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From construct to type – the transformation of constituents in the development of trusses

M. Rinke & T. Kotnik
Chair of Structural Design, ETH Zürich, Switzerland

ABSTRACT: When large span structures have been composed of single elements the incorporated structural members were direct responses to certain structural needs. Basing on the antique girder principle load bearing units have been developed consisting of struts and hanging columns. These units, relying on the early antique model, represented the constituent parts of the overall structural entity and were arranged and adapted in respect to boundary conditions and formal requirements. The establishment of theory-based simplified truss types in form of overall models and a formal structural classification system saw the framework members step back behind the overall truss layout. Their role and function was then suppressed by the regime of the truss type not admitting any formal variation in order to satisfy the explicit postulation of a regular triangulated pattern. Apart from the deficiency of specific articulation the narrow understanding of trusses also limits the understanding and judgement of such structures.

1 INTRODUCTION

Over the past centuries structural frameworks of roofs and bridges but also of many other composed structures have undergone an enormous change not only in their appearance but also, much more importantly, in the way these structures are being developed and understood. Today frameworks and trusses are used for many purposes and in different types and forms. In our modern understanding of structures, the proper application of this construction type leads to a regular arrangement of rather similar members, i.e. a uniform pattern of structural components. This understanding certainly also influenced the architectural use of such systems in favor of its rational articulation and restrained appearance.

The understanding of trusses we possess today with the clear distinction of available types and the common procedure of using and analyzing them has predominantly been shaped by modern engineering science. This is why there is first the idea of an overall structural type, e.g. truss, and then follows the determination of its components, which are derived directly from the given structure of the model type. Before scientific approaches established that view there were other understandings of composed framework structures. These relied on the determination of the components, which as a result generated an overall framework.

Compared to the common approach we have today, composed framework structures have been 1) generated more flexibly and directly related to certain boundary conditions and more over 2) understood as the interconnection of single load bearing mechanisms forming a larger structural system. In the following paragraphs some stages of development of composed structures will be explained in more detail. In order to gain insight into the various forms of understanding the designers or expert's view will be examined both verbally and visually. The latter will be achieved by decomposing the respective structure according to the appropriate verbal description. For reasons of a more consistent narrative this study is limited mainly to the German-speaking region.

2 BUILDING UPON THE ANTIQUE GIRDER PRINCIPLE

Descriptions of timber framework structures date back to Vitruvius' treatise, the oldest still existing writings on architecture and construction. Vitruvius (ca. 70-10 B.C.) described the contemporary building knowledge but only in writing. In doing so he also mentioned the conventional type of roof trusses, which were formed by struts standing on a beam and leaning against each other („transtra cum capreolis“); in case of larger spans the struts and the beam were connected by a vertical element, which was described as a hanging column. The antique girder thus already functioned as a framework using all basic components like struts, tie bar and hanging column. The antique standard type varied for different purposes but its mode of functioning stayed the same.

This construction knowledge was common and widespread among builders and craftsmen. Later in the Renaissance when for the first time a large number of treatises were produced, also due to technical progress in printing technology, lots of interpretations of Vitruv’s writings appeared including numerous illustrations (Figure 1).

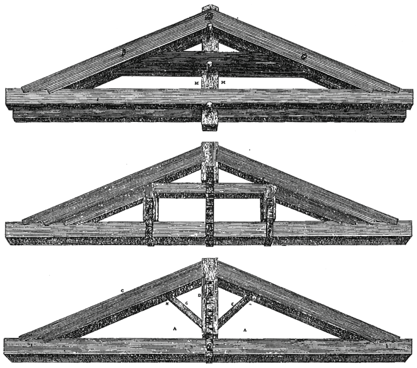

Figure 1. The antique girder according to Nicola Zabaglia (1664-1750)

Many treatises reflected the antique knowledge and understanding of construction. And in some cases there are construction details presented together with own “inventions”. Sebastiano Serlio (1475-1554), Italian architect and writer, mentioned the principal framework types („armamenti di legname“) in his famous “I sette libri dell'architettura” (Seven Books of Architecture) together with a few own framework developments (Serlio 1584). For one “invention” Serlio proposed a similar framework like the antique girder concept but extended the hanging column beyond the tie bar to include two more struts supporting the tie bar from below, which, according to Serlio, would give the whole girder a greater strength. Despite some minor conceptual errors in the construction proposals, the extended hanging column with its additional struts is an interesting variation of the ancient column-strut pairing and a further combination of it.

Another example is the treatise of Andrea Palladio (1508-1580) „Quattro libri dell’architettura“ (The Four Books of Architecture). Among some built examples of stone and wooden bridges there are a few new construction principles Palladio proposed for wooden bridges. He repeatedly considered them „strong because all the parts mutually support each other.“ Explaining the components in his short descriptions of the bridges Palladio referred to the load bearing principle of the antique girder, which relied on the same kind of hanging column: “[I]n that way the colonnettes end up supporting the beams […], and they are in turn supported by the struts that extend from colonnette to the other, so that all the parts sustain each other.”(Palladio 2002) This way, the hanging columns and the respective strut are involved in a continuous load carrying mechanism, which superimposes the single column-strut units.

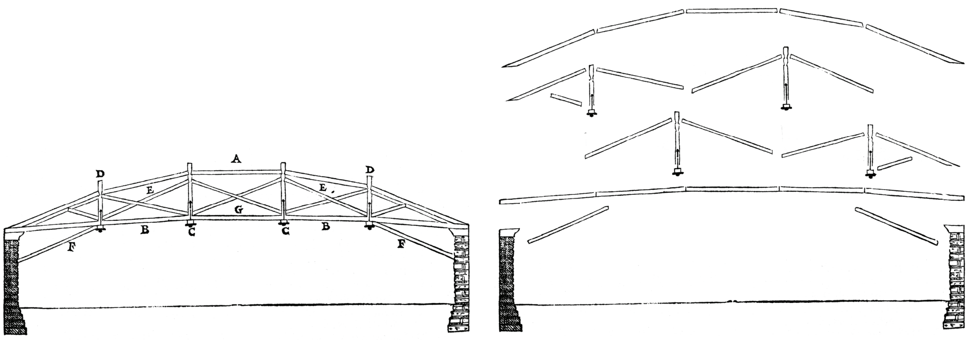

Figure 2. Palladio’s structural description of his 2nd bridge concept

Looking at Palladio’s second bridge concept and the accompanying description the same type of load bearing column-strut units can be identified. Figure 2 shows the original bridge drawing from Palladio and an exploded view of the bridge structure separating the load bearing members according to Palladio’s explanation. What appears first as cross bracings between regular columns is actually designed in a very similar way as the continuous load carrying mechanism was described. Here, the units consist of a pair of struts connected with a hanging column – fully complying with the antique girder model – and they are, again, superimposed to form a larger entity enabling a larger span of the bridge. The superposition of the struts "extending from colonnette to the other to cross in the interspace between the colonnettes" makes the regular crosses; the crosses are thus a consequence of the superposition process and not discrete elements of the design process.

3 THE CONCEPT OF SUPERIMPOSED CONSTRUCTION PATTERNS

The description and circulation of building knowledge has also been very popular in the rather technical treatises of carpenters and other craftsmen. This form of writing was established during the 17th and 18th century, above all in England, France, and Germany, and stands formally between the architectural treatises in the tradition of the Renaissance and the machinery books of a contemporary engineering tradition established at the same time. Consequently, the carpentry treatises intended to give both a comprehensive collection of state of the art construction examples in order to maintain the store of knowledge but also to give own inventions of new construction principles and details.

Continuing the basic principles of superimposed single elements in order to form an overall load bearing entity the carpentry treatises revealed a much more differentiated use of the structures' constituent parts. Instead of only arranging them linearly side by side the load bearing parts were treated geometrically flexible to provide a specific structural system for each of the many different and sometimes complicated Baroque roof shapes. Therefore, a basic framework was initially generated consisting of several structural levels each as high as a building story. Within these framework levels the actual structural units have then been arranged according to the size of the overall structure but strictly limited by the size of a framework level. This method of abstractly arranging basic construction elements together with load bearing elements can be understood by looking at one of the many construction examples of that time. Figure 3 shows a roof structure presented by Christian Gottlob Reuß (1716-1792), a well-known German master carpenter, in his treatise „Anweisung zur Zimmermannskunst" (Instructions for the art of carpentry) published in 1764 (Reuss 1764).

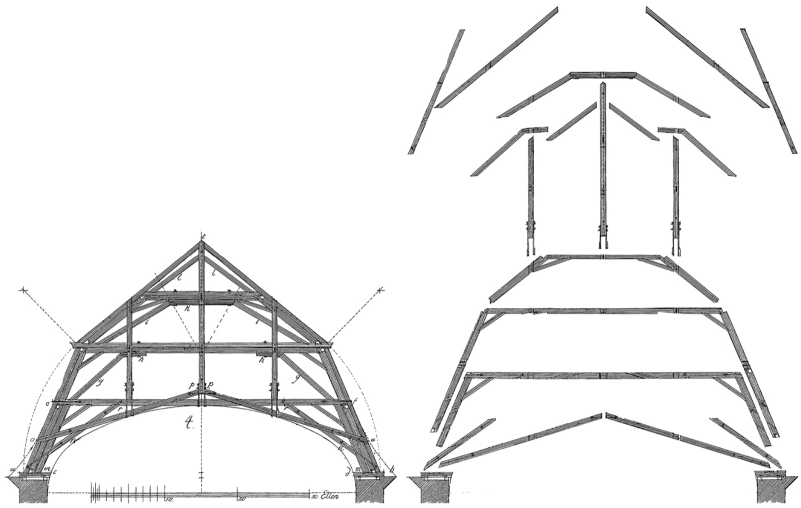

Figure 3. Structural components in Reuss' gambrel roof

According to the size of the structure a certain number of hanging columns are used to support the horizontal beams of the basic framework. Each of these hanging columns were then held by one or two struts (preferably reinforcing the central column). These structural elements were arranged separately from each other in a spatial overlay and functioned independently. By this means, the components were used for any type and any form of structure. In contrast to the presented roof structures structural solutions for bridges were only different in respect of the spatial arrangement over the construction height because there was only one level of basic framework available to incorporate all structural components. This particularly lead to a more dense form of spatial overlay because the different struts spread fan-like from the abutments to reach one of the hanging columns respectively mostly not connecting to the other adjacent units.

The hierarchical development of structural solutions by establishing a basic framework first and then incorporating the load bearing units is especially interesting for geometrically complex roof shapes, e.g. the baroque imperial roof or domed roofs. Even for these special types of roof structures the common construction patterns are applied using horizontally aligned basic frameworks and geometrically adjusted load bearing elements.

4 SYSTEMIZING AND CONCEPTIONALIZING COMPOSED STRUCTURES

At the time of the popular and widely spread carpentry treatises also other forms of writings on construction principles can be found. There were a few theoretically educated practitioners from the fields of architecture or machine engineering often closely connected within the community, which formally met in scientific societies and clubs. Publications from these people exceeded the aim of presenting construction examples by showing the fundamentally wish to include a theoretical framework to the matter of building. In this attempt they sought to rationalize and expatiate upon the reasonable design of structures and buildings but also to explain mechanisms behind the structural works they considered worthy to mention.

An illustration of this is the work from the German architect Leonhard Christoph Sturm (1669-1719) on the development of structural frameworks including own construction inventions and basic thoughts on the mechanisms behind the structural concept of hanging and strutted frames. In his short book "Gründlicher Unterricht von Häng- oder Sprengwercken“ (Thorough instructions on hanging and strutted frames) published in 1713 he introduced his three „elements“: “All hanging frames necessarily consist of struts and hanging columns, struts and top chord, or eventually of all of them, namely struts, hanging columns and top chord. […] Everything therein apart from that is dispensable and of no use” (Sturm 1713). Sturm’s first “element” is a kind of reinforced beam with two struts above the beam and hanging rods in between. The second is a beam supported by two struts from below. The third “element” is a queen truss.

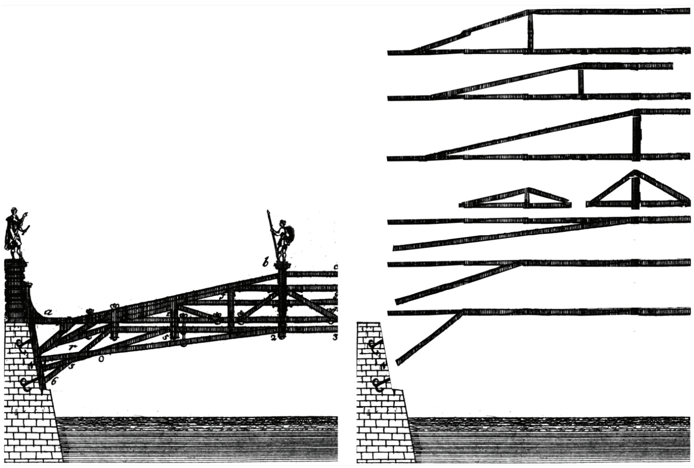

Figure 4. One half of Sturm’s bridge proposals consisting of his three “elements”

As part of his own construction inventions Sturm proposes a 170 feet single span bridge (Figure 4). The overall structure is composed from single “elements” to support all “10 hanging joists” by two “elements” each. This was particularly important to ensure the replaceability of each strut. “Again, in this bridge all three elements can be found; the first and third above, the second below the bridge.”

Sturm’s “elements” also represented single load bearing units just like the antique girder but he used them differently. The “elements” were partly superimposed to work with each other in a continuous mechanism, sometimes even in different hierarchical levels. And there were also elements used independently from adjoining parts resulting in a multiple overlay of load bearing units. The overall framework thus appeared like a compacted concurrence of many different load bearing measures though obviously resulting from simple boundary conditions such as clear span, regular cross beam support, redundancy, and preferably direct load transfer. Sturm’s approach was a very early implementation of rational load bearing measures, which were each rationally developed and then combined to create an overall structure. The composition of the units was rather intuitive and did not follow a specific rational order besides having each hanging column supported twice.

The great influence of theoretical background, which has been further institutionalized through schools and writings, can be observed among architects in the early 19th century when designing large span structures. Many of them managed to organize and dimension the load bearing structures for their buildings, especially when it was about conventional building types and common building materials. Among these there were a few architects who tried to incorporate structural principles into their overall design. One of which was the German architect and city planer Georg Moller (1784-1852). In his „Beiträge zu der Lehre von den Construktionen" (1833) Moller demonstrated the construction principle of his node system, a construction technique he deduced from the gothic building period: "all long lines from walls, vaults, and roof trusses are relatively weak but connected in small distances in fix points, or nodes." (Moller 1833)

One of Moller's structural achievements, also presented in his book, was the new dome roof of the cathedral in Mainz, Germany. For the design of the new roof structure, which had to be carried out in wrought iron because of weight restriction, Moller chose a surprisingly modern approach. He firstly identified all possible failure modes by virtually deflecting the overall structure in all directions one after another. Subsequently, he derived from each of these failure modes one single structural measure, which stood for the respective resistance force (Figure 5). The vertical common rafters were connected with the horizontal rings to avoid any movement of a rafter towards another. Therefrom, a grid emerged providing a basic homogeneous framework for further additional structural measures: To prevent the rafters from bending inwards the dome Moller arranged four rims in regular distances in the lower half of the structure; against the rotation around its vertical axis he incorporated large diagonals.

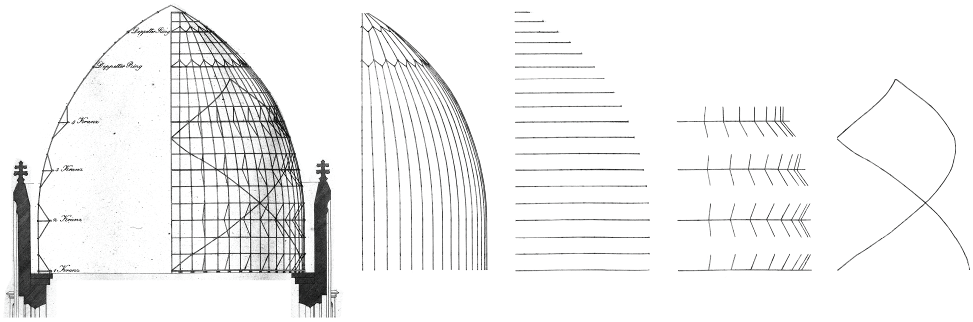

Figure 5. Moller's systematic approach of component superposition

Moller's primary intention was to design a structure with light slim construction elements that gains its robustness and strength by arranging them in a specific pattern: "This way a great number of firm triangles are generated in the perimeter wall of the dome." In consequence, as a sum of all measures a construction "of a short, reticulated and undisplaceably knotted mesh" emerged. However, this was still developed from a conventional basis, because Moller started with an orthogonal framework basing on the common alignment of rafters and their horizontal connection with purlin-like rings. Only now the integration of triangulated elements began. The structurally important triangular-shaped measures have been applied after the formal overall shape was defined. Thus the measures were supplements and not dominant character defining means. Moller thus units both the rational establishment of structural measures and the rational composition of them.

5 THE BEAM MODELL AND THE PROJECTION ONTO FRAMEWORKES

The newly established polytechnique schools across Europe dramatically changed the intellectual and technical education of structural engineers and institutionalized the form of knowledge transfer at the beginning of the 19th century. Since the teaching concept strictly relied on natural sciences and mathematics and much less on training in engineering and building practice, young engineers increasingly approached technical problems in a more abstract and model-based way. In the building treatises of that time theoretical chapters, which have been lately attached at the end of the book (Rondelet 1817), now appeared as a general introductory part at the beginning. The technical problem has thus become a specific application of the general theory.

Claude Louis Marie Henri Navier (1785-1836) is one very important figure of that time, when a dramatic paradigmatic change can be observed. He studied at the polytechnic school in Paris, which was the first of its kind worldwide and turned out to be the prototype for many other schools in Europe. Navier's influence on the changing role of engineering mechanics on the understanding and analysis of building structures was enormous. As early as 1819 he tought at the École nationale des ponts et chausses and published his very popular lecture notes in 1826

(Navier 1826). Together with the other intellectuals in charge for the basic training of the engineering students in mathematics and physics Navier sought to establish a new rational engineering culture. (Kranakis 1996)

According to Navier's established theoretical work also framework structures based on the theory of the elastic beam, whose inner stresses and strains were expresses through the beam's internal coordinate system strictly aligned with the beams' "fibers". This was done by projecting the entity of the beam onto the assembly of single components. Thus every framework possesing the outline shape and overall effect of a beam was considered a variation of the basic model of the beam, i.e. a beam equivalent. Figure 6 shows some examples of such beam equivalents.

a) Combined main bars   b) Arched bars with cross pieces

Figure 6. Navier: Composed beams considered as massive continuous beams

As long as the constituent members are definitely connected the framework was to be considered a solid and continuous entity. In this method it was not specified how the major parts, the upper and the lower bar, were hold in place; the inner components were neither specified nor determined. The only important aim was that the formula of the solid beam could be used. The constructive requirement – the connection parts between upper and lower bar – could not be expressed analytically in the theoretical model. In Navier's framework description the actual constituent components were not reflected but all served to establish and maintain an equivalent beam performance.

One of the many forms of direct application of the beam model can be observed in Karl Culmann's (1821-1881) analysis of American timber bridges in 1851, which culminated in a theoretical model of truss bridges. Culmann's definition of the truss construction principle declared "the upper and the lower members as the major bearing components […]. The filling in between them […] only conduces to force them having the same center of curvature when folding in, and to enable them to function like the outermost parts of a solid beam with the depth of the framework." (Culmann 1851)

Due to their type of construction these structural entities consisted of a series of single elements. Similar to the traditional timber-frame construction of buildings the construction space was structured into frames by setting vertical members in regular distances. After Culmann, this applied to all composed structures of that kind, "which can be understood as composed of multiple slidable rectangles." To gain stiffness there was a need for a strut or – to ultimately eliminate sliding – a St Andrew's cross in every rectangle. Figure 7 shows the systematic configuration of the constituent components of such a structure, which is a bridge developed and patented by Stephen Long in 1839.

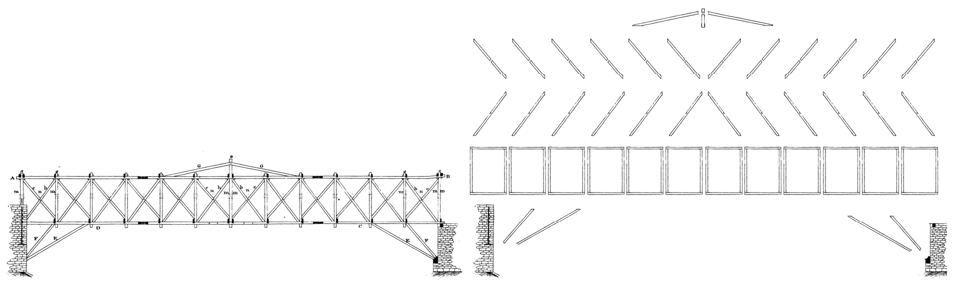

Figure 7. Culmann's description of Long's Truss Frames

In this structural conception the overall structural entity was composed of rectangular units, often referred as panels, which string together to form a beam equivalent. The strut has been abstracted from its initial function of direct strutting and load transfer; it no longer was assigned to a certain hanging column with which it formed a load bearing unit since the antique girder. It was now rather a single member used to block any possible sliding of the structure's constituent elements, the rectangular frame units. Only together with the incorporated strut a rectangular unit proves to be an effective load bearing unit, which then is – as the smallest structural entity – the actual constituent element of the beam equivalent structure.

6 APPLYING TYPES AND SHAPES

Together with a rational survey of existing structures and the standards of clearly defined method-based analyses those formulations of composed structures and frameworks ended up in a stipulation of basic types and their classification in formal categories. This made first an appearance in the early engineering and construction handbooks in the 1850's. The strict application of truss and girder types could also be found when large span trusses were developed. Johann Wilhelm Schwedler (1823-1894) demonstrated this common approach in 1846 when demonstrating the composition of roof trusses from smaller structural systems and girder types.

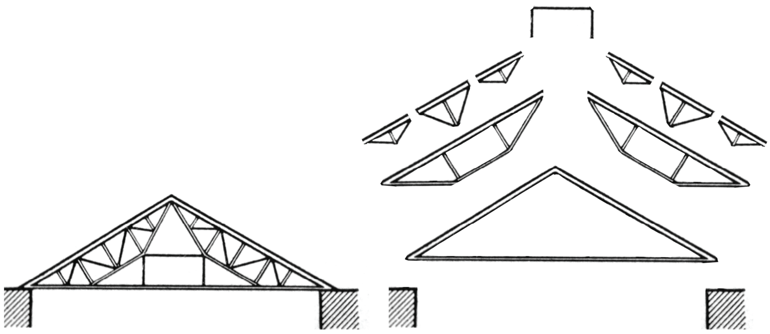

Figure 8. Schwedlers description of a typical conceptual composition for a roof truss

Schwedler sought to show "the formation of complicated girders from simple ones" and how they could be analysed (Schwedler 1846). Figure 8 shows such a construction example and an exploded view of the breakdown of structural systems according to Schwedler's description: "The calculation of the resistance of the single structural components can be done the same way as the overall structure was composed." For the given example one had firstly to calculate the simple roof truss and subsequently the added systems, which have been used to provide additional supporting points. "For those structural members, where components of different structural systems are stacked, appropriate dimensions have to be chosen according to the sum of the resistances of each overlaid component."

By the end of the 19th century truss types have been widely defined and cultivated through the circulation and demonstration in many popular engineering textbooks and other writings, e.g. Warren, Howe, Lenticular, Pratt, or Lattice Truss. When Georg Christoph Mehrtens (1843-1917) published his chronicle of 19th century German bridge building (Mehrtens 1900) he described the established types as modern achievements originating clear and rational truss layouts. His retrospection bares the long history of the key principle to form triangles, which has made crucial progress with the influence of scientific methods. Figure 9 shows a bridge truss equivalent to Mehrtens' explanation, "revealing the Warren system with integrated auxiliary members." In the modern structural classification system of composed structures the constituent members stepped back behind the overall truss layout; their role and function was suppressed by the regime of the framework or truss type not admitting any formal variation in order to satisfy the explicit postulation of a regular triangulated pattern.

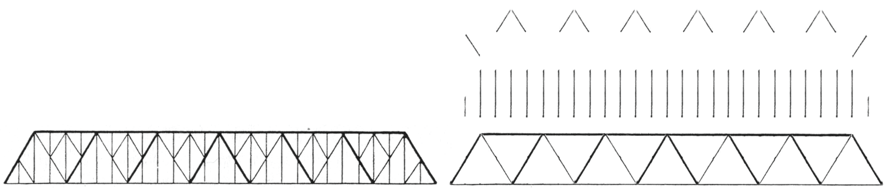

Figure 9. Mehrtens' understanding of a typical bridge truss

7 CONCLUSION

The role of the constituent framework members has dramatically changed during the last centuries, particularly since its concept is theoretically reflected and knowledge is circulated. The load bearing units consisting of struts and hanging columns, combined serially or in a superimposed manner, were increasingly organized and interpreted as larger formations, but also universalized in their role and function. The demand of a pragmatic engineering handling of the numerous framework variations and direct application of calculation models but also simplified construction members for building purposes led to simplified truss type diagrams and a formal structural classification system. This development is commonly reflected as both the progress of structural systems and the clarifying influence of emerging structural theory. However, the presented trend also identifies the increasing inability of flexible framework generation leading to standard-only forms of composed structures. Apart from the deficiency of specific articulation through flexible component arrangement, the type-based understanding of trusses in abstract categories also limited the understanding and judgement of such structures.

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