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Natural structures: strategies for geometric and morphological optimization

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Abstract

For centuries, architects and engineers have been searching the most efficient structural arrangements for their projects. Some of them have founded their proposals on the principle of *biomimesis*. The aim of their approach was to check how useful were –for structural purposes– some geometrical patterns displayed by Nature on organic or inorganic bodies.

Nature develops its structures in order to reach always optimal energetic solutions on a long term basis. The most usual arrangements are: pneus, shells, trees, webs and skeletons. All of them are controlled by four main factors: nature of forces, global form, local design and quality of material. Additional parameters, like pattern or material lightening, sometimes changes substantially the resulting geometry, and also some other general features as flexibility, integration, continuity, or self-straining are surrounding in most examples.

This paper presents the achieved results on this topic by relevant authors of diverse fields: from the drawings of micro-organisms by the naturalist Häckel and the descriptive studies of the biologist Thompson, through the topological analysis of the patterns by the engineer Wester, the studies of natural lightweight structures by the architect F. Otto, to the final applications to light mega-structures by the engineers R. Le Ricolais or Buckminster Fuller

Keywords: biomimetics, natural structures, efficiency, topological patterns, lightening, pneus, shells, trees, webs, skeletons

1. Introduction

Always man has taken inspiration and knowledge from Nature, in many different issues: Art, Philosophy, Technology, Physics, Politics, Medicine, and of course Architecture and Engineering. But specifically in the field of structures, surprisingly someone can find that this link has been produced very late in comparison with other issues: it has not been until the 20th century when engineers and architects have been able to develop those extremely efficient lightweight structures that we can admire in Nature.

In a general sense, we can distinguish four load-bearing mechanisms (Figure 1):

1. Massive (masonry: walls, arches, vaults, domes): Compression, stability, weight, rigidity.
2. Beam-and-column system: Bending, some flexibility.
3. Lightened skeletons: Division of compression and tension, flexibility.
4. Active-form surfaces: Load-bearing by morphology, curvature, folding.

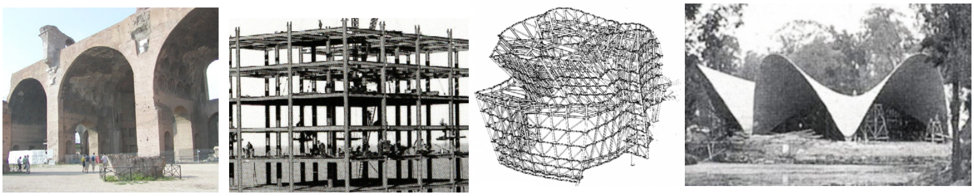

Figure 1: Load-bearing mechanisms (massive, beam-and-column, skeletons and surfaces)

Until 20th century, the only possible prototype for man-made structures was the first one, which is not found in Nature (except caverns). Only some kind of lightening wood construction or tensile tents are such close examples. However, with the development of new materials as steel or reinforced concrete, it finally became possible to achieve the other three structural prototypes (Jordá [12]).

Also in these first decades some studies of natural bodies appeared: *Art forms of Nature* (Häckel [8][9][10]), where the naturalist Häckel showed pictures of microorganism, which incited also the artistic style of "Art Nouveau"; and *On growth and form*, where the biologist D'Arcy Thompson explained animal forms as funiculars of forces.

This combination of knowledge about structures in Nature and the possibility of constructing new structural prototypes made architects and engineers turn back their eyes to Nature to learn about optimal morphology, extreme lightening, functional integration and efficiency. It is not a coincidence that the first triangulated dome was constructed in Jena in 1919, the same city where 15 years before was edited *Art Forms of Nature* (Figure 2)

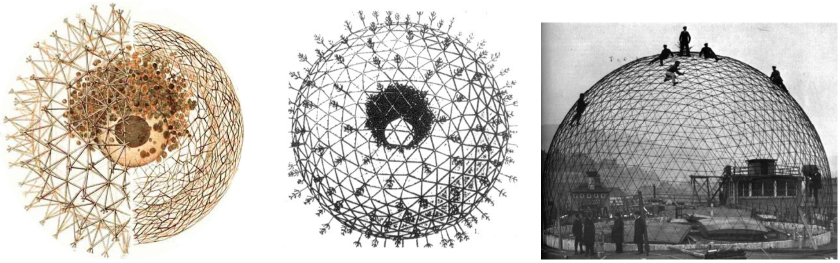

Figure 2: Pictures of radiolarians (E. Häckel) and Planetarium in Jena (C. Zeiss)

2. Biomimesis

The term "biomimesis" involve using ideas from Nature for further technology; artificial systems that copy some function from natural ones (Vincent [31]) This idea should be carefully taken: it presupposes that man can take the "answers" of Nature in order to solve the "questions" of the engineering, which is not always a direct way. This is called the problem of the "technology transfer", and a specific theory has been developed: the TRIZ (Altshuller, [1]). This theory argues that the most basic and abstract property you make it, is more portable. In the case of structures for architecture or engineering, the possibility of extrapolation should be carefully studied attending to:

- The load case: a lot of nano-arrangements work in zero-gravity medium, as water; or have to load-bear live changing loads.
- The scale, size, kind of loads and proportion between structure's weight and whole load: not in every situation a pattern can be directly scaled, it must be done adapting the sections (Aroca [2]) (Figure 3).
- The freedom of movements that we need or must avoid: natural structures are normally designed for having much more kinematical freedom that man-made ones, which do not need larger movements or deformations.

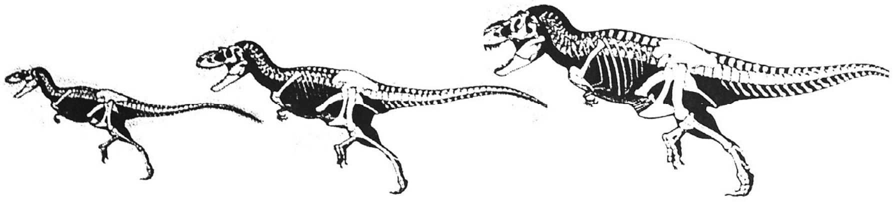

Figure 3: Natural adapted structures through growth

3. Efficiency

The practice of biomimesis presupposes that Nature is energetically the most efficient "machine", much more than human technology. Let us think about the meaning and links between efficiency, functionality and economy.

Nature evolves by "natural selection", a trial-and-error mechanism which has had a lot of time to improve its designs. "Maximum diversity with minimum inventory" (Pearce, [27]). The result is a "conceptual design which is extremely appropriate in its morphology, well adapted to the surroundings, structurally and functionally optimized, and has a refined appearance, all in one single configuration" (Wester [32]). Does this means energetic efficiency? Yes, broadly. For Nature, "economy" is directly related to saving material, because the "manpower" and the "runtime" are virtually infinite. That is why Nature emphasizes in optimal form-finding, which is related to the formal concept of "continuity".

However, these two factors are extremely important for efficiency in man-made structures: until technological development is high enough to produce difficult forms without effort, the economic way to construct is by repeating relatively simple and geometrical forms.

Also we cannot forget that the optimal energetic balance in Nature is produced in each step of the evolution, i.e., in some situations it is "cheaper" not to remove an unprofitable element but keep it as "rubbish". For that reason it becomes necessary to examine patterns keeping in mind that idea.

4. Structural prototypes in Nature

In the subsequent lines, we go through the five prototypes of structural arrangements in Nature: pneus, shells, trees, webs and skeletons (Arslan [3]). We analyze them studying their structural mechanisms, signalizing some particular features and offering some possibilities of extrapolation. All are lightweight structures: active-form ones (pneus, shells and webs), lightweight column (trees) and lightened skeleton (skeletons). Thus, we can assure that Nature pursues the objective of "zero weight, infinite span" (Le Ricolais [14])

4.1. Pneus

The pneumatic structures are the most efficient ones in terms of span/weight. A pneu "consists of a ductile tensed envelope, internally pressurized by a fluid and surrounded by a medium" (Otto [18]). So they are self-stabilized element, and because of this dependency of the internal pressure made by a fluid, the result is a very adaptable structure which can easily change its form to accommodate to the surrounding geometry. In Nature, they can clearly be seen in mist droplets, soap bubbles, worms, jellyfish, bacteria… (Figure 5)

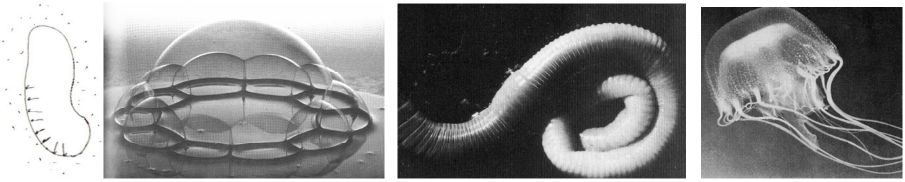

Figure 5: pneumatic mechanism and pneus in Nature

4.1.1. Pneumatical growth

The key of the issue is that the cell itself is a pneu: a flexible stressed envelope (membrane) enveloping a filling. The growth is produced by cell divisions which re-locate themselves strategically, so it can be assured that growth is the result of a pneumatic behavior. And in most cases, final structures are only the solidification of pneus: eggs, bones, skeletons, shells, also webs. This point helps to understand the origin of some patterns in other arrangements. All these reflections made Frei Otto say that "at the beginning was the pneu", "all is pneu" or "the pneu is the basis of living Nature" (Otto [18]).

Also this new point of view made possible to explain in terms of structural mechanisms the "Thompson's transformations". D'Arcy Thompson analyzes the form differences between species like a distortion of a hypothetical grid. Then, Otto considers that this phenomenon is a consequence of a pneumatic non-homogeneous growth (Figure 6).

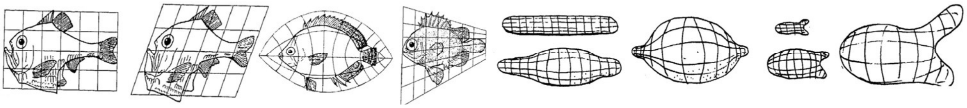

Figure 6: Thompson's transformations and Otto's reading

As the pneu system is the responsible of the growth, also the definitive form is influenced: the bodies keep the "funicular" arrangement that the loads produced in the flexible pneu.

This is a very high technological process of optimal form-finding. Also for this generation of the final form it is usual to combine the pneu base with other structural elements like fiber meshes, membranes, which helps to model it (Schaur [29]) (Figure 7).

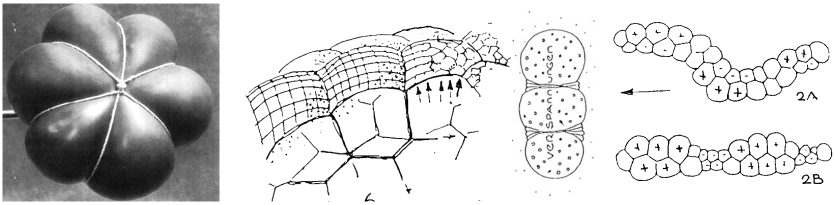

Figure 7: Restriction in pneus by other structural elements as webs

4.1.2. Combination of pneus

Another important quality of the pneu model of living objects is the way they combine themselves producing optimal grids with least-energy behavior. This is the principle of the "closest packing": optimal ways of join solids in the plane or in the space, and is one of the most common geometric phenomena in Nature (Pearce [26]) (Figure 8). As a consequence of the packing of elements some geometrical patterns appear, composed by regular or quasi-regular polyhedron. This is the "regular division of the plane/space" (Figure 9). All of these arrangements obviously are structural and energetically efficient; other quality to study and extrapolate of this phenomena is the kinematical behavior of the ensemble (4.2)

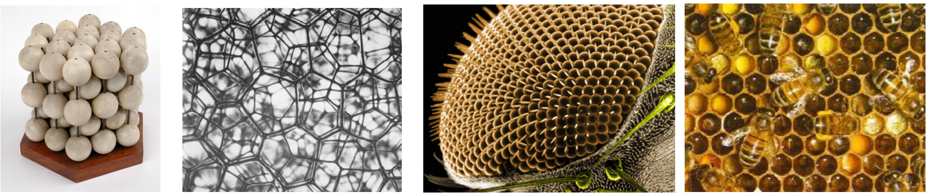

Figure 8: Closest packing and examples in Nature

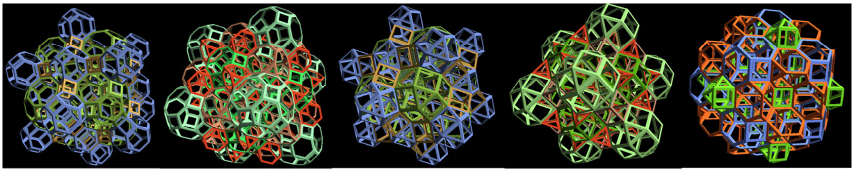

Figure 9: Geometrical arrangements that make regular division of the space (Carvajal)

4.1.3. Tensegrity in pneus

Finally, it is interesting to zoom to the pneumatic cell again. In a closer approximation this system of exterior mobile envelope linked to an interior nucleus has been explained also as a tensegrity system (self-assembly structure composed of compression and tension elements in which load-bearing capacity comes from pre-stressing of the ensemble). Thus, cytoskeleton of cells is a framework of interconnected microtubules (compression) and filaments (tension). (Figure 11). The efficiency of the arrangement lies in the possibility of changing its shape easily and adapting to the exterior surfaces and constrains only by automodifying the pre-stressing value so every tension changes and also the global form (Ingber [11]). Thus, we can assure that pneus and tensegrity travel across the scales in Nature.

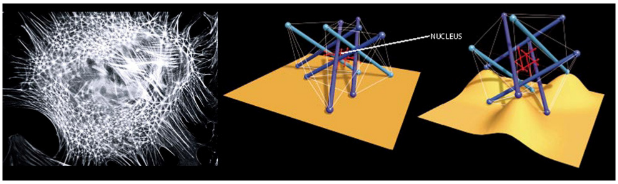

Figure 11: Cytoskeleton of a cell and tensegrity model

4.2. Shells

Both shells and tents are active-form structures (they have got load-bearing capacity by their spatial configuration, working in an axial regime). While tents are flexible and only in tension, shells are rigid and have got normally tension and compression. In Nature we can distinguish clearly two types of shells: continuous ones, without lightening holes; and discontinuous ones, with some pattern of lightening

4.2.1. Continuous shells

They are located mainly in exterior protections of mollusks, aquatic or terrestrial. In general, they have to load-bear continuous pressures (more important in water) and impact forces (more important in earth). Usually these kind of shells are double-curved ones with successive thin elements for stiffness gaining (Figure 12)

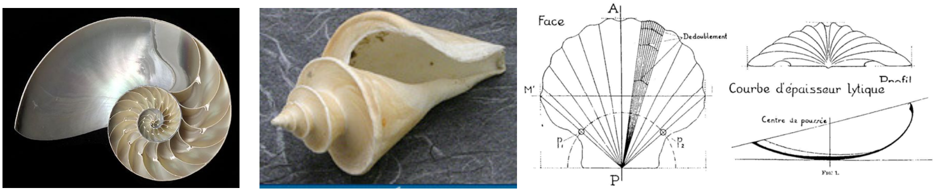

Figure 12: Ribs in Nautilus, Thatcheria and bivalve shell (Le Ricolais)

Another important strategy for stiffening the ensemble is by folding the membranes to gain inertia. Depending on the different geometrical relations between lines and points in the folding pattern (tetravalent or senary), it will have more or less degree of mobility (Delarue [6]) (Figure 13). Going further, these folding patterns can be used for obtain real movements, generating deployable structures. In Nature this strategy is visible in some leaves (Vincent [31]), and some experiments have been done in an attempt to apply these features to man-made structures (Lim [15]) (Figure 14)

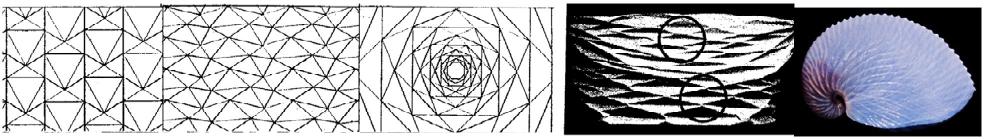

Figure 13: Different folding patterns (Delarue) and folded seashell

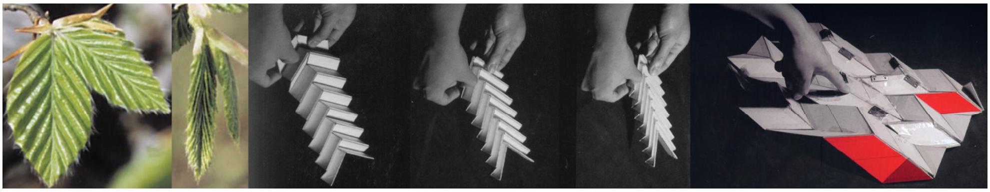

Figure 14: Extrapolation of the geometry of the beech leaf to a deployable roof (Lim)

Sometimes shells work in a different way, as in the case of the sea urchin shell. This structure is apparently a folded shell reinforced by spicules. But some experiments have demonstrated that actually it is not an axial-work shell but an ensemble of multiple semi-articulated plates with bending work (Figure 15). In this case, pure plate action is more efficient than pure lattice action because it allows growth in a more natural way without interfering each other, in a very elegant solution (Wester [32]). Some other proposals have been studied, as a pneumatic behavior (Philippi [28]), but they have not be proved.

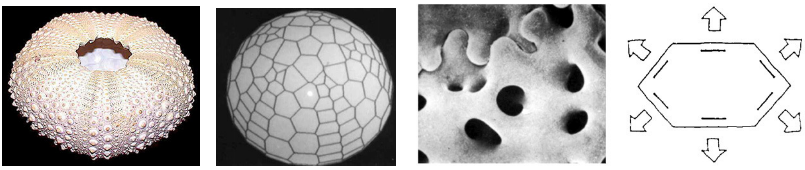

Figure 15: Structural model of a sea urchin, toothed hinges between plates, growth

4.2.2. Discontinuous shells

They can be observed mainly in exoskeletons of microorganisms as radiolarians, which do not need a closed protection membrane but a soft veil for substances exchange; also they moves in a zero-gravity medium. Thus, they are extremely lightened, and a lot of different patterns can be found: closed/opened, round/plane, regular/irregular mesh, single/multiple layer, grids of triangles, rectangles, pentagons, hexagons… (Otto [21]) (Figure 16).

Certainly, the graphic investigation of Häckel had a quick effect in engineers and architects, who started to be interested in the applications of these soft arrangements for covering great spaces with very lightweight structures. That is the case of Buckminster Fuller, who utilized those geodesic geometries for his domes and also to develop an interesting research about an alternative geometry theory, based in the triangle and tetrahedron as the basis for reaching “synergy”: the quality of an ensemble which is more efficient than the addition of the part’s efficiency (Baldwin [4]) (Figure 17).

The engineer Le Ricolais was always interested in the structures composed by “opposite elements” which work together creating a very efficient ensemble (Figure 18). He suddenly was fascinated with the complex and complementary structure of the radiolarian: a compressed core protected by successive layers of triangulated scaffolding (globally compressed but locally both compressed and tensed), linked by compressed spicules and surrounded by a tensioned minimum-surface membrane, in a way that potential energy is equilibrated. Topologically it is “isomorphic” (opposites), “enantiomorphic” (opposites are images), “automorphic” (hierarchy) and “bimorphic” (equilibrium) (Le Ricolais [14]).

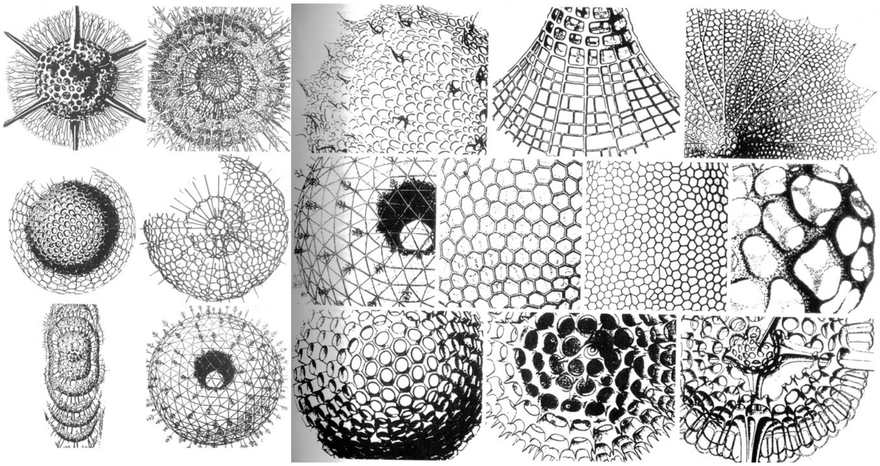

Figure 16: Different examples of radiolarians and diatoms

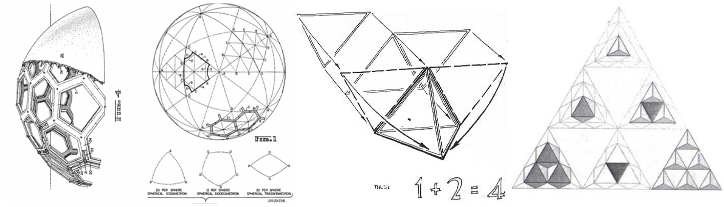

Figure 17: Buckminster Fuller's geodesic dome and the concept of "synergy"

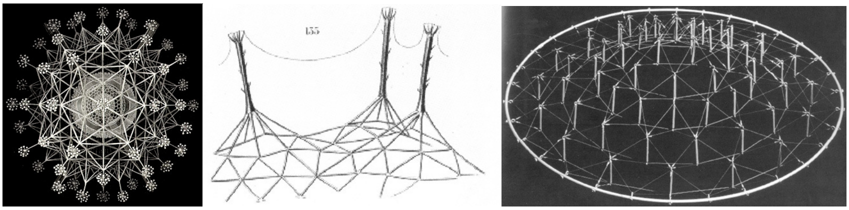

Figure 18: Pheodaria (Häckel) and some "bimorphic" experiments by Le Ricolais

In the same line of morphological and topological investigation on patterns, Wester has studied the concept of "dualism" between pure-lattice and pure-plate action in trivalent configurations of some radiolarians and echinoderms (Wester [32] [33]). While in radiolarians the lattice work is prevalent, in echinoderms is the opposite: in this case it is more difficult for Nature to develop complex nodes and to concentrate loads than to spread loads and to load-bear by bending plates connected in shear lines. Also sometimes the two structural configurations appear together (Figure 19), compensating reciprocally.

Moreover, it is important to remark that almost all these arrangements are nearly isostatic, i.e. kinematically neutral. Low redundancy is efficient because it implies a low consumption of material, but specially because isostatic structures do not get secondarily stressed as a result of changes in this configuration (growth), and also they are more flexible to avoid loads (they oppose low resistance to the forces and simply go along with them). This feature can be a good inspiration for certain flexible man-made structures.

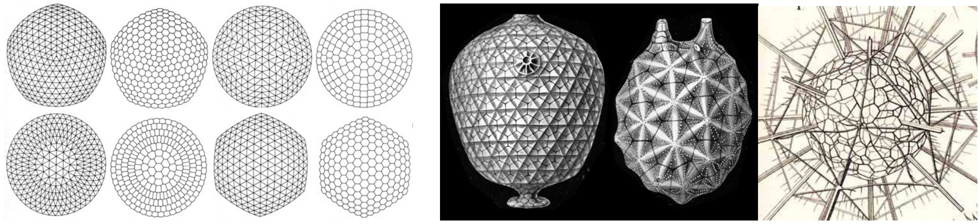

Figure 19: Lattice-plate dual structures and some examples of dualism in Nature

4.3. Trees

Tree-like structures always have been extrapolated to man-made structures as branched columns of stone, wood and later steel or concrete. Nothing new to add in this field, so we particularize in some other intrinsic properties related to their pneu origin and growth. Again, growth is based in the multiplication of pneumatic cells which harden later. Trees are composed broadly by a solid core surrounded by a cork protection layer, and the growing cells are located between them. This pneumatic layer plays several benign roles when its internal filling expands (Otto [18]) (Figure 20):

- It compresses laterally the core column confining it, so its compression strength gets increased and the risk of buckling decreases hugely
- It helps to make straight the growth alignment of the core, solving some imperfections.
- It increases the transverse and longitudinal tension of the membrane, which is "fixed" to the core in the top, generating such a pre-stress phenomenon in the piece that helps enormously in the bending action against the wind (Fournier *et al.* [7]).
- In oblique branches, the gravity action places more pneumatic material under the core, so its expansion raises the branch, causing a movement against the natural deformation.
- It is modeled by the wind, adopting an elliptical section when it harden, so the final configuration has more inertia where needed.
- When it hardens, this young material starts to bend from zero, so the linear state of tension and deformation becomes a brook one and it never gets maximum values

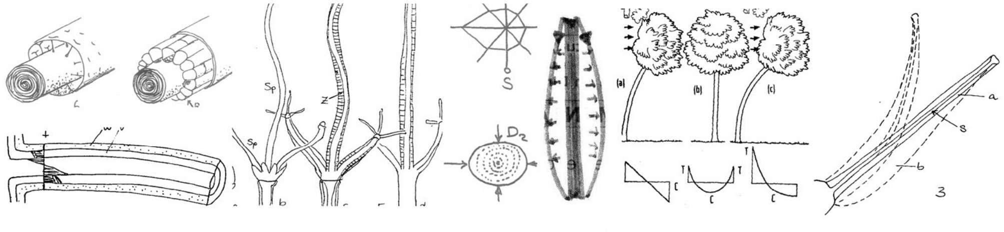

Figure 20: Pneu phenomena in living trees

4.4. Webs

These structures belong to the tensioned active-form prototype, like tents. They are constructed with materials which only work in tension regime, so the shape is determined by the anchorages and loads. But the main difference between them is that webs can easily adapt their shape when those conditions changes, while tents would "wrinkle". As in 4.2.2., this ability to adapt by deforming is highly linked with the geometrical pattern.

Studying spider webs, we find that the most common pattern is the radial tetravalent plane net, which is just stable (Wester [33]) (Figure 21a). However, as these webs are pre-stressed to reach a plane configuration, when they are over-loaded they lose the pre-stressed and adopt the corresponding funicular shape. Once more, efficiency means adaptability.

Spider webs have a higher efficiency (span/weight) than man-made nets, due to the quality of the material but also because of the design of the nodes: spiders just join the threads and wrap together with a softer one, while our nets are joined by metal brackets (Figure 21b)

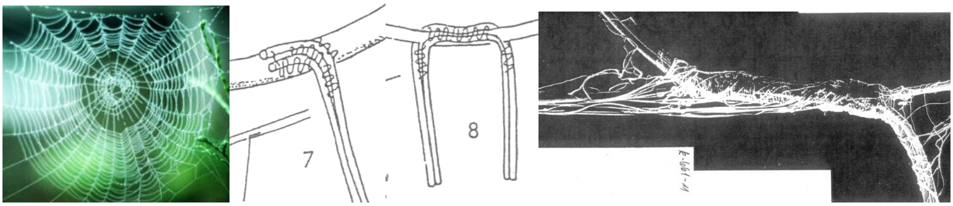

Figure 21: Radial tetravalent plane net and node details

Related to the issue of optimal form-finding of nets, there is the concept of natural "minimal surface" that is produced in soap membranes (Figure 22); this is only one of some natural processes in which the forms are found in a self-shaping process (Burkhardt []). A minimal surface is the smallest one within a boundary closed on itself; at every point the sum of the radii is nil, and it has similar surface tensions in all directions. All these properties make it optimal, so it is very useful to take directly the resultant shape of a minimal surface in an experiment for tensile tents (Otto, [19]).

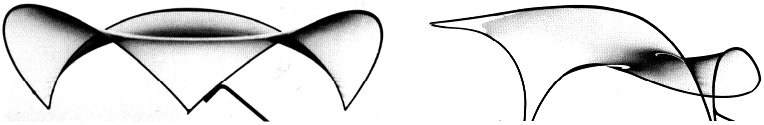

Figure 22: Minimal soap surfaces

4.5. Skeletons

Once more, man has always taken inspiration from animal skeletons: flying buttress, ribs, columns, nerves… It is enough explained, so we focus in a different task. If we understand skeletons as "lightened masses" (as Le Ricolais said: "The art of structure is where to put the holes" (Le Ricolais [14]), we find that skeletons are not only the ones composed by bones but also the tissue inside the bones: spongious trabecular tissue (Figure 23), which is produced also by the solidification of pneumatic "hose" nets (Otto [22])

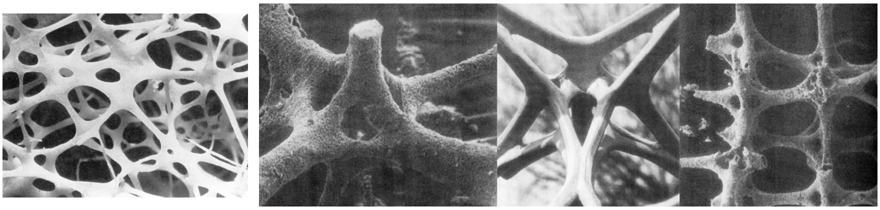

Figure 23: Trabecular human tissue and “hose nets”

The majority of the examples have a tetravalent 3-D grid, in which two of the directions match clearly with the theoretical trajectory of forces, (Kummer [13]); and the other direction stabilizes them (Figure 24). This kind of arrangement, seen as a pure-lattice system, needs a fix boundary to be kinematically neutral, so it appears the “compacta”, a stiffer tissue in the covering. But it is not enough to have a totally fixed boundary, so the nodes take a little bending resistance, becoming semi-rigid (Wester [32]). The outcome is an almost-isostatic pattern, flexible but stiff, lightened in an optimal way and stable to torsion effects due to the irregular geometry (one of the biggest problem of our space triangulated trusses).

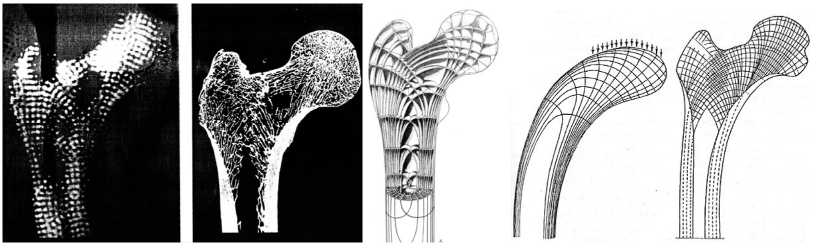

Figure 24: Tissue of a femur and models of the trajectories of forces

As we have mentioned, the local design “fattens” the nodes, and “slims” bars for an optimal load-bearing work. The most important concept in this case and in general when we talk about natural structures is the continuity, which is the main strategy of Nature to reach efficiency within a long time (see point 3). Continuity has been demonstrated to be profitable by highly decreasing corner strains (Mattheck [16]) and has been applied to experimental structures (Otto [20]) (Figure 25).

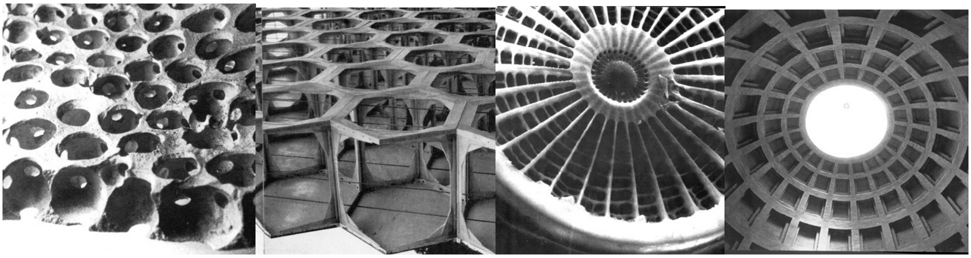

Figure 25: Natural continuity, modular experiment (Otto) and relationship between natural continuous dome and man-made one

As it happens with minimal nets, the form-finding mechanism for this continuous lightened patterns is a self-shape process related to "viscosity" (Otto [20]). These arrangements can be obtained by separating two planes with a viscous material in between, forming lots of fungi form columns when it hardens (Figure 26), in a so optimal way that the buckling length is half reduced and also the punching is avoided. Thus we can observe that this process looks like an "antifunicular" form-finding one: it seems that the shape obtained by tensioning a deformable element is the optimal one to load-bear compression forces.

Finally, it is important to notice that in these skeletons, structure fulfills other functions, like fluid channels (Mosseri [17]), what can inspire us to use hollow structural truss bars as the pipage of buildings.

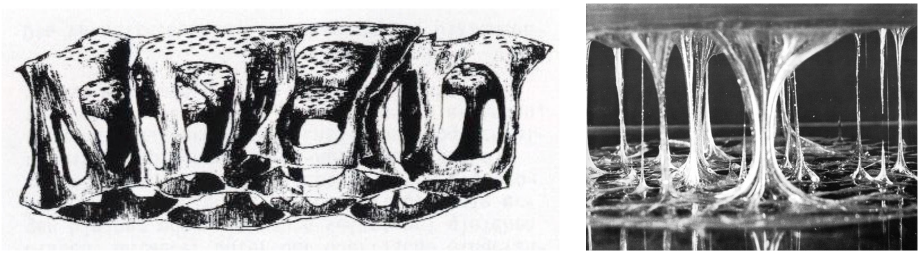

Figure 26: Viscous analogue (Otto)

5. Conclusion

Our aim was to find clues about the efficiency of natural structures that could be exploited in man-made ones. After this little tour across natural structures, we are able to separate these optimal properties in two groups: direct and indirect features.

The direct characteristics to be extrapolated are:

- General morphology of the arrangements attending to the optimal form-finding process: the topological properties of the pattern, the economy of structural elements or the direction of them.
- Local design strategies for anchorages, semi-rigid nodes, hinges…
- Geometrical solutions for a proper rank of mobility when needed

The indirect properties to inspire on are:

- Mechanisms for an optimal lightening
- The flexible way to avoid loads instead of bearing them
- The continuity in the design, keeping in mind the economy limits
- The integration of functions in the structure and with the rest of the arrangement
- The auto-regulation by self-straining processes
- The growth as a continuous process of self-adapting shape to the constrains

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