Bio-Inspiration in Architectural and Structural Design: Learning from Nature

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Abstract. The recently developed design tool, Performance Control (PC), incorporates both the essence of the classical concepts and the newer procedures and addresses the observed performance of the building system during its known history of service and loading. PC attempts to utilize bioinspiration by applying the known theories of architecture and structures to the design of case-specific building systems, rather than investigating their results for compliance against prescriptive criteria. Here, parametric examples of structural forms have been provided to illustrate the applications of the conceptual design similarities between trees and manmade support systems. It has been shown that an understanding of the structural performance of trees can enhance the architectural and structural design of framed system and that bioinspired PC can lead to a minimum weight moment frames under lateral loading. The analogous performances of the natural and manmade structures may help explain the structural response of trees to similar loading scenarios.

Introduction

Nature has always been a source of inspiration for the design of the human environment. The analysis of biological constructions can not only lead to astonishing technical solutions but can also inspire the design of the architecture as a whole. Bionics is a fascinating interdisciplinary area between pure research and practical applications: biologists, chemists, physicists, mineralogists, and paleontologists meet up with material scientists, engineers and architects and transfer the benefits of their knowledge to architects and construction specialists.

Nature makes purpose-specific materials one atom at a time, such as spider silk, wood, etc. Humans have been inspired from nature by creating synthetic materials also one atom at a time, e.g. Nylon, Kevlar, etc. It is therefore natural for humans to wish to understand how the same natural materials are used to create such magnificent structures as spider webs, trees, etc.

In the physical sense, the word ‘structure’ implies arrangement or putting together of material parts or elements in a purposeful manner and as such may apply to nano-systems, manmade objects as well as the entire universe. In the present context, the structure is referred to as manmade load-bearing engineering frameworks. “Design” in this context implies the thought or natural processes that may lead to the realization of a structure or system.

Corporeal entities may therefore be characterized either as natural or manmade structures/systems. Natural structures or systems may be exemplified by such familiar objects as mountains and coral reefs, bird nests and eggshells, cobwebs and honeycombs, trees and plants, etc. Bridges, buildings, dams, transmission towers, pipelines, reservoirs, etc., are well-known examples of engineering structures.

While the history of earthly natural structures is as old as the planet itself, the history of modern structural engineering is hardly two centuries old [1,2]. While the ancient Egyptians, Greeks, and Romans are credited with establishing the art of structural engineering, the analytic understanding of the physical phenomena, underlying structural theories began during the Renaissance.

Earthquake engineering, a sub-discipline of structural engineering, is only decades old and is still being evolved [3,4]. Both natural and manmade structures are realized through evolutionary design scenarios, both systems obey the same laws of nature and are subject to the same environmental conditions [5]. Loading energizes all structural systems, unloading discharges or reduces stored energy. The passage of time tests and deteriorates all structures. All structures are expected to withstand lifetime normal (service) as well as extraordinary (survival) environmental conditions.

Natural, design-build methods tend to result in the most desirable (optimal) structural systems concerning their functional response and environmental conditions, whereas the same cannot be claimed for manmade systems. Matteck [6] has shown that "Trees optimize their mechanical design by adaptive growth, and react by self-repair to loads disturbing their optimum mechanical state."

The purpose of this article is not to present a discourse on natural systems, but rather to propose a basis for a parallel approach between natural and synthesized design methodologies for type and loading specific structures. Nature does not preplan construction as humans do. Nature simply creates or builds as needed.

Nature imposes its laws of physics on things that it creates. Humans follow their limited knowledge of materials and applied mechanics and check the validity of computer-generated results against prescribed criteria.

Natural designs do not depend upon number crunching. Nature provides what is best for the purpose under the prevailing environmental conditions. Contemporary architecture and structural engineering rely mainly on investigating design-related numerical output. The question that arises often is under what conditions and to what extent can humans inspire nature and impose their current knowledge of architecture and engineering sciences to what they plan to build? In other words, what are the differences and similarities between natural and human design philosophies and how can humans use natural design strategies, if it exists, to build engineering systems? The answer to these queries may be found in Vogel and Davis's [7] assertion that the fundamental differences between natural and human strategies are in how these plans originate during the processes we refer to as design.

The article introduces a new facet of bio-inspiration which attempts to unravel the natural design strategies involved in the structural performance of trees, rather than synthesizing new load-bearing forms, substances, and/or utilizing them as raw materials.

The forthcoming parametric studies suggest that bio-inspiration can help transfer basic design concepts from trees to simple framed load bearing systems under lateral and/or combined loading conditions. Performance Control is a rational procedure that can help improve the design of manmade structures. The paper does not discuss the biological traits and evolutionary development of trees.

Natural systems, bio-inspiration, related to architectural and engineering structures

Bio-inspiration and adaptations from nature are the exercises in learning from nature and applying to manmade systems, and as such, are not new sources of inspiration for architects and civil/structural engineers. Humans have been imitating nature since the beginning of time. The recorded history of learning from nature, inspiring a natural water tunnel, dates back to Ghanat (subterranean waterways) technology, in the Persian Empire, developed by an unknown genius some 3100 years ago [8]. The next noteworthy nature-inspired structure, inspiring mountains and still standing, is the Step Pyramid in Egypt built by Imhotep, the first structural engineer / builder known by name in 2700 B.C. [9]. Humans are still using wood, dirt and rocks as basic building materials. Bio-inspiration has already become part of formal architectural/civil engineering studies and has been utilized rather successfully to discover new materials, functional shapes, and methods of achieving purposeful goals [10].

Nature does not use processed or unnatural materials such as plastics, concrete, and/or steel to build, it does not limit itself to such primitive design methodologies as elastic and/or plastic methods of approach. Civil/structural engineers are expected to design their structures to withstand loading combinations hypothesized by their peers. While bio-inspiration has helped engineers and architects achieve purposeful forms and functions for certain applications [11,12], it remains to be seen if the underlying natural design concepts, in distinction to prescriptive methodologies, can be transferred into practical embodiments with true utility in manmade structures. To prepare for an answer, it seems reasonable to first identify as many natural characteristics as possible that may be in congruity with our current knowledge of the manmade world. Once the demand-response characteristics of a natural system are understood, they may be translated into feasible design/demand requirements for prospective prototypes. An excellent account of the transfer of micro-structures to the bionic lightweight design of technical components may be found in Ref. [13].

The case for manmade structures

It is instructive to review the ways and means manmade structures, such as multistory frames that are built-in contrast with how natural structures, for example, trees are created. The process of building a manmade structure generally begins by planning an imaginary, preliminary architecture/configuration, at times aesthetically motivated, with no definite ideas of its methods of realization and/or performance concerning its function and environmental conditions. Contemporary engineering knowledge, means, and rules of general guidance are then put together to investigate the validity of an initial design. The process is repeated until certain prescriptive conditions are satisfied. The questions of suitability of forms and materials, methods of construction, performance goals, optimization of costs, etc., are seldom addressed at the inception of the design process.

These questions are usually dealt with too late to add value to the project. Engineering frameworks, including timber structures [14] are commonly analyzed and investigated for compliance with rules set in Allowable Stress Design (ASD), Load-resistance Factor Design (LRFD), Plastic Design (PD), or Performance-Based Design (PBD) methods of approach [14–16]. They are not, to the true meaning of the word, "designed", but are investigated and/or tested for compliance against knowledge-based criteria. Nevertheless, these methodologies have served mankind well and have paved the way for further improvements through experience, bio-inspiration, and applied research. Nature does not prefer form over function – it imposes its design requirements on whatever it builds. Nature does not engage in structural analysis, instead, it creates purpose-specific, practically optimal configurations with built-in performance controls. In other words, it induces and controls the performance of its design. PC, as an architectural and structural design methodology [17] is the most applicable feature of bio-inspiration adopted in this article. PC in this context implies the ability to design a structure in such a way as to expect predetermined modes of response at certain stages of loading, extents of damage, and/or drift ratios. PC can help regulate the sequences of infliction of damage or formation of plastic hinges rather than treating them as casual results of the analyses. In PC, as in nature, failure mechanisms and stability conditions are enforced rather than tested.

Architectural and Structural characteristics of trees

Trees are one of the most successful natural systems that have existed on earth long before humans discovered their multitude of benefits [18]. They are the most abundant and familiar natural structures on the planet. Trees have been providing habitats and environmental conditions to humans and other forms of life for millennia. Human survival has been closely linked with trees and their byproducts since the beginning of time. It is therefore instinctive for the human to try to understand and imitate the underlying design concepts of the most successful natural structure. However, the following organism-specific features may also be identified, from a structural engineering point of view, for trees as natural frameworks [5,7,10-12,14,18]:

- Trees are three-dimensional, structurally determinate natural structures.
- Trees are made out of time-tested materials and elements that can adjust themselves for changing environmental conditions, e.g., the leaves can orient themselves in such a way as to absorb/deflect sunlight, high winds, and shed snow.
- Trees orient their construction in such a way as to avoid maximum external forces.
- Trees can be classified as upright cantilevers and/or simple branched load support systems.
- Self-weight stresses are minimal in comparison with wind and/or snow-induced effects.
- Trees are structures of uniform response, stresses and strains of all sections are nearly the same under constant loading.
- All members of a tree are made out of the same materials with varying strengths as required.
- All tree members have singly connected cantilevered members, there are no simply supported or closed-loop elements.
- All cross-sections of the stem and the branches are as symmetric as possible, torsional, local, and global instability effects are minimized.

- Trees are structures of minimum weight. Each member is optimized for its function and form.
- Lack of mechanical ductility in trees is compensated by higher flexibility and damping.
- Trees sustain relatively large lateral displacements during extreme wind conditions.
- Tree joints can achieve a quasi-plastic response at extreme loading.
- Tree joints possess higher toughness than the stem and the branches.
- Mechanical strength is highly optimized concerning local form and function.
- Trees are multi-degree freedom systems with high damping characteristics.

Because of high damping and the multitude of independently vibrating elements (leaves and branches), trees seldom experience resonant vibrations.

- The circular/oval cross-section of tree trunks can withstand greater compressive loads than any other solid cross-section with the same amount of material.
- Tree trunks are naturally pre-stressed in both axial and circumferential directions.
- Tree roots are designed to be deformed and uplifted to a certain extent to prevent permanent damage to the base of the trunk.
- Trees are known to shed leaves and fruit, even mature branches to reduce extreme stresses on the stem and the roots.
- Trees grow on firm foundations with ample access to moisture and nutrition.

Design methodology transfer from trees to building structures

While there are countless numbers of natural systems and materials, there are only limited numbers of manmade structural types and synthesized materials of construction, consequently not all desirable features of natural systems could be incorporated into the design of all known forms of engineering structures. Scientific studies, including the statics and dynamics of trees [19,20], have suggested that green trees can serve as ideal models for bioinspired structural prototypes, in that their performance can be assessed in terms of known principles of material sciences and applied mechanics. The results of such studies have helped establish meaningful analogies between trees and engineering structures. A study of the characteristics of natural structures in general and living trees, in particular, leads to the following lessons for the materialization of idealized bioinspired structures.

- The laws of conservation of energy should be observed as the fundamental guidelines for the conceptual design of prospective structures.
- Theories of design and construction should be applied rather than followed.
- The fundamental idea expounded here is that the response of manmade structures should be a function of design and construction rather than analysis.
- The building of things should be based on design-led analysis rather than analysis of design.
- Architectural and architectural and structural design should be performance-based rather than instruction-oriented. In other words, structures should be designed by observed rather than expected behavior.
- The form should suit function. The function should not be compromised for function.
- Desirable response characteristics should be provided for (induced) rather than investigated.
- Constitutive elements of structures shall be repairable, environmentally friendly, and recyclable.
- All structures shall be designed and constructed promptly and in such a way as to consume the least amount of energy and materials.
- As much as possible, structures should be constructed out of similar members and materials.
- In a progressive collapse scenario, the premature failure of the base or foundation of the structure should be avoided at all costs.

Basic rules of methodology transfer from natural to manmade structures

While the natural world may be looked upon as a lesson book for engineers, the established principles of architectural and structural design should also be taken into account for practical projects. However, to comprehend and utilize the functional, economic and technical relationships that may exist between natural models and their manmade prototypes, both the inspired and the established principles should be coalesced without compromising one for the other. Therefore, to capture and transfer design knowledge from a living organism, such as a tree, to an engineering framework, e.g. a moment frame, the following basic rules or conditions of affinity should be considered:

- Structural applicability (geometric and framing similarities, use and behavior of materials),
- Functional similarity (being subjected to similar loading and environmental conditions),
- Response homology (behaving the same way against comparable external effects),
- Economic viability (being as cost-effective and as energy efficient as possible).

Bio-inspired design recommendations

The challenge here is not only to satisfy the conditions of affinity and to mimic as many natural characteristics as possible but also to try to understand the design philosophies that have lead to the materialization of the natural model. The following practical recommendations come to mind [10-17]:

- Develop a feel for the response of the real structure under all functional conditions,
- Develop a design strategy that is based on observed bio-inspired performance rather than expected response. Begin with planning a firm foundation for the proposed structure,
- Induce and/or apply the desirable design conditions to the proposed structure rather than checking the analytic results for compliance against prescribed criteria,
- Generate a statically determinate or quasi-determinate structure of uniform response for combined gravity and lateral loading,
- Arrange the constituent materials/elements of the system in such a way as to maximize their stiffness and to lower their center of gravity,
- Reduce dynamic effects by increasing the fundamental period of vibration. Provide as much damping as possible,
- Induce uniform drift to minimize secondary and instability effects,
- Allow for service and extreme functional displacements throughout the loading history of the structure,
- Minimize the self-weight of all load-bearing elements with respect to ultimate loading conditions,
- Prevent catastrophic failure through increased ductility, local and global stability as well as installation of fail-safe devices, etc.,
- Allow for preplanned sequences of formations of plastic hinges at all beam-ends,
- Implement the strong-column weak-beam principle and prevent and/or delay the premature formation of plastic hinges at column feet [21].

Branched load support system

Branched systems are of fundamental importance in all domains of nature. In the context of building construction, systems that transfer forces are of a tree, the reinforcing veins in the wings of insects, the widely spread web of a spider, or the inner structure of a bone. The latter consist of many small bone trabeculae that from a branched system of compression and tension struts, which stabilizes the bone at the exact points where loads impact it.

By contrast, plants, bones and other natural branching systems are generated in a continuing growth process. In this process they not only grow in size but, at the same time, continuously adapt their shape and inner structure to the forces acting upon them, and in that way change and improve their loadbearing capacity. There are no joints or other discontinuities. Like the bone trabeculae, all twigs and branches of a tree are homogeneously grown together. Plants are of particular interest because they develop quite different forms of ramification. Some feature a main axis from which significantly smaller side shoots branch off. In others, the main axis itself divides into two or three main axes of (almost) identical size, which in turn undergo further ramification. Within these two main groups in the world of plants we can find innumerable different types of ramification, which are capable - sometimes with very different structures - of reliably supporting the load of their own weight, as well as the wind and snow loads impacting on them [22].

From plant branching to technical support structures

Bridges and roofs are often supported by branched steel columns. Their production is usually expensive and consumes a great deal of energy. In nature, plants manage to form similarly strong and frequently even more complex branch systems through natural growth processes. They can effortlessly withstand mechanical loads, such as their own weight, wind pressure, snow load, or the heavyweight of fruit. In order to find out about the success strategies of ramified trees and shrubs and to learn from them for architecture, we need more than a detailed look at the form of ramification and inside the plants. We also need computer models and new materials and methods for the production of branched support structures in building construction to succeed in transferring the biological concepts to technology.

Plant branchings as an example and inspiration. Trees and shrubs look very different from one another. Even within one species, there are sometimes big differences in size, appearance, and the form of growth. The same applies to the connections between trunk and branches, and the branch ramifications themselves. Depending on the form and size of the plant, as well as various external factors, a wide range of branching patterns are formed. An important role is played by external and internal forces acting on the plant, such as the plant's own weight, sometimes involving mighty branches or heavy loads of fruit, and strong effects of the weather such as wind or precipitation. In addition, plants constantly compete for sunlight. The successful plants are the ones that can outdo their competitors in height and width, by growing taller and/or by more effective ramification. As a result of all these factors, a huge diversity of branching patterns exists. How can we find suitable models from this profusion for the optimization of architectural support structures for buildings or bridges?

In this context, one must always remember that a direct transfer is not possible. Even though they look similar, the ramifications of plants and architectural structures differ in many aspects (Fig.1).

Fig. 1. Detail of the ramification of the Oriental paperbush (Edgeworthia chrysantha), with three branches of almost identical diameter (left), and branched columns at Stuttgart Airport each with three or four equivalent struts (right)

Plants can react to specific local loads through increased growth and by depositing material in certain regions. By contrast, support structures in construction are static. Likewise, the functions of the support structures differ in nature and technology. In plants, these structures are responsible not only for mechanical stabilization but also for the transport of water to the side branches, leaves, and fruit, and the transport of photosynthesis products (sugars) from the leaves to the storage organs. In technical applications, support structures primarily serve structural stability but, increasingly, are also used for other functions, such as integrating, for example, drainage, ventilation, heating, or lighting. Plant ramifications are not connected at their apices. When exposed to load, they are forced to bend downwards (e.g., under snow loads or fruit hanging from the tree) or are deformed laterally (e.g., through wind load). This leads to bending stresses in the branches. In architecture, branched columns mainly carry roofs or flat elements that connect the ends of the columns firmly with each other. In this case, the imposed forces act for the most part in the direction of the columns. Consequently, when looked at in more detail, the term "tree column" does not fit very well for the designation of these branched architectural columns. A direct transfer or a copy of nature is not something that promises to be successful for the reasons stated. If we want to draw lessons from natural branching for technology, simplification, and abstraction of the basic functional principles are always necessary.

Why branched columns? One success strategy of plants is to create as large a (leaf) surface as possible for harvesting energy from sunlight with as little building material as possible. The ends of the trunks and branches are not restrained. At these points, the plant continues to grow. By contrast, the ends of the branched supporting elements in buildings are firmly attached to other parts of the building. Often, they are directly attached to the roof of the building. The advantage of branched columns versus unbranched columns is obvious: the structure to be supported-for example a roof-can be more slender and more lightweight because the distances between the endpoints of the branched supports are smaller. Furthermore, a roof construction with branched columns at the same height as a roof construction using unbranched elements with the same quality of support provides significantly more open space on the floor. Because the form of the branched columns affects the load transfer and the thickness of the columns, the design is aimed at finding the most favorable form.

A wide choice. Most trees we are familiar with from our local forests and parks have substantial lateral branches. These "typical tree ramifications" are characterized by their size, their mechanically strong wood, and their growth rings, which in our latitudes are quite pronounced.

However, when searching for biological role models, our attention is also frequently drawn to branching of a somewhat different kind. These sometimes don't reveal their special features until looked at more closely, but there's more to it. For example, columnar cacti are frequently (much) thinner at of all places, their points of ramification - seemingly the points where strength matters most than at their stem and side branches, which is a result of the way the side branches are grown. Together, biologists and engineers were able to demonstrate that the form of this narrowing at the point of branching constitutes a special adaptation of the columnar cacti, which store large and heavy quantities of water in the cortex of their stems which enable them to survive phases of drought. This form of the branching region facilitates the distribution of mechanical loads in the main stem and the side branch, making it possible to support greater loads.

The dragon tree too (genus Dracaena), which ranges from small houseplants to imposing trees (Fig. 2), employs a special trick for forming strong ramifications. Lignified fibers embedded in soft ground tissue are adapted in arrangement and orientation to the loads acting on them (Fig. 3). In this way, the branching region is reminiscent of fiber-reinforced composite materials like those used in lightweight construction for the manufacture of sports articles or parts of automobiles, as well as, increasingly, in building construction.

Fig. 2. Canary Islands dragon tree (Dracaena draco) with numerous hierarchical ramifications

Fig. 3. Longitudinal section through the branching of a Dracaena marginata tree

New branched loadbearing structures in Architecture

Branched loadbearing structures have a long tradition in architecture. After centuries of application, the principle of this construction method is still valid today and results in good structural systems. It is obvious why this is so: owing to the form-active design, slender branched columns are effective supports for roofs and floor decks.

Form-active loadbearing structures permit wide spans. As early as the Middle Ages, master builders knew how to use arches and vaults in their designs to create large open spans that appeared very elegant. To this day, many of these structural systems baffle us with their "audacity" (Fig. 4). Here too, a construction method inspired by nature played a role, but only at an esthetic or formal level rather than a functional one. Whereas in the Middle Ages stone was still the main building material, in recent decades it is primarily steel that has been used for branched pillars and columns, for example in bridges or buildings (Fig. 4). However, the manufacture of branched nodes, which frequently consist of cast steel, is expensive. An alternative could be a hybrid construction with an outer hull of fiber-reinforced plastic and a concrete core.

A well-known example of branched columns is the structural system of Stuttgart Airport. Whereas the space close to the ceiling and above the heads of the air passengers is available for the branched loadbearing structure, the circulation level is large and generous and encumbered only by the widely spaced lower parts of the columns (Fig. 5). The loadbearing characteristics of a branched column are quite different from those of a natural tree, which is why the frequently used designation "tree column" is misleading. The ends of branched columns - the column heads - are connected via horizontal loadbearing elements, as in the slab of a building or the road deck of a bridge. The loads are primarily transferred as normal compression forces. By contrast, the branches of trees have free ends and respond to loads - such as their own weight and external loads such as those of wind and snow - by bending. For this reason, natural ramifications in plants are primarily exposed to bending loads.The difference can be clearly seen in the diagram of internal forces (Fig. 6, 7).

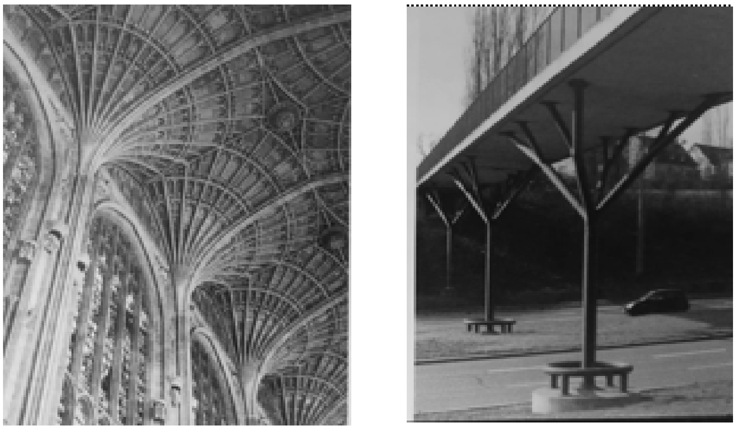
A B

Fig. 4. A-King's College Chapel, Cambridge (1515): masonry
B-branched pillars of Pragsattel Bridge, Stuttgart (1993): steel construction


Fig. 5. Branched columns support the roof of
Terminal 3 at Stuttgart Airport

Branched columns, as shown in Fig. 5, are of a slender construction. This means that the ratio of the diameter to the length of the bars is small. The loadbearing capacity of slender structures exposed to compression depends on the strength of the material used as well as on the resistance to buckling (i.e., to stability failure). Stability failure occurs when the loadbearing structure deforms under a load-like ruler that deflects when exposed to axial compression.

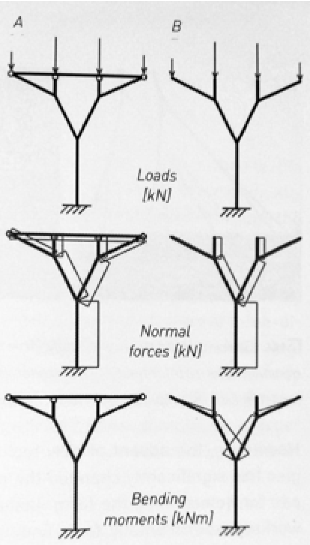

Fig. 6. A-Branched columns with a reduced cross-section height of the horizontal element, B-the horizontal element spanning nonbranched columns with the same spacing as in (A) needs to be thicker because the spans and the bending moments are larger.

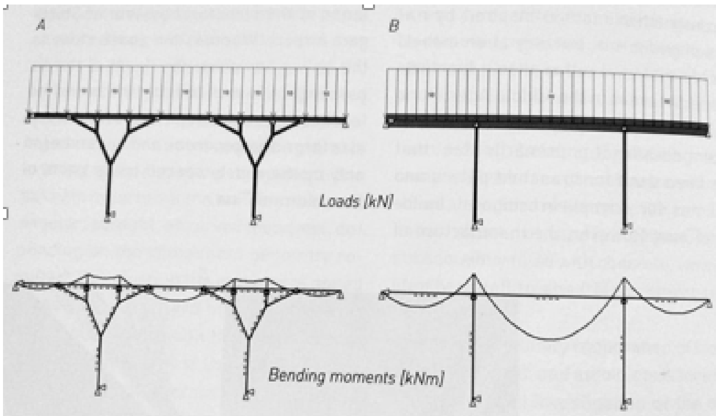

Fig. 7. Comparison: A - internal forces of a branched column with tension member, B - example of internal forces in a tree. Branched columns not only make efficient use of space, they also have other advantages: the branched columns provide many support points for the horizontal loadbearing element, such as the roof or the deck of the bridge. This effectively reduces the distance between two columns to be spanned by the horizontal element. Smaller spans lead to a reduced construction height. In turn, this means that less material is needed for the horizontal element, reducing the overall weight of the construction.

Finding the form of branched columns. In the design of branched columns, their geometry plays an important role because it determines the distribution of the internal forces. A geometry needs to be found in which the bending moments are as small as possible, therefore requiring only small cross-sections in the members. To achieve this, several different experimental and analytical methods are available.

An experimental approach was taken by Gaudi, for example, he used hanging models for designing the main loadbearing structure of the Sagrada Familia (Barcelona). To do this and to define the form of the ribs and vaults, he hung define weights from a cable network and used the deformed model as the basis for the design of the building.

In the second half of the last century, Frei Otto's working group continued the development of experimental methods for determining the geometry of branched structures. By hanging weights from threads, it was possible to identify branch configurations that are suitable as effective loadbearing structures. Branched structures can also be formed experimentally by fibers saturated in resin that, at one end, are attached to the grid of a plate and, at the other end, converge at one point. Owing to surface tension, a balance is achieved between the resulting attractive force and the retained threads (Fig. 8A, B).

Nowadays, the advent of new technologies has significantly changed the methods for determining the form. Instead of working experimentally, form-finding processes can be simulated using a range of computer programs (Fig. 8C). For example, the structure optimizing methods help to find a branching geometry that transfers a certain load with the minimum amount of material.

Fig. 8. Experimental determination of form: A - thread model (ILEK),
B - project study "Tree structures" (ILEK), C - digital determination of form: computer simulation

How branched columns are built today. Today, branched columns in buildings or branched pillars in bridge buildings are frequently manufactured from steel or reinforced concrete. The disadvantage of the reinforced concrete construction lies in the comparatively expensive formwork and reinforcement work.

When steel tubes are used, several tubes have to be cut precisely and then welded together. As a rule, the surfaces of the cuts are complex and therefore the welding work is expensive. Alternatively, a connection node made of cast steel is used at the intersection of the bars (Fig. 9). This ensures a continuous transfer of forces at the transition between the individual bars. In this constellation, each tube is welded to the connection node instead of joining several tubes at one point. In view of the fact that the manufacturing of cast steel nodes requires complex molds for high-temperature casting, they only make sense when the node geometry is repeated several times in the building.

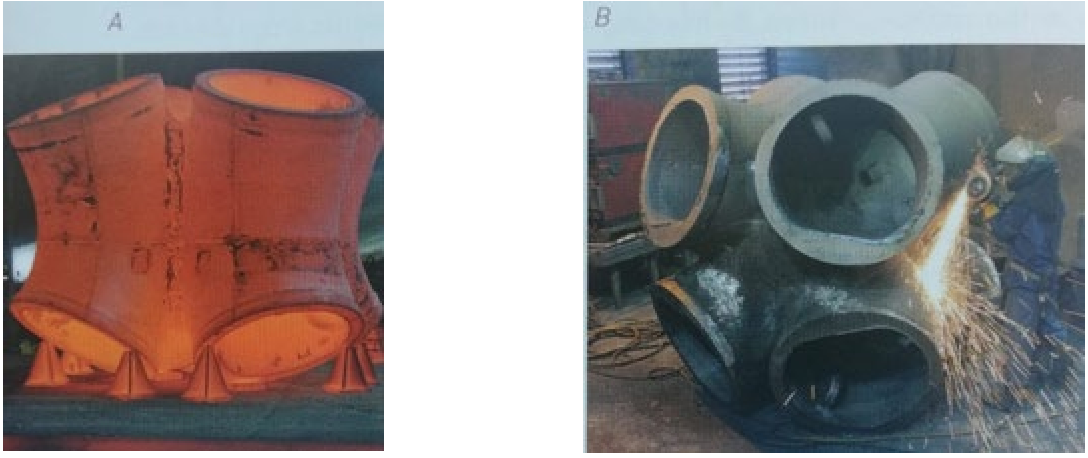

Fig. 9. Manufacture of a cast steel node: A - cooling of the cast, B - mechanical finishing work on the component

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