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The changing concept of truss design caused by the influence of science

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ABSTRACT: Using the example of trusses the paper demonstrates the strong influence of a scientific view on structures and structural concepts arising at the beginning of the 19th century in Western Europe. By then structures have been considered as assembled constructs arranged according to utilization and boundary conditions. In most cases, such structures were designed and built based on samples, which had been promoted in circulating textbooks and treatises during the 17th and 18th century. Shortly after the establishment of technical colleges in Western Europe at the beginning of the 19th century, the education of engineers dramatically changed and thus also the basis of the design thinking. The paper traces the characteristics of the new scientific approach examining the theories and views of Schwedler and Culmann, theorists and engineers publishing the first widely recognized truss theories, and exemplarily shows the consequences. These were a different perception of common structures and a new concept of structural design leading to a systemization and optimization of the structural form for both the overall structure and the members. This paradigmatic change from continuous adoption to a materialization of what is found to be theoretically sound is also the change from a functional to a morphological understanding of structure.

1 INTRODUCTION

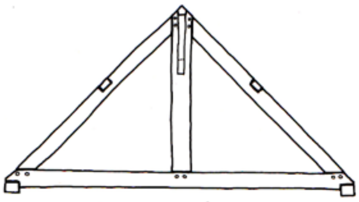
When science found its way into the building practice there was a shift initiated that, besides some other technical innovations, also brought a whole new view of structures and how they were developed. The influence of a science-based view of structural aspects marks the transition from craftsmanship-oriented to a theory-oriented construction, which was then to be rational, systematic, and highly efficient.

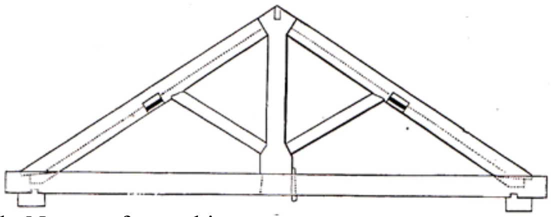
In order to understand this phase and the ideas behind that movement, but also its impact and consequences, it is therefore useful to have a deeper look all phases: How trusses were designed before the putative change, how they were treated differently afterwards, and eventually how they were described in between.

2 TRUSSES IN THE AGE OF CRAFTSMANSHIP

2.1 *Origin and idea of the truss*

The roots of the truss construction principles as we know today can be traced back to the early wooden roof structures. Ever since wooden roofs were often constructed by forming an overall triangular shape. With increasing span or lower pitch a post was often used below each pair of rafters or only few posts in combination with a purlin at the ridge (Figure 1a). These posts were put directly onto the ceiling beam, which had to withstand all loads with its own bearing capacity. Often there were additional members added from below to provide additional support for the beam of the ceiling and thus to reduce the span. The same principle has been used for wooden bridges such as trestle bridges when intermediate diagonals have been implemented.



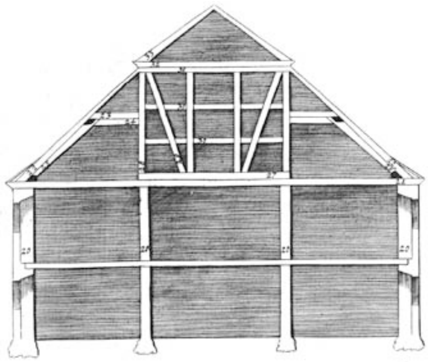


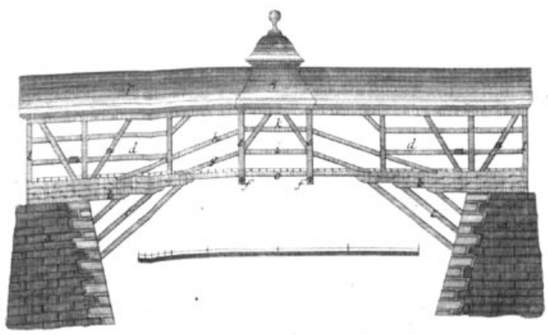
a. Traditional roof type, (truss) frame b. New roof type, king post truss
Figure 1. Transition in roof design (Yeomans 1992).

The actual structural invention was the introduction of a detail, which attached the ceiling beam to the post and turned the latter from compression into a tension member taking now much of the load from the ceiling. The now hanging post was anchored at the ridge where the pair of rafters met. This caused much higher compression forces in the rafters and as a consequence much larger forces at the bottom where these forces had to be transferred to the ceiling beam. Accordingly, this turned the ceiling beam into a tie beam. The overall consequence of this little change in construction was the shift from members being subject to bending to those being primarily axially loaded. The individual members require, therefore, smaller dimensions, which are essential to allow for larger spans, which are greater than the natural length of wood. The heavily loaded principals were mostly supported by additional struts, which were brought to the foot of the post (Figure 1b). The definition of the minimum number of members for a framework to work as a truss is not very precise and there is some confusion about whether the morphological or the structural aspect of a truss shall be used as dominant aspect for a definition. Yeomans (Yeomans 1992) discusses this problem of definition for the early roof types and proposes the term 'frame' for roof structures not using a hanging post (Figure 1a).

2.2 *Role of Diagonals*

Basically there are different roles of diagonals within a truss system. They can be described as serving for the load transfer of vertical and horizontal loads. Since diagonals for the lateral load transfer do not contribute to the major load case, which is gravity in the vertical direction, they can be called stiffening measures. Figure 2a shows an example where the diagonals are used to stiffen the construction but not to help supporting vertical loads. The additional beam at their bottom is a clear indication that the diagonals do not transfer the loads from the posts. Struts were also used in bridge structures for stiffening purposes. Figure 2b shows both functions of diagonals: In the upper part the outer diagonals stiffen the structure while the diagonals in the upper center and in the lower part form an arch to take vertical loads to the abutments.





a. Stiffening measure in a roof (Vogel 1708) b. Truss Frame in a Bridge (Walter 1704)
Figure 2. Craftsmanship-based structures with intuitive and traditional use of elements.

3 THE DEVELOPMENT OF CONSTRUCTION TYPES

3.1 *Addition and Variation of Struts*

As there are two different functions of the diagonal members, which is load distribution to the upper and lower chord, and stabilization of the construction, there are also two different approaches to how trusses might have been developed in their early forms of use. One way to give additional support to a simple beam used as a major structural element in a bridge or a roof is to add some elements at both ends of the beam to push the latter and so reducing the effective span (Figure 2b) or, on the other hand, diagonals were simply added within the framework of a roof or a bridge in order to stiffen the whole system.

Additional struts were in most cases added regularly within a simple pattern of posts. Intuitively there were struts added wherever it was felt necessary to provide a robust structure. There was often an arrangement, where connection points of larger compression are reinforced with additional wooden elements beside the rafters or ceiling beams. Also, more for bridge than roof structures, there were struts arranged in such a way to form a structural polygonal arch. Figure 2b can therefore be read as a combination of several arch-like structures, which are simply overlaid. Struts are put inclined upwards towards the middle of the bridge and there is again an additional horizontal member at their top to form a double bent compression system. Figure 2b also demonstrates how independently the struts were implemented, not being geared to the post layout. Also there were additional struts added for stability reasons. Thus, there was not an overall structural layout, but a general idea of each sort of element.

3.2 *Extention and adaption*

This system with a single post under tension as it is shown in Figure 1b is called a king post truss. This principle of redirecting internal forces by using an overall structural system rather than making the members acting individually can be easily extended by secondary posts or even tertiary posts and additional struts.

Additional struts have been extended to form arch-like structures; either the design of the structure included a series of polygonal arches in order to increase the stiffness over a larger area or the arch-like polygon was enhanced to work as a very rigid and solid arch. At the beginning of the 19th century arch structures were considered the most suitable structural system for large span bridges. When it had to be constructed out of timber, designers and builders used the concepts of Gauthey (1732 -1806) and Wiebeking (1762-1842), which were widely known.

Roof and bridge structures working as trusses had been surely developed long before the Renaissance, but it is not until then when its idea began to spread throughout Europe. The use of this truss principle can be traced back to Italian sources. The spreading took place by word of mouth when people heard from other people who visited buildings or builders saw them by themselves.

A revolution in sharing information was the possibility to attach printed images to treatises from the beginning of the 15th century (Carpo 1998). Many types and examples of constructions using trusses were published and spread. Carpo analyses the impact of the introduction of images as a 'predesign' process in architecture, but this can surely also be said about the spreading images of constructions and structures. There are many building examples where a truss structure was constructed according to a nearby building or a reference example in a book (Fig. 2), although the idea of that respective type of structure has not been fully understood. Instead, some fragments were used but not adopted correctly (Yeomans 2002).

Later, during the 17th and 18th century, many craftsmen published books following the idea and style of architectural or military engineering treatises. Important examples for the circulation of truss constructions are the books from Price (Price 1733) and Nicholson (Nicholson 1833) in England or Wilhelm (Wilhelm 1649), Vogel (Vogel 1708) and Walter (Walter 1704) in Germany as well as Jousse (Jousse 1627) in France. For this kind of vivid exchange of information it is characteristic that certain buildings were promoted to be exemplary and their construction was depicted like a recipe. For many builders or carpenters this meant the transition from know-that to know-how, but still far away from a substantiated know-why.

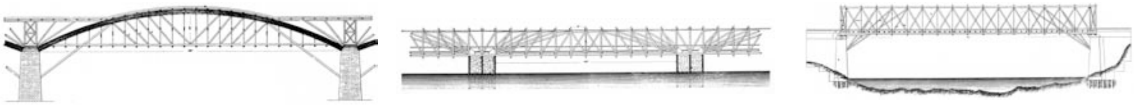
3.3 *Overlay of systems*

The use of struts and their various arrangements lead to many different forms of structures. In order to increase the load bearing capacity and the overall stiffness, additional elements were often further developed and formed an entirely separate structural system. The combination of different systems and the simple overlay was, in a way, characteristic for the first half of the 19th century (Peters 2009). From about 1830 on, many railway networks were established in Europe, and within a very short period an appropriate infrastructure was to be built. When bridges needed to be constructed for larger spans and higher loads, traditional systems were used and scaled and extended for larger purposes. Carpenters, architects and engineers built up on building techniques from timber and stone constructions and had little experience with loads such as a heavy moving train.

Systems developed quickly and innovation was always a further step in front of a solid background of experience and tradition. A very particular situation was the development of structures in North America at that time. Builders originally used their knowledge which they brought from Europe and thus their first attempts of bridge building was rather a copying of old types of structures. However, North American builders developed their structures quite differently when large span bridges were to be designed for the new railway networks. Culmann extensively describes in his much acclaimed report (Culmann 1851) of his journey to North America in 1851 how systems developed here and what types emerged. Culmann draws the background of a very profit oriented, high competitive situation, which let the builders here seek the minimum of time and effort to build bridges. He discusses several examples and a logical development from different builders. Figure 3 shows examples of Culmann's view on the evolution of timber truss bridges in North America. His explanations can be summarized with the following stages:

1. Adoption of the arch as a high-capacity structure
2. Single bracing to increase stiffness (a)
3. Straightening of the arch to strengthen ends and simplify construction (b)
4. Additional trussing overlayed to increase stiffness at the ends of each span (c)
5. Secondary trussing arranged in pairs with primary trussing (d)
6. Activation of secondary trusses as tension members
7. Optimization of construction by introduction of tension bars to replace posts (e) and refinement of arch-truss combination by new means of connection (f)

For Culmann stage 5 is already the best type of structure, which elegantly brings together an excellent structural understanding and a good construction in equivalence. All bridges after Long's system are solely optimization regarding construction issues and the introduction of structural iron. The most interesting step is the transition from stage 4 to 5 where Culmann praises the achievement of a homogenous universal system (Culmann 1851). Here is a new understanding established when the entire structure is thought of as a systematic addition of single cross braced frame and not as before (type c in Fig. 3) the structure is developed within each span. Although compression and tension members are detailed differently due to the constructive capabilities of timber, it is the repetition of a single subsystem – stiff and robust in its own – that makes the definitive system. This is also an important change in the understanding of form in terms of scale. The overall truss system is not any more a visible gesture between the supports of the structure but a continuous homogeneous structural pattern. The truss has become a constructive logic – forming rigid triangles – rather than a single structure that arises directly from the use of the structure and its supports. In the era of experimental structural engineering, Long "certainly deserves the credit for having set the structural systems still fluctuating and brought them into a system" (Culmann 1851).



a. Delaware, Trenton (Burr) c. Potomac, Washington e. Chikapoe (Howe)

b. Desplain, Joliet d. System Long f. Connecticut (Burr)

Figure 3. Development of structural systems for timber bridges in North America (Culmann 1851).

As an advocator of a systematic and consistent approach Culmann denies the structural value of the overlay of several structural systems. If there are two systems, each of which with a different stiffness, then there is no chance for the two systems to take the load equally. “The truss system has a lot more joints than the arch where there is actually none. Thus, the same force in the truss causes larger deflections than it would do in the arch. The bearing capacity of the truss will therefore always be taken only in cases where the arch is completely exhausted” (Culmann 1851).

4 SCIENTIFIC PERSPECTIVE ON TRUSSES

The perspective on the very different building industry in North America given by Culmann is also a very distant one. He is a well-educated engineer in the tradition of the rather scientific schools in Germany (Maurer 1998) and observes a building practice, which is dominated by a building community with little theoretical background (Kaiser & König 2006). Eventually, he expresses his astonishment about the mostly fameless Colonel Long: “The American engineers are still too much practical to pay attention to their most competent men. […] Only then, when in this country the best engineering practices will be raised to science, one will also appreciate its smart engineers” (Culmann 1851).

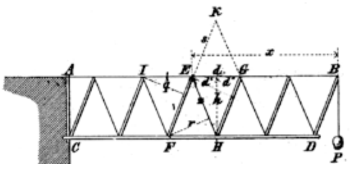
4.1 *Truss theories*

In the account of his journey from 1851 Culmann also proposes a theory of trusses, which he also applied to the discussed bridge examples. In the same year Schwedler (Schwedler 1851), a young academically educated German engineer, proposes independently his theory on trusses. Both contributions are commonly considered the first complete and consistent theories on truss structures, although there were two earlier writings on that issue: Whipple, 1847 and Jourawski, 1857. However, the Russian engineer Jourawski (Jourawski 1857) published his theory not until 1857, and the essay by the American engineer Whipple (Whipple 1847) was almost not perceived.

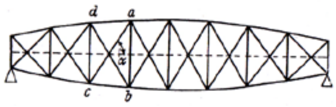
All these theories demonstrate a very systematic approach but they have different characteristics. It is the grade of abstraction of their explanatory models between the two poles: complex reality and the abstract tool of mathematics. But also it is the way structures are considered for both their basic establishment and their various modifications.

4.2 *Explanations on the basis of the beam model*

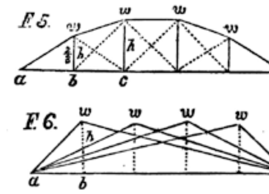
Culmann develops his theory in a series of investigations beginning with a cantilever truss beam. He clearly distinguishes between compression and tension members already by drawing cables and beams. Generally Culmann emphasizes a descriptive analysis. In his figures he clearly simplifies the complex reality but still he indicates with many details what the sketches are standing for (Figure 4a). By considering the connection of members as flexible and so to assume a hinge, he formulates moment equilibrium at a certain point where members meet. This way he deduces the internal forces of all truss members analytically. However, this method is limited to statically determined structures and does not allow for trusses with an arbitrary number of bracings.



a. Culmann, 1851



b. Schwedler, 1851



c. Whipple, 1847

Figure 4. Explanatory models for the truss theory.

Schwedler is much more abstract in his approach. In his article “Theory of bridge beam systems” he firstly derives equations for the computation of a general beam and uses these basic findings to explain trusses of several kinds. He transfers the assumption of horizontal resistances of the upper and lower beam sections while bending in order to specify the role of the bracings in a truss (Figure 4b). Through differential analysis Schwedler derives the relations between the internal forces. His theoretical construct with cross bracings is only computable because of some important requirements such as uniform elasticity and equal lengths and cross section areas for both bracings. But he also states that these requirements “will not be practicable when producing such a system” (Schwedler 1851). Although adhering so strongly to his theory he recognizes the danger of thinking according to a diagrammatic plan: “The theory is only a general scheme by which the stability of a structure should be considered, it is thus left to the individual builder to fill this scheme in each particular case with his thoughts” (Schwedler 1851).

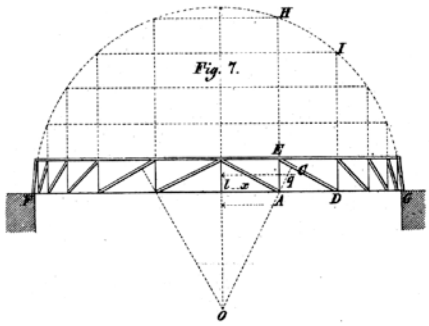
Both Schwedler and Culmann appraise the truss as a structure representing beam behavior. Bracings are considered structural filling to give the overall system stability. Also they analyze complete systems as how they were built many times before and so became specific types. This perspective to clarify structural characteristics of a system is comparable with a dissection.

Whipple interestingly uses a different approach, although eventually developing his theory very similarly to Culmann’s way. It is the way he describes the principles of load transfer that is different from the theoretical introduction of Schwedler and Culmann. In his work Whipple begins his structural explanations with a simple element to carry a single load to each side using two straight bars forming a triangle. In order to avoid horizontal thrust at these points resulting from the oblique bars there is a tie element added connecting the two points. This closed system, which directly results from the single load, is then extended to a system with four loads. Whipple discusses two systems as possible concepts (Figure 4c): One is analogue to the single load system, which gives an overlay four such triangles (Bollman and Fink developed a similar system but in reverse as a multiple overlaid cable-braced bridge beam) and the other one is an arch taking the four loads and additional vertical members to connect arch and tie. For stability reasons he also suggests cross bracings between these vertical elements, which leads to the same stability-dominated interpretation of bracings as Culmann and Schwedler expressed. But here it is eminent that Whipple composes a truss system from subsystems – with focus on stability and without respect to interweaving subsystems. The effect of a combinatory arrangement of single elements within a greater truss system becomes here slightly apparent.

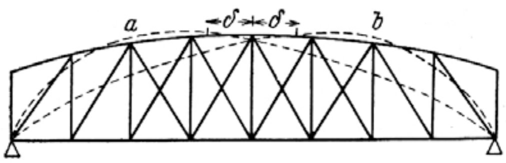
4.3 *Optimization strategies*

Both Culmann and Schwedler also analyzed formal modifications under specific criteria. After developing a method to determine the internal forces of bracings, Culmann tries to find a corresponding form for the condition that all bracing forces should be equal. Given the system is uniformly loaded, the bracing’s inclination will change: steeply inclined next to the supports and gradually less inclined towards the middle of the truss (Figure 5a). Culmann considered this formal variation as an academic demonstration only. Although interesting enough to demonstrate several effects occurring in truss systems or as a model for other situations, this approach has not been taken on by subsequent investigations.

Schwedler was heavily oriented towards economic objectives such as the optimization for a minimum of used material, which was very common at this time as iron was expensive and labor comparably cheap. For steel structures, where connections also work under tension without difficulty, he therefore proposed bracings to be designed as tension members only, requiring smaller dimensions and thus less material. Furthermore, Schwedler analyzed the form of the truss structure's upper chord depending on the changing load position (Figure 5b). As a result – still demanding all bracings to be tensioned only – he obtained an arched truss with a bend in the middle from a simple overlay of catenaries subjected to unilateral load. For aesthetical reasons he later evites the bend, straightens the arch in the middle, and adds cross bracings here according to his tension only bracing design. This truss design was extensively used in Germany during the last 40 years of the 19th century. Schwedler's design principles had a large impact on the development of bridges during that time since he was Prussian top-ranking government building officer and professor in Berlin (Hertwig 1930).



a. Culmann (Culmann 1851)



b. Schwedler (Schwedler 1851)

Figure 5. Theoretical investigations on the form of chords and bracings.

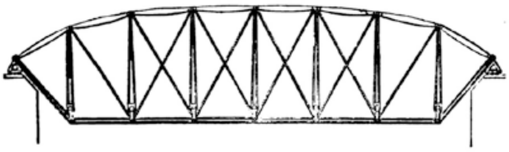
4.4 *Design cultures*

During the second half of the 19th century many different truss designs have been developed from both builders and scientists. There were, however, also different sources of further development. While many countries in Europe followed the French prototype of Ecole Polytechnique, England as an industrial precursor did not focus on an extensive scientific based engineering education. There was much distrust and reluctance against the influence of science and the use of theoretical findings in the building industry. The art of bridge building was believed to be taught best within the industry from engineer to engineer (Kaiser & König 2006).

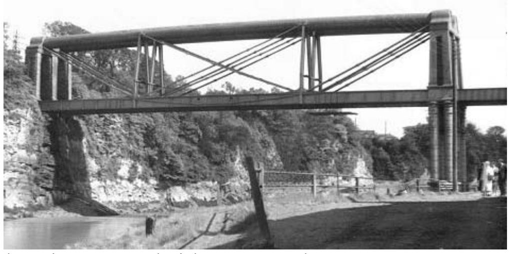
In the middle of the 19th century, when many technical colleges were already successfully established in Germany and France and theoretical knowledge found its way into building practice, the coexistence of design cultures was quite considerable. British engineers rigorously followed a great building tradition of monumental and mostly heavy, material intensive structures, while the limited resources of iron and the theory-dominated, newly formed school culture lead to strictly economic and highly rational concepts. Figure 6 gives one comparison of such kind: Pauli developed a modified and highly specific arched truss system for the railway bridge near Guenzburg, Germany, and on the contrary Brunel based his truss-like structure for the River Wye bridge on the idea of a strengthened and stabilized beam.

4.5 *Towards a structural understanding of an elementary grammar*

Driven by the numerical treatment of structures for the computer-based analysis of structures, trusses are mostly considered as a triangulated network of beams connected by hinges (Figure 7a). This trend has been set with early purely systematic descriptions of structures during the second half of the 19th century (cf. Schwedler Figure 4b.). "The structural action […] is like that of beams with the chords taking on the role of flanges in resisting bending moment and the bracing members performing the functions of webs as far as shear transfer is concerned" (Jennings 2002). Although the behavior of trusses is more elementary and actually also more descriptive, it is mostly referred to beam behavior, which was formulated much earlier (Timoshenko 1953). However, trusses can be easily understood using overlay models, such as the addition of a simple bowstring element (like Whipple described his basic structural element).

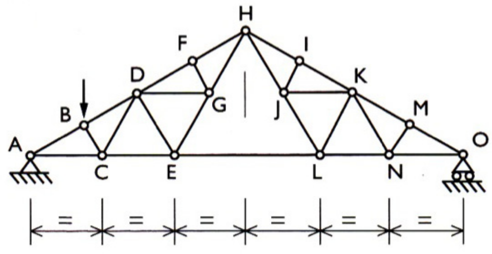


a. Guenzburg bridge, Pauli, 1853 (Culmann 1866)

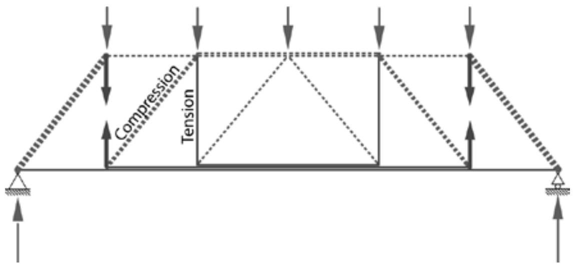


b. River Wye bridge, Brunel, 1852

Figure 6. Structural forms deviated from experience and scientific investigations.



a. Triangulated pattern (Jennings 2002)



b. Overlay of hanging and strutting elements

Figure 7. Morphological and functional description of trusses.

Figure 7b shows such an overlay where the role of members and the addition of forces become evident. These kinds of compositions can then also be used to describe many other types of structural elements, such as a beam. A simply composed truss system is therefore an excellent basis to head towards an elementary grammar of only two basic elements: compression and tension elements. As an immediate consequence, structures can not only be understood better but also be shaped more consciously and with more flexibility released from fixed types and standard shapes.

5 CONCLUSIONS

In the comparison of exemplary design cultures, here Germany and England, the difference between functional and morphological understanding becomes apparent. The impact of science can be considered as the systemization and optimization of structural form for both the system and the members and a strong dogma of overall theory consistency, which mostly becomes manifest in a specific structural type. This can be called a paradigmatic change from continuous adaption to a materialization of what is found to be theoretically sound. This process of changing ideals has also readjusted the focus from the composition of individual parts of a structure to an image based application of specific structural types.

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