The Framework Truss: Development and structural analysis of framework trusses in the USA at the beginning of the 19th century

Tim Brengelmann
Rainer Barthel

THE DIRECTLY EUROPEAN PREDECESSORS

When you look at the European bridge construction context of the later part of the eighteenth century as it might have influenced American bridge builders, you are left with the impression that American builders did surprisingly little borrowing for their own development from the Old World for their structural ideas, despite the fact that some European wooden bridges were well known.

The significant difference was the lacking of a structural design clarity of the most European bridge structures, which were burdened with complicated, wood-wasteful carpentry, involving multiple Queen-post trusses within a given bridge, resulting in many diagonal members between the vertical posts, and with the most dazzling, labourintensive use of continuous zig-zag joints, secured with wedges, to laminate several timbers into a larger chord member.

The bridges of the Grubenmann family in Switzerland were internationally well known in its own time. Like the Schaffhausen bridge, Figure 1, the Wettingen bridge, Figure 2, was very famous and was frequently visited by interested travelers, resulting in a variety of written descriptions, dimensions and details. So if any European bridge can be said to have influenced an American bridge, it was probably the Wettingen bridge. It is a multiple Queen-post truss with a very high and stiff arch, consisting of multiple members of wood, fastend on each side to the abutments.

The further development in European wide span structure was determined to perfect both the wooden and the stone arch and later on, at the end of the eighteenth century, the arch made of cast-iron, particularly in France, the Pont d’Austerlitz, 1802–05. and in England, the Sunderland bridge, 1796.

So the first wide span structures in the USA started even with the arch as the substaning member of long-span wooden bridges.
**Overview about the Developments in Building Framework Trusses in the USA**

In 1804–05 Trenton Bridge, over Delaware, was planned and built by Theodore Burr. The superstructure consisted of five laminated wooden arches with the longest span about 60 m in the clear. The following bridges of Theodore Burr commonly used an arch truss. The truss is of the multiple kingpost type with a diagonal timber brace, sloping up towards the center of the bridge, between each panel post.

The multiple kingpost truss is among the most famous trusses and wide spread over the country. Built by local men in many modifications, variations, and reinforcements of the basic designs. They were used for spans of 15 m to 35 m.

1820 Ithiel Town designed and patented a covered bridge truss which could be quickly built by any good carpenter. The Town Truss consisted of a web of light planks criss-crossed at an angle of 45° to 60° like a lattice and fastened together with wooden pins or trunnels at each intersection. It was light and cheap and could be assembled in a few days’ time. This design was well received and soon became most popular both for highways and later for railroads.

Colonel Stephen H. Long patented two types of trusses, the first in 1829 and the second in 1839, a further development and improvement of the first patent. The truss was essentially a multiple kingpost with counterbraces. The patent showed two single diagonals, but practically all bridges were built with two braces and one counterbrace in each panel, and with either one or two post.

The Warren Truss is a well known steel bridge design, that was initially built in wood. James Warren and T. W. Morzani patented this simple light-weight truss in 1838. There are two different types of the Warren Truss, the single and double system. The single type consists of series of diagonal timbers placed in the form of a W with no rods or panel posts. The double system has a second similar set of diagonals which intersect the first.

The 1839 patented Haupt Truss shows a panel-type truss using single-latticed diagonal braces sloping up...
towards the center of the bridge, each spanning three short panels and also braced with a full-length kingpost, serving in place of an arch.

Squire Whipple was the first man who built a diagonal braced steel bowstring arch in the USA in 1840. The arch itself was made of cast iron and the tension members were carried out in steel. Whipple was even the first to publish theoretical investigations about framework-trusses. He started his investigation of a framework at the abutment and then he gradually calculated the forces of every single member. He solved this problem also by using the polygon of forces.

In 1840, William Howe, conceived and patented a truss similar to the Long but with a most important improvement. He substituted iron rods for the wooden post as tension members, eliminating one heavy timber and providing a means of easy adjustment by having screw ends with washers and nuts. The rods could be easily shipped and the truss timbers prefabricated. The Howe Truss gradually replaced other trusses and it became the most popular design during the last half of the nineteenth century (Wilson).

**Reconstruction and Structural Analysis of some Important Stages in Early US Framework Design**

**Structural Analysis**

The structural analysis of different bridge types should inform about the structural behavior of each framework system and its used connections. In the first step the connections between the members were approved as unplibly hinged together and in a further calculation the connections were looked upon to be pliable and they were described in the statical model as linear-elastic springs. Thereby the different framework systems could be compared to each other by their structural behavior and you can give an opinion of the reaction influenced by the connections to the whole system. As further step the behavior of the framework was examined for asymmetrical loading. Thus a uniform load of 5.0 kN/m was applied on half of the bridge length.

**The Long Truss**

The relevant way of joining the members of the bridge represented in Colonel Longs patents was still the treenail although steel connections already had a far spreading. Main changes of the connections, not concerning to their material, referred the improvement in its second patent but primarily to the arrangement of the connection of the posts, chords, braces and counterbraces among themselves. To be able to readjust developed lowerings wedges were imported to the significant places. The basis of the computation became the truss of the Brownsville Covered Bridge from the year 1840 (Historic American Engineering Record). It was selected, because this bridge is documented exactly in it dimensions and detail remarks. The light span of the wooden bridge amounts to about 44,80 m with a system height of 5.10 m. The upper, like lower chords consist of two $30 \times 14$ cm and two $30 \times 16.5$ cm strong timber beams. In each panel there are two posts measuring $30 \times 20$ cm. The diagonal struts are...
implemented and by means of a front disalignment with the posts as two bars 23 × 20 cm. Circulating steel strips secure the situation of the connection. A 20 × 20 cm timber beam is serving as diagonal tie. The connection of the chords, the panel posts and the diagonal tie becomes secured on the one hand over a 2 cm strong steel bolt and on the other hand over a releasing of the panel posts as well as the diagonal tie with the chords.

The connection of the members of the Long Truss was idealized separately for the connection of the steel bolt as well as the connection of the front disalignment in the computer model:

Pliable connection of the posts and tie beams
(Informationsdienst Holz)

Connection Static Model

Pliability \( \nu \) Change of Length \( \Delta s \)
Displacement Stiffness \( C_N \)

Pliable connection of the diagonal struts
(Informationsdienst Holz)

Connection Static Model

Pliability \( \nu \) Change of Length \( \Delta s \)

\[ \nu = \frac{N/C_N}{C_N'} \]

\[ \Delta s = \frac{N \cdot s/E \cdot A}{C_N} + \left[ \frac{N/C_N}{C_N'} \right] + \left[ \frac{N/C_N}{C_N'} \right] \]

\[ \frac{v_{\nu}}{v_{\nu}} = 1.5 \text{ mm} \]

\[ v_{\nu} = \Delta u \cdot \alpha \cdot h \cdot \sin \alpha \]

\[ \Delta s = \left[ \frac{N \cdot s/E \cdot A}{C_N} \right] + \sum [v_{\nu} + v_{\nu}] \]

The following graph represents the deformations of the Long Truss under self load with and without consideration of the pliable connections on the one hand and on the other hand the additional influence of a half-sided load:

**Figure 5**
Displacements of the Long Truss
### Conclusion Long Truss

The consideration of the pliable connections leads in the case of the Long Truss to a substantial deformation increase, which amounts to 255% deformation surname in the center of the truss. Thus one receives a span / deformation relationship of L/1500 for the load case self load. The system of the Long framework reacts under the influence of an asymmetrical load by the presence of the counterbraces to a balanced deformation figure.

### The Howe Truss

Howe completely maintained the system of Long in view to the structural arrangement of the structural elements. He did not take a construction member away added, also none, but only the wooden posts, which are designed as suspenders, were replaced by steel tension bars. He solves the connection of these tension bars with the braces, counterbraces and chords by a counter bearing made from oakwood, this detail was later substituted as a cast-iron shoe whatever in the most diverse forms.

For the computation of the Howe Truss the model is based on a bridge represented in a report on a journey through North America published by K. Culmann in 1851 «Der Bau der hölzeren Brücken in den Vereinigten Staaten von Nordamerika» (Culmann). The light span of the wooden bridge amounts to about 32,00 m with a system height of 3,40 m. The upper chords consists of three $25 \times 22$ cm strong timber beams, in different to the lower chords which consists of four $25 \times 16$ cm beams. The diagonal struts and ties have both the dimension of $23 \times 16$ cm, but the diagonal struts are built with two braces in each panel. Two 4,5 cm traction ties are used as vertical rods instead of common wooden posts. They are fixed at the end with cast-iron washers against wooden blocking elements. A cast iron shoe is used to connect the chords, braces and counterbraces.

The traction forces that vertically rods and the thrust forces from the diagonals cause pressing transverse to the wood fiber in the chords. The resulting deformations are considered as spring elements in the computer model:

| Pliable connection of the diagonal struts (Informationsdienst Holz) |
|---|---|---|---|
| **Connection** | **Static Model** |
| Pliability | $V$ | Change of Length | $\Delta s$ |

![Diagram of Howe Truss](image)

A single panel of the Howe Truss  Upper and lower chords  Diagonal struts  Vertical rods

Figure 6: Redevelopment of the Howe Truss
Figure 7
Displacements of the Howe Truss

The graph represents the deformations of the Howe Truss under dead load with and without consideration of the pliable connections on the one hand and on the other hand the additional influence of a half-sided load (Figure 7).

Conclusion Howe Truss

The deformation increase of the Howe Truss due to the consideration of pliable connections precipitates relatively small. This is in particular because of the fact that the intelligent construction of the Howe Truss works without tension-stressed connections. By pre-stressing the vertical rods around 1mm/m the deformation of the system can be reduced more under dead load even by 20%. The truss receives a span / deformation relationship of L/2500 for the load case dead load. The Howe system behaves also durably in relation to asymmetrical load, which the even process of the deformation figure shows.

The Warren Truss

The Trent bridge, 1851 delighted by Cubitt after the system Warren, represents the first iron bridge in a consistent frame-work construction (Dietrich and...
The Framework Truss

Under uniformly-distributed load all construction units are trained demand-fairly in form and material, the struts consist continuous of cast irons members and accordingly the tension members are manufactured from iron. The upper chord is poured as cast-iron tube, outside with an octagonal cross-section and inside with a circular cross-section, with a diameter of about 12 cm and a minimum wall thickness of about 3 cm. The diagonally struts are cast-iron hinged columns with a cross-shaped double-T cross section, which becomes broader the center of the column. The lower chords and the diagonally ties are both tension ties with rectangle cross-sections. There are two diagonally ties each panel measuring about 18 x 2 cm. The lower chords could be assembled accordingly to the tension and measured about 22 x 2 cm each. All members were connected by iron bolts, about 3 cm in diameter. The light span of the Trent bridge amounts to about 72.00 m with a system height of 4.70 m. (Figura 8)

The pliable connections of the Warren Truss are principally based on the bending of the bolts caused by the eccentric connection among each other.

The graph represents the deformations of the Warren Truss under self load with and without consideration of the pliable connections on the one hand and on the other hand the additional influence of a half-sided load (Figure 9).

### Pliable connection of the diagonal struts and ties

<table>
<thead>
<tr>
<th>Connection</th>
<th>Static Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pliability</td>
<td>$v_N$</td>
</tr>
<tr>
<td>Change of Length</td>
<td>$\Delta s$</td>
</tr>
</tbody>
</table>

$$v_N = \frac{[N]}{C_N}$$

$$\Delta s = \frac{[N \cdot s]}{E \cdot A} + \frac{[N]}{C_N} + \frac{[N]}{C_{N2}}$$

### Conclusion Warren Truss

The Warren Truss shows a uniform increase of the deformations due to the consideration of the flexible connections at a value of 106% in each panel. The span / deformation relationship in case of self load is

![Displacements of the Warren Truss](image)
about L/1150. Although the Warren Truss shown here is trained outstanding according to the framework theory for the case of a uniformly-distributed load, it reacts very sensitively to an asymmetrical load situation. This is above all of the fact that pressure-forces arise in the tension bars under an asymmetrical load within certain ranges of the truss itself. This leads to a loss of the diagonals concerned and thus to a rigidity loss of the structure here.

**SUMMARY**

The first half of the 19th Century draws out in three-ways regarded as particularly important for the development of framework systems. The building material wood is replaced gradually by the more efficient material steel. The system formations achieve a variety at structure combinations, never known, to obtain larger spans and higher load-bearing capacities and the theoretical bases for the calculation of a framework were found.

The comparison of the three selected framework systems shows the efficiency of the building material steel as a basic element and by the example of the Howe Truss, although it is importantly shorter in its span however the same system formation is used as the Long Truss, shows itself already clearly its outstanding constructional training by the displacement behavior.

Consulting the influence of the used connections on the load-bearing behavior under dead load for the evaluation, the chronological classification of the systems is to be equated to the way the different framework systems react on their connections. Accordingly the Warren Truss behaves most durably to the resulting deformations in the used connections.

By the consistent employment of steel and cast iron in the Warren Truss it has been possible for the first time to reduce the necessary construction height strongly compared with the timber construction methods. However if the weight of the construction is the relevant evaluation parameter, then the Howe Truss obtains a outstanding result due to its extremely intelligent construction. However the question remains openly whether an appropriate Howe Truss for example of double span could be judged just as favorably.

**Figure 10**

Representation to scale and comparison of the displacement behavior
Long Truss

Howe Truss

Warren Truss

System height in relationship to light span of the truss:

Truss weight per meter:

Figure 11
Span / deformation relationship with pliable and non pliable connections:

REFERENCE LIST


Heinzerling, F. 1882. Die Eisernen Balkenbrücken mit gegliederten Parallelträgern. Fig. 85–86. Berlin: W. & S. Loewenthal.
