Long-term creep in wooden-iron bridges: a comparative study of different truss types

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ABSTRACT: Since mid-nineteenth century iron was widely introduced into wooden bridge truss types. A long-term creep evaluation, based on linear elastic model, is here presented in order to compare the effects of dead load in six different kinds of trusses in which iron is used in different truss members. The structural efficiency of the different truss forms has been evaluated in terms of initial elastic deflection and time needed to viscous deformation induced by creep so as to double the initial elastic deflection.

1 INTRODUCTION

The advantages of using metal ties to build bridge members working in tension were recognized in Europe since the late XVI century (Verantio 1595). Iron ties in wooden bridge construction were used by Hans Hulrich Grubenmann when he built in 1757 the Schaffausen bridge (Fig. 1).

However, iron production methods were so expensive that an extensive use of this material in bridge construction was practically impossible. During the industrial revolution, the development of new techniques resulted in strong reductions of iron costs, which induced in Europe the substitution of many wooden bridges with iron bridges since the beginning of the second part of the 19th century. In the United States, the large availability of timber kept lumber price very low; hence lumber use was economically convenient also after the industrialization of the iron production methods. This condition induced the development of many hybrid structural types in which iron was used for tensioned members and wood for those subject to compression (Fletcher & Snow 1976).

The use of iron elements, besides eliminating some wood tensile connections, carried other significant improvements to the structural efficiency of the different truss forms. First, it made it easier and more effective to apply and maintain pre-stressing (Gasparini & da Porto 2003), that was first introduced in ordinary St. Andrew's cross type all-wood trusses by Stephen Harriman Long (Long 1830). Second, iron, if compared to wood, does not show to be subjected to creep: hence its introduction is effective in counteracting the effect of creep due to the dead load of the bridges.

In the present contribution, six kinds of trusses, built with wooden and iron elements, are compared. Each of them differs from the others in terms of overall geometry and of distribution of the iron members. The effect of long-term creep is studied in a simplified manner, by means of linear elastic analyses. The structural efficiency of the different truss forms is thus analyzed taking into account the effect of the iron elements.

2 ANALYZED TRUSS TYPES

Table 1 summarizes the six analyzed bridges, built with a combination of wood and iron elements. Figure 1

Figure 1. Iron counterbraces in the end panels of the Schaffausen bridge built by Hans Ulrich Grubenmann in 1757.
Table 1. Analyzed bridges.

<table>
<thead>
<tr>
<th>Num.</th>
<th>Bridge name</th>
<th>Truss type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>** Burr</td>
<td>Truss</td>
<td>Trautwine (1895)</td>
</tr>
<tr>
<td>2</td>
<td>Connecticut River Bridge*</td>
<td>Howe</td>
<td>Trautwine (1895)</td>
</tr>
<tr>
<td>3</td>
<td>** Pratt</td>
<td>Truss</td>
<td>Trautwine (1895)</td>
</tr>
<tr>
<td>4</td>
<td>Standard bridge of the NY</td>
<td>Whipple</td>
<td>Whipple (1899)</td>
</tr>
<tr>
<td>5</td>
<td>*** Child</td>
<td>Truss</td>
<td>Child (1846)</td>
</tr>
<tr>
<td>6</td>
<td>Newburgh RR Bridge*</td>
<td>Post</td>
<td>Davies (1908)</td>
</tr>
</tbody>
</table>

* built bridge.
** standard Burr & Pratt trusses described in Trautwine's book.
*** standard Child truss as described in Horace Child's Patent.

2.1 Burr truss

The Burr truss is a compounded structure – an arch plus a truss – patented by Theodore Burr in 1817. In its most advanced version – the one reported by Trautwine – it has arch suspension rods and counterbrace ties.

2.2 Howe truss

William Howe deposited the patent of a truss bridge with wooden diagonals and iron posts in 1840. The first bridge built according to this structural scheme was on the Western Railroad, spanning over the Connecticut River at Springfield. Timber Howe trusses, as those described by Trautwine in his manual (1895), were still used for railroad purpose till the end of 19th Century.

2.3 Pratt truss

Thomas and Caleb Pratt patented their truss in 1844; it consists basically in a Long truss in which braces and counterbraces are substituted by iron ties.

Trautwine gives in his handbook (1895) a description of the dimensions of a standard Pratt truss.

2.4 Whipple’s truss

This truss invented by Squire Whipple is described in the second edition of his book (1899). It consists in the superposition of three trusses based on triangular...
scheme and in a series of vertical ties to which the deck beams are suspended.

2.5 Child truss

Horace Child patented his truss in 1846. The geometry of the truss is very similar to a Long truss: the difference is that counterbraces are substituted by iron ties.

2.6 Post truss

Simeon Post introduced this type of truss in 1865. It was made completely of iron or of iron in combination with wood. This second version had timber upper chord, timber inclined post, iron diagonals and iron lower chord. The here analyzed Post truss bridge was on the Connecticut Railway at Newburgh, Dutchess. The relative description appears in Davies (1908).

3 TRUSS ANALYSIS

3.1 Finite element analysis of the bridge

The structural behaviour of the six bridges was predicted by computer analysis of two-dimensional, linear elastic frame models. The geometry of the models is shown in Figure 8.

Dimensions and member cross sections were obtained from the sources quoted in Table 1. For the analysis, it was assumed that the bridges had been built with Eastern White Pine (*Pinus strobus*), which was considered a suitable material for bridge construction (Long 1830) and was the most common timber used during all the first part of 19th century (Fletcher & Snow 1976). The following assumptions were made about the mechanical properties of Eastern White Pine. The modulus of elasticity was taken equal to 8550 N/mm² and the Poisson’s ratio to 0.33.

Wrought iron used for the rods was assumed to have a modulus of elasticity equal to 186 kN/mm², Poisson’s ratio equal to 0.3 and yield stress equal to 207 N/mm². The models were used to predict the effects of dead load, in terms of initial elastic deflection at midspan (Table 2), and the effect of creep.

Creep is a time-dependent phenomena related to the behaviour of wood under load, and consists in increase of strain under a constant stress. Actually, if a wooden element is restrained, creep is hindered and the element is subjected to effective axial forces from creep. The corresponding behaviour of the truss under creep can be evaluated by computing the axial forces from nodal displacements in the truss elements when all the creep nodal loads are applied, and by superposing the effect of the fixed end forces. A predictive creep model, described more in detail in §3.2, which does not take into account the effects of cyclical variations of temperature and of moisture content within the analyzed period, was assumed to estimate the value of creep strains. The effective nodal loads, *C_i*, due to the creep deformation for loading parallel to the grain were therefore calculated for each element by using eq. (1):

\[
C_i = \varepsilon_i(t) \cdot E \cdot A_i
\]

where \(\varepsilon_i(t)\) is the creep strain, \(E\) the modulus of elasticity of wood and \(A_i\) the area of the *i*-element.

The effect of creep was thus evaluated in terms of time needed to viscous deformation to increase of a certain rate the initial elastic deflection due to dead load at midspan. Besides the effect of environmental conditions, also the effect of prestressing,
achieved in some of the analyzed structures by tightening nuts or using similar devices, was neglected in these simplified analyses.

3.2 The proposed creep model

A long-term, five parameter model was used to estimate the value of creep strains at different times \( t \), taking into account the constant actual state of stress \( \sigma_i \) of the elements before creep starts. The model was based on the following equation, proposed by Dinwoodie (1984):

\[
\varepsilon_i(t) = \sigma_i E \left[ \beta_1 + \beta_2 \left( 1 - e^{-\beta_3 t} \right) + \beta_4 t \beta_5 \right] \tag{2}
\]

where \( \sigma_i \) is the compressive stress parallel to the grain in the \( i \)-element before the creep starts and \( \beta \) are the model parameters that depend on the wood species, temperature and moisture content.

Being not known to the authors the values of the five parameters of eq. (2) from experimental tests on wood samples of Eastern White Pine, they were set on the bases of different long-term creep analyses proposed by Tissaoui (1996). Tissaoui analyzed three structures: a kingpost truss, shown in Figure 9, a space structure found in the Varax dome of the Church of the Nazarene, shown in Figure 11, and a three-hinged arch, shown in Figure 13. The creep analyses performed by Tissaoui on the kingpost truss and the Varax dome follow Gamalath’s model (1991):

\[
\frac{D_0 \varepsilon}{D_0} = p_1 t^{p_2} \tag{3}
\]
Figure 13. Three-hinged arch.

Figure 14. Comparison between deflections at mid-span of the arch calculated by Tissaoui [a] and according to eq. (2) [b].

where $D_{cr}$ is the creep compliance, $D_0$ the instantaneous compliance, $P_1 = 0.0749 - 2.291 \times 10^{-8}$ E and $P_2 = 0.3358$ are constants from regression analysis and average on experimental data. The results of the analyses are given in terms of deflection at midspan under constant load, corresponding to three point loads applied at the nodes in the case of the kingpost truss, and to dead load and a uniform distributed load in the case of the Varax dome.

Equivalent geometrical models were defined and analyzed under long term loading, by applying eq. (2), in order to set the five parameters. Elements dimension and mechanical properties of wood and loading conditions were taken equal to those described by Tissaoui (1996). First, the value of the parameter $\beta_1$ in eq. (2) was set on the kingpost truss, by imposing the condition that the initial ($t=0$) deflection of the truss at midspan is equal to the initial elastic deflection.

Subsequently, the parameters $\beta_2, \beta_3, \beta_4, \beta_5$ were set in order to fit the curve describing the displacement at middle of bottom chord that had been calculated by Tissaoui. This latter curve is reported in Figure 10 [a], together with the curve based on eq. (2), Figure 10 [b]. The said values are: $\beta_2 = 0.3; \beta_3 = 0.31; \beta_4 = 0.142; \beta_5 = 0.48$.

After calibrating the values of the $\beta$ parameters on the bases of the kingpost truss, eq. (2) was used to calculate the vertical displacement due to wood creep at the apex of the Varax dome. The results of the analysis were compared to those obtained by Tissaoui (1996), in order to check the applicability and reliability of eq. (2). Despite the differences between the structure on which eq. (2) was calibrated, the kingpost truss, and the structure of the dome—different wood species, different dimensions and kind of trusses—the two analyses on the Varax dome gave consistent results. The average differences between the vertical displacement at the apex of the dome evaluated according to Tissaoui (curve [a] in Fig. 12) and according to eq. (2) (curve [b] in Fig. 12) were equal to 4%, and were considered to be acceptable.

Finally, Tissaoui (1996) applied a different creep model, the power law proposed by Nielsen (1992), to calculate the creep deflection at the apex of a three-hinged arch (Fig. 13), under dead load and a uniform distributed load. The same structure was analyzed by applying eq. (2), and the results were again compared to those obtained by Tissaoui. In this case, the results obtained by applying eq. (2) seems to overestimate the creep deflection, therefore the two deflection curves diverges, as can be seen in Figure 14. However, the maximum divergence in the long term, at 50 years, is equal to about 13% that can be still considered an acceptable variation. The broader difference depends on the fact that the law used to calculate the deflection of the three hinged arch, compared to eq. (3) on which the proposed creep model (eq. 2) was calibrated, introduces other phenomena, i.e. considers wood as a damaged viscoelastic material.

In conclusion, it was considered acceptable to use the five parameter eq. (2), as calibrated on the bases of Galamath’s long-term creep model, and it was applied to study the effects of creep in the described bridge trusses. The procedure followed to study the effect of creep has been already illustrated in §3.1.

4 EFFICIENCY OF DIFFERENT TRUSS TYPES

4.1 Effect of dead load

The instantaneous elastic deflection at midspan due to the effect of dead-load, as calculated by means of linear elastic analysis of two-dimensional frame models, is given Table 2. The ratio obtained dividing such deflection by the truss span was calculated so as to evaluate the initial efficiency of different structural types. The length of the spans and the ratios between the initial elastic deflection at midspan and the span length are also reported in Table 2.

4.2 Effect of creep

The midspan deflection due to creep induced by dead-load was evaluated by applying equation (2) at different times $t$, taking into account the actual state of stress $\sigma_i$ of the elements before creep starts, and assuming
the five parameters found in the analysis of the king-post truss. Curves representing the ratio between the creep deflection and the initial elastic deflection versus time, for the various analyzed trusses, are reported in Figure 15. The period of time $t^*$, after which the vertical deflection at midspan results twice as the initial elastic deflection due to dead load, is reported in Table 2.

Creep deflections after two years were calculated for each truss according also to the exponential creep law proposed by Le Govic for the use in building codes, and reported in Tissaoui (1996):

$$e_t(t) = \frac{\sigma_f}{E} \left[ t + 0.30 \left( t + 0.30 \left( t - e^{-t} \right) \right) \right]$$

(4)

Table 3 reports the values of deflection due to creep after two years, calculated according to eq. (2) and eq. (4).

### 4.3 Comparison of different trusses

As it may be easily seen in Table 2, the response of the analyzed bridges to dead load varies considerably with the different truss forms, with values of ratio between initial elastic deflection and bridge span ranging from about $1.5 \times 10^{-4}$ to about $3 \times 10^{-4}$. The same can be said about the creep behaviour, with time needed to viscous deformation induced by dead load so as to double the initial elastic deflection varying from about 30 to about 55 years.

As for the long-term creep (Fig. 15, Tab. 2), similar behaviour and values of time needed to double the initial elastic deflection, around 50 years, may be found on the Child and the Pratt truss, both having iron ties used for diagonal elements. These two trusses are also characterized by low values of ratio between initial elastic deflection and bridge span, respectively equal to $1.58 \times 10^{-4}$ and $1.84 \times 10^{-4}$ (Tab. 2), thus revealing a good behaviour both under instantaneous and long-term loading.

Similar analogies may be seen in Howe and Whipple's truss, both built with iron vertical posts, for which the time needed to double the initial elastic deflection is around 30 years. These two trusses are also characterized by high values of ratio between initial elastic deflection and bridge span, respectively equal to $2.1 \times 10^{-4}$ and $3.14 \times 10^{-4}$ (Tab. 2). Conversely, the Burr truss, that presents similar values of time needed to double the initial elastic deflection, shows the lowest value of ratio between initial elastic deflection and bridge span ($1.45 \times 10^{-4}$). In this case, the efficiency of the arch plus truss structure in increasing the stiffness of the bridge is revealed, but this does not correspond to a similar efficiency in the long-term behaviour of the bridge. Finally, the Post truss revealed an intermediate behaviour both regarding the initial and the long-term response to dead load.

5 CONCLUSIONS

In this paper, a comparison of different trusses, in terms of truss response to dead load and of time needed
to creep so as to double the initial elastic deflection, is shown. The presented results may be not considered of general validity as they are influenced by the geometry—aspect ratio of the panels and member cross sections—and the overall characteristics of the analyzed bridges.

In order to determine the influence of the iron members in the truss response and to evaluate the effect of the design proportions, it would be significant to analyze the same truss forms built with all wooden members, or to vary the ratio between length and height of panels within each truss form.

If more detailed information about the bridges were available—e.g. the condition of wood used during construction, the occurrence of periodical retightening of the nuts on iron rods, etc.—it would be significant to analyze the trusses more in detail, introducing also the effects of shrinkage and pre-stress.

Finally, it has to be highlighted that for more reliable creep study, viscoelastic analyses where stress redistributions under constant loads are taken into account, with creep laws formulated and applied for variable stresses, should be carried out instead of simple linear elastic analyses.

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