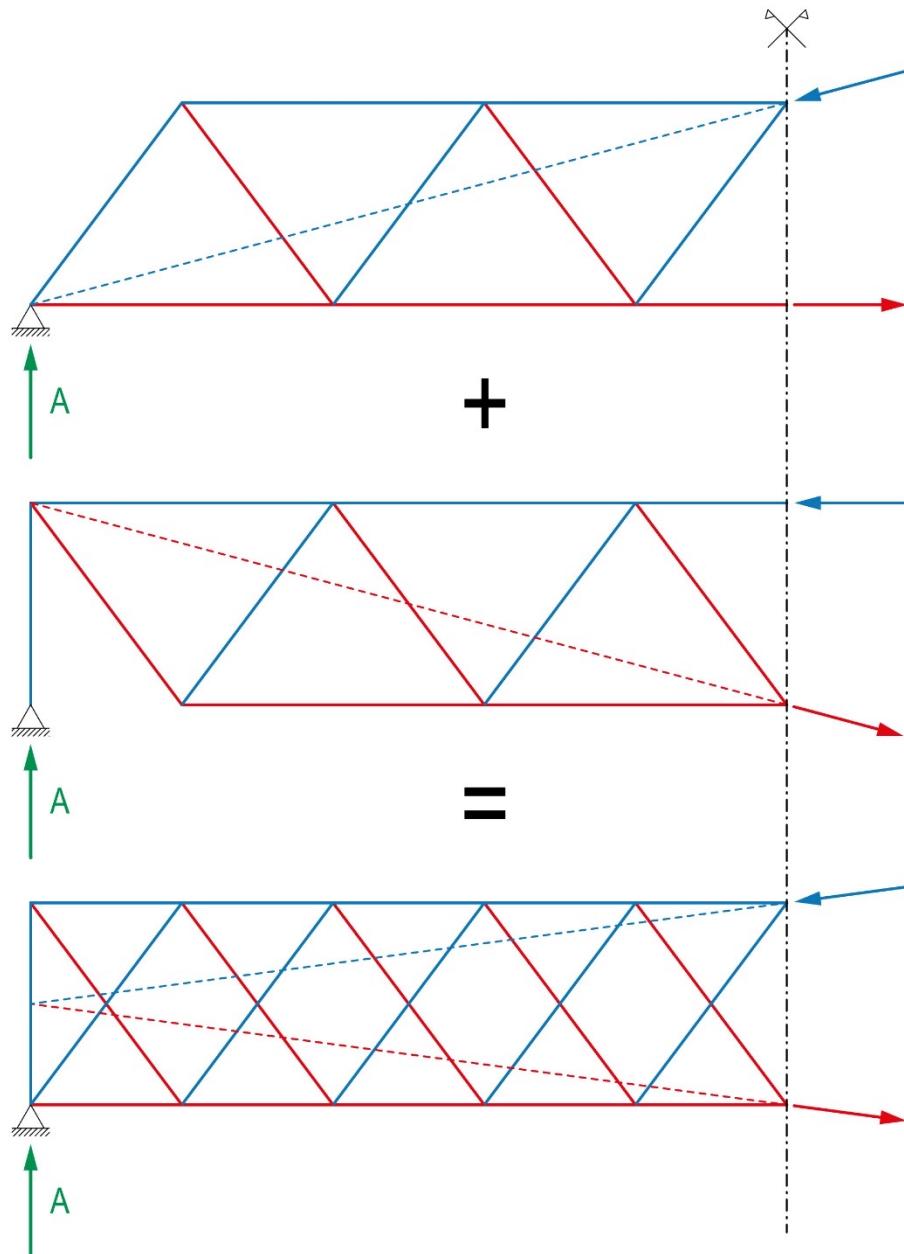
*Truss with V-shaped diagonals: System Warren*

*Types of trusses*

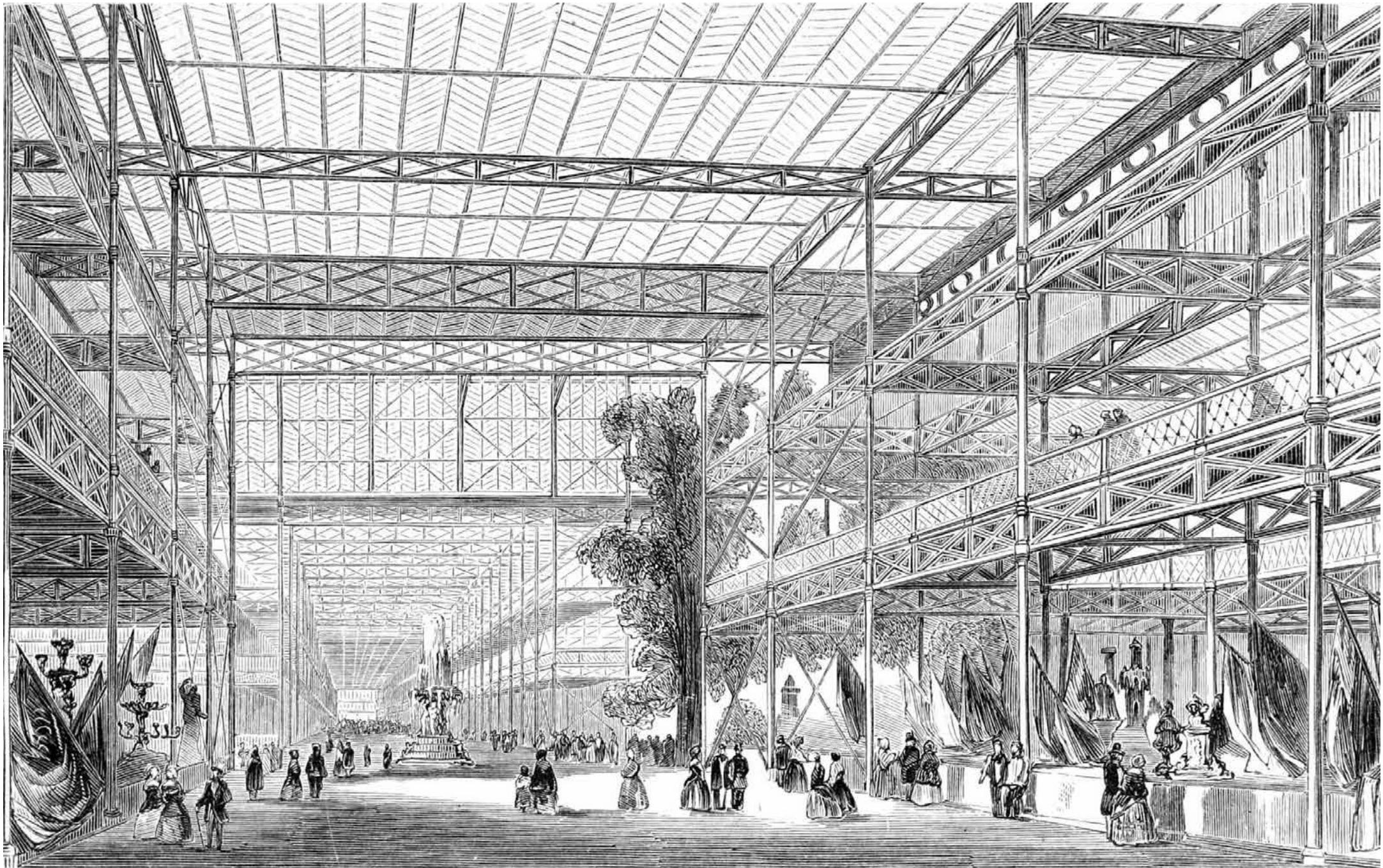
*Types of trusses*



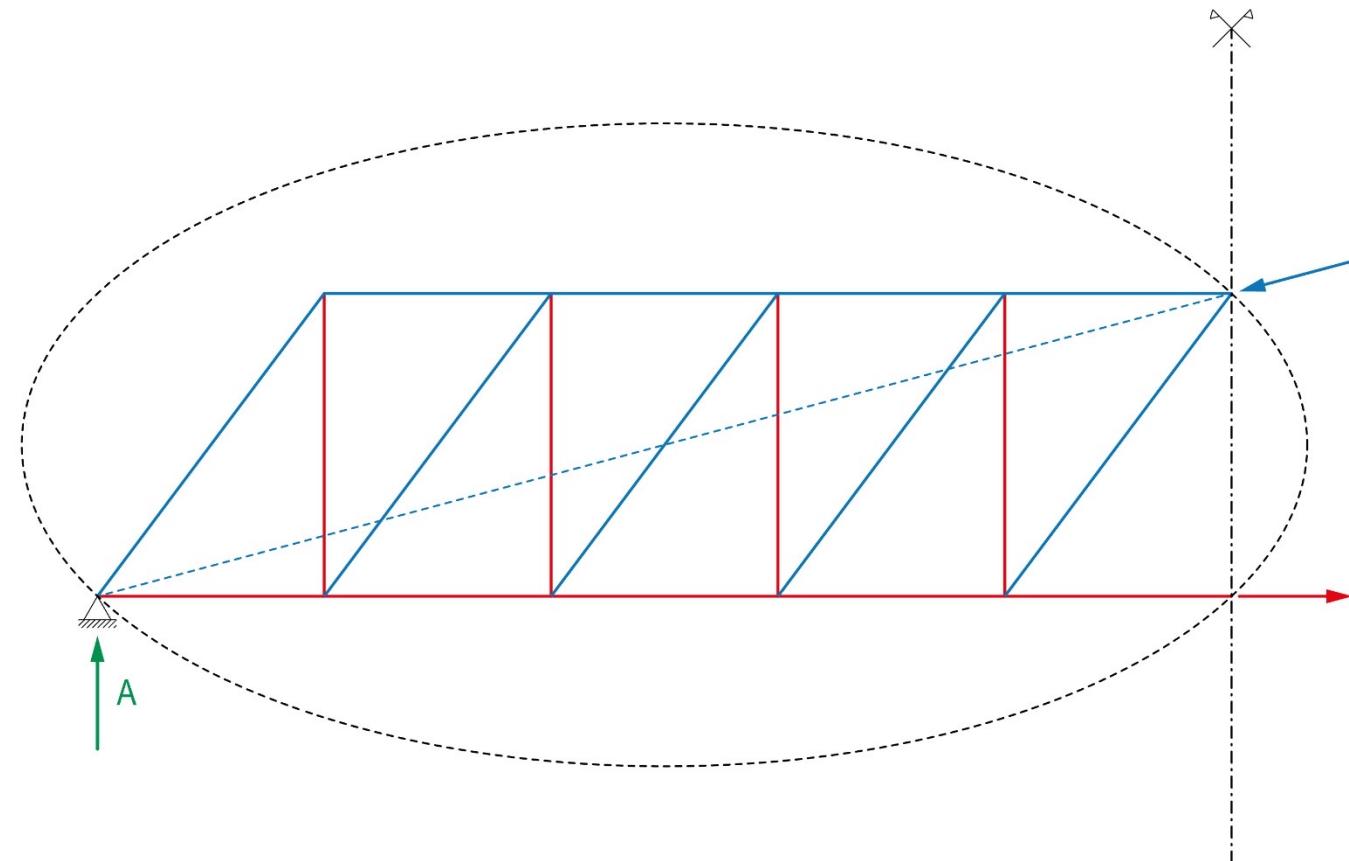
R. Piano, R. Rogers, P. Rice: Centre Georges Pompidou, Paris, 1977

*Types of trusses*

*Types of trusses*

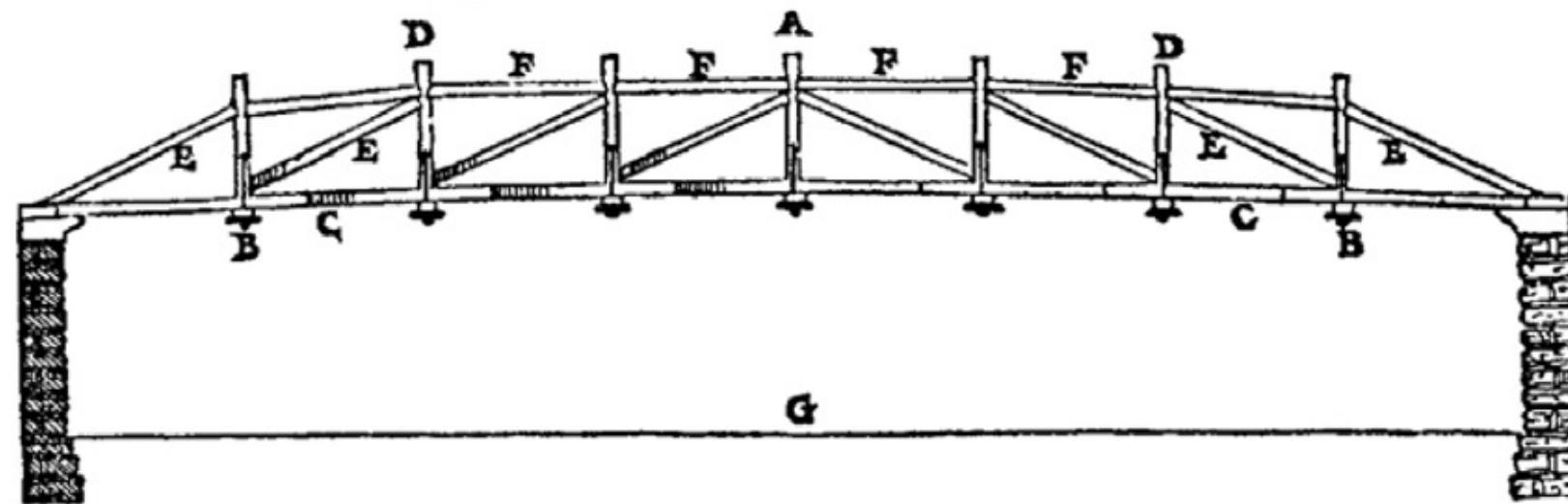


Joseph Paxton, Fox Henderson: Crystal palace, London, 1851



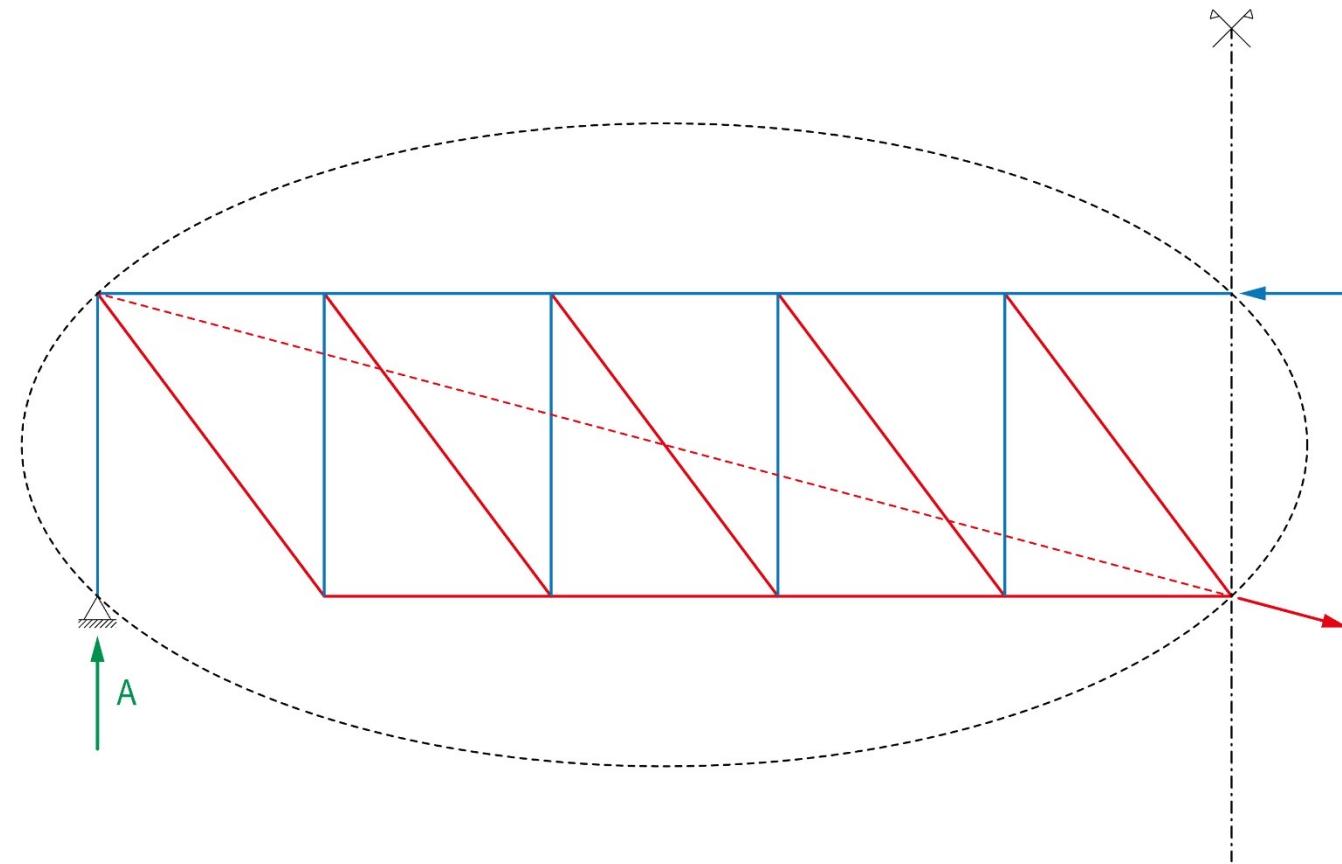
Fachwerk mit N-Förmigen Diagonalen: System Howe, Patent 1840

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



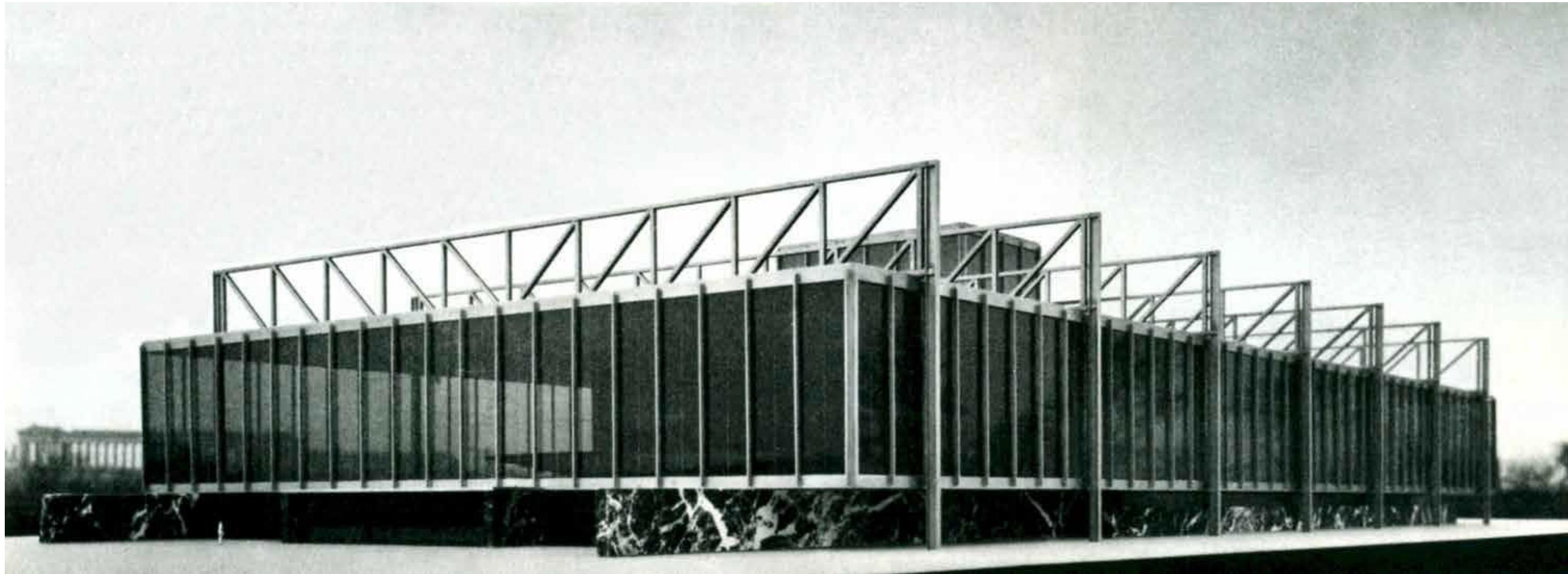
Von A. Palladio vorgeschlagenes Tragwerk, 1570 (in: "Die vier Bücher der Architektur", 3. Buch, Kapitel VIII)

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

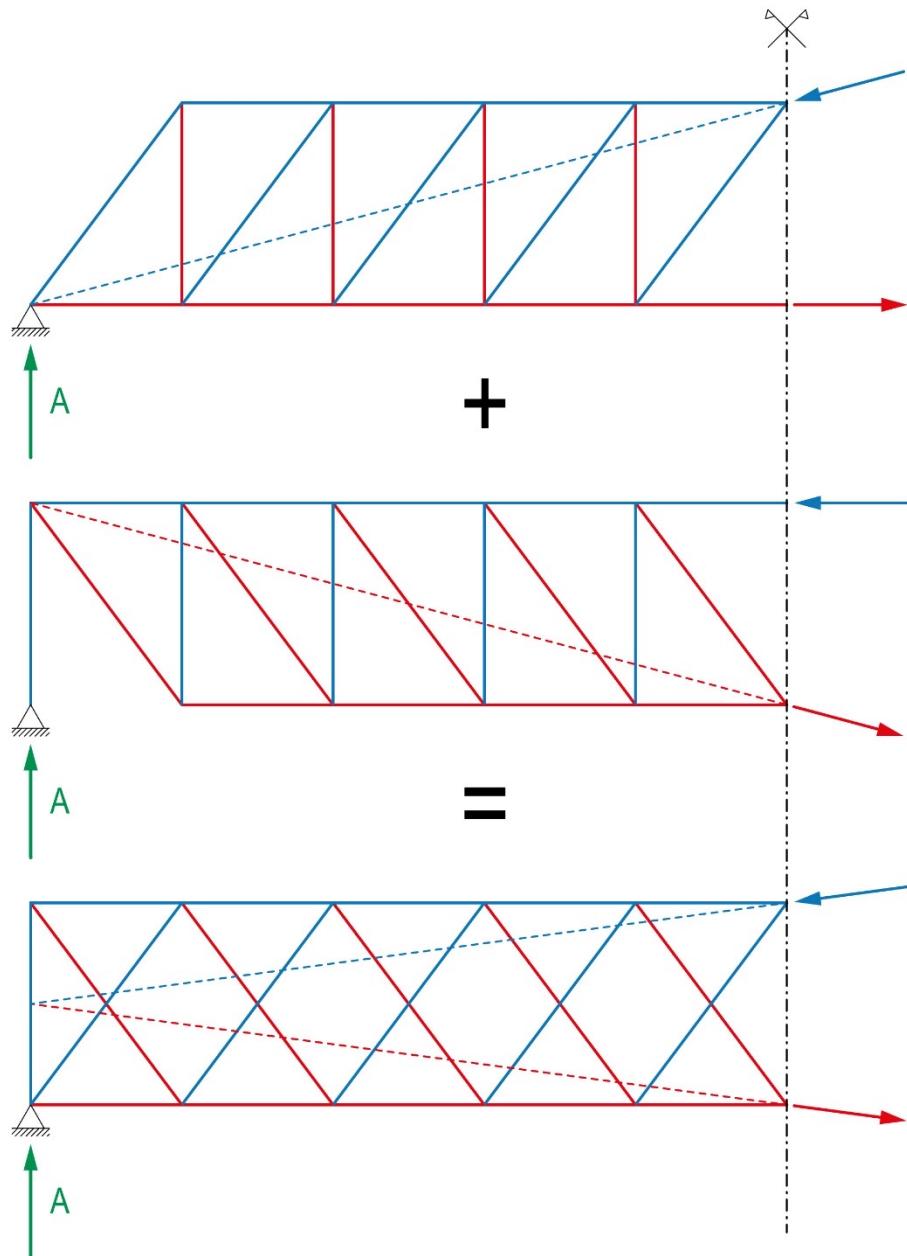


Fachwerk mit N-Förmigen Diagonalen: System Pratt, Patent 1844

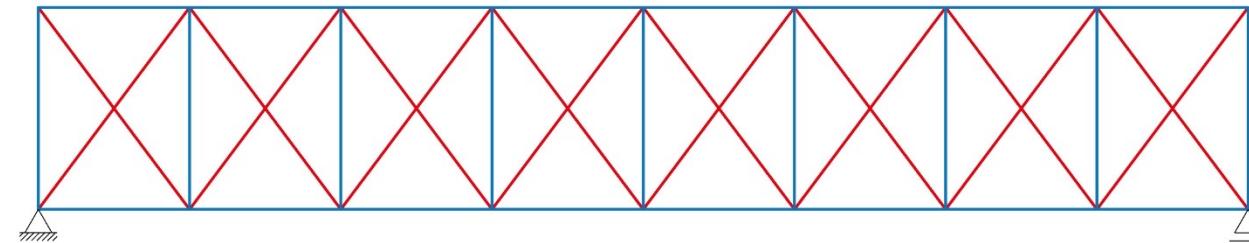
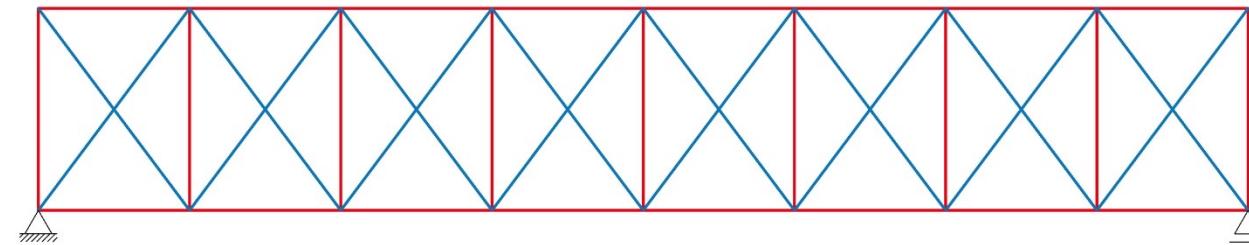
*Truss with N-shaped diagonals: System Pratt, patent 1844*



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

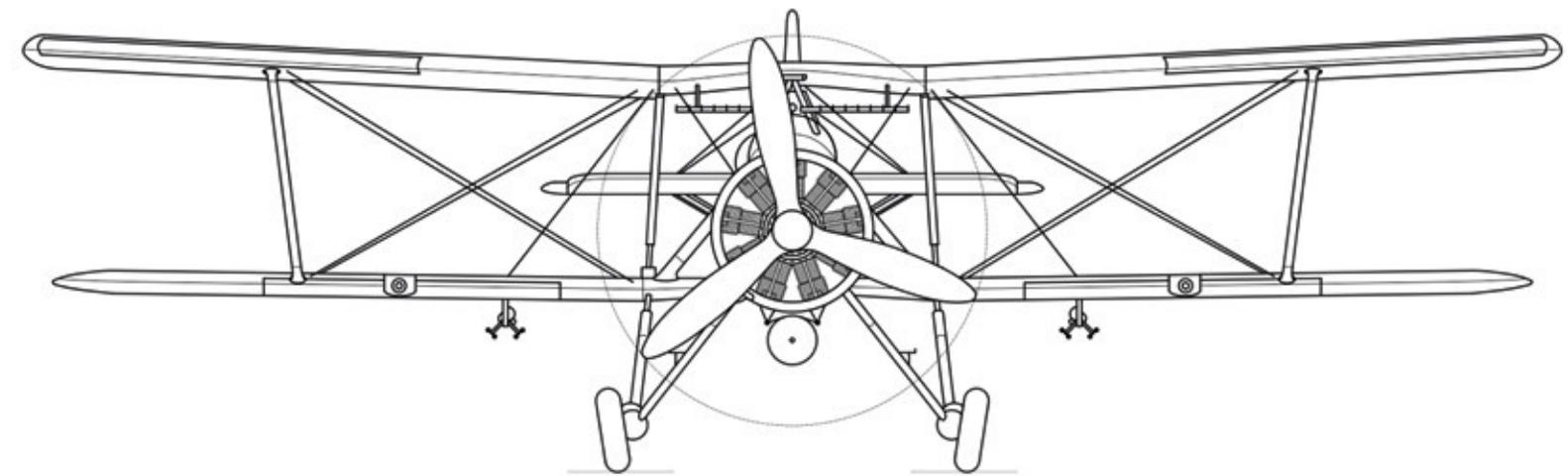
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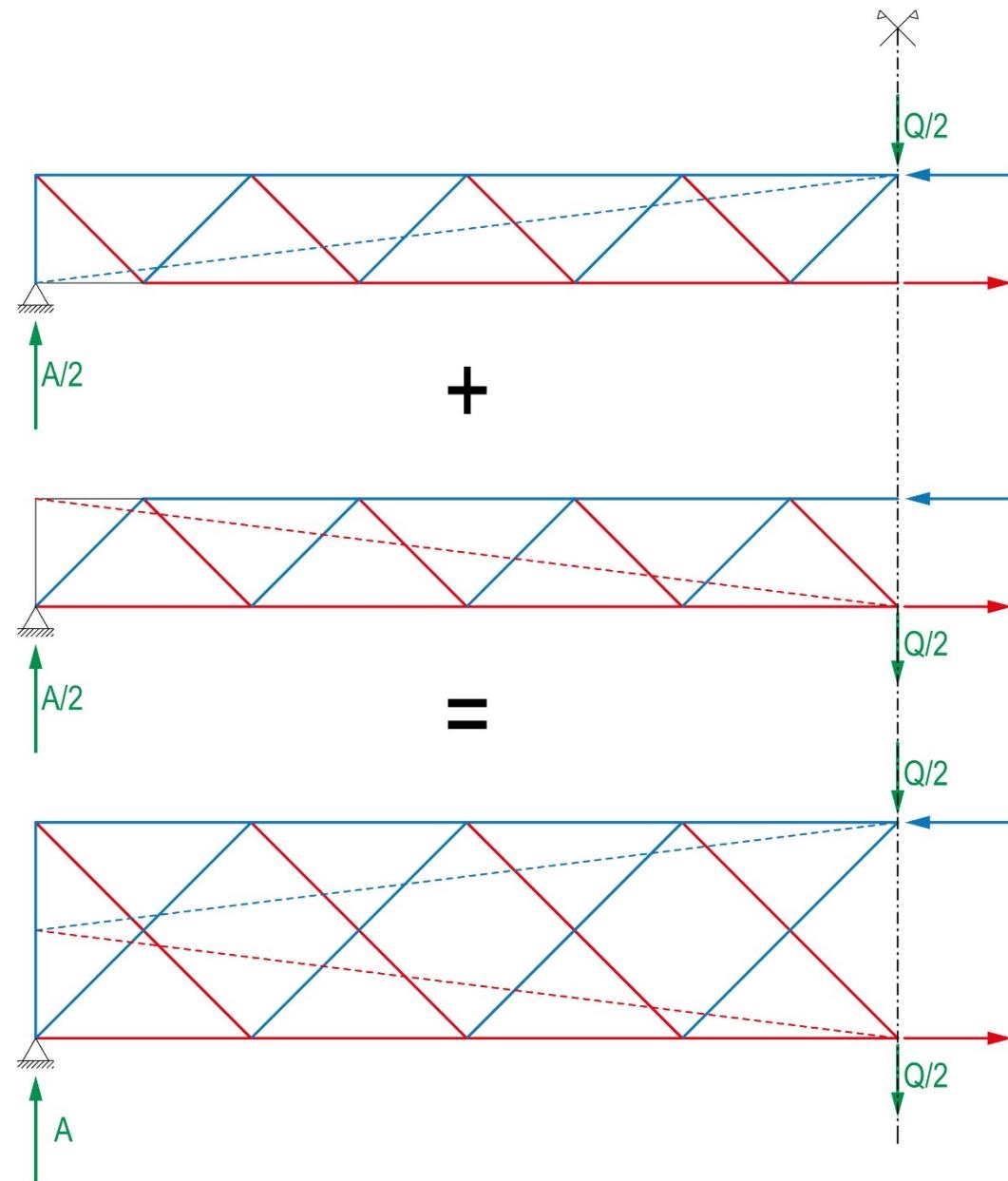


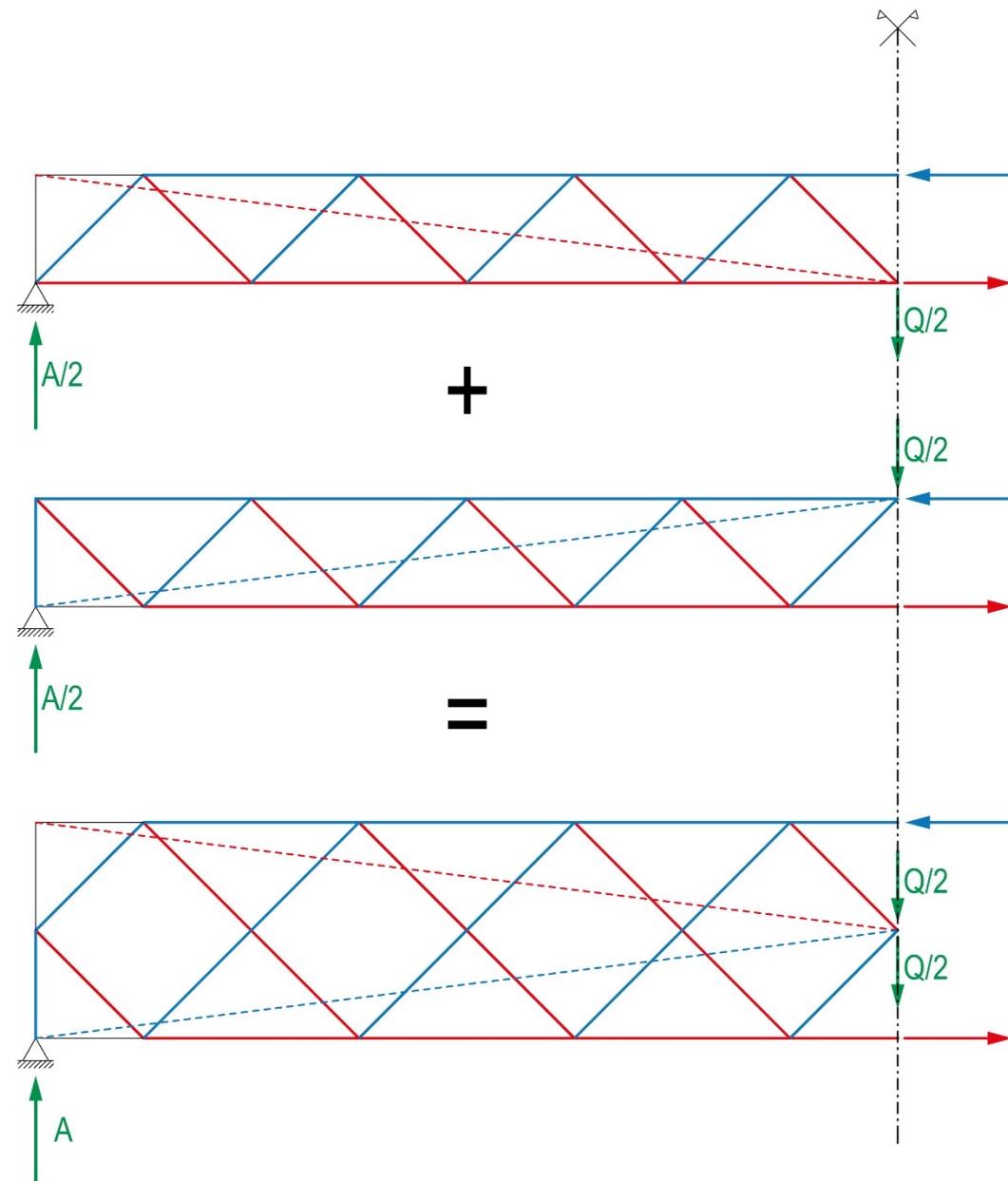
Fachwerk mit X-Förmigen Diagonalen: System Long, Patente 1830 & 1839

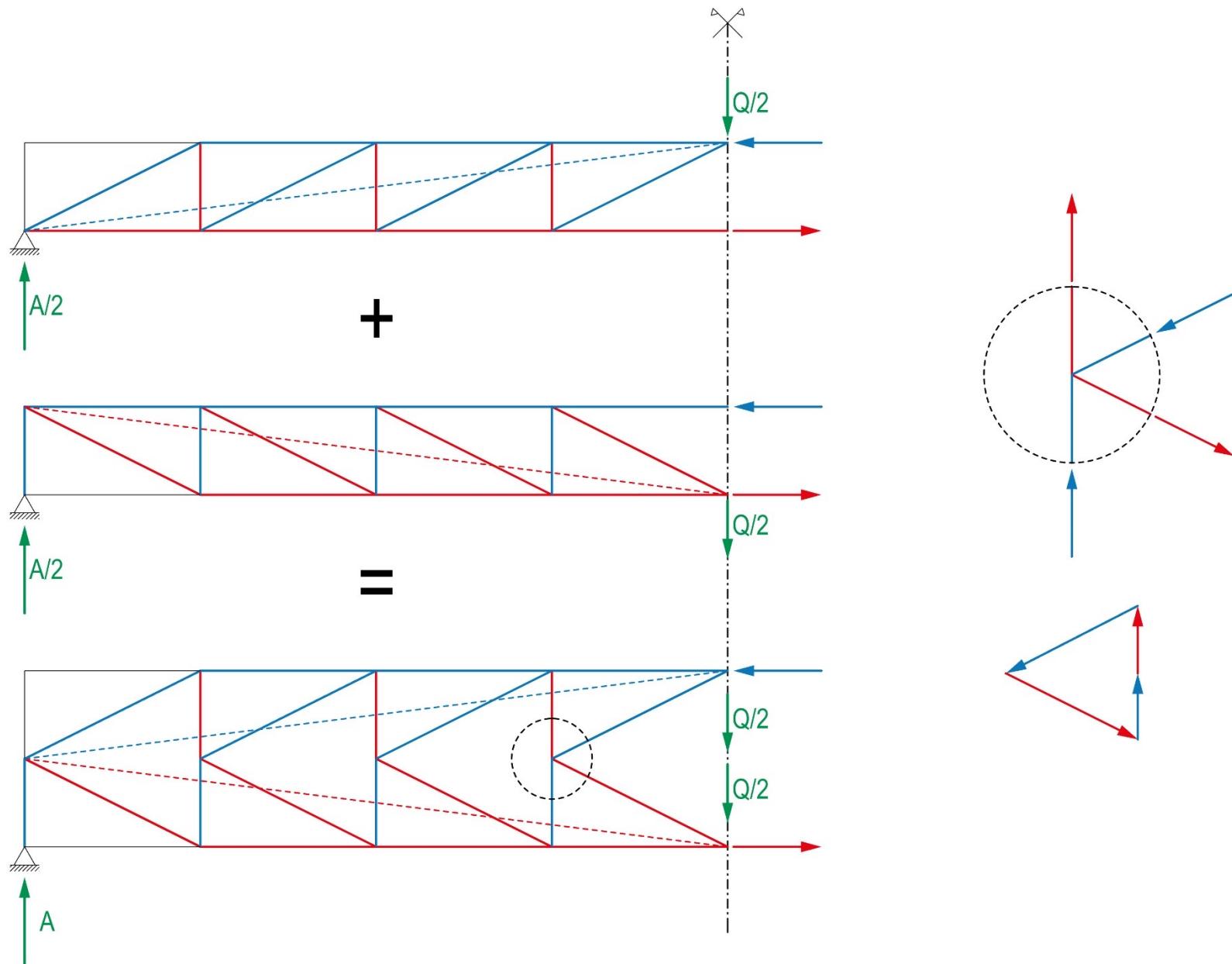
*Truss with X-shaped diagonals: System Long, patents 1830 & 1839*

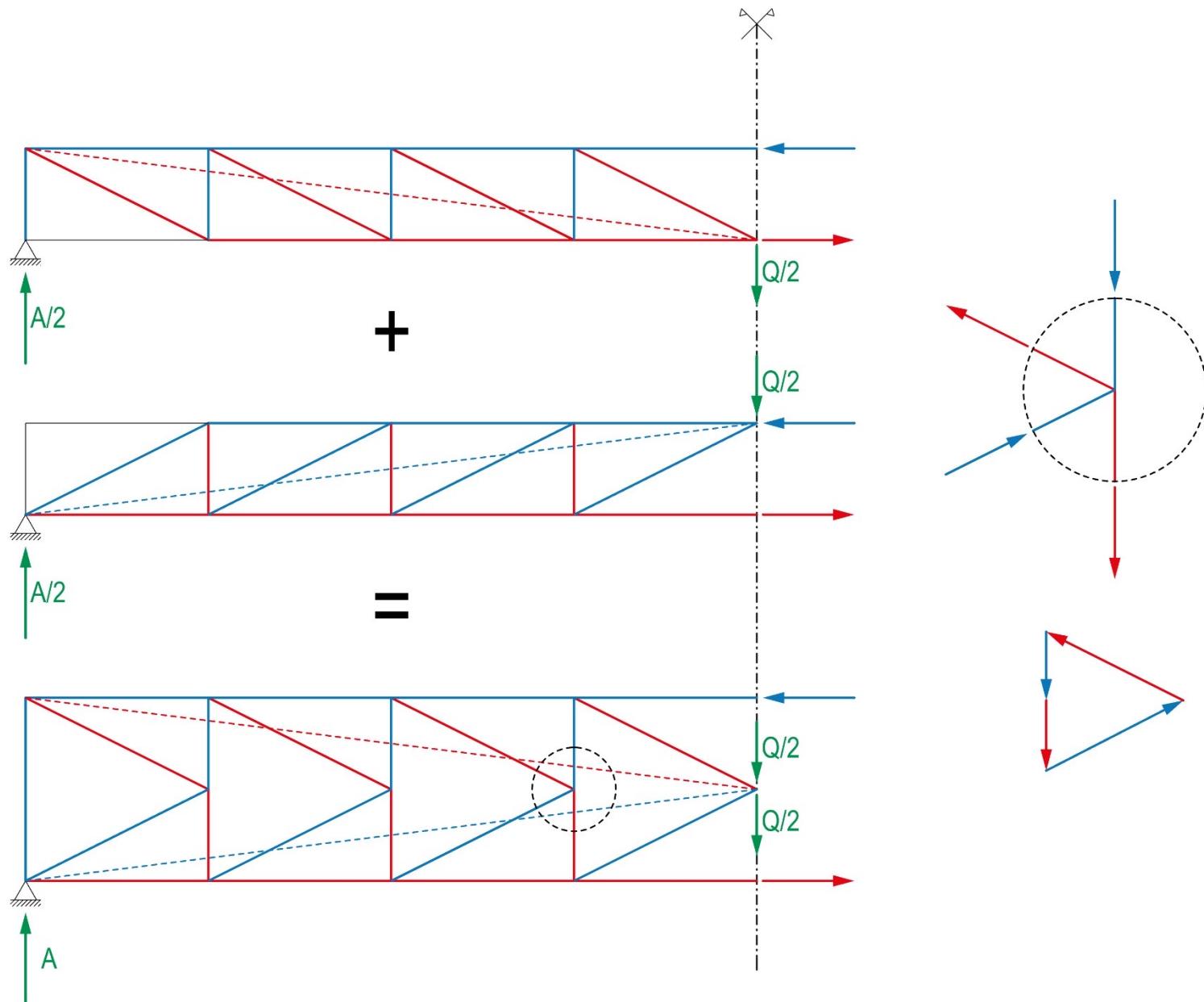


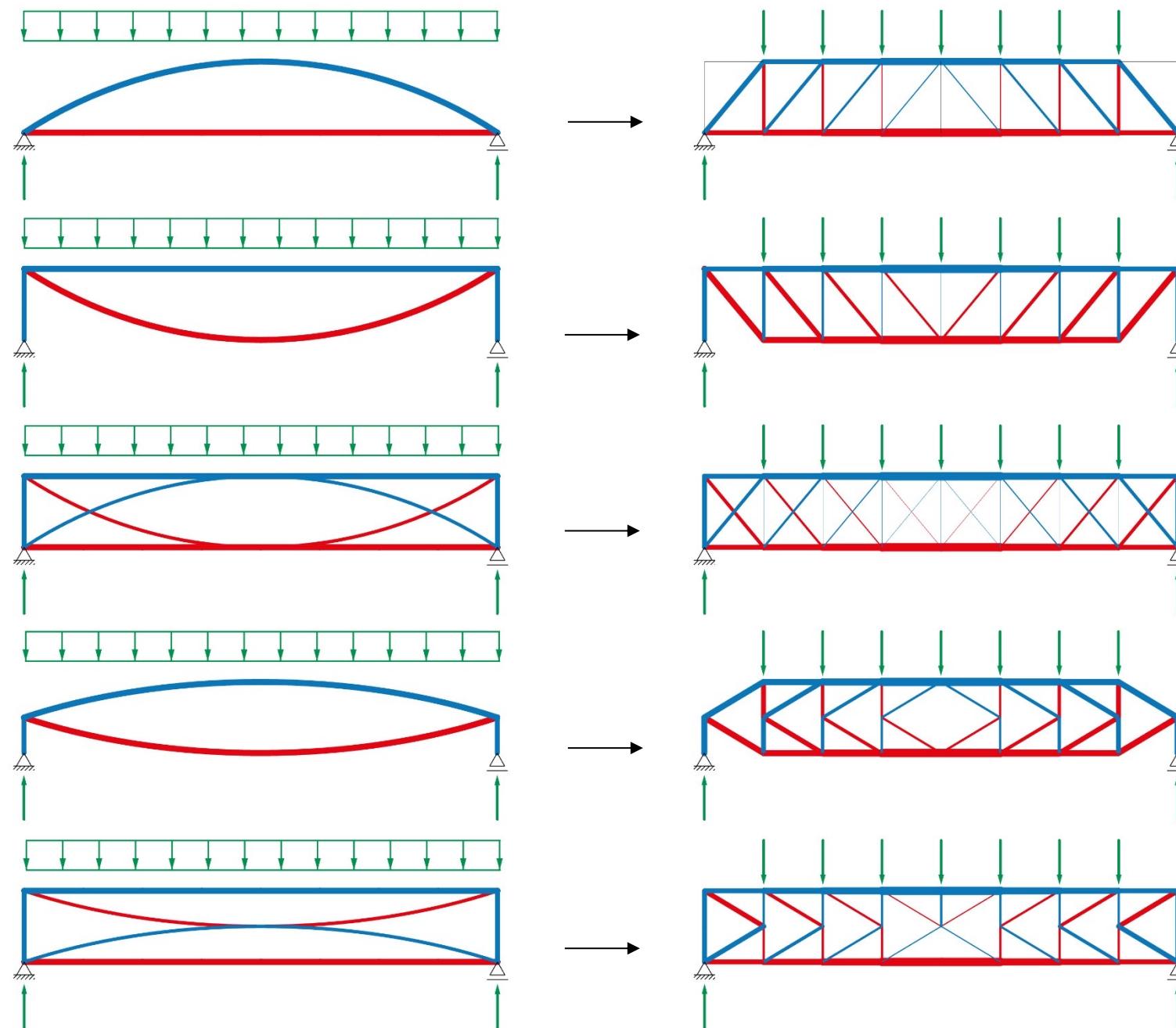
Doppeldecker Fairey Swordfish I, GB, 1934

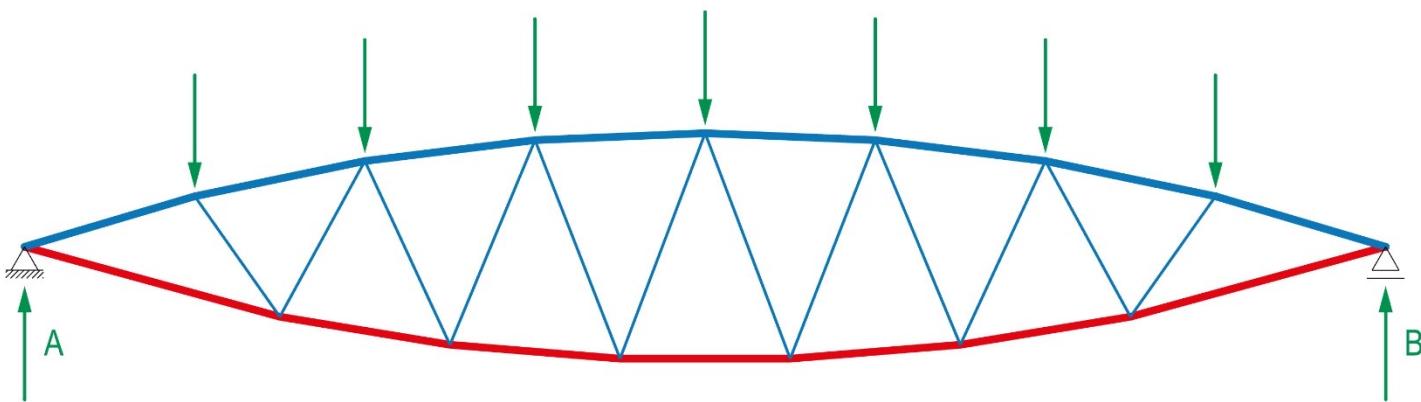
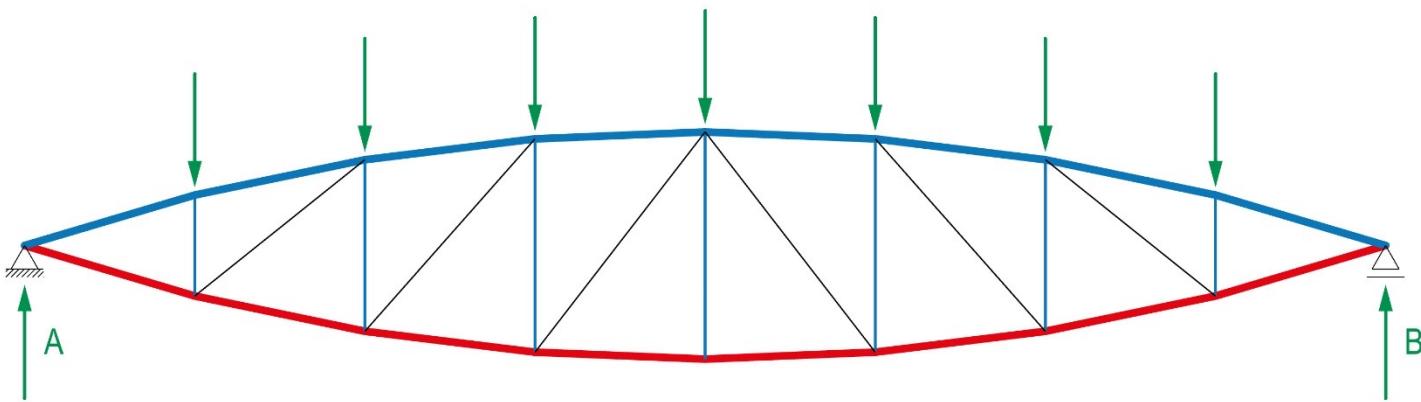
*Types of trusses*



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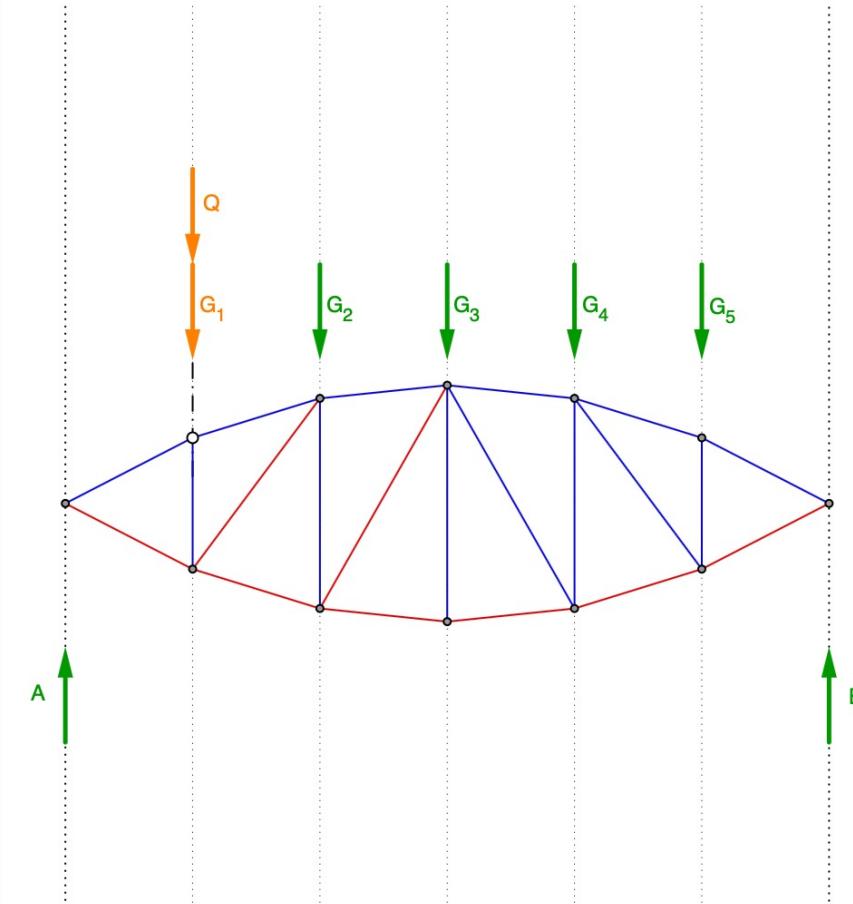
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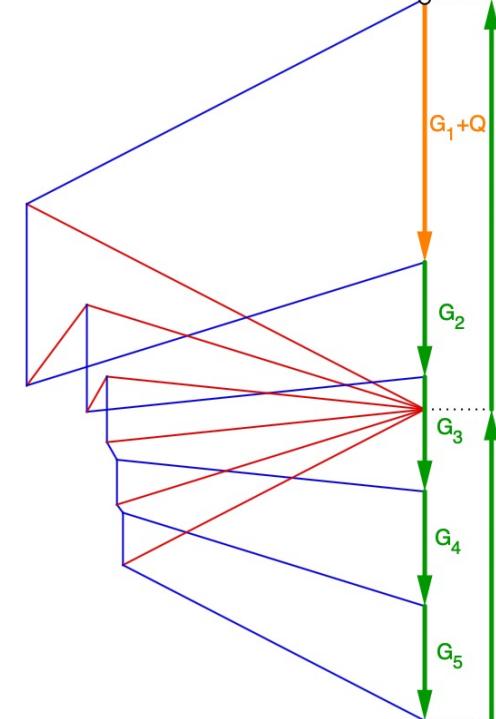
*Types of trusses*

**eQ:** Pratt / Howe truss

Form Diagram



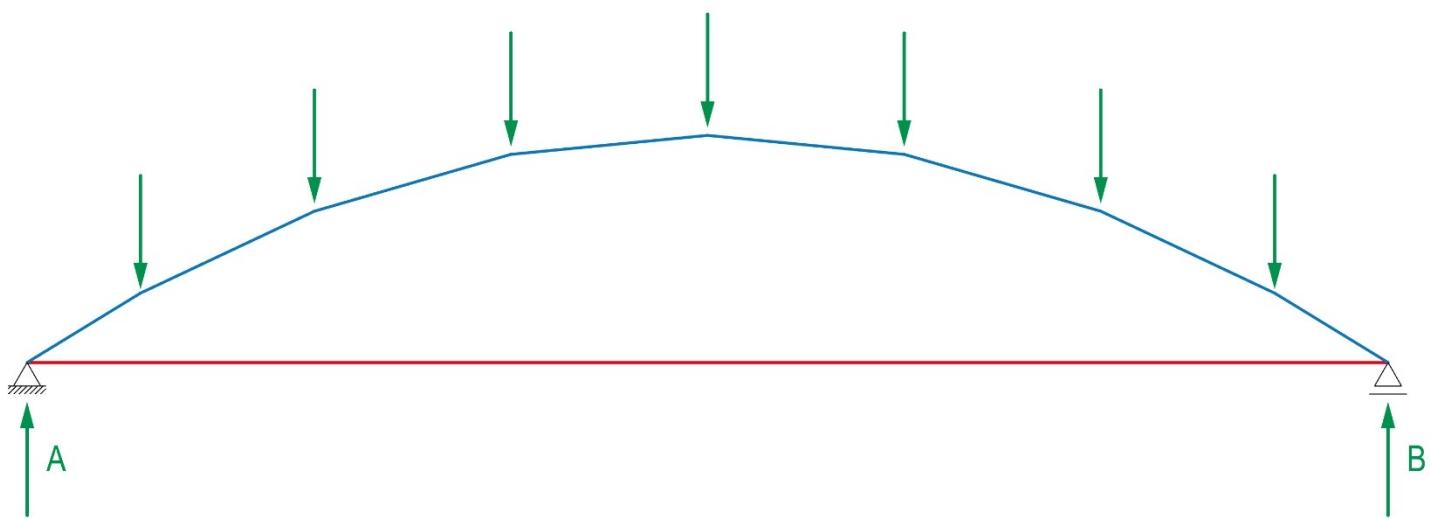
Force Diagram

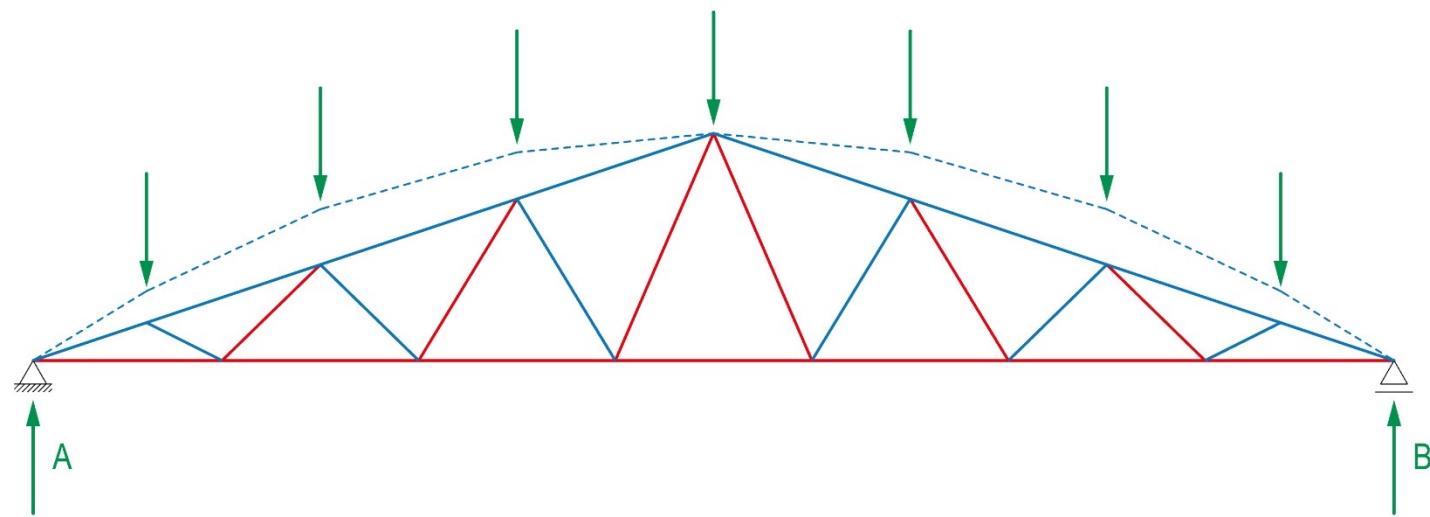


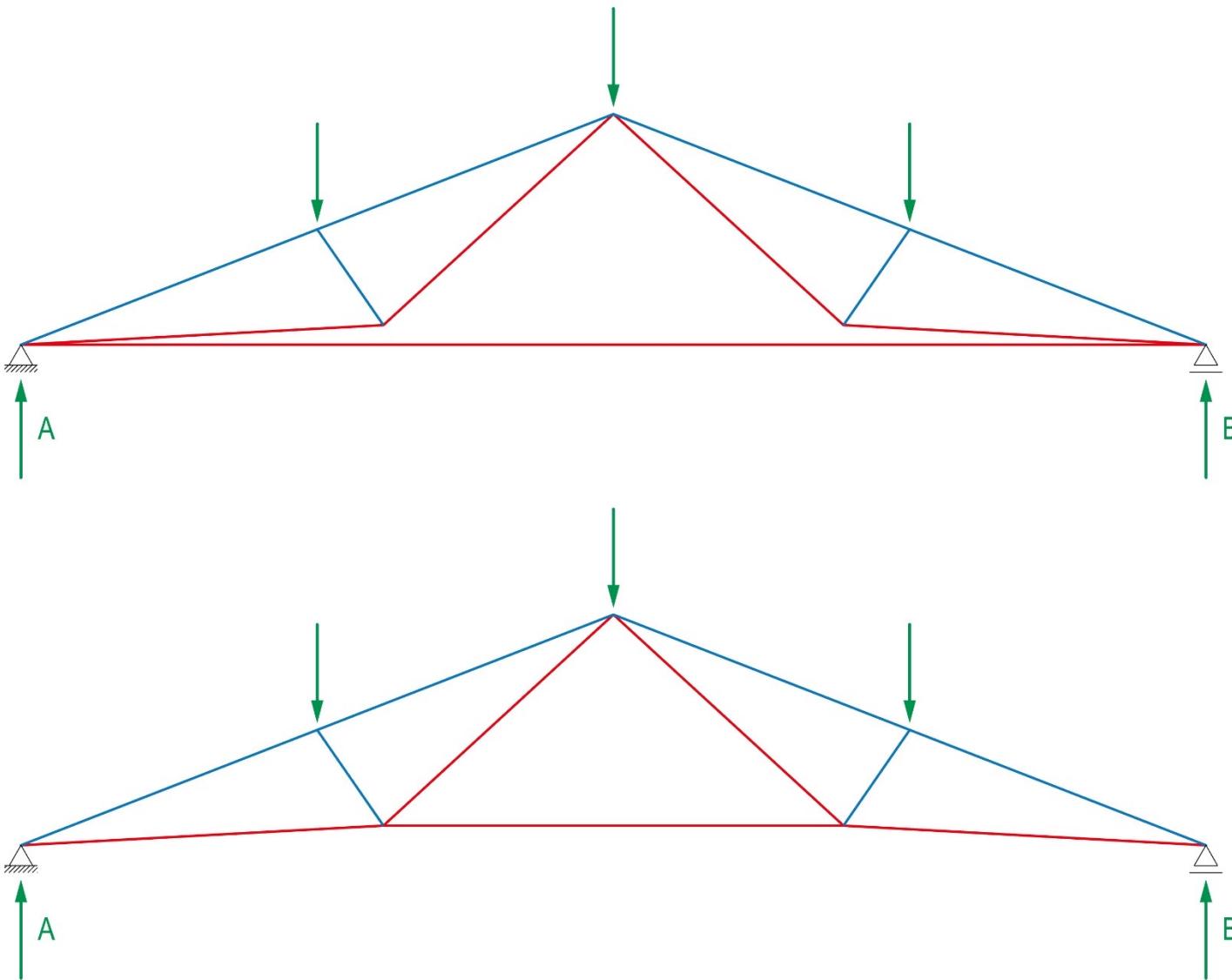
<https://block.arch.ethz.ch/eq/drawing/view/38#>



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

*Types of trusses*

*Types of trusses*

*Types of trusses*

*Types of trusses*



Jakob Ignatz Hittorf: Gare du Nord, Paris, 1865

# Fachwerke

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>> Variation der Randbedingungen

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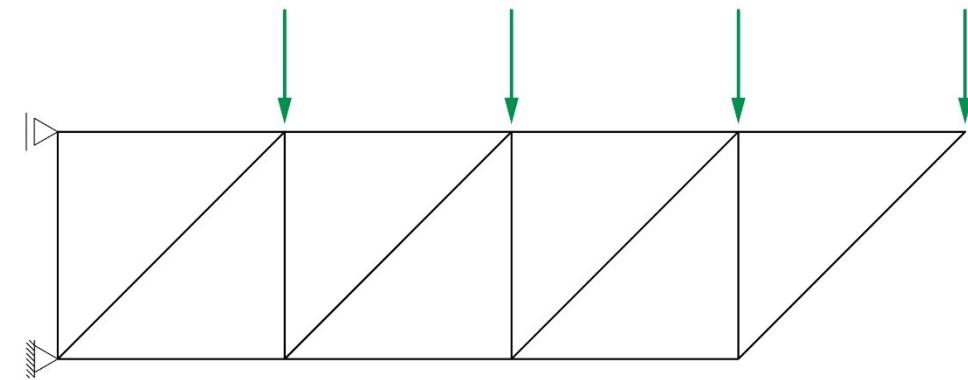
*Slender trusses*

Konstruktion von Fachwerken

*Construction of trusses*

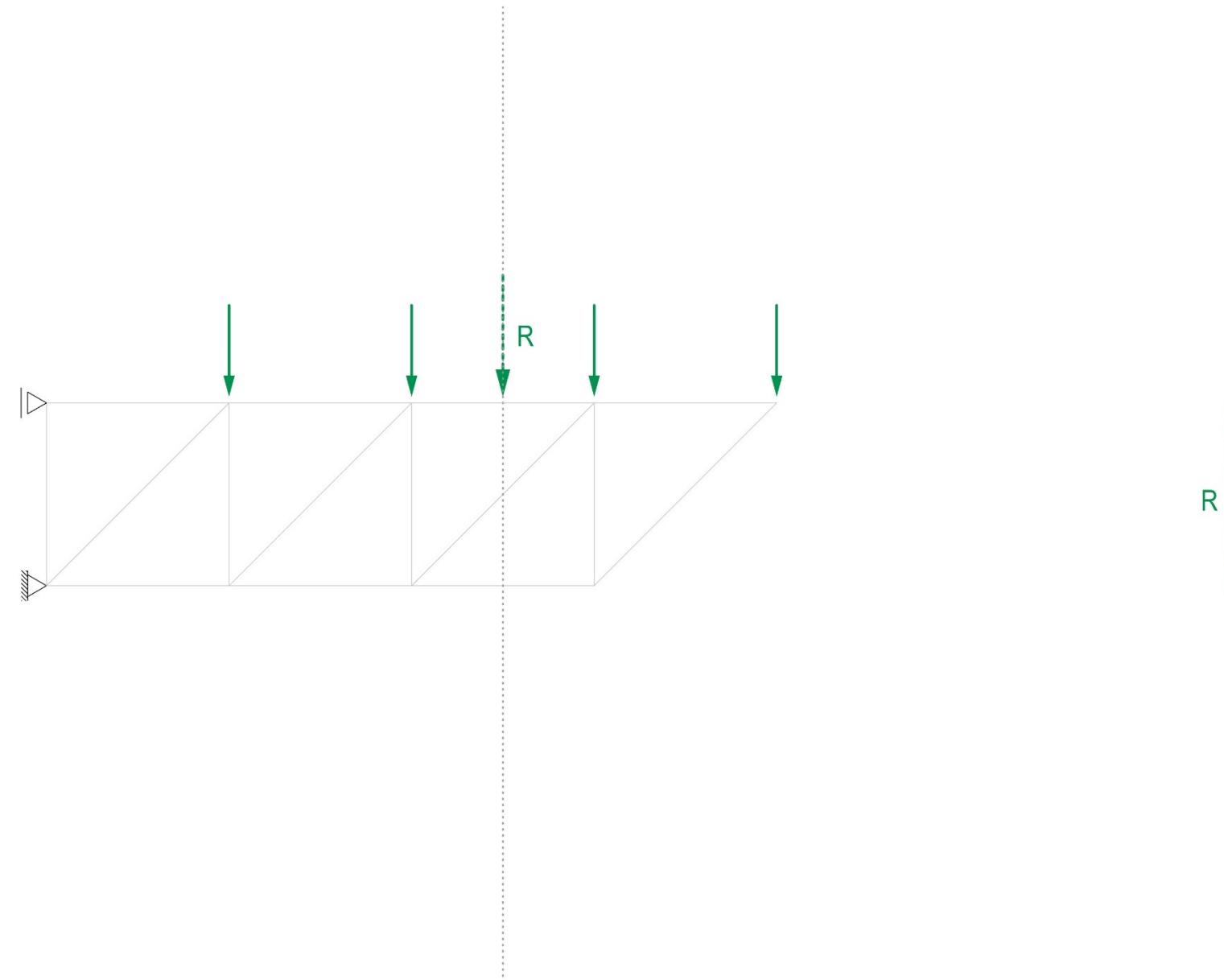
Räumliche Fachwerke

*Spatial trusses*



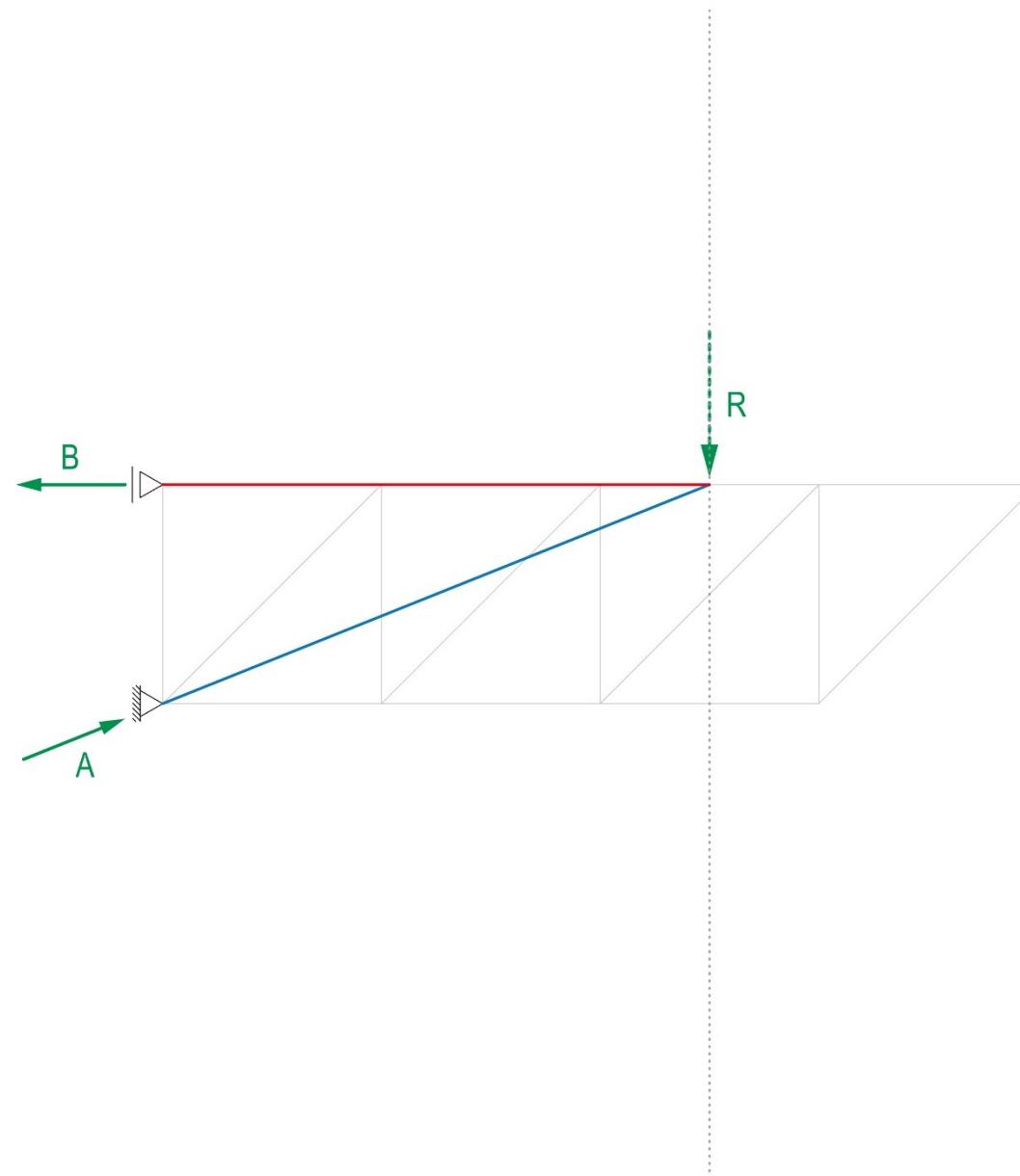
Lageplan 1:100  
*Form diagram 1:100*

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



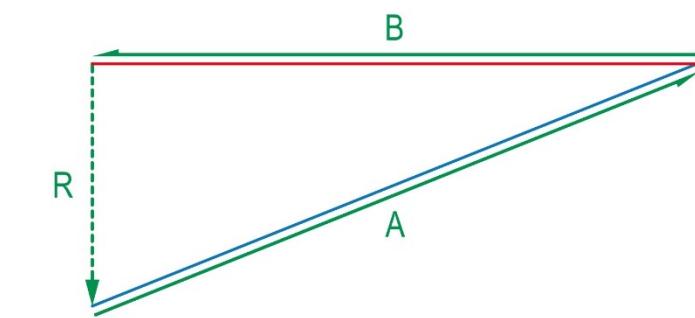
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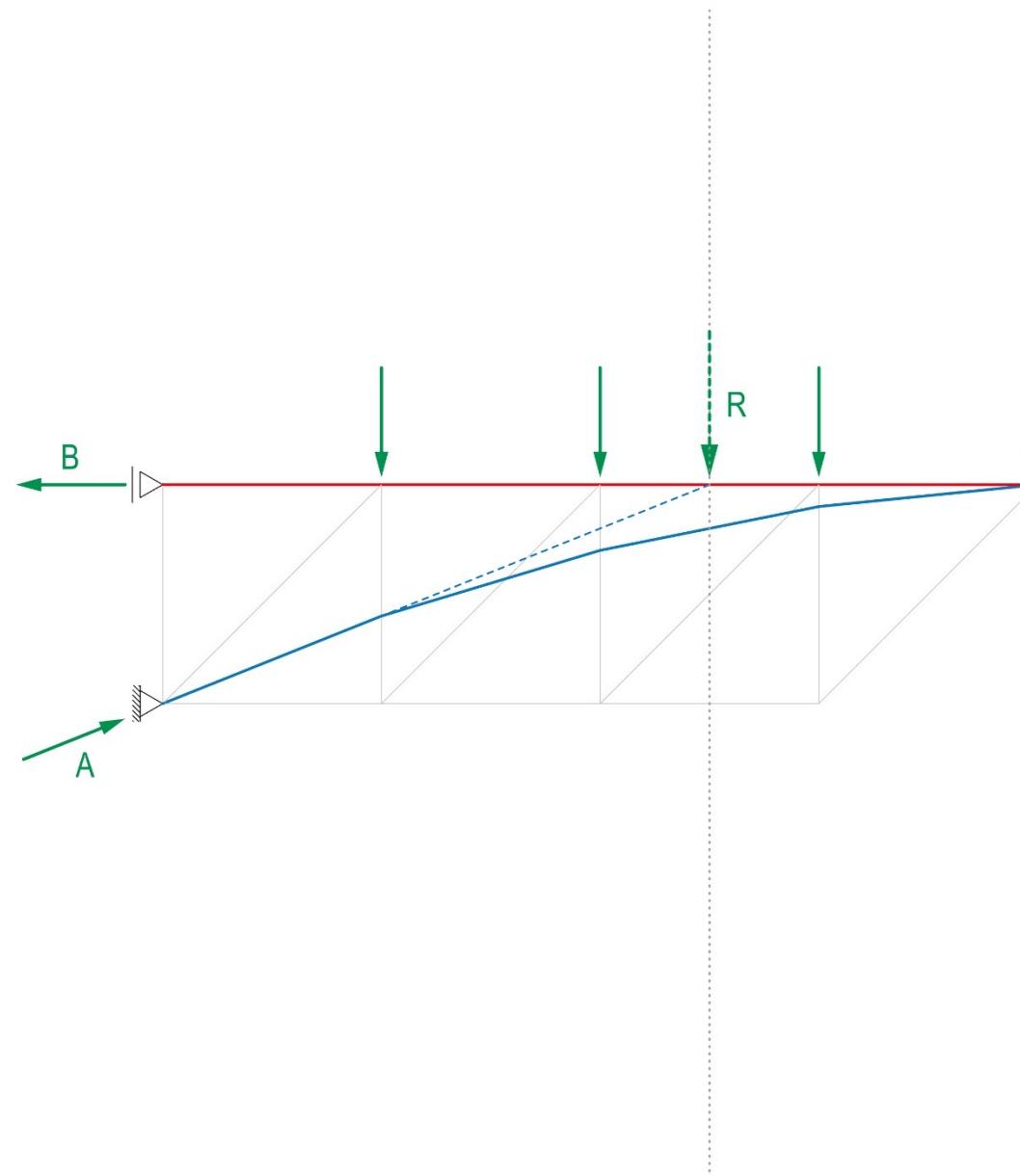
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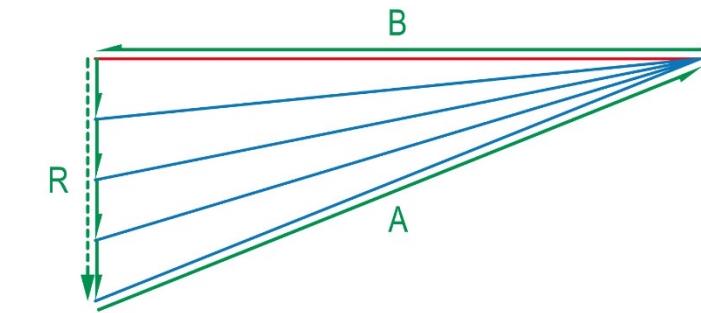
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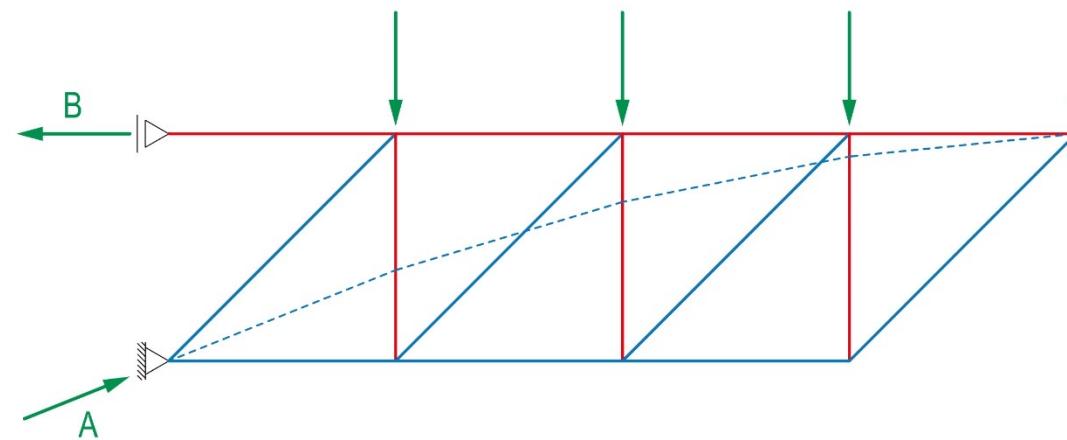
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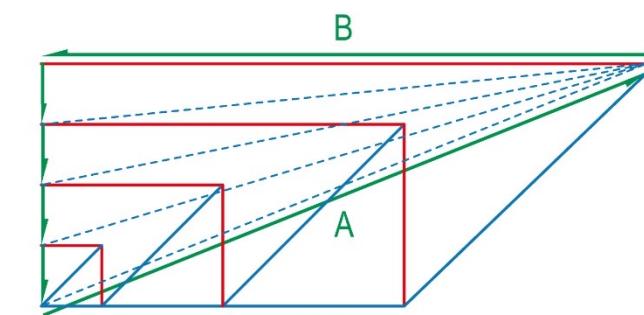


Kräfteplan 1 cm  $\triangleq$  1 kN

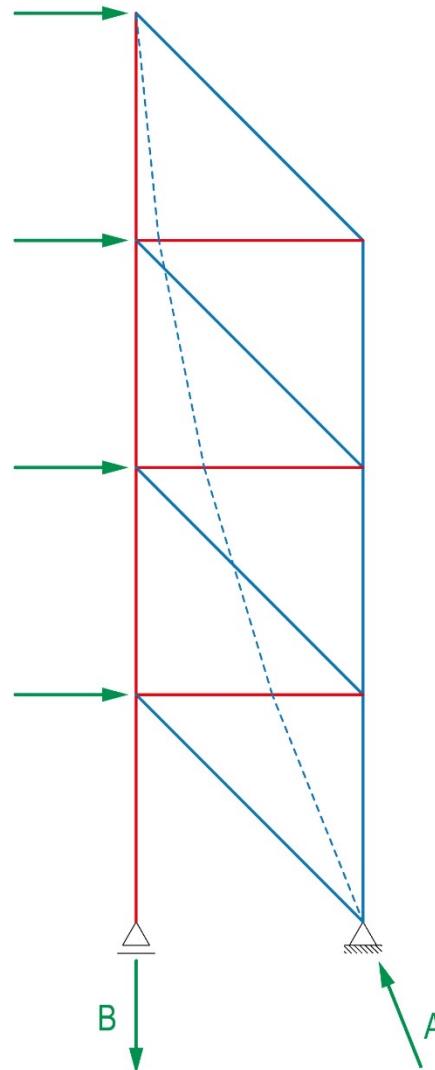
*Force diagram 1 cm  $\triangleq$  1 kN*



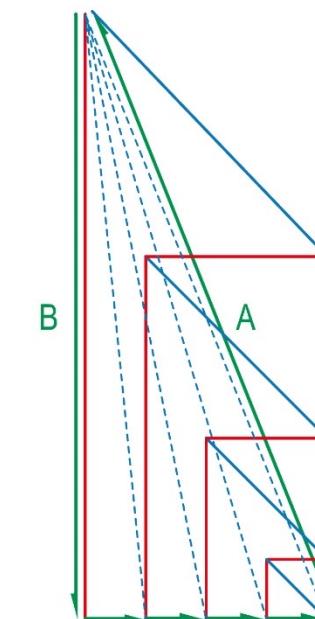
Lageplan 1:100  
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Kräfteplan 1 cm  $\triangleq$  1 kN  
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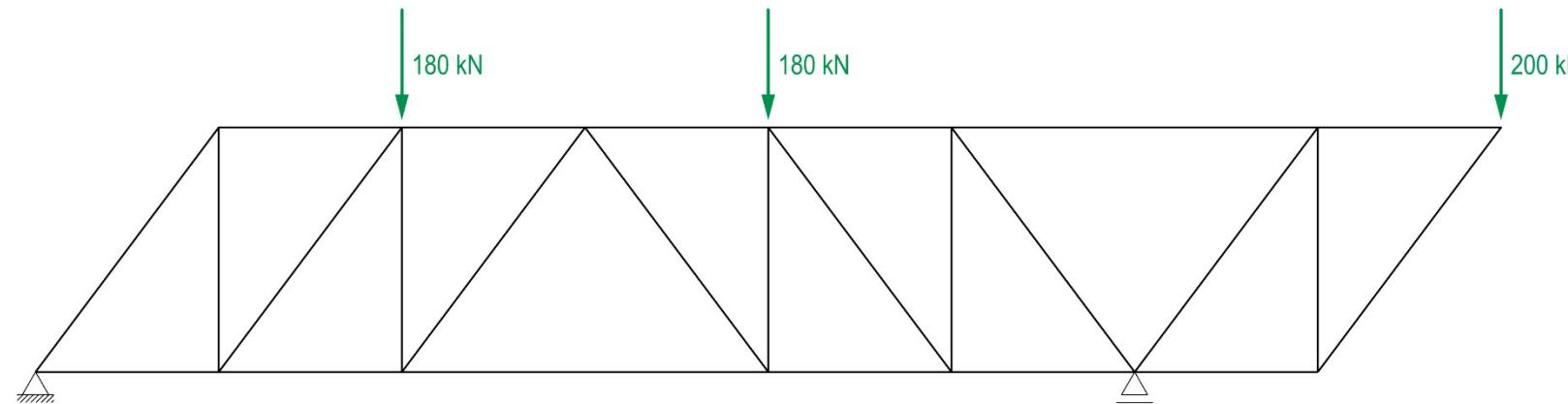
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Kräfteplan 1 cm  $\triangleq$  1 kN  
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SOM, F. Kahn: John Hancock Center, Chicago, 1969

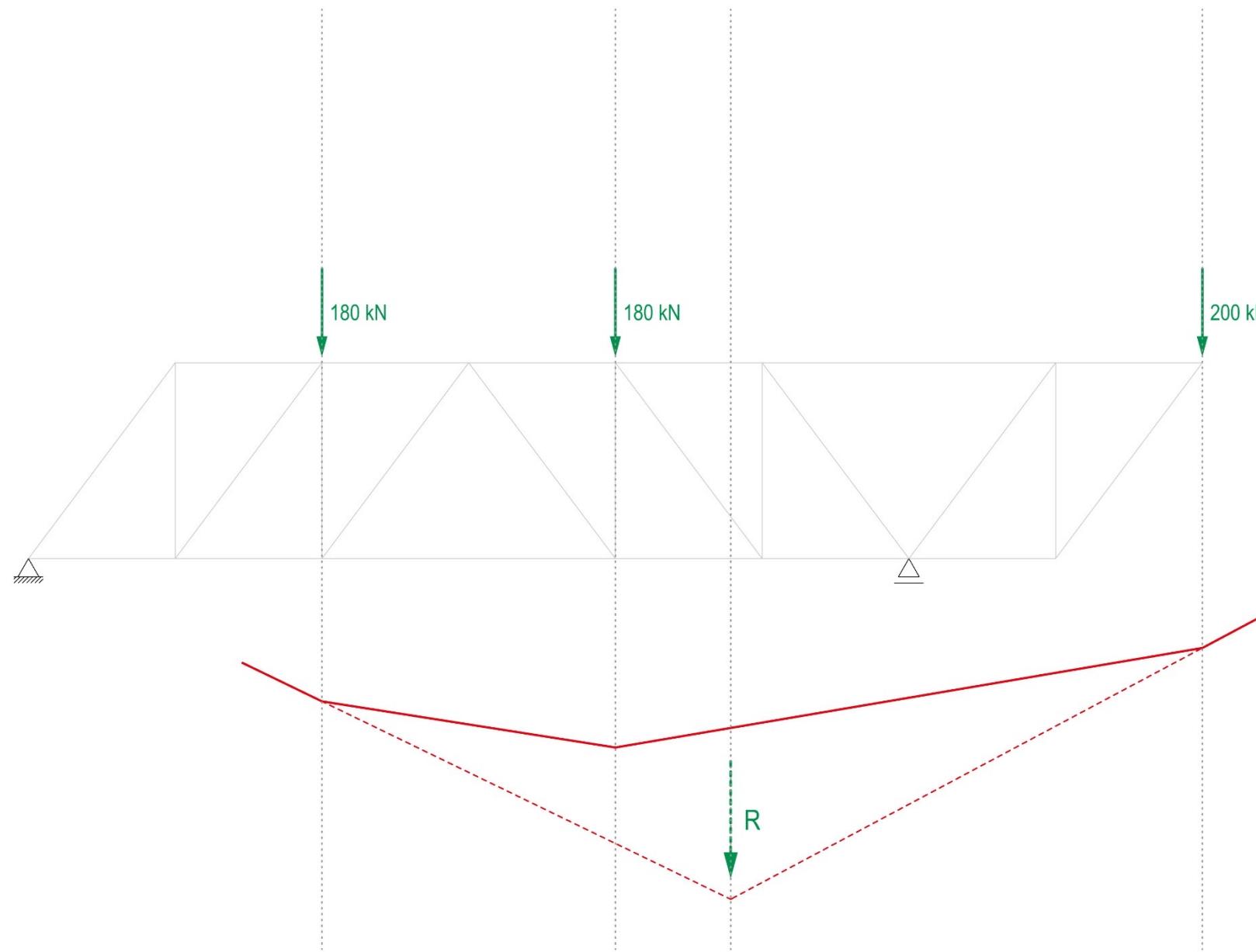


Lageplan 1:100

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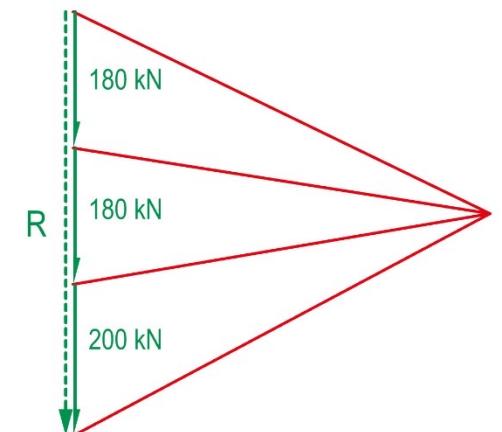
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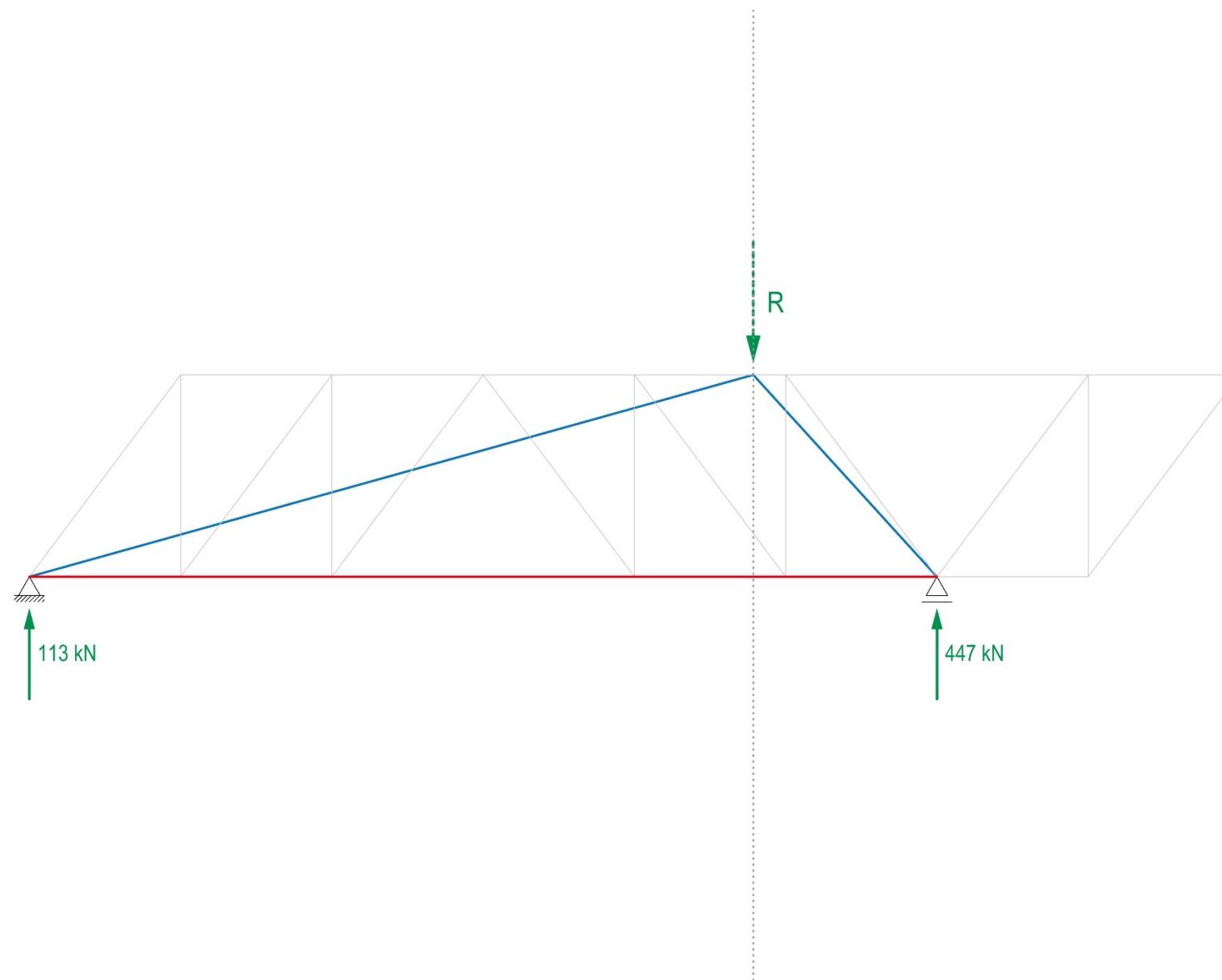
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Lageplan 1:100

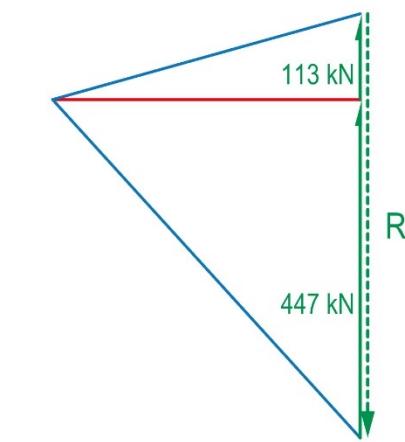
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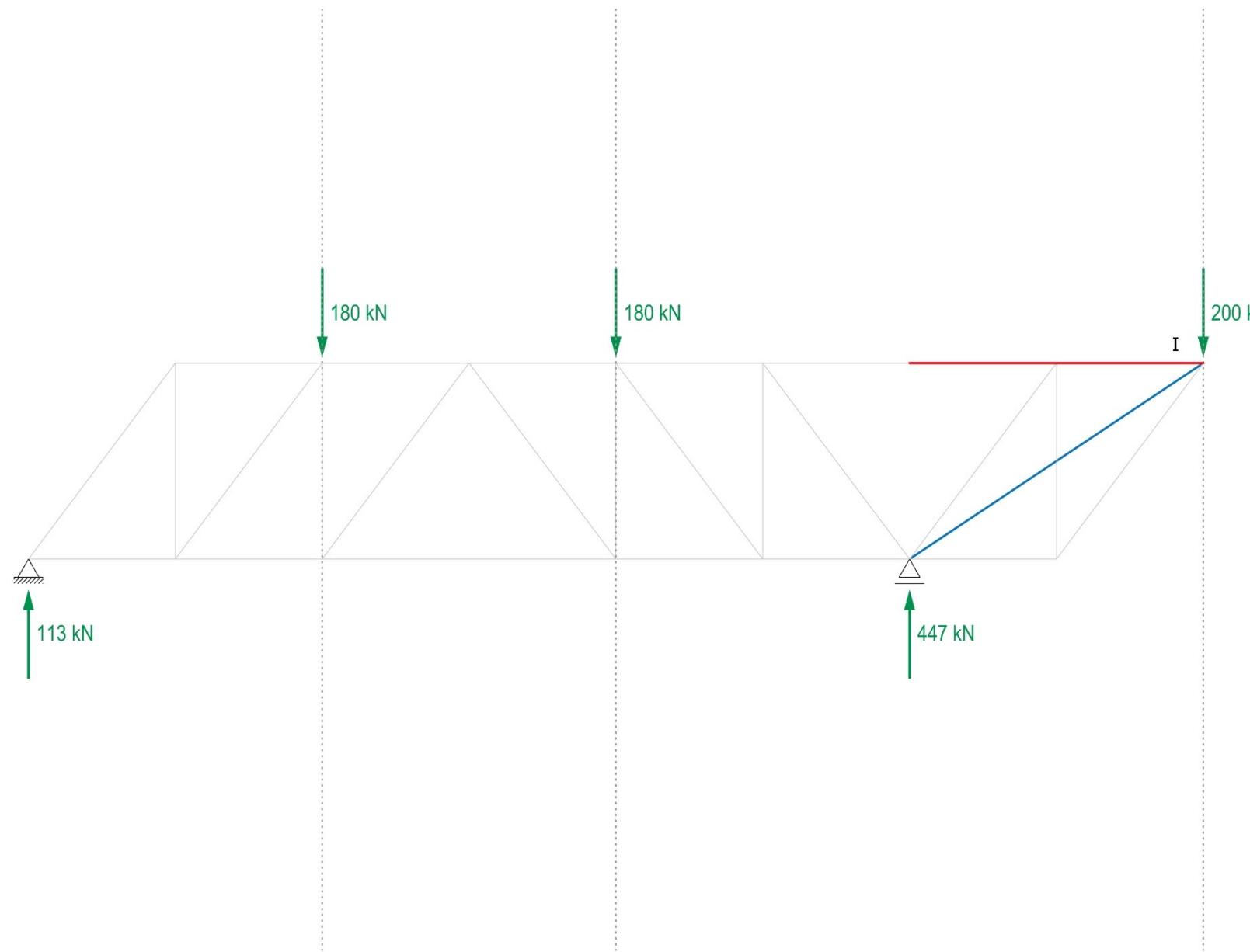
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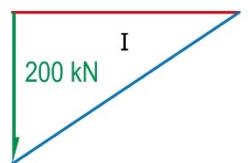
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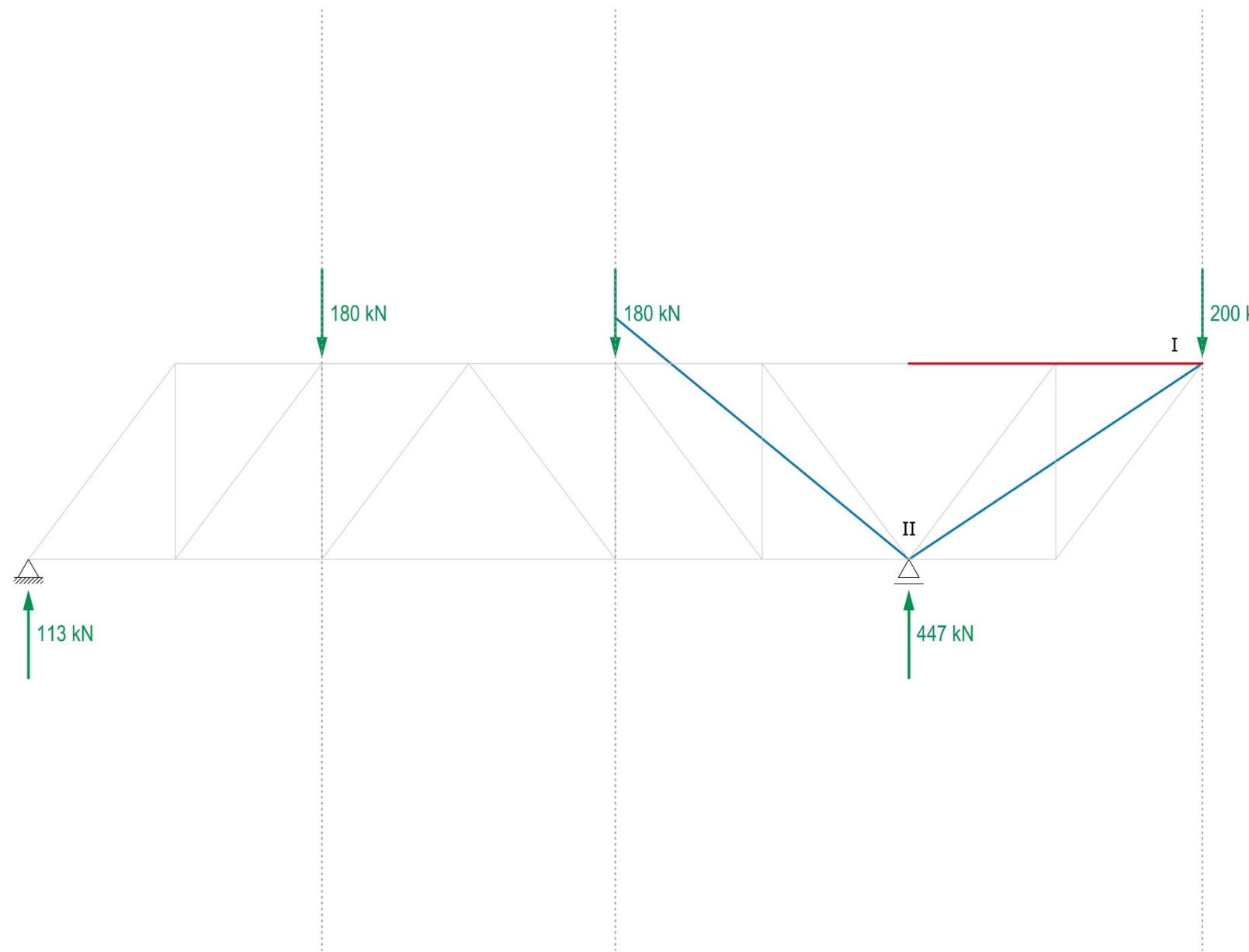
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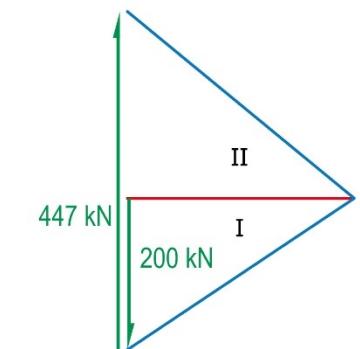
Form diagram 1:100

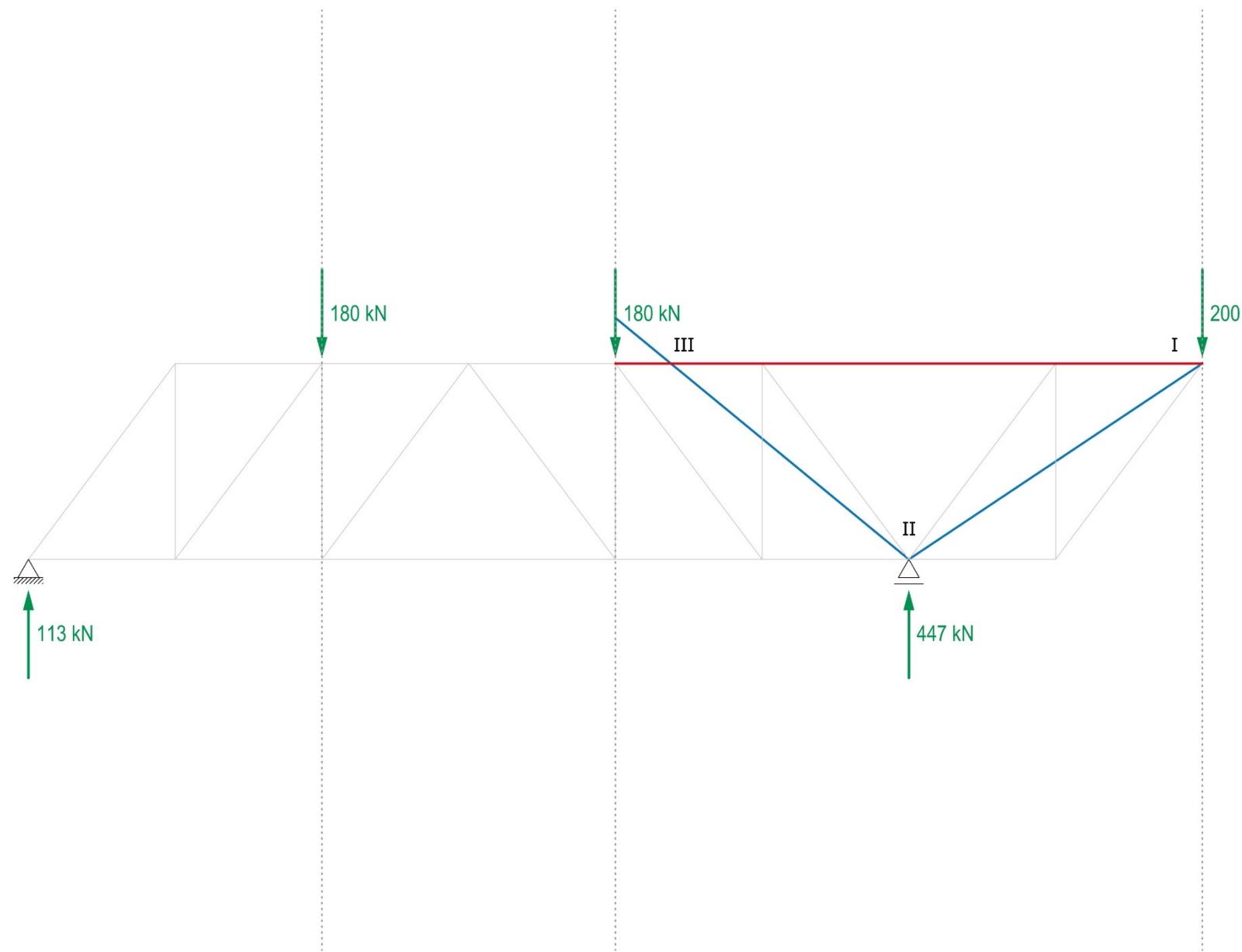
Kräfteplan 1 cm  $\triangleq$  1 kNForce diagram 1 cm  $\triangleq$  1 kN



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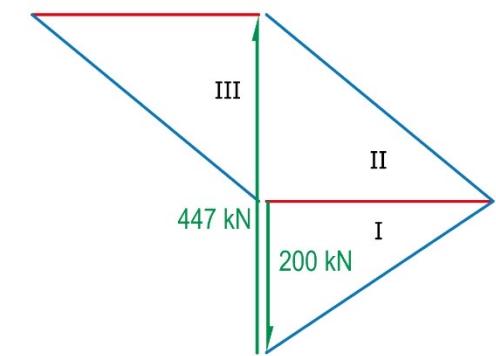
Form diagram 1:100

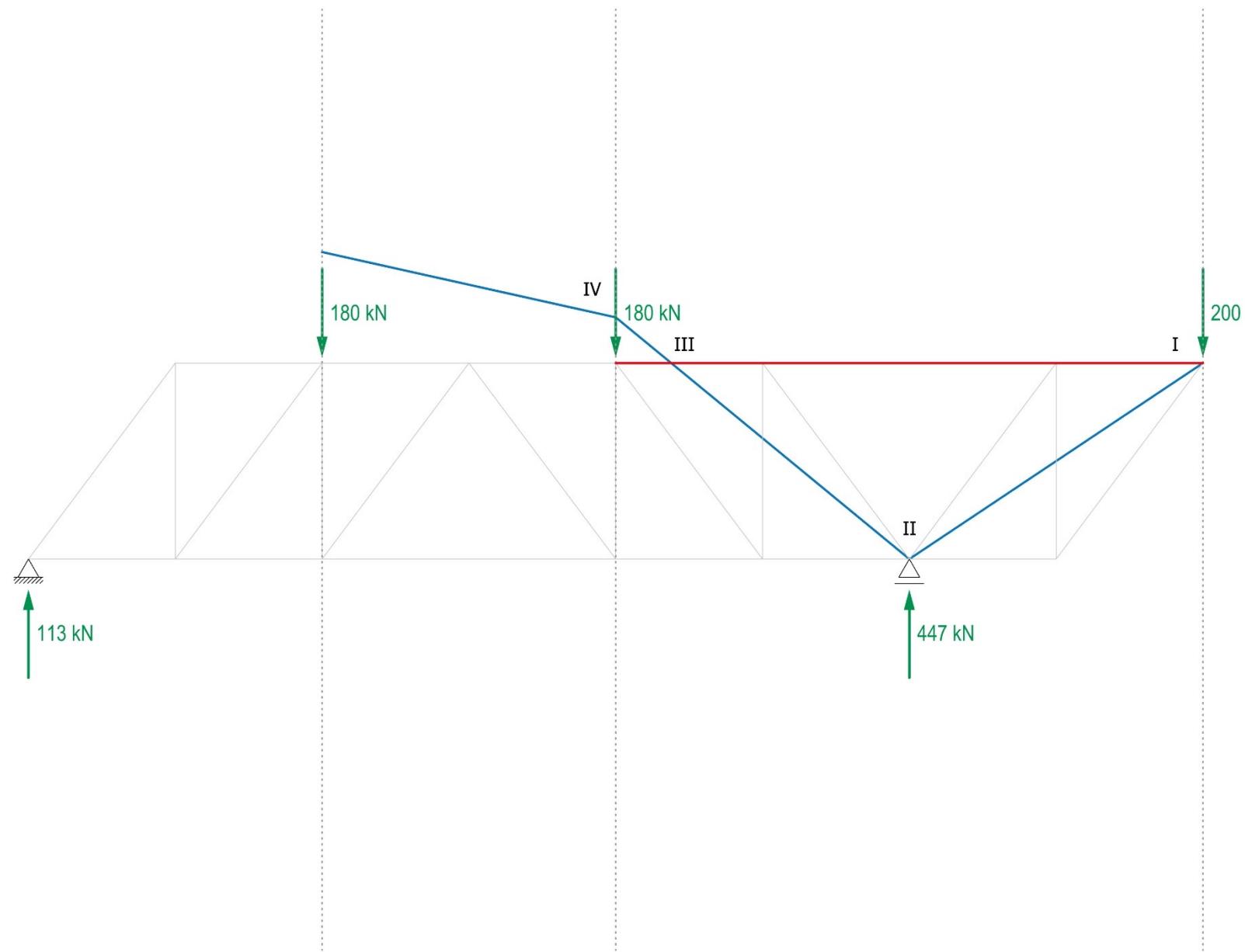
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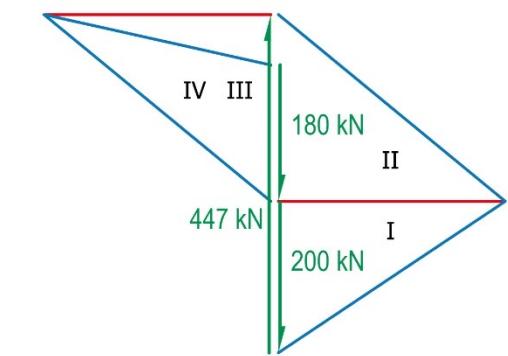
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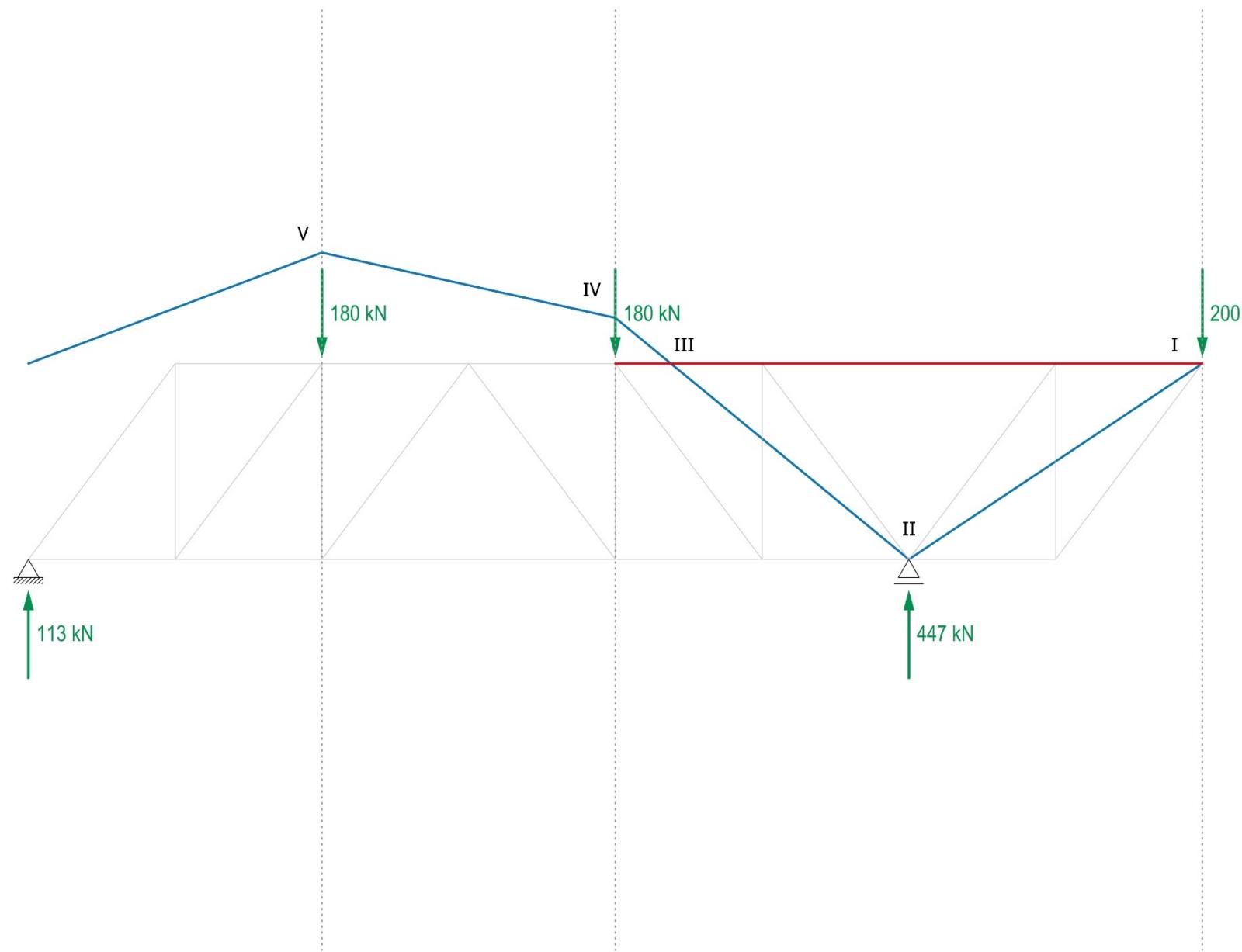
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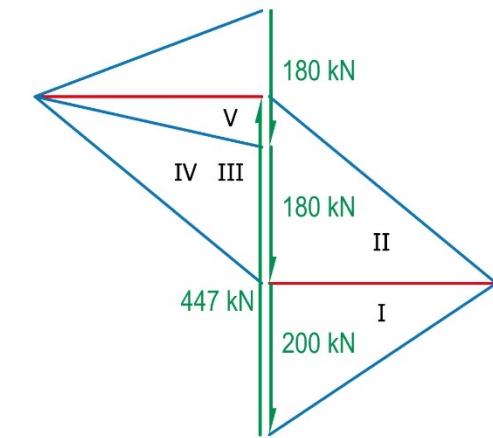
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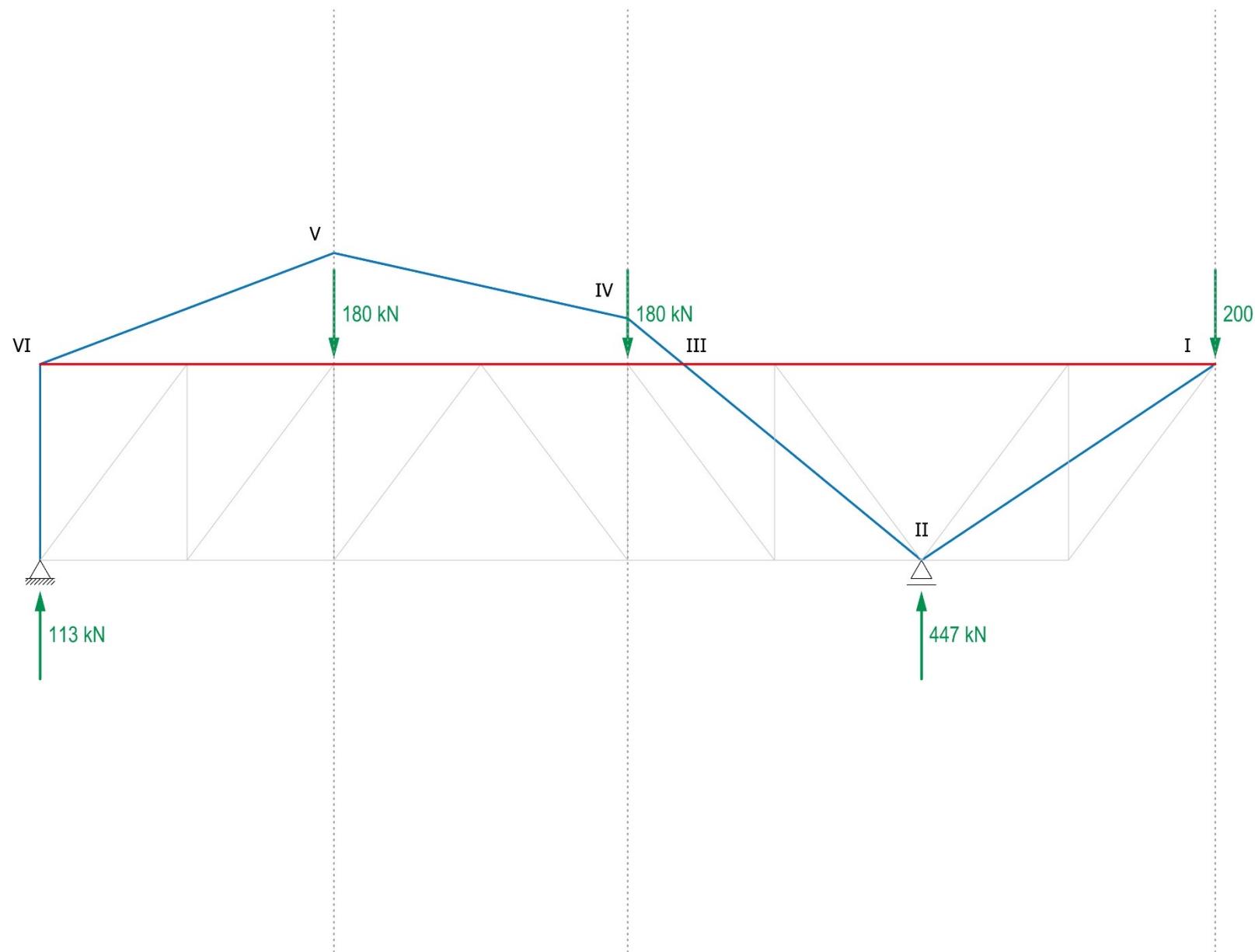
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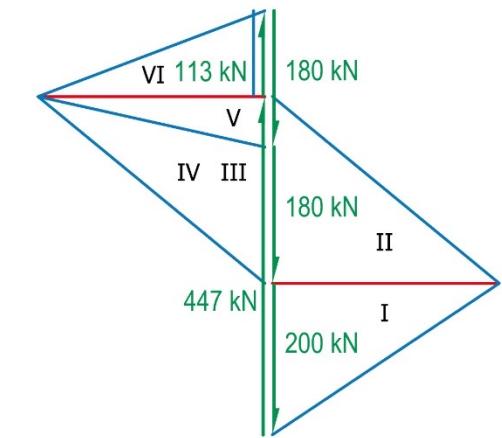
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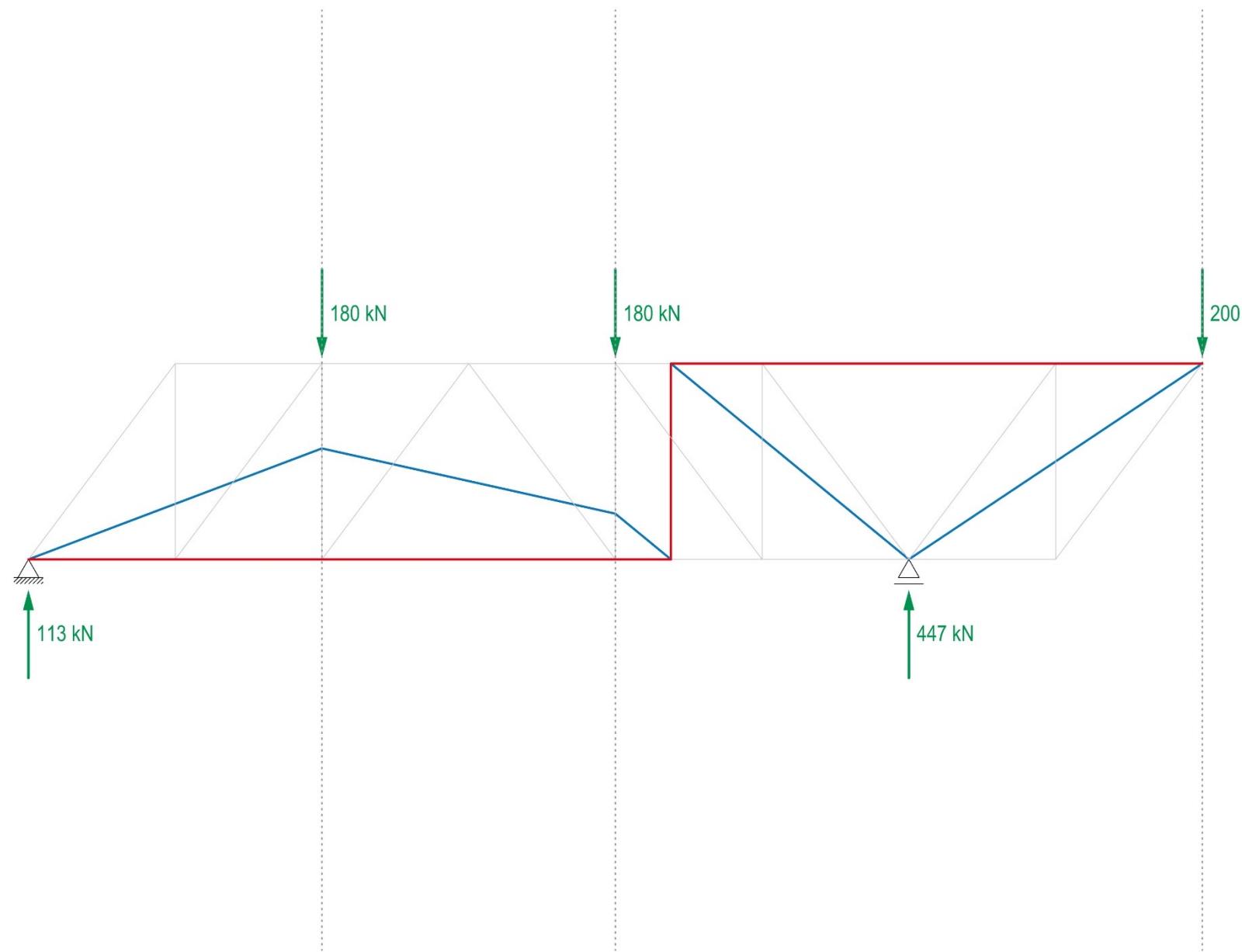
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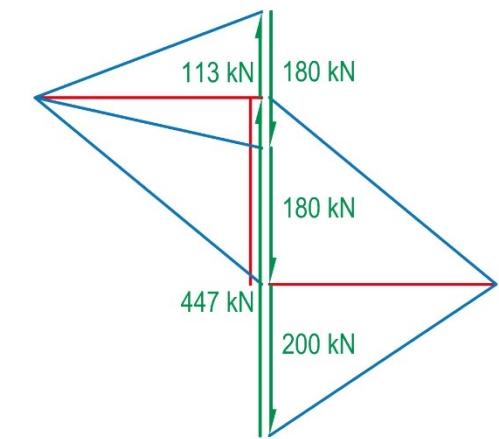
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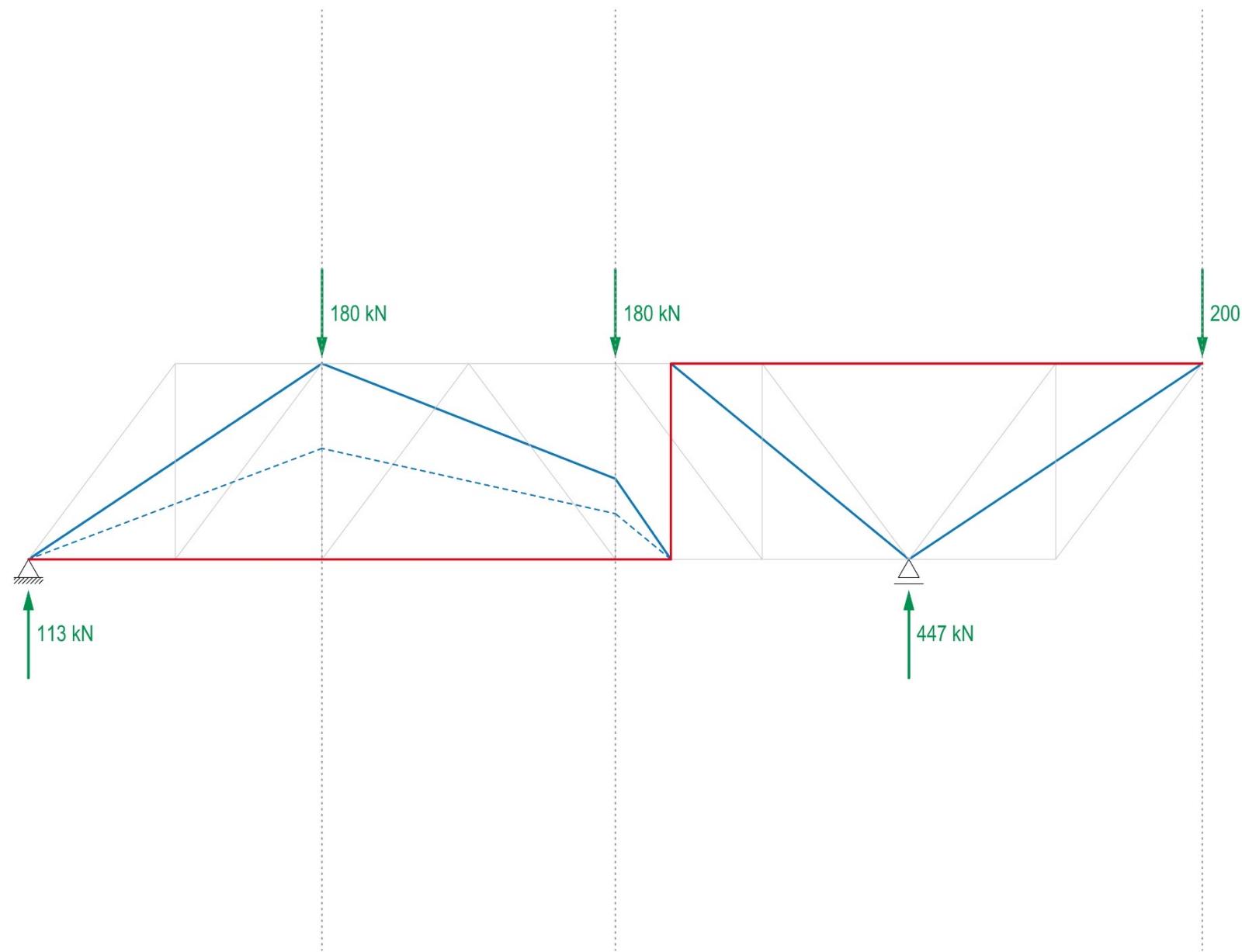
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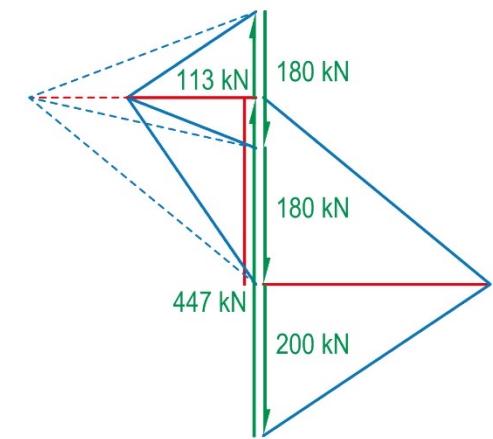
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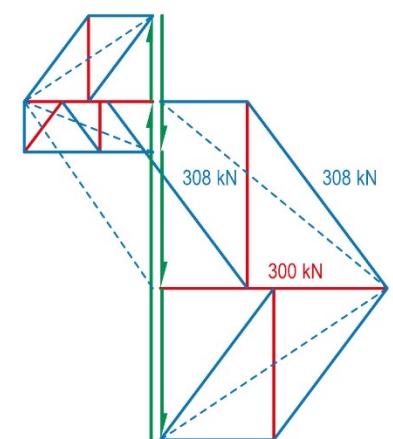
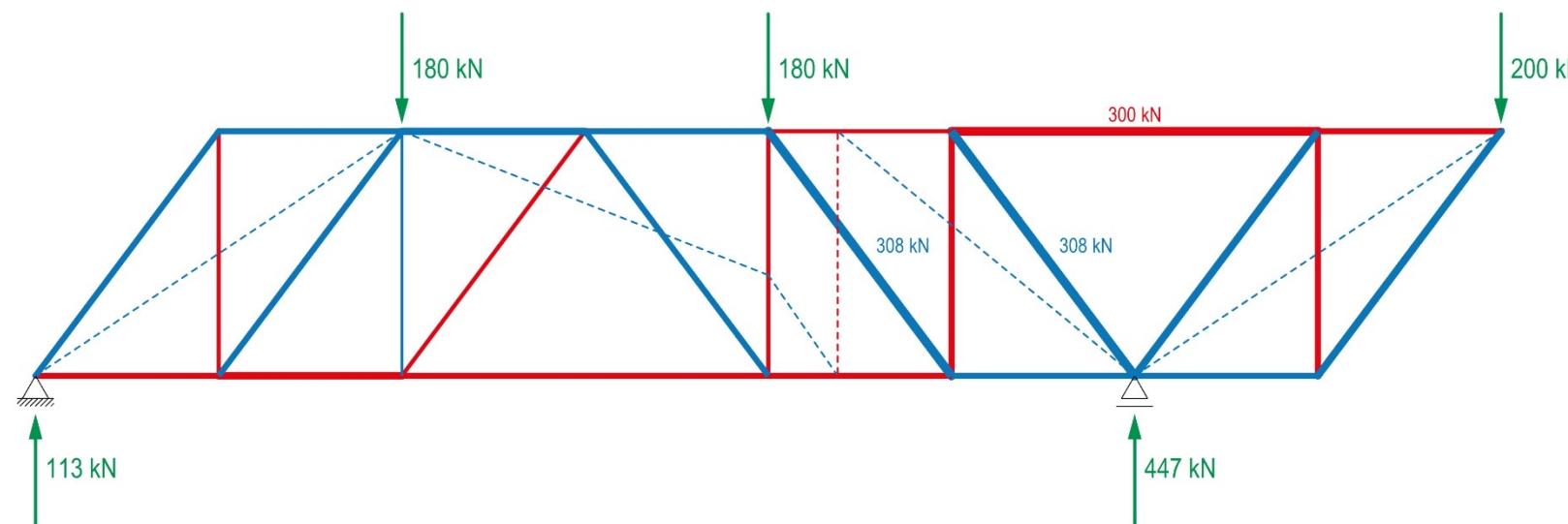
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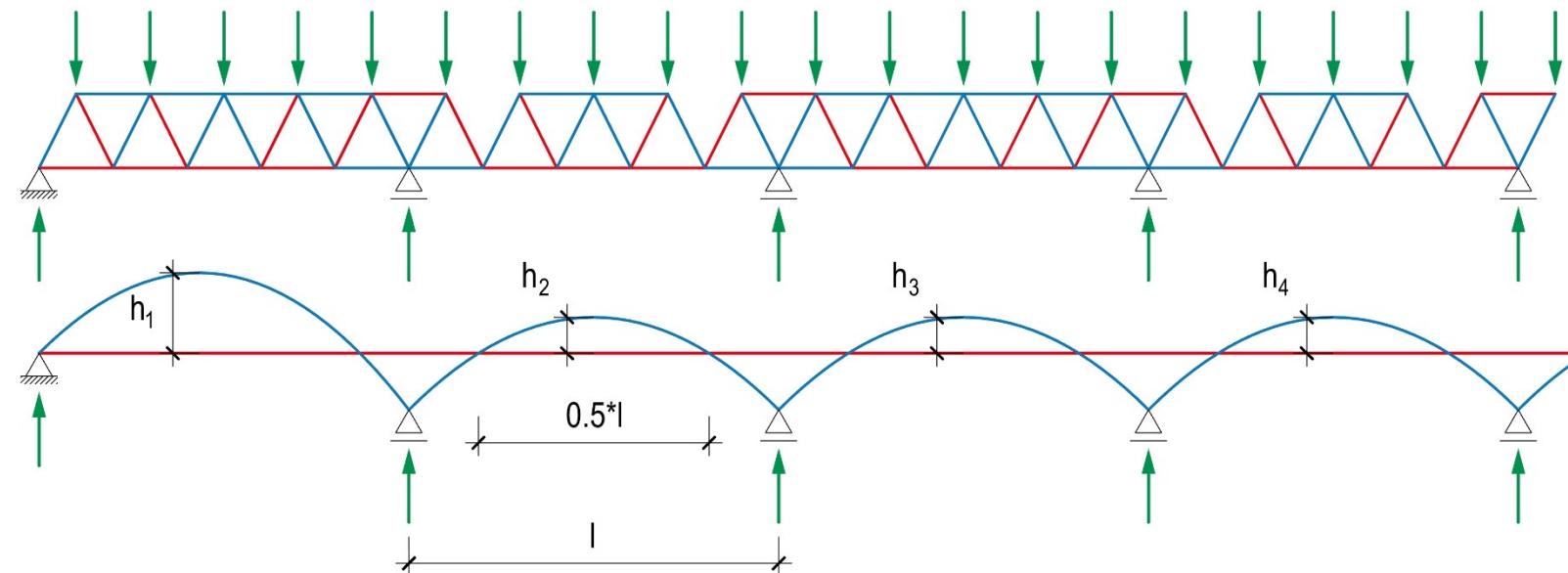
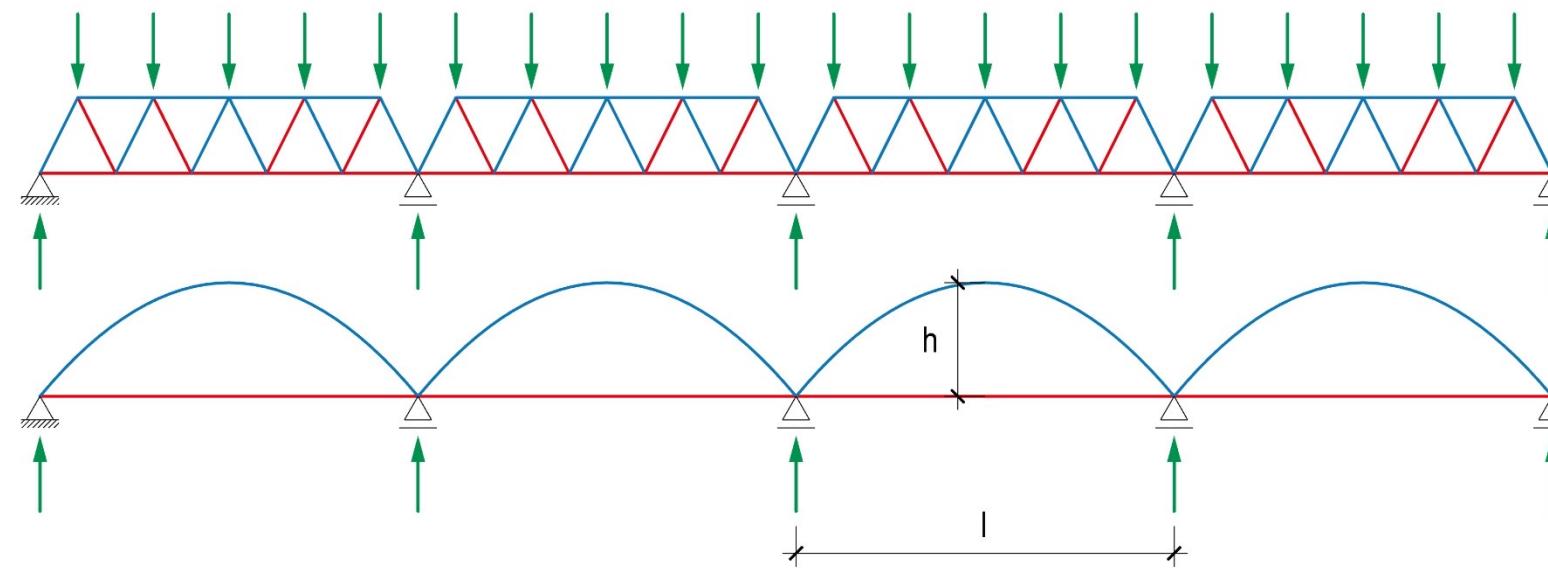


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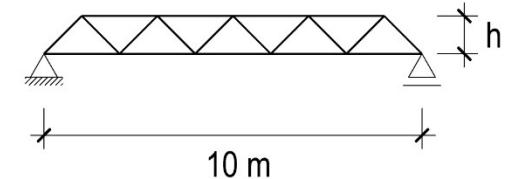
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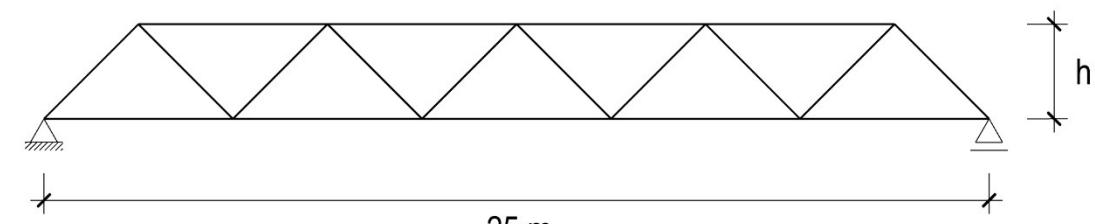
Material	Tragwerk	wirtschaftliche Schlankheit $l/h$ für einfache Balken *
Stahl	Vierendeelträger	7 - 10
	Fachwerkträger	10 - 15
	Raumfachwerk	12 - 18
	Balken	15 - 20
Stahlbeton	Balken	12 - 18
	Platten	20 - 25
Spannbeton	Balken	18 - 25
	Platten	28 - 35
Holz	Balken	15 - 20

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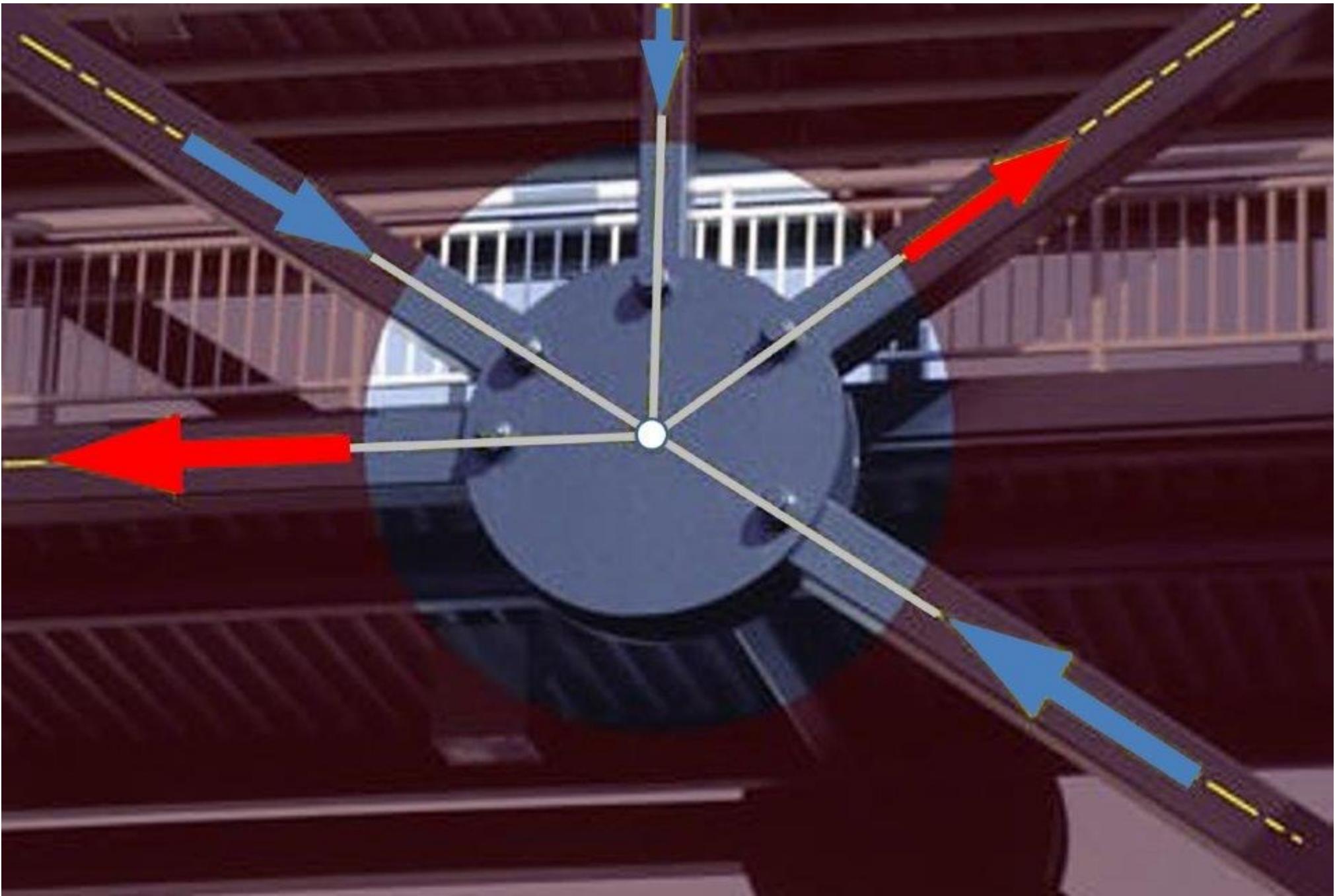
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Gustav Eiffel, Theophile Seyring: Maria Pia Brücke, Porto, 1877



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



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

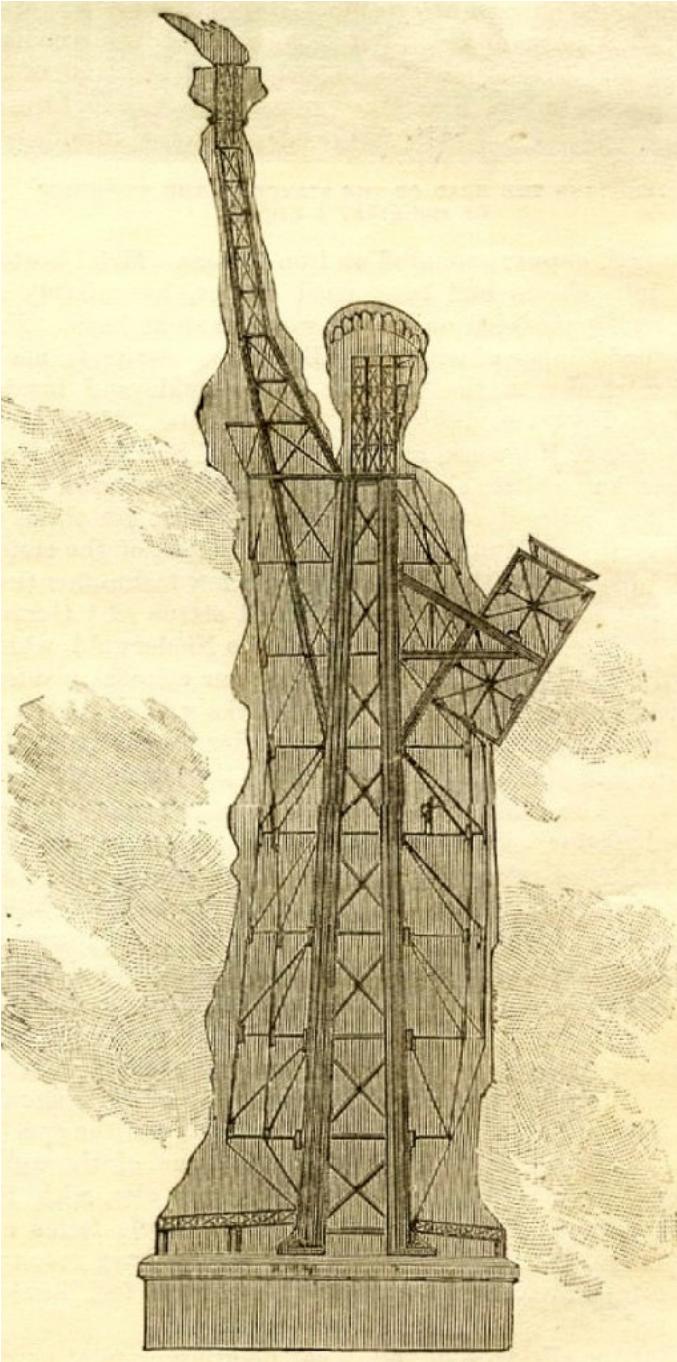
*Construction of trusses*



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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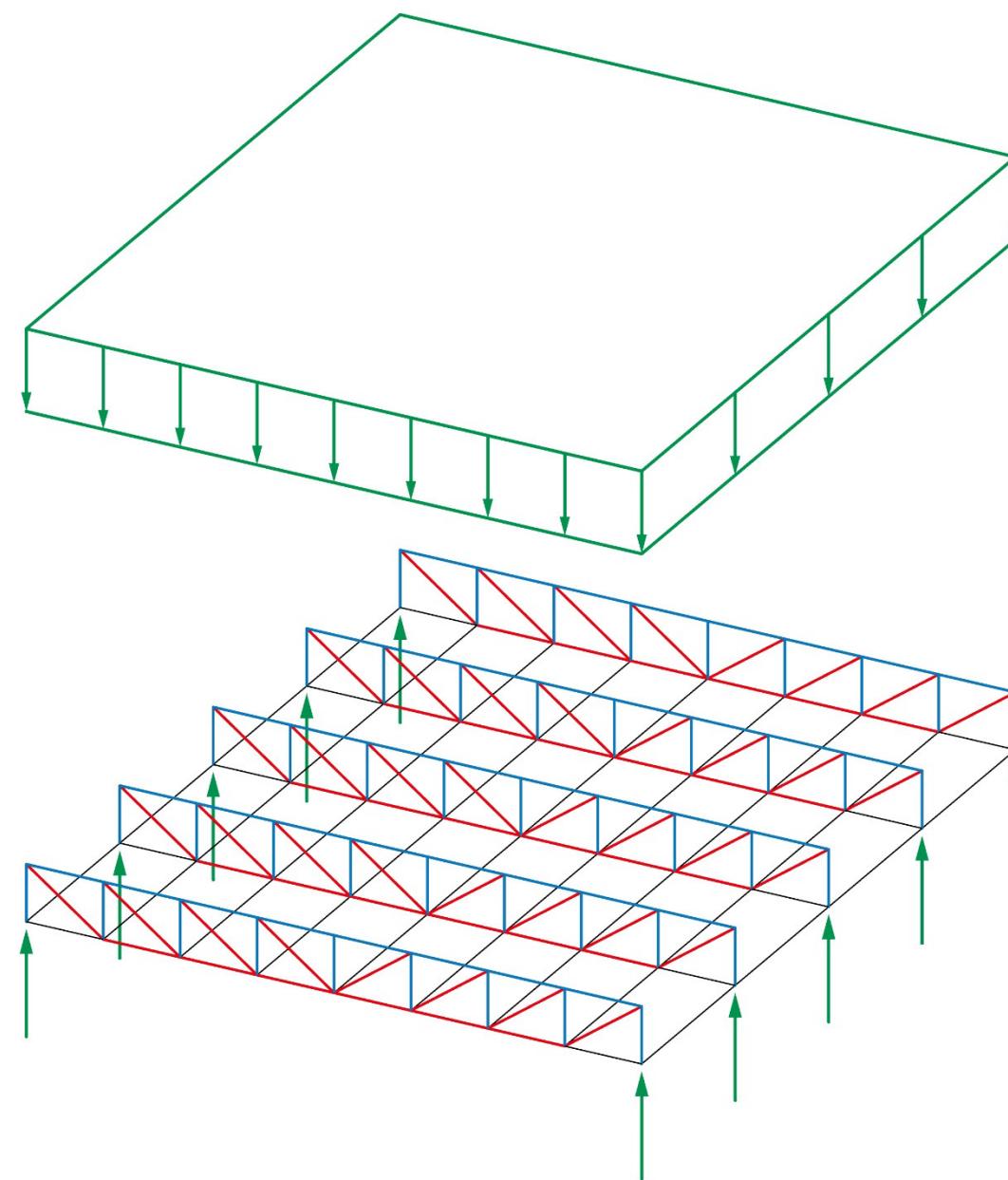
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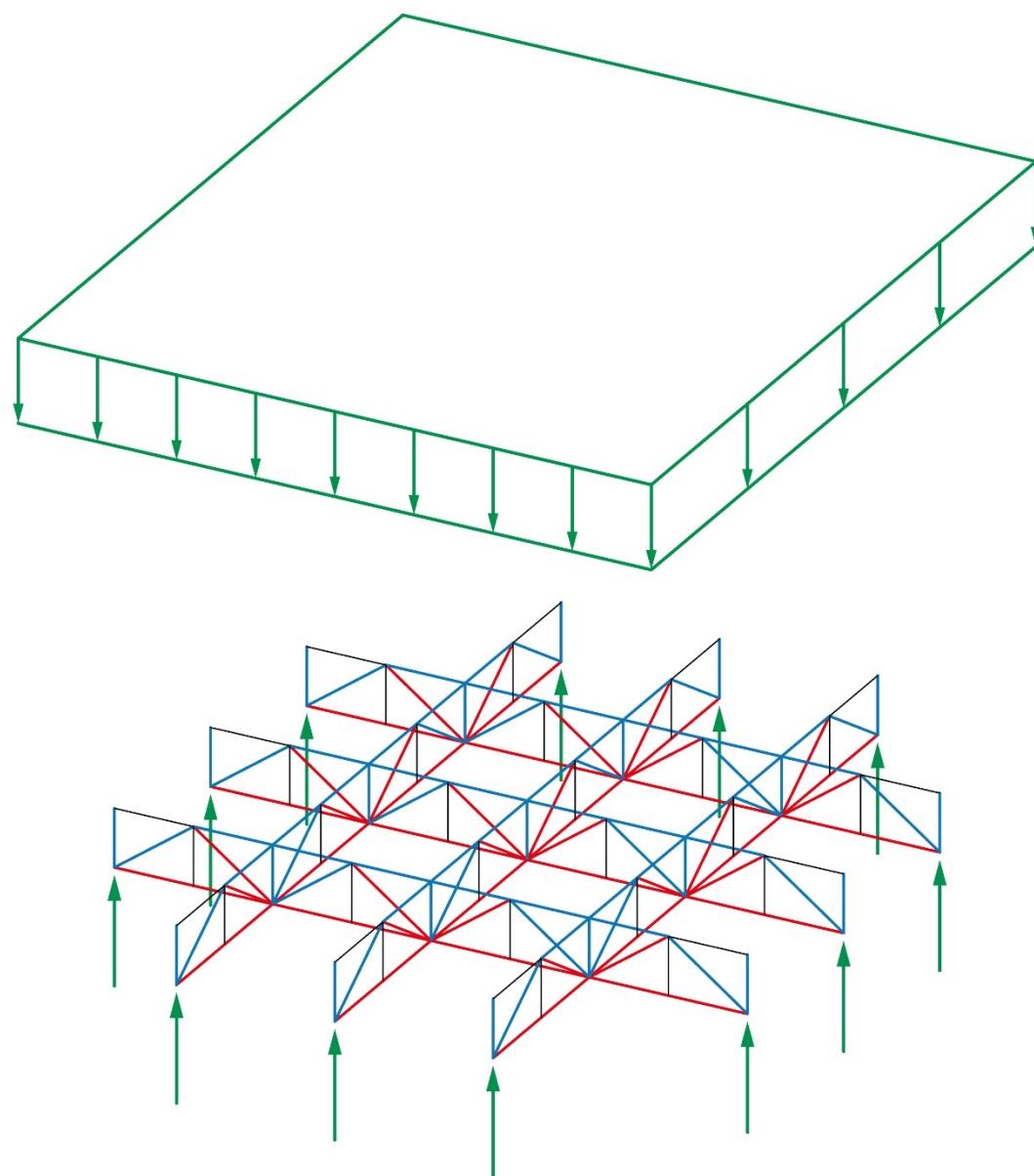
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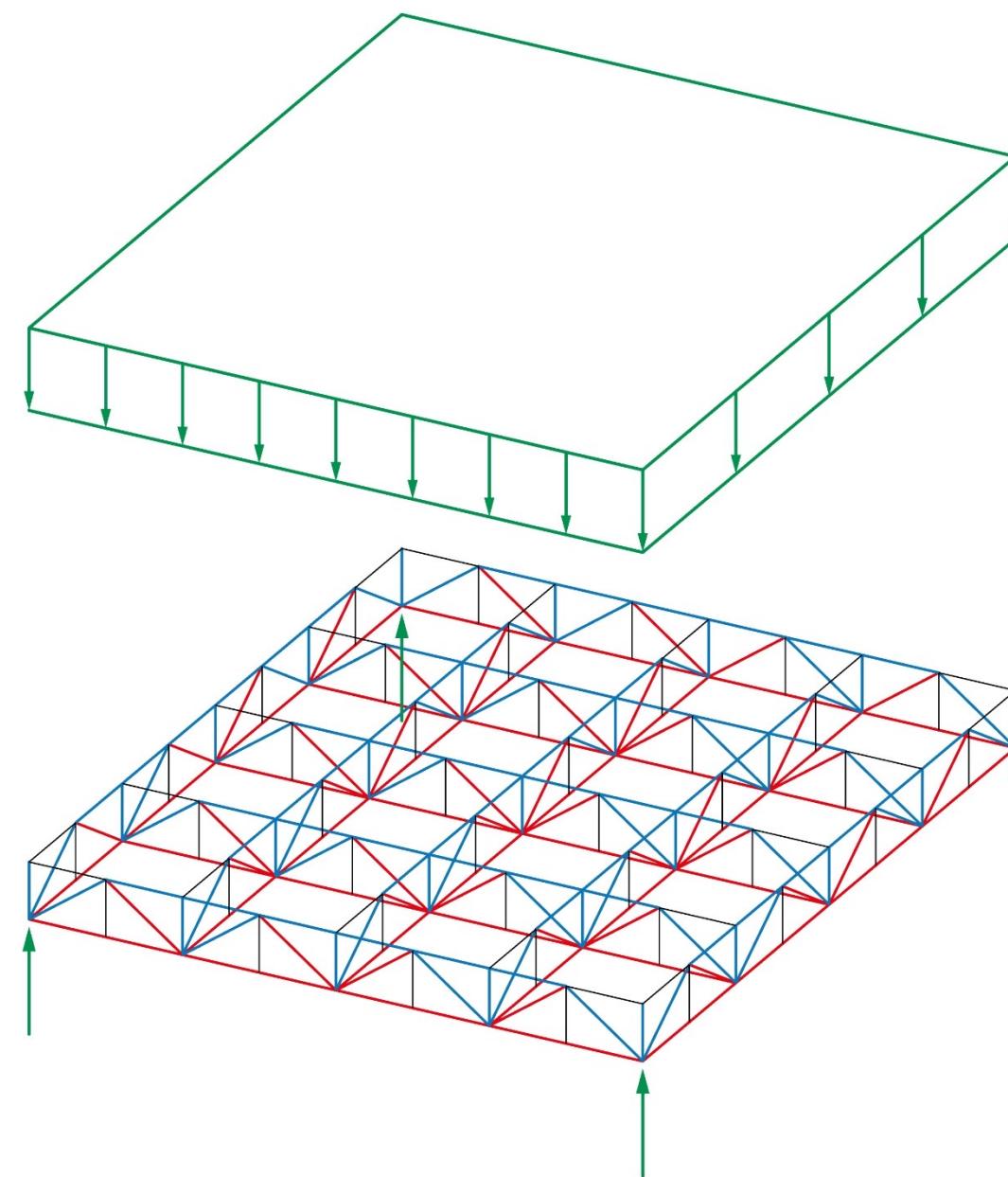
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*Spatial trusses*





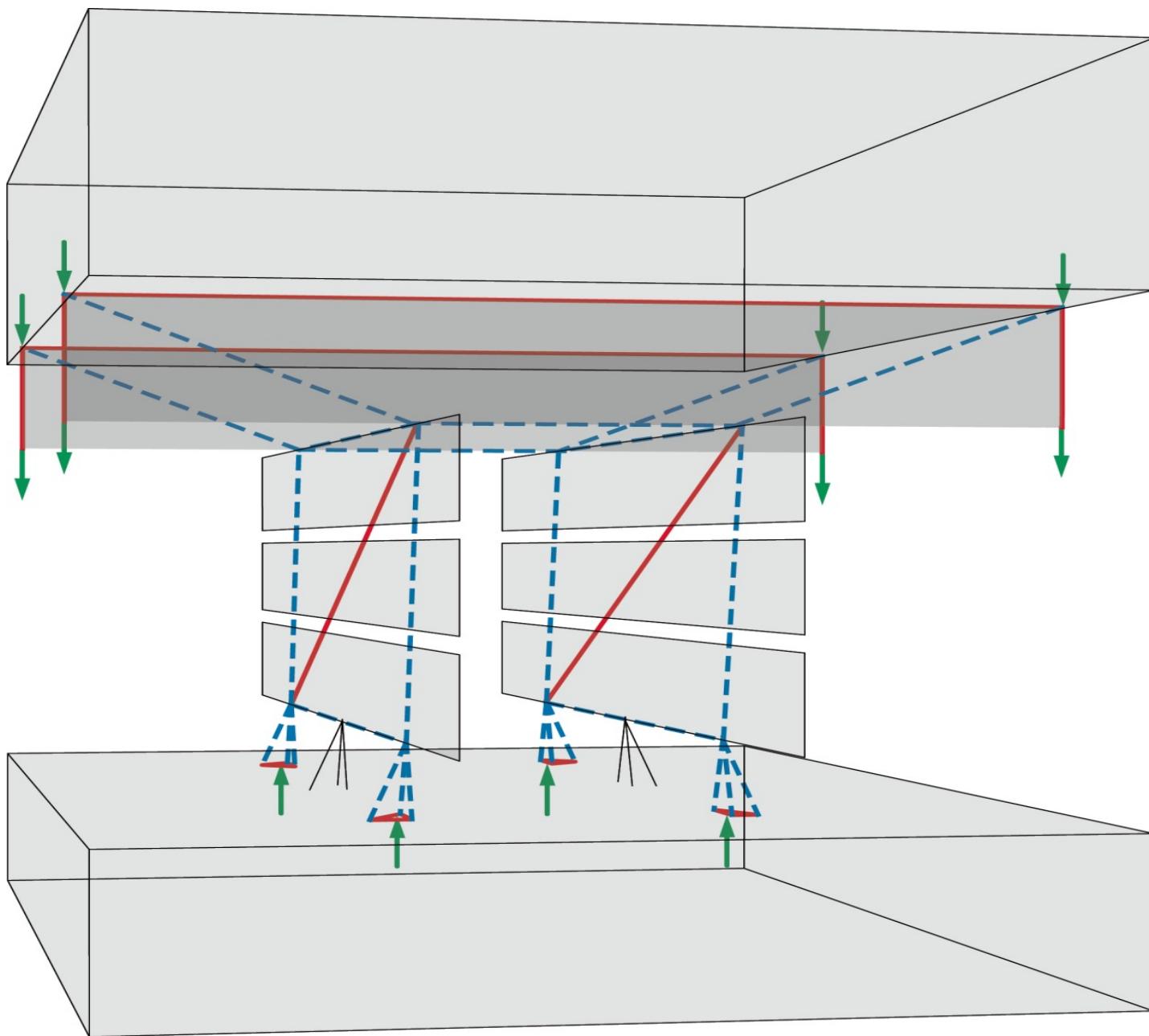




Bruno und Fritz Haller, Emch & Berger: USM-Fabrik, Münsingen, 1964



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



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



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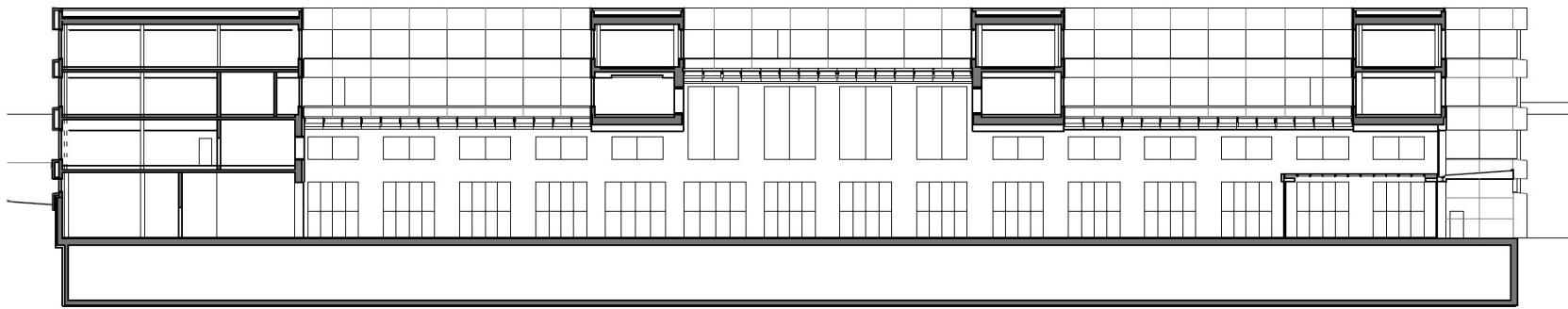
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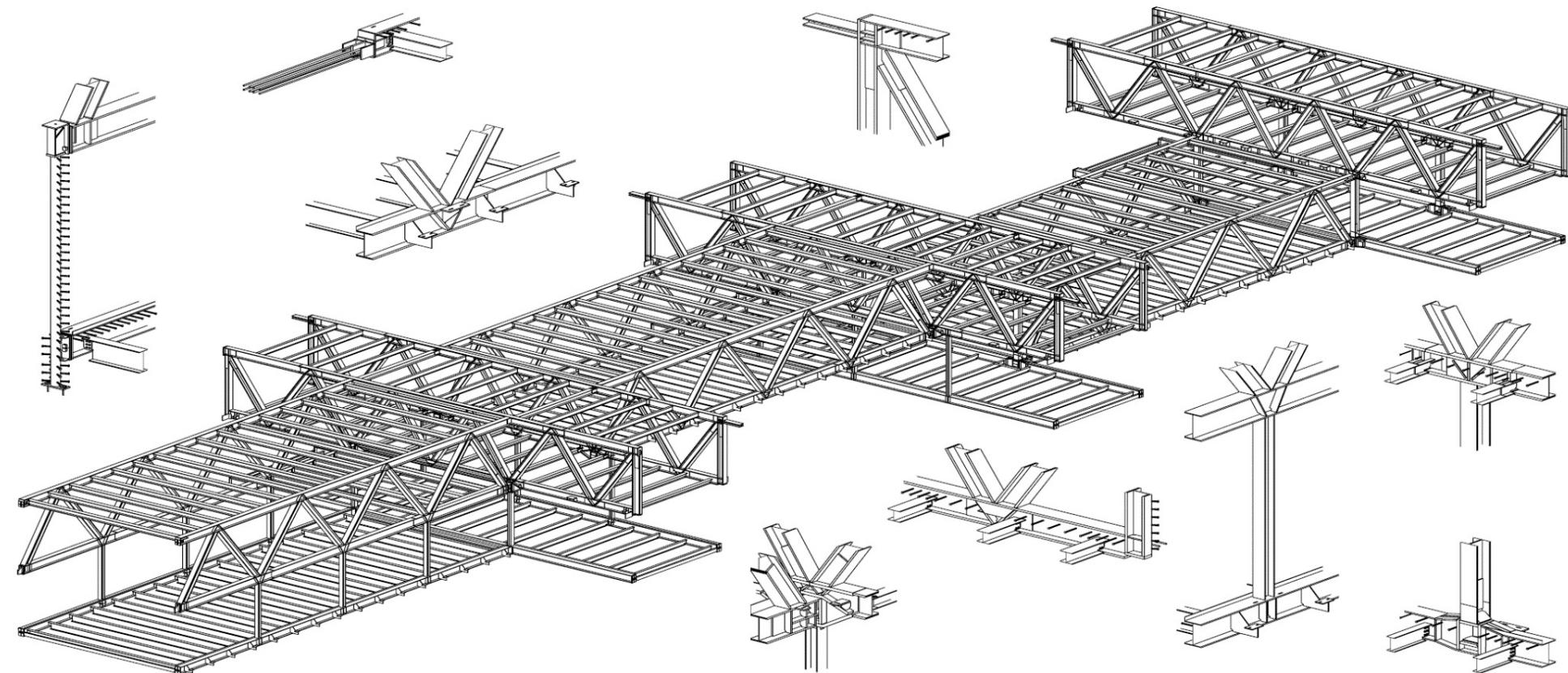
L. Giuliani & C. Hönger, J. Schwartz: Innovationszentrum Hilti Schaan, 2014



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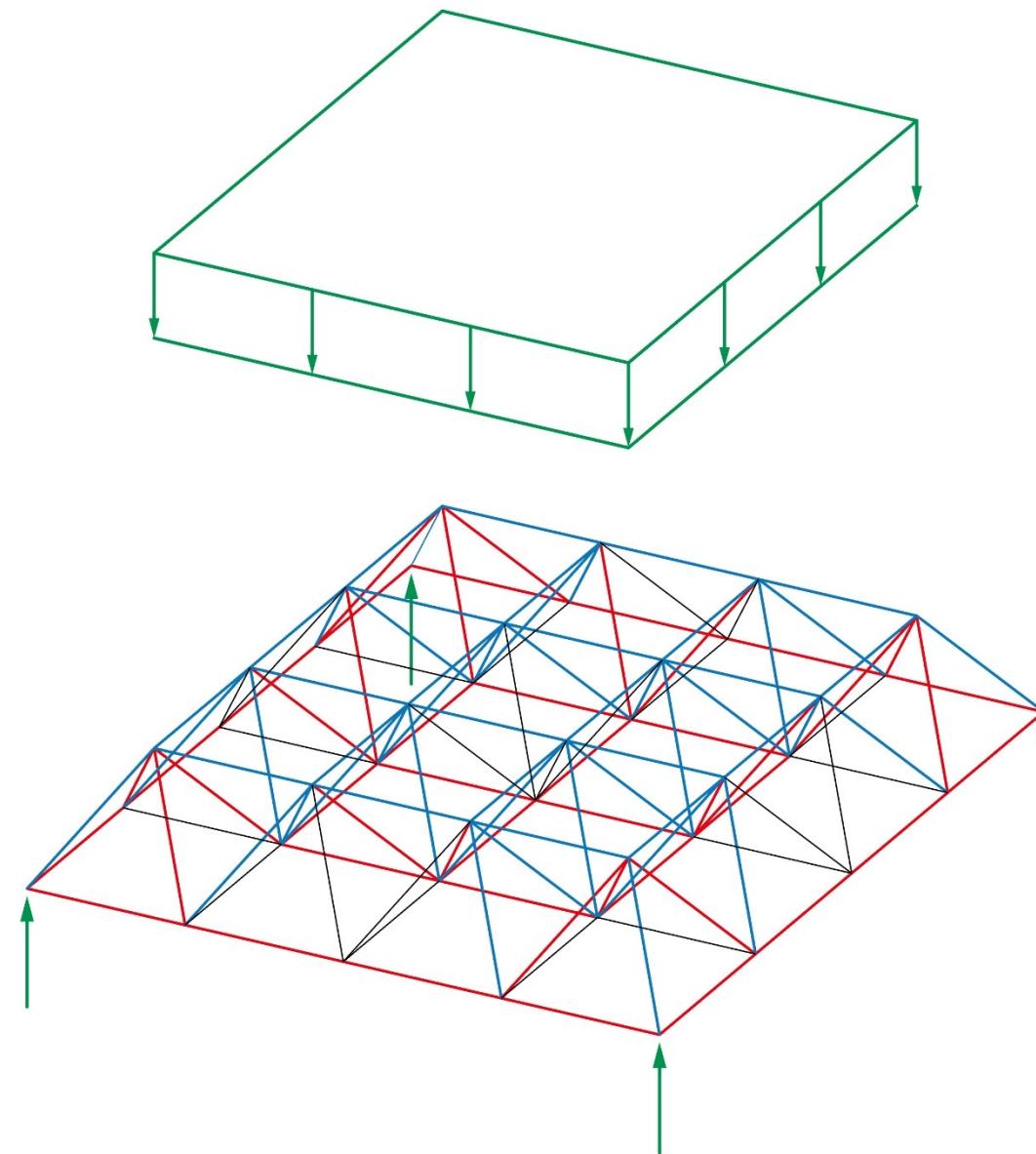
L. Giuliani & C. Hönger, J. Schwartz: Innovationszentrum Hilti Schaan, 2014

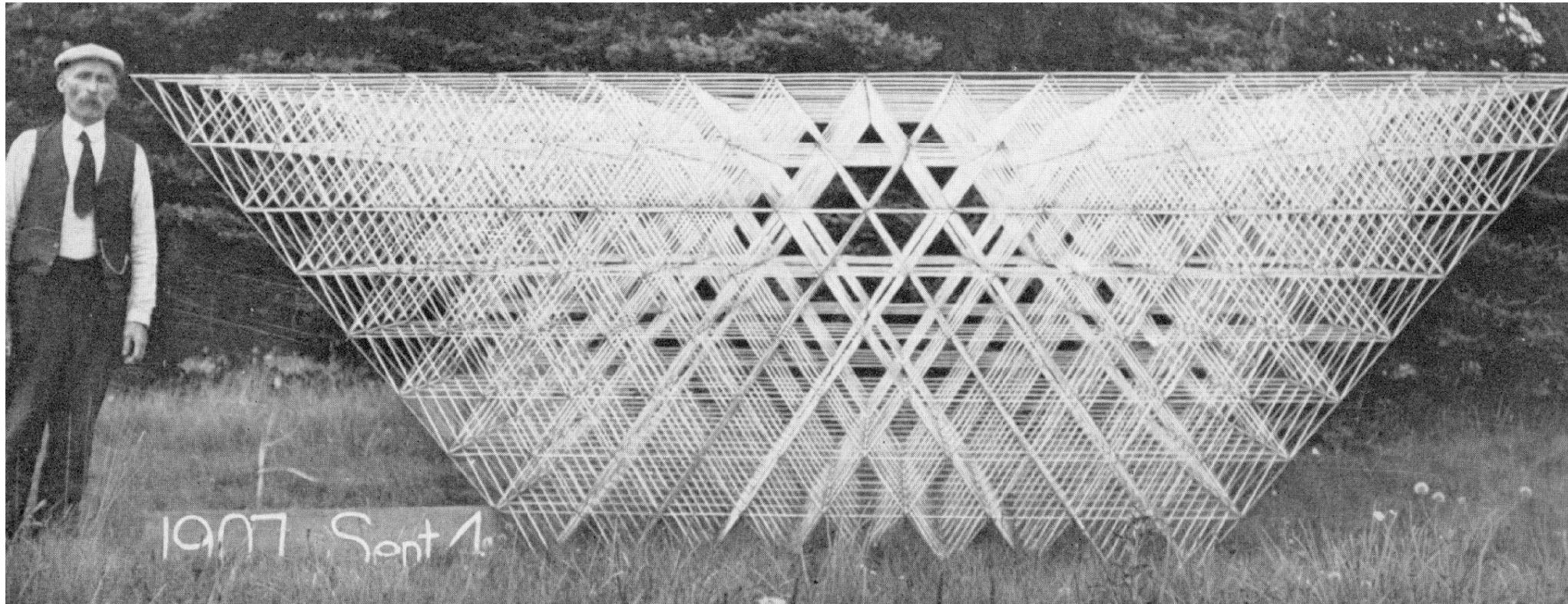


L. Giuliani & C. Hönger, J. Schwartz: Innovationszentrum Hilti Schaan, 2014

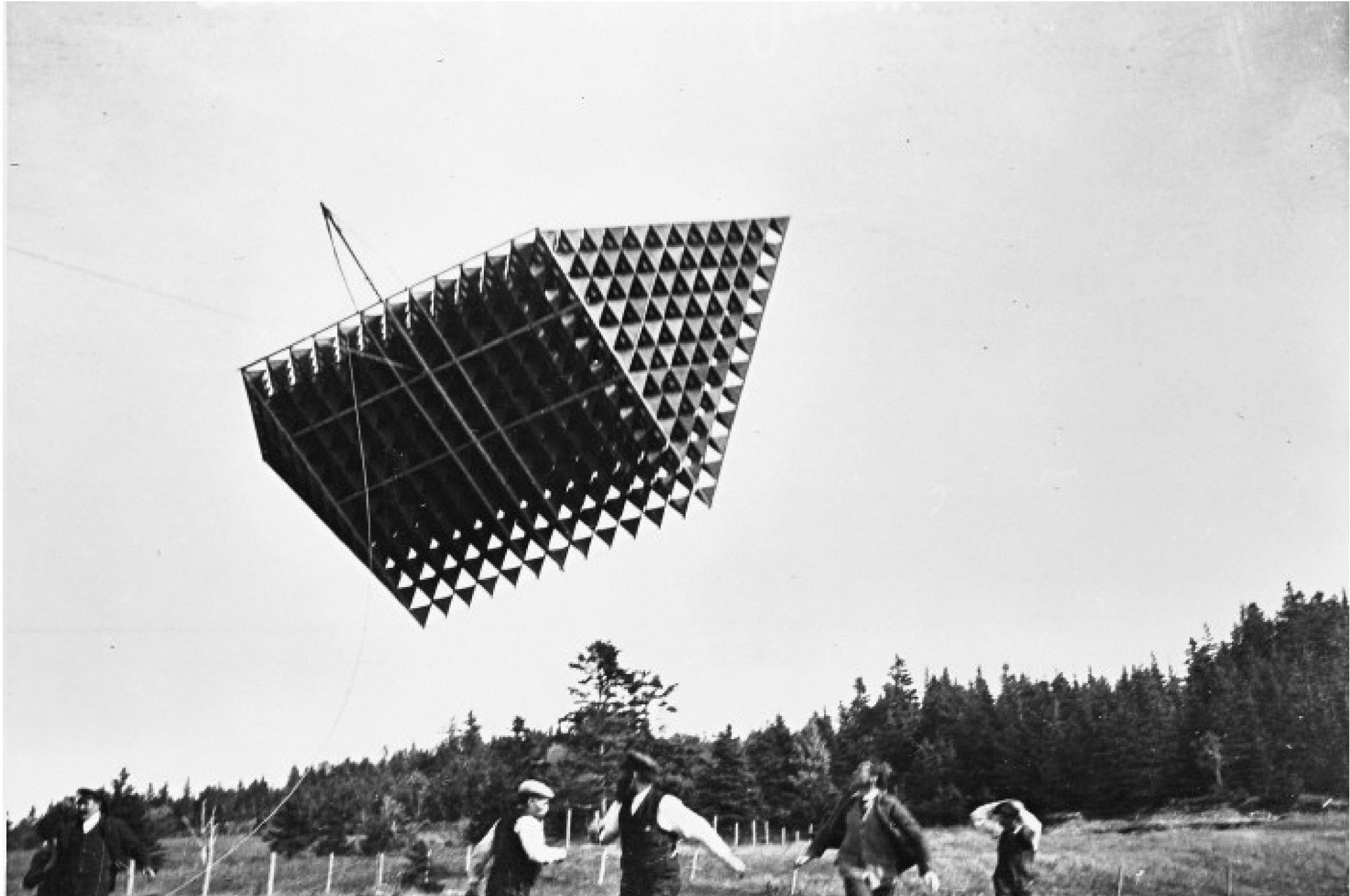


L. Giuliani & C. Hönger, J. Schwartz: Innovationszentrum Hilti Schaan, 2014

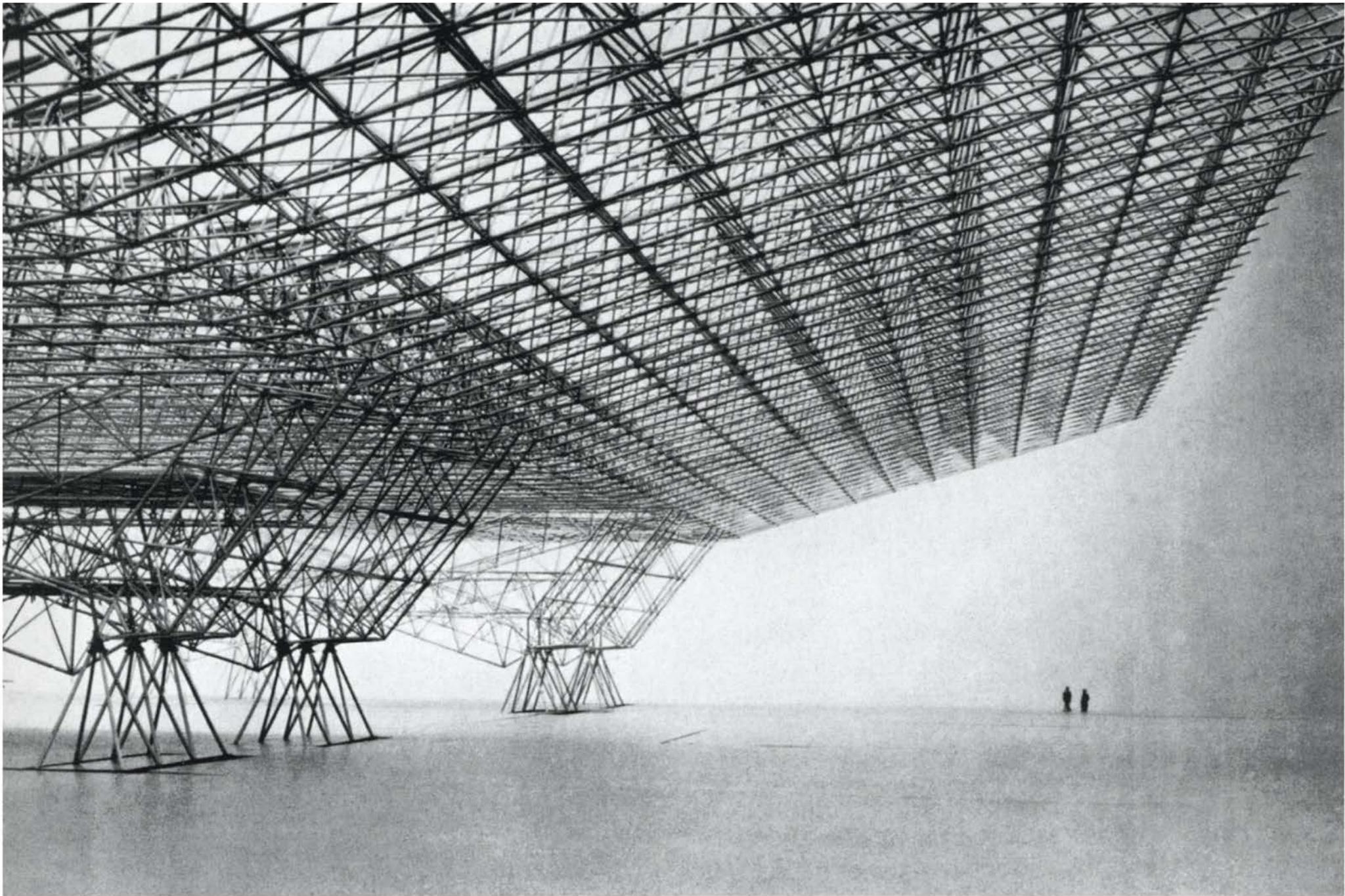




Alexander Graham Bell: Verbunddrachen als Raumfachwerk aus vorfabrizierten Tetraedern, 1907



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



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