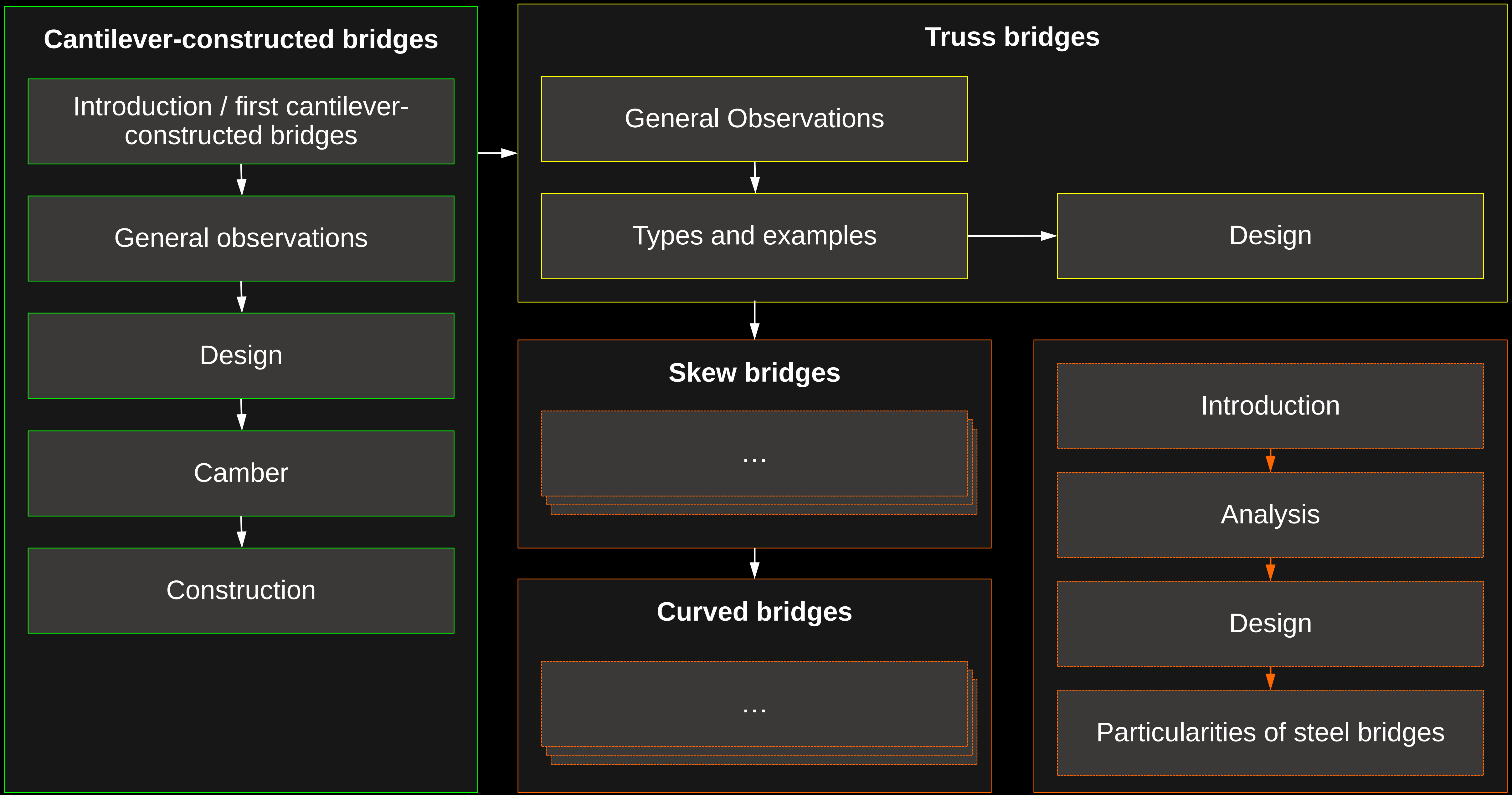
Special girder bridges

Truss bridges


Cantilever-constructed bridges
Introduction / first cantilever-constructed bridges
General observations
Design
Camber
Construction
Truss bridges
General Observations
Types and examples
Design
Skew bridges
…
Curved bridges
…
Introduction
Analysis
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Particularities of steel bridges

Special girder bridges

Truss bridges

General observations

Truss bridges – General observations

Advantages and drawbacks of truss bridges

Truss bridges are structurally very efficient: The top and bottom chords, connected by truss members rather than a solid web, provide

- high bending stiffness and strength at
- low self-weight

Trusses are in fact close to a pure stringer cross-section (see superstructure / structural efficiency).

For these reasons, truss bridges found widespread application in the 19th and early 20th century, when steel was expensive and scarce, and minimising material consumption was therefore a main concern of bridge designers.

Truss bridges – General observations

Advantages and drawbacks of truss bridges

However, the joints connecting the truss members, which may be

- welded (common in Europe),
- bolted (common in US), or
- riveted (common in historic bridges)

need to be carefully designed and detailed, and require a significant amount of labour.

Hence, truss bridges may be economical today merely for larger spans, where the corresponding cost is compensated by savings due to the structural efficiency. Even for long spans, however, other bridge types (e.g. cable stayed bridges) are often less expensive today.

This is the main reason why few truss bridges were built in the last decades.

Truss bridges – General observations

Advantages and drawbacks of truss bridges

Another reason why few modern truss bridges were built is their appearance. Trusses are

- transparent, yet often only in frontal view, but
- require more depth than other girder types (see design)
- may appear old-fashioned, particularly trusses with bolted connections (gusset plates) and through trusses

Example: Few people would bet that the Milton Bridge (photo) was built only in 2015, even if the bridge ends, with vertical end posts, differ from typical solutions used historically.

This solution was chosen here since the bridge replaced an existing through truss bridge with shorter span.

Truss bridges – General observations

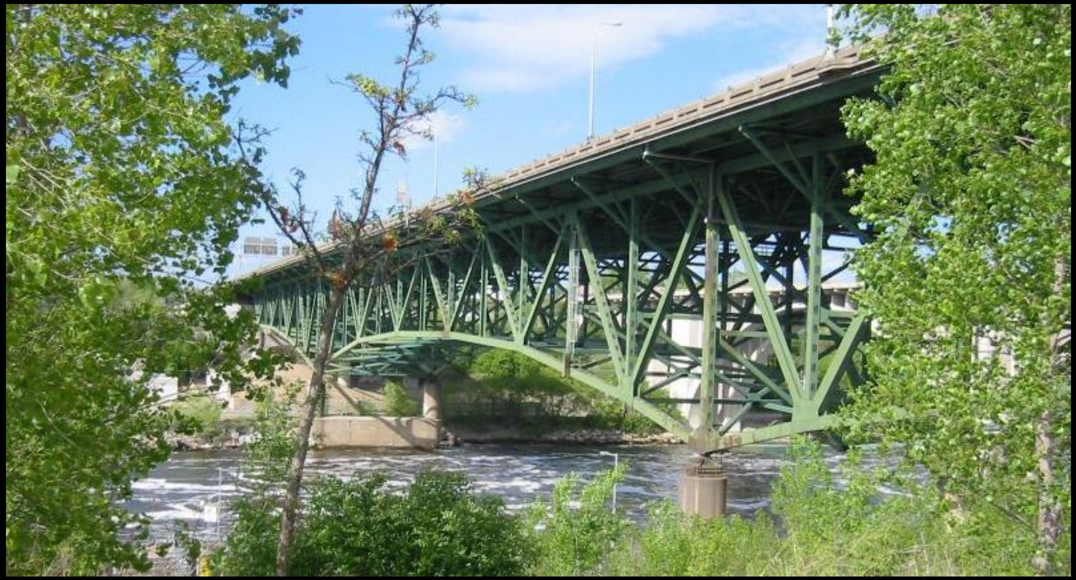
Advantages and drawbacks of truss bridges

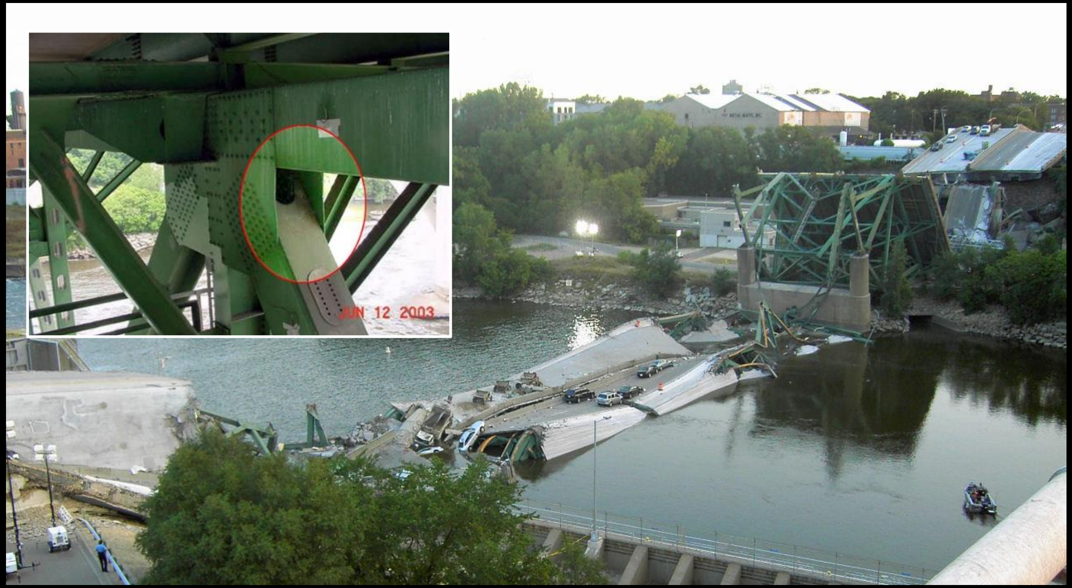
Further disadvantages of truss bridges, limiting their use in modern bridge design, are:

- High maintenance demand due to large exposed surfaces, particularly in through and pony trusses not protected by the deck
- Typically trusses are isostatic, such that all individual members are “fracture critical”: Failure of one member will lead to a global collapse.

The photos show the I35-W Mississippi bridge, which collapsed in 2007 during resurfacing works. Presumably, failure of undersized gusset plates triggered the collapse (construction equipment and up to 5 cm concrete/pavement added since original construction caused high loads).

Note that redundancy can be achieved by providing extra trusses running in parallel, such that one truss may fail without causing global collapse. However, this causes high extra cost.





Special girder bridges

Truss bridges

Types and examples

Truss bridges – Types and examples

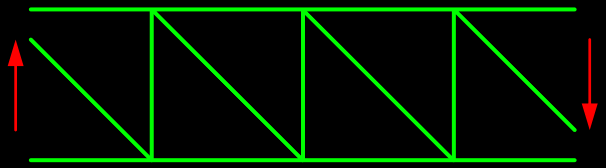
Types of trusses

Trusses can be classified according to the configuration of the (main) truss members.

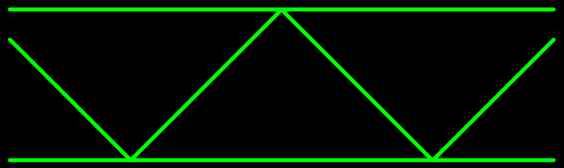
This slide compiles the most important truss layouts. Note that some designations are subject to regional preferences.

In some cases, secondary members are introduced to reduce buckling lengths of compression members and/or reduce the span of the chord carrying the deck (see also next slide).

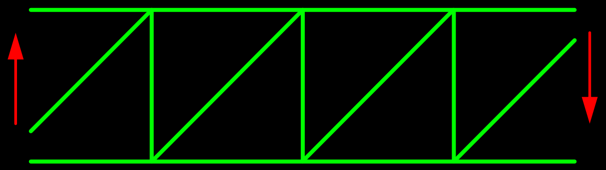
Pratt truss / Ständerfachwerk (Zugdiag.)



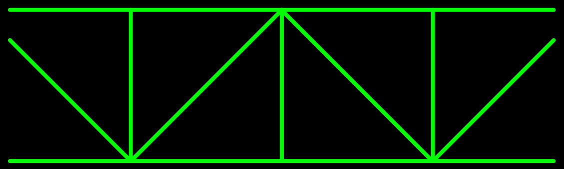
Warren truss / (ständerloses) Strebenfachwerk



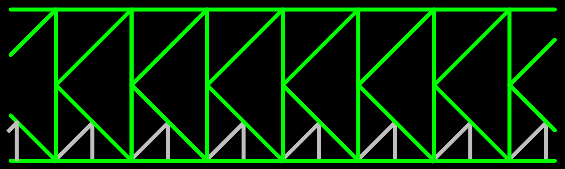
Howe truss / Ständerfachwerk (Druckdiag.)



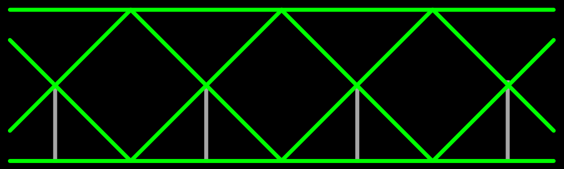
Modified Warren truss / Strebenfachwerk



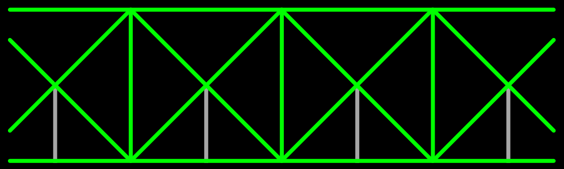
K-truss / K-Fachwerk



Brown (Diamond) truss / Rhombenfachwerk



Long truss / Kreuzfachwerk



[Illustrations adapted from

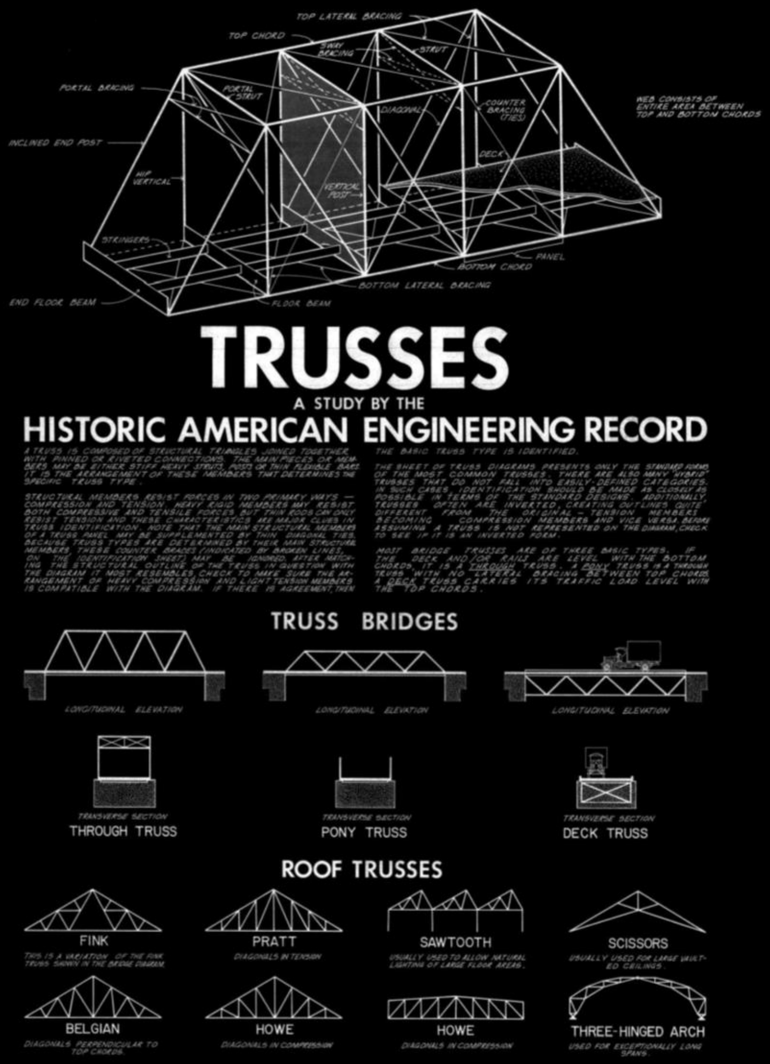
P. Marti, Theory of Structures, Section 11.3: Trusses]

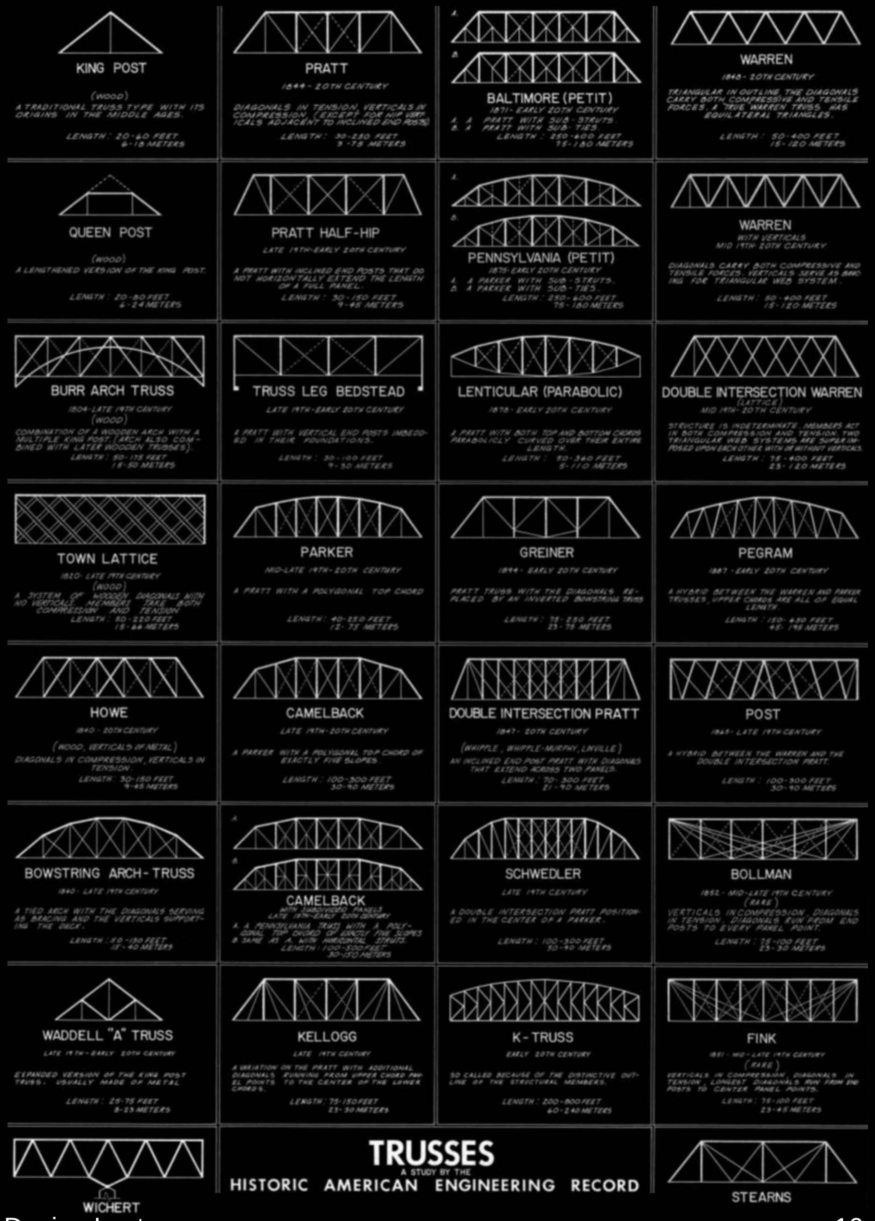
Truss bridges – Types and examples

Types of trusses

More examples of truss types and designations, used mainly in the U.S.

(nomenclature merely of historical interest)





Truss bridges – Types and examples

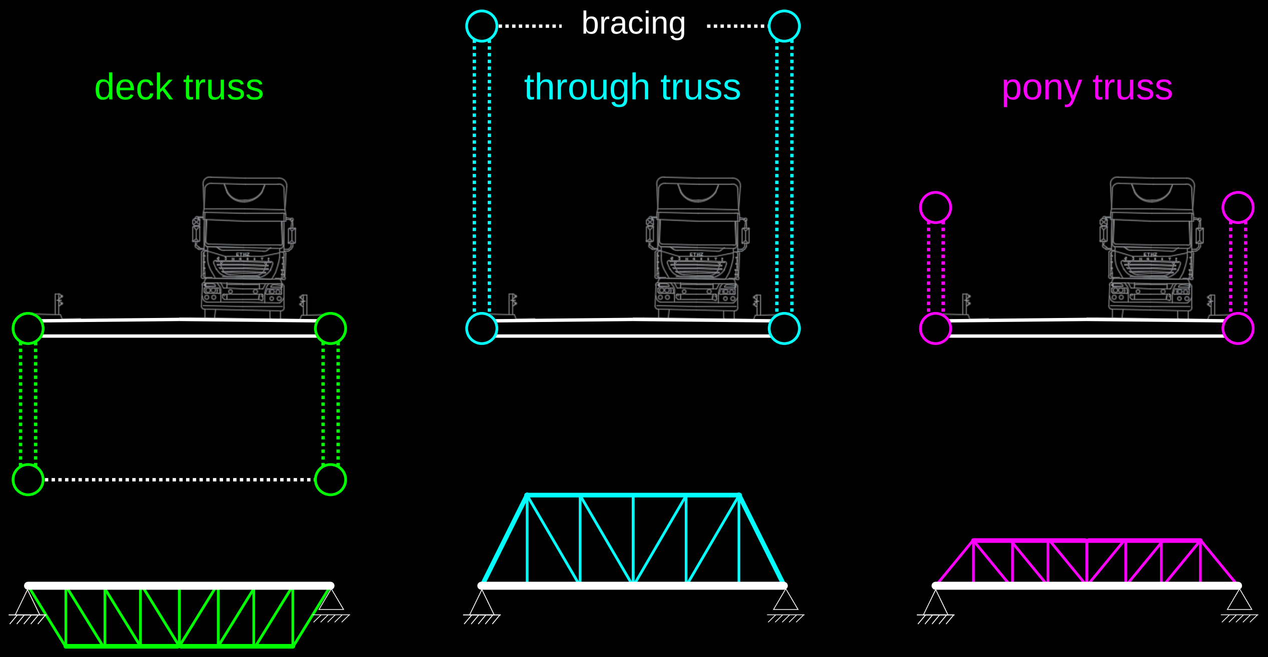
Types of truss bridges

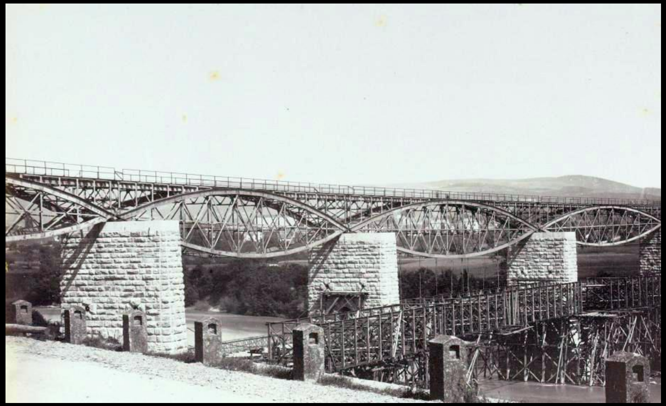
Truss bridges are usually girder bridges. Apart from the truss type, they can be classified according to the arrangement of top and bottom chords respective to the deck:

- Deck truss bridge: Truss(es) below the deck
- Through truss bridge: Trusses running along deck sides, bottom chords at deck level, connection of top chords above deck
- Pony truss bridge: As through truss, but with reduced height and hence, without top chord connection

Many truss bridges have parallel chords, i.e. a constant depth (“Parallelträger”), though end posts are often inclined (“Trapezträger”).

Variable depth trusses are often structurally more efficient, but their production is more demanding (varying joint geometries).

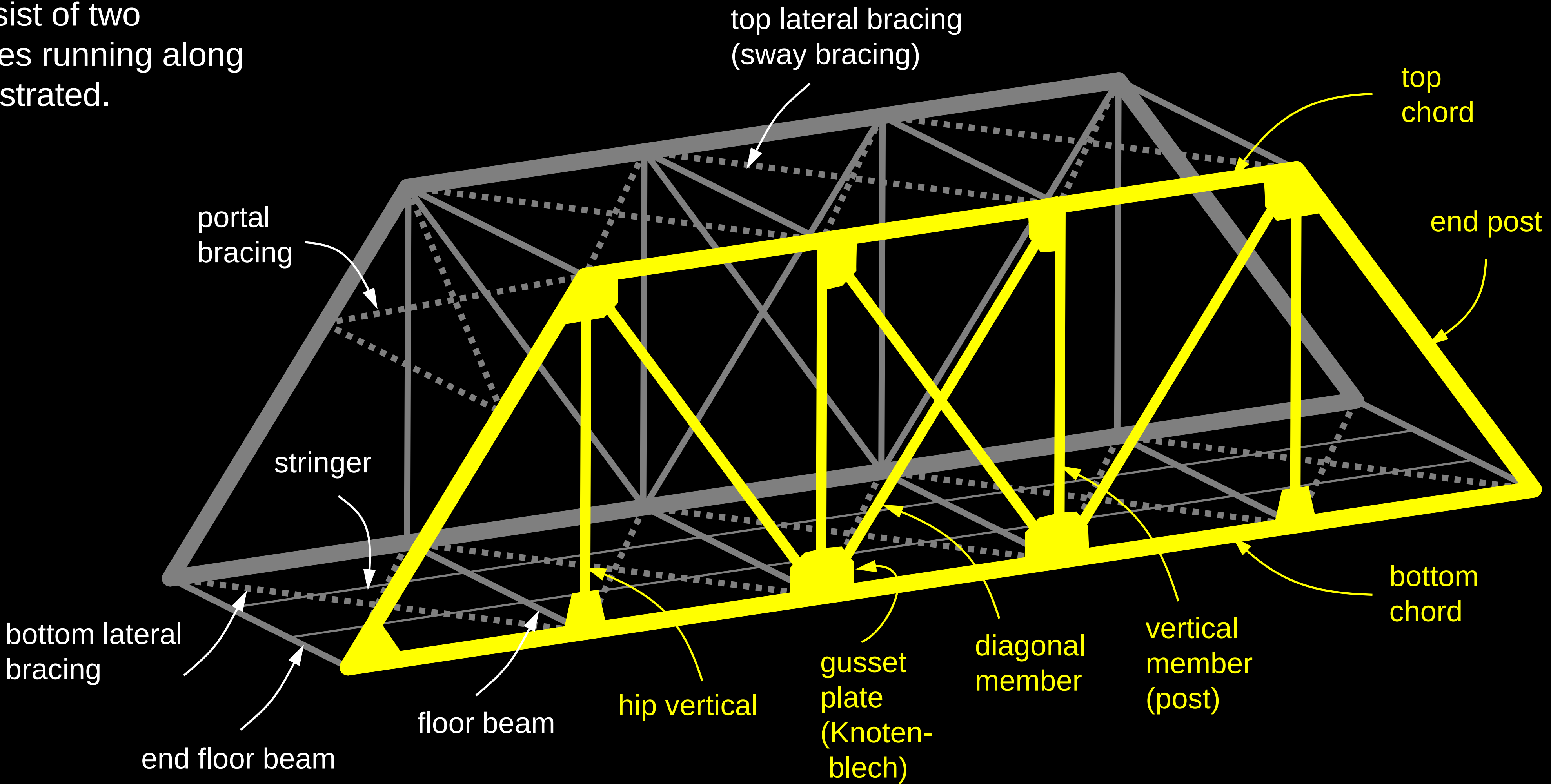




Truss bridges – Types and examples

Truss bridge components (nomenclature)

Many truss bridges consist of two longitudinal, plane trusses running along the bridge edges, as illustrated.



Truss bridges – Types and examples

Truss bridge examples

On this and the following slides, typical examples of parallel chord trusses and variable depth trusses are shown.

Common truss types with parallel chords:

- Pratt truss / Ständerfachwerk (mit Zugdiagonalen):
  Reduced buckling length of compression members (Rheinbrücke Eglisau, 1897)

- Howe truss / Ständerfachwerk (mit Druckdiagonalen):
  Used mainly for timber trusses due to simpler vertical tension members (Cascadia Park Bridge, 1928).

  Note: As usual in timber bridges, many Howe trusses are covered. The system is often combined with additional, diagonals (X-bracing with double compression diagonals, single tension diagonals and vertical tension posts).

Truss bridges – Types and examples

Truss bridge examples

Common truss types with parallel chords (continued):

- Warren truss / ständerloses Strebenfachwerk: Simple, clean geometry, unpretentious appearance, low weight, equal member length if triangles are equilateral (Itztalbrücke, 2005).

- K-truss: Reduced buckling length of bracing members (Speers railroad bridge, 1931).

Truss bridges – Types and examples

Truss bridge examples

Common truss types with parallel chords (continued):

- Long truss / Kreuzfachwerk: Crossed diagonals and vertical posts (Saaneviadukt Gümmenen, 1901).

- Brown truss / Rhombenfachwerk: Crossed diagonals without vertical posts (Saaneviadukt Gümmenen, 2021).

  Note: The replacement of the Saaneviadukt Gümmenen is remarkable, as the truss panel length is varied along with the shear forces – an innovative design based on a truss type patented in 1846.

Truss bridges – Types and examples

Truss bridge examples

Common variable depth truss types:

- Parker truss / (Halb-)Parabelträger: Variable depth truss, one chord aligned with deck
  (top: Lake Oswego Bridge, Oregon, 1910, Parker Truss;
  bottom: SOB Sitterviadukt, St. Gallen, 1910, inverted Parker Truss)

  Parker trusses are strictly speaking only those having a Pratt bracing. In the U.S., depending on the layout, many different names exist, such as «Pennsylvania» or «Petit» (Parker provided with sub-struts or ties) and “Camelback» (Parker where top chord has exactly five different inclinations). See behind for more examples.

  In German, Parker trusses are sometimes also referred to as “Schwedlerträger” (although Schwedler’s original design, intending to avoid compression in the diagonals, involved a downward kink in the top chord at midspan)

Truss bridges – Types and examples

Truss bridge examples

Common variable depth truss types:

- Lenticular truss / Paulitráger: Variable depth truss, both chords curved, typically Pratt or cross bracings (top: first SBB Aarebrücke Brugg, 1875; bottom: Royal Albert Bridge, 1859).

  Note that this layout is inefficient since neither of the chords is aligned with the deck. Few bridges were built for this reason.

Truss bridges – Types and examples

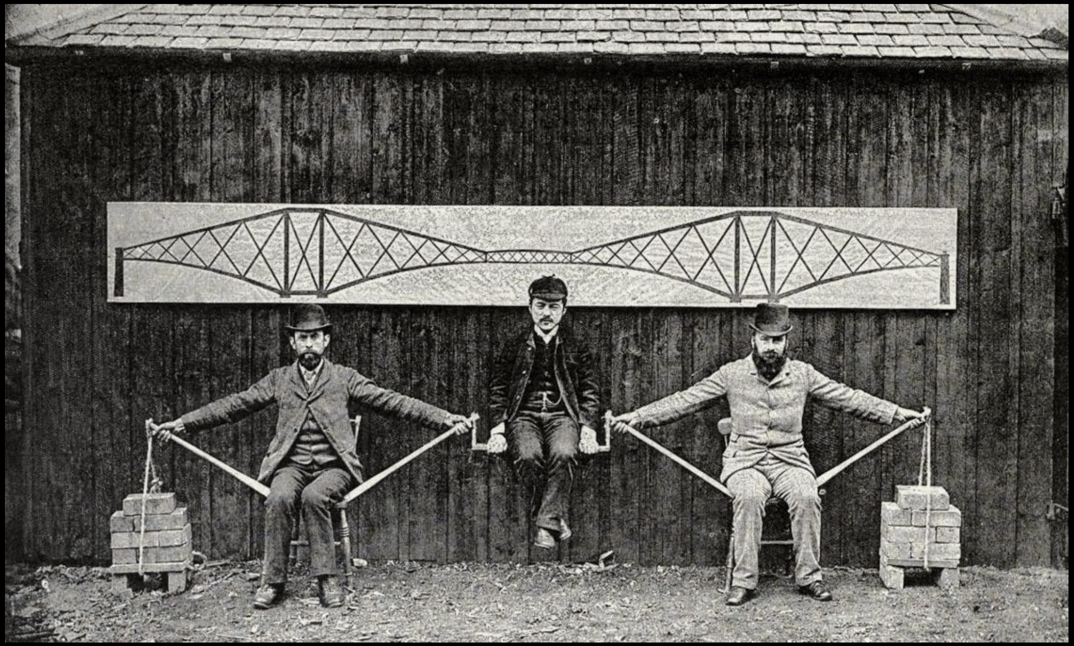
Truss bridge examples

Common variable depth truss types:

- Cantilever truss: Variable depth trusses, with maximum depth over piers to enable cantilever construction of the bridge.

  This typology is very useful particularly for crossing obstacles without temporary supports.

  Two cantilever truss bridges held the world span record (which is usually the domain of suspension bridges) from 1890-1929: The Forth Bridge, designed by John Fowler and Benjamin Baker (1890, span 520 m), shown on this slide, and the Québec Bridge (1918, span 549 m), see next slide.



Truss bridges – Types and examples

Truss bridge examples

Common variable depth truss types:

The Québec Bridge was rebuilt 1918, after having collapsed in construction 1907.

This was one of the most tragic bridge construction accidents in history, killing 75 workers. Although it was known before that the steel weight had been substantially underestimated in the design, construction had not been stopped in time.

In addition, the centre section of the reconstructed bridge fell when lifted first in 1916, killing another 13 workers.

Truss bridges – Types and examples

Truss bridge examples

Uncommon yet interesting truss types:

- Fink truss / Fink'scher Träger: Multiple overlapping diagonal members and vertical posts (puente de Fierro / Bolívar, 1882).

- Inverted Fink trusses have seen a revival for footbridges over the past years, due to their expressive character (Frank Gehry Bridge, 2015).

Truss bridges – Types and examples

Truss bridge examples

Uncommon yet interesting truss types (continued):

- Wichert truss: Isostatic truss with continuity at intermediate supports, thanks to a rhomboidal truss layout over the piers (Homestead Grays bridge, 1936).

  Note: Understanding the behaviour of Wichert trusses is not as intuitive as for other trusses – see e.g. D. Steinman, The Wichert Truss, 1932.

- The Wichert system has also been used for concrete girders in soft soil, with concrete hinges (Smithy Wood Footbridge, 1965).

Truss bridges – Types and examples

Truss bridge examples

Vierendeel “trusses” (no trusses, though sometimes the term is used: they would be unstable with pin-connected joints).

- Vierendeel girder: Frame made up of parallel chords and vertical posts, with rigid connections (transfer of bending moments), but no diagonal members (Gustav Heinemann Brücke 2005).

  Vierendeel girders are flexible since global shear forces contribute significantly to the deflections → structurally inefficient, even higher depth required than for “real” trusses Suitable primarily for short span and/or footbridges (bridge shown is provided with vibration absorbers).

- Vierendeel arch: Vierendeel girder with curved top chord. May also be interpreted as tied arch bridge with stiff hangers (Gellik Railway Bridge, 1934).
  Vierendeel arches are more efficient than Vierendeel girders, see Arch Bridges chapter.

Truss bridges – Types and examples

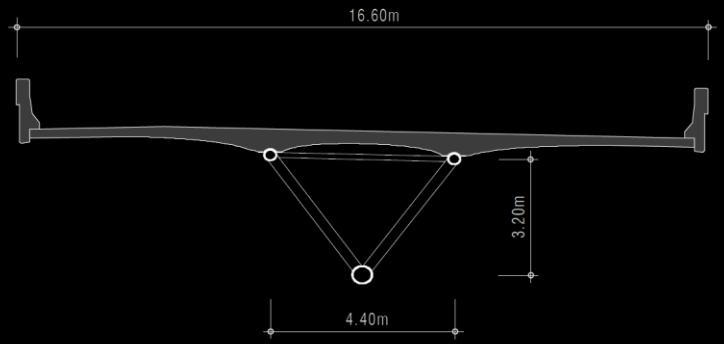
Truss bridge examples

Tubular steel trusses minimise many of the disadvantages mentioned in the previous section, and have seen a revival in the last years thanks to recent developments. Such trusses have several advantages:

- modern sleek appearance
- smaller exposed surface (compared to other trusses)
- high member inertia (slender compression members possible $\rightarrow$ higher transparency)

Swiss Engineer Hans-Gerhard Dauner (1937-2007, founder of DIC Ingénieurs at Aigle) was a pioneer in these developments.

(Note that tubular members were already used in the 19th century, e.g. Firth of Forth, but construction was highly complicated particularly for the joints).



Truss bridges – Types and examples

Truss bridge examples

The efficiency of tubular steel-concrete composite truss bridges can be further enhanced using concrete for both chords, combined with prestressing.

Mainly in France, several impressive bridges using this technology, with external prestressing tendons, were built in the 1990s.

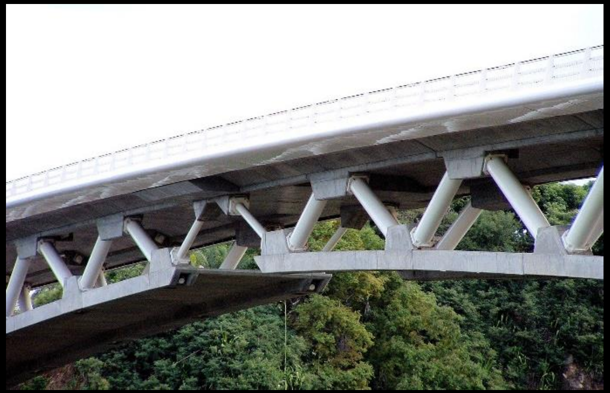
Note that proper corrosion protection of the external tendons is essential for the durability of such bridges (several of the bridges built in the 1990s had to be repaired after 30 years of service due to improper grouting of the tendons).

Truss bridges – Types and examples

Truss bridge examples

An impressive example of a tubular steel-concrete composite truss bridge is the Bras de la Plaine bridge on La Réunion island, which was built by free cantilevering in 2002 (281 m span).

No external prestressing is provided in this bridge, but the tension diagonals are post-tensioned (and the inclined bottom chord transfers a significant part of the vertical shear forces in compression).



Notes: Massive abutments (7’250 t weight each) are required as counterweights to guarantee the stability of the bridge. The missing continuity of the bottom chord at midspan emphasises the cantilever action, but is structurally inefficient (the original design even had a hinge in the deck).

Truss bridges – Types and examples

Truss bridge examples

Concrete trusses have also been used in bridges to save weight.

Using prefabricated ultra-high performance concrete elements, slender truss elements are possible.
(top photos: Viaduc de Glacières 1989). Nonetheless, achieving transparency is difficult.

Cast-in situ concrete trusses (with post-tensioned tension diagonals) tend to appear even heavier, making the choice of material difficult to justify: Why not use steel struts here?

Truss bridges – Types and examples

Truss bridge examples

An aesthetically convincing concrete truss bridge is the Ponte Mosteirô, by the eminent Portuguese engineer Edgar Cardoso (designer of the more famous Ponte da Arrabida).

Truss bridges – Types and examples

Other applications of trusses in bridges

Trussed members may also be used for other bridge types, such as in trussed arches (photo, see arch bridges).

Trusses are also common as bracings and diaphragms, and are used for piers and pylons / towers.

Such truss members are not treated in this chapter.

Special girder bridges

Truss bridges

Design

Truss bridges – Design

Particularities in Design – Shear deformations / slenderness

As mentioned, trusses are very efficient structural systems, since they closely match the optimum stringer cross-section to resist bending (see superstructure / structural efficiency).

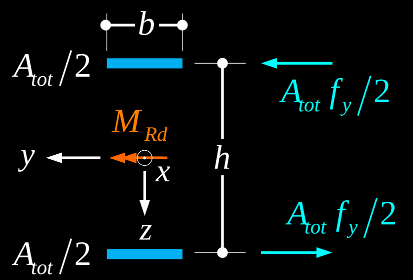
However, other than in girders with a solid web, shear deformations (caused by axial strains of the diagonals) are not negligible in trusses.

When modelling a truss as a beam without shear deformations (e.g. in preliminary design, to check the suitability of truss girders as alternative to beams in a spine or grillage model), the bending stiffness of the stringer section must be reduced accordingly (typically by about 30%).

Therefore, trusses require more depth than solid-web girders. For parallel chord trusses, the following slenderness ranges are common:

- simply supported truss girders: h/L ≈ 1/10…1/12
- continuous trusses: h/L ≈ 1/12…1/16

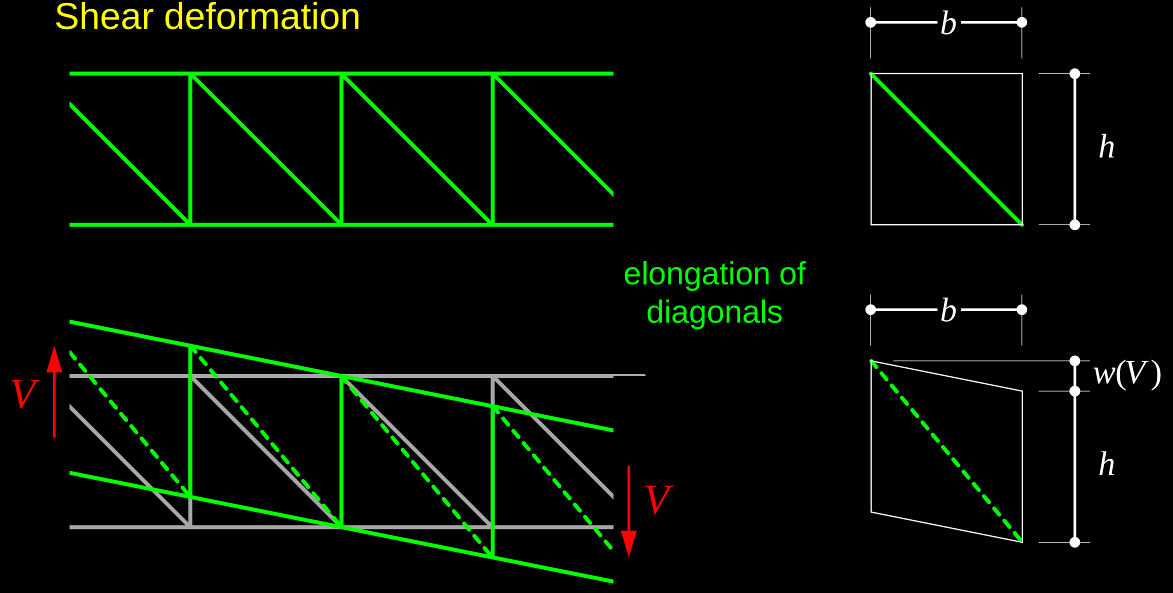
Stringer cross-section



$$EI_y = 2\frac{EA_{tot}}{2}\left(\frac{h}{2}\right)^2 = E\frac{A_{tot}h^2}{4}$$

$$M_{Rd} = \frac{f_y A_{tot}}{2}h = f_y\frac{A_{tot}h}{2}$$

Shear deformation



Truss bridges – Design

Particularities in Design – Structural analysis (1)

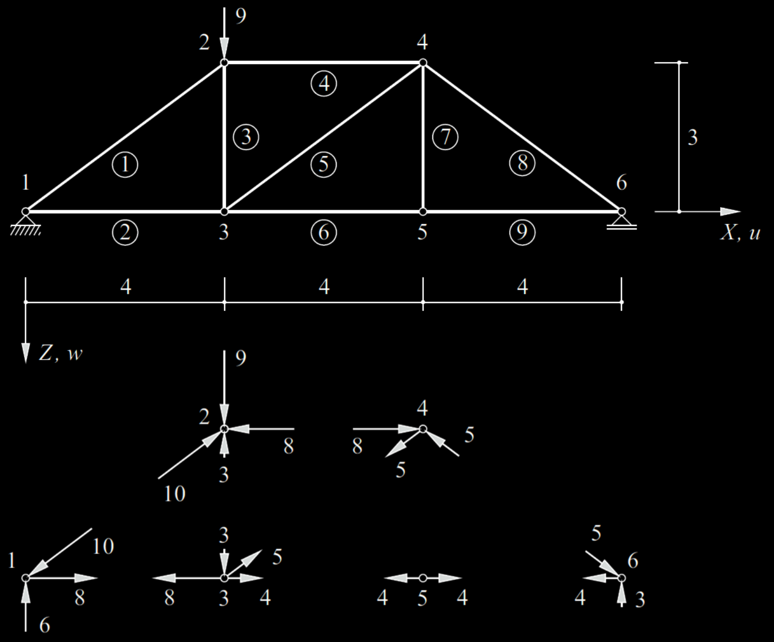
Trusses are treated in Theory of Structures and Steel structures lectures in BSc curricula (Baustatik and Stahlbau I at ETHZ). Here, some key aspects are recapitulated.

Ideal trusses transfer loads by tension and compression of truss members pin-connected at all joints. Bending moments are merely caused by loads applied to truss members between the joints.

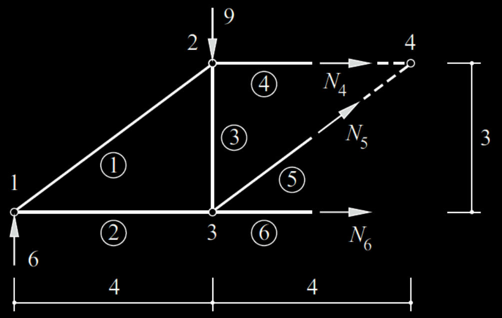
In real trusses, the joints are hardly ever pin-connected, causing secondary bending moments in the truss members. Still, the global load transfer is ensured predominantly by truss action.

The forces in isostatic ideal trusses follow from equilibrium alone. Known methods for their determination (illustrations on right) are joint equilibrium, Ritter's method of sections, and the kinematic method.

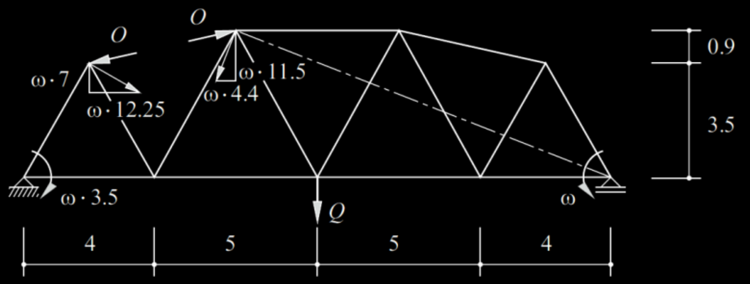
Joint equilibrium method



Ritter's method of sections



Kinematic method



[Illustrations and further information:

P. Marti, Theory of Structures, Section 11.3: Trusses]

Truss bridges – Design

Particularities in Design – Structural analysis (2)

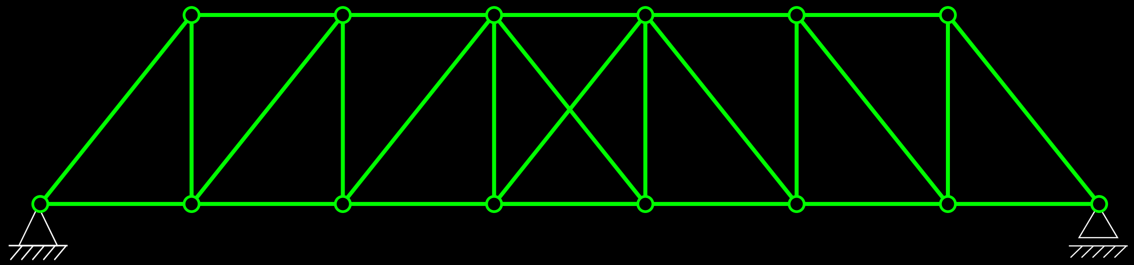
Historically, trusses were modelled as ideal trusses even if rigid, rather than pin-jointed, connections were provided, since this greatly simplifies the analysis (see previous slide).

The resulting axial forces and deflections closely match those of a truss with stiff connections, but do not capture the secondary bending moments caused by joint rotations imposed to the truss members. The latter are, however, important in bridges, where fatigue is relevant.

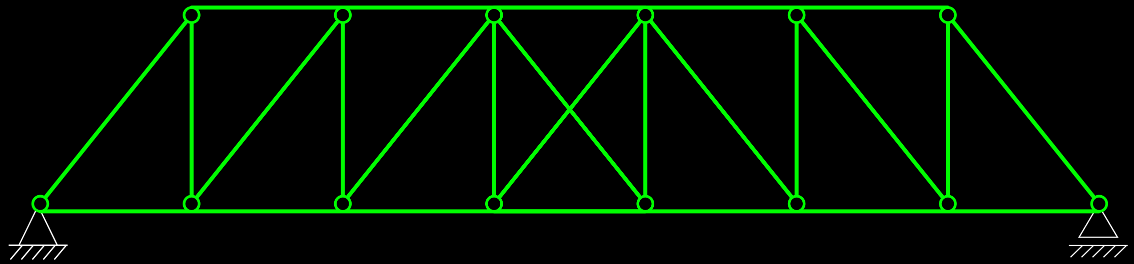
Today, using computers, it is common to analyse trusses with continuous chords, or even accounting for the rigidity of all connections. Secondary bending moments are thus obtained from the global analysis. Still, standards allow analysing ideal trusses and estimating secondary bending moments by multiplying the obtained axial stresses by amplification factors (typically in the range of 1.5…2) for fatigue verifications, see e.g. EN1993-1-9, Tables 4.1 and 4.2.

In any case, eccentricities of the truss members – causing high bending moments – should be minimised. Such eccentricities must not be neglected in the analysis.

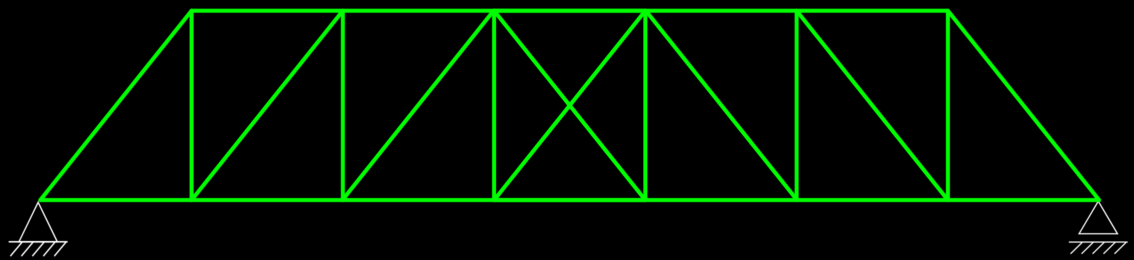
Ideal truss: All connections pin-jointed (ideal truss)
(most simple model for analysis of trusses)



Possible analysis model: Continuous chords, web members pinned
(simplified model for analysis of trusses with stiff connections)



Real truss (welded connections): All connections rigid
(accounting for secondary bending moments in all members)



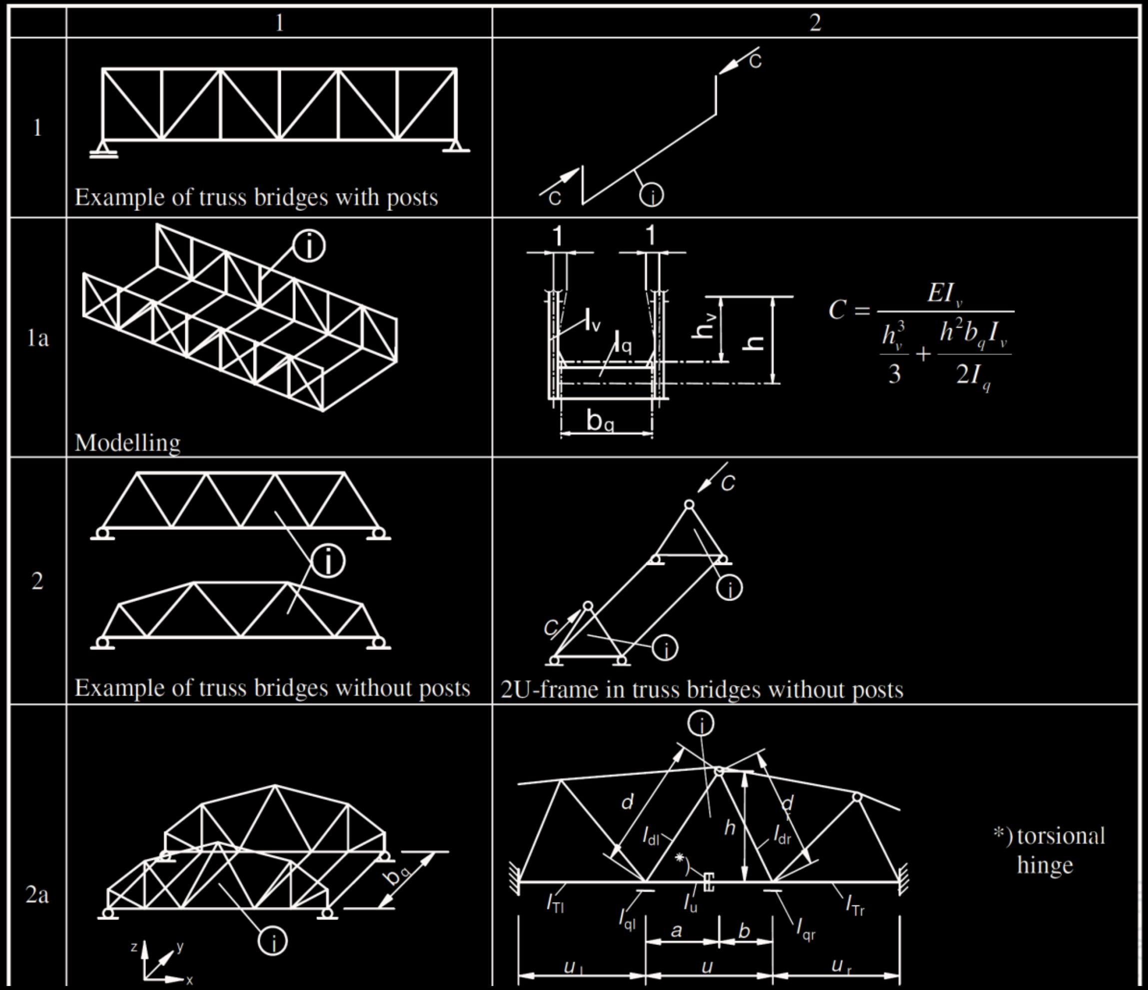
Truss bridges – Design

Particularities in Design – Required verifications

The following verifications are required when dimensioning trusses (see also lectures Stahlbau):

- Cross-section resistance and fatigue strength of all truss members (tension or compression), accounting for local instabilities of cross-sections in compression.
- Structural safety and fatigue strength of all connections.
- Stability of compression members. Unless a more refined analysis is carried out, a verification as columns is possible, assuming conservative buckling lengths of
  … in-plane buckling of diagonals and posts: 0.9·L
  … in-plane buckling of chords: 1.0·L
  … out-of-plane buckling of diagonals and post: 1.0·L
  … out-of-plane buckling of chords: depending on bracing
  (see EN1993-2, Annex D, Table D.2 for more details)
- Global stability of compression chords, particularly relevant in open bridges (pony trusses). Their unbraced compression chords can be analysed as columns laterally stabilised by transverse frames (see illustration).

Excerpt from EN1993-2, Annex D, Table D.3
(global stability of unbraced compression chords)



Truss bridges – Design

Particularities in Design – Connections

The design of the connections is essential for the structural safety and fatigue strength of trusses. In bridges with relevant fatigue loads – particularly railway bridges – they must be carefully detailed to minimise stress concentrations.

Welded connections have become standard in most European countries, and hollow sections ("tubular trusses") are preferred since they

- have a smaller exposed surface and a reduced tendency of accumulating debris at the joints
- are aesthetically more appealing, particularly if gusset plates are avoided

Corrosion protection on the inside of hollow sections is achieved by airtight sealing. This can hardly be achieved with bolted connections, since even small gaps (pinholes) may be sufficient to cause harmful humidity inside the cross-sections, that "breathe" under temperature variation. Therefore, tubular trusses are less popular in North America, where bolted connections are favoured.

Truss bridges – Design

Particularities in Design – Tubular truss connections

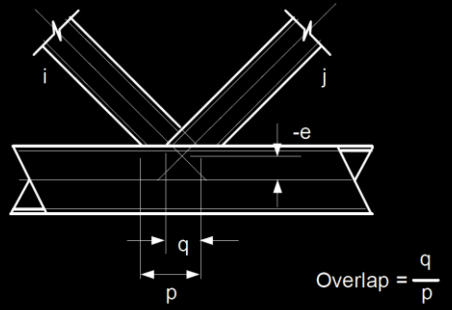
Welded connections in tubular trusses (rectangular or circular cross-section of members) may be designed using semi-empirical design equations, published by the CIDECT, see notes. They were derived by considering possible failure modes, differentiating between cases where the connecting members overlap or provide a gap at the chord.

In either case, additional plates (particularly internal stiffeners) can be avoided, even for relatively high utilisations of the connecting members (particularly for thick-walled circular chords).

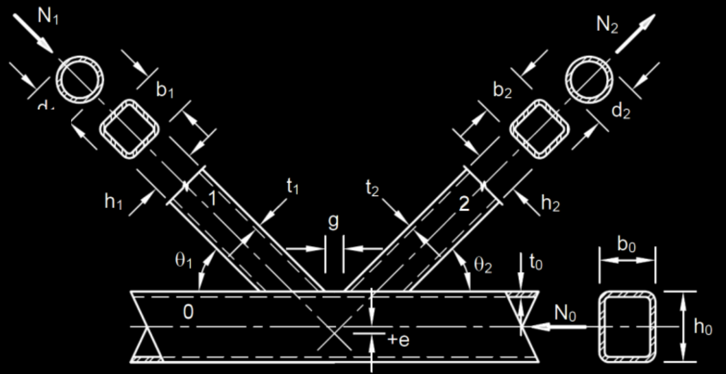
For fatigue verifications of connections, EN1993-1-9, Table 8.7 provides detail categories (36…90 MPa), to be used with the amplification factors accounting for secondary bending moments mentioned previously (EN1993-1-9, Tables 4.1 and 4.2).

Note precise cutting and welding to ensure full penetration welds (very complex geometry in circular member joints) have become available only recently. As an alternative, expensive cast steel nodes may be used. Thanks to the smoother transition of stiffnesses, such nodes usually provide a higher fatigue strength.

Tubular truss: Overlap joint

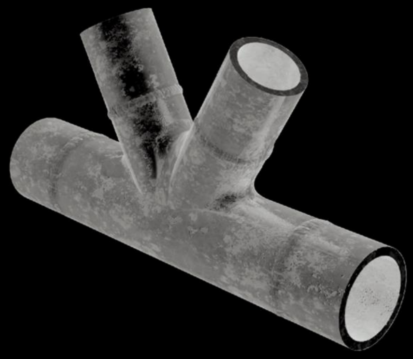


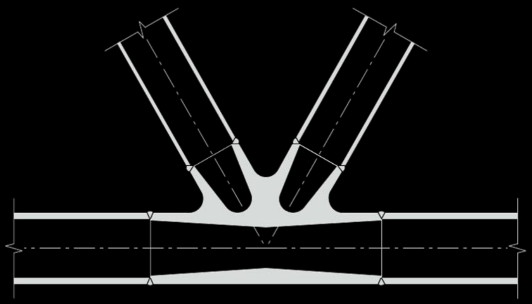
Tubular truss: Gap joint



[https://www.cidect.org/]

Cast steel node





[J.P. Lebet and M.A. Hirt, Steel bridges]

Truss bridges – Design

Particularities in Design – Refined analysis methods

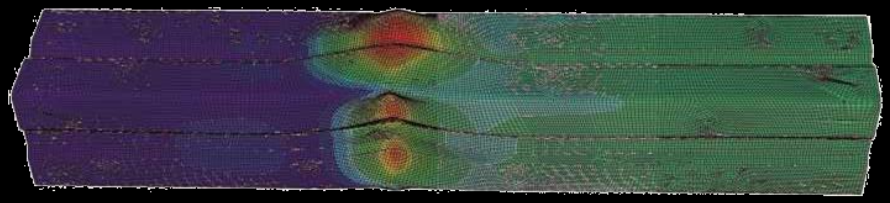
The design methods presented on the previous slides enable dimensioning truss girders in accordance with design codes. However, they contain a number of simplifications and arbitrary assumptions, such as:

- buckling lengths for compression members
- assumed imperfections underlying code-based verifications of plate buckling and member stability
- amplification factors for the estimation of secondary bending moments in fatigue verifications
- semi-empirical design equations for tubular truss nodes

Obviously, these simplifications require a certain conservatism of the design equations.

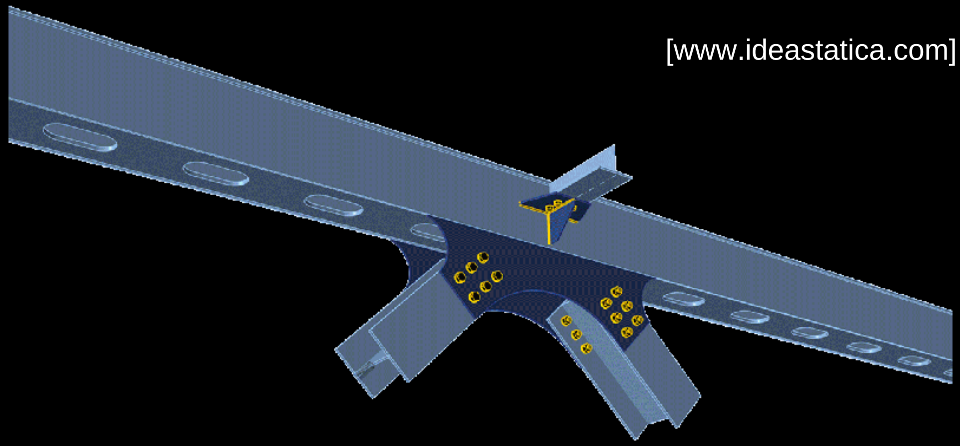
More refined analysis methods, mainly based on nonlinear FE-analyses, are already available today (see illustrations), and further research is ongoing (e.g. at ETH Zürich, Chair of Steel Structures and Composite Structures). It is expected that these methods will soon become established in design practice.

FE-Analysis accounting for geometrical and material nonlinearities and imperfections
(local instability of a hollow section)



[Chair of Steel Structures and Composite Structures, ETH Zürich]

Steel connection analysis based on NLFE
(commercial software IDEA StatiCa Connection)



[www.ideastatica.com]