Structures of Nature in Modern Buildings
自然の構造と現代建築

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A just recently discovered dualism (i.e. an unambiguous and unique connection) between the two most basic kinds of structural principles, the lattice structure and the plate structure, enables a far more comprehensive and sophisticated use of spatial plate structures than today. Further it gives rise to the explanation of the behaviour of several complex biological structures such as the test of the sea urchin, which is so perfect, that it even might be an inspiration for architectural and structural designers.

INTRODUCTION

The present article is a revised translation of ref.[6].

Spatial plate structures are as a pure structural type at the same time very new and very old. The members of a project, granted by the Danish Technical Research Council, located at the Architectural School, Royal Academy of Fine Arts in Copenhagen, have in recent years investigated the principles of plate structures and their possible practical application to buildings.

The possibility of creating firm and stable structures by the use of planes—plates—is certainly not new. Animals as sea urchins have used this principle for millions of years. The sea urchin surrounds its soft parts with a rigid calcite test, consisting of almost plane plates. The test meets in a very sophistcated way all the requirements for forming a perfect plate structure[4].

Other microscopic animals with a hard skeleton, i. e. radiolaria and foraminifera, sometimes produce the same kind of geometry (Fig. 7)[8]. It seems that "Mother Nature", as usual, has been millions of years ahead of contemporary architects and engineers, who just recently have started to recognize the possibilities of the plate type of structures.

For spatial lightweight structures the lattice kind has been absolutely dominant so far. Examples are trusses, latticed cranes, braced domes, space frames —and a treasure as the one hundred year old Eiffel

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Tower.

However, the underlying principles for lattice and plate structures have a lot in common, and the present comprehensive knowledge of lattice structures has turned out to be useful in an almost direct way for the design and structural calculation of plate structures.

The project at the Architectural School has opened up for a world of new possibilities for the design of suitable plate structures. A view of the traditional North European buildings (Fig. 6) clearly shows that plate acting may be brought into consideration, without any change of the present geometrical concept. Using the plate principle it is easily avoided that load-carrying walls stand directly on top of each other, and attics need not contain room-destructing crisscross bars of the traditional lattice girders. These are a few of the easily obtainable advantages by using the plate principle.

LATTICE CHANGES TO PLATES AND VICE-VERSA

One of the major achievements of the project is that the lattice principle and plate principle are shown to be inverse, reciprocal, symmetrically mirror imaged, unambigouosly polar or, as is used in the following, dual systems[7]. This means that any arbitrary plate structure can unambiguously be transformed to its dual lattice structure.

As a lot of different computer programs already exist for the structural analysis of arbitrary lattice

structures, a lot of work by developing special software for the analysis of plate structures can be saved. By pre- and post-processing, all lattice data for the geometry, forces and elastic properties can be turned into plate type of data[2)4]. During this transformation, lattice nodes become plates and bars become force-transferring lines of intersection between plates, so-called "lines of support", hence the axial forces in the lattice structure are turned into corresponding shear forces across the lines of support, and of course vice-versa.

Another interesting property by the dualism is that new light is thrown on both types of structure. Impenetrable and unclear properties of the one type may be clear and easily realized after dual transformation. The dualism can therefore be used for better understanding of a structure on the qualitative as well as the quantitative level[2].

This short-cut for the structural analysis of plate structures, combined with an increased knowledge of the nature of plate structures, might stimulate the interest for this type of structure and inspire to investigate the practical applications to plate structures[8].

OLD SHAPES WITH NEW POSSIBILITIES

The basic inspiration for these observations is hidden in the five ancient geometrical solids, the so-called regular polyhedra or Platonic solids[1]. These are the five classical spatial polyhedra (Fig. 3), where the best known is the hexahedron, alias the cube, and the tetrahedron, alias the pyramid. The remaining three polyhedra are called by their greek names: octahedron, dodecahedron and icosahedron.

They have been frequently used for far more than 2000 years, and geometers have, since Archimedes ascribed great importance to them.

The name "Platonic" polyhedra is due to Plato (427-347 B.C.), who used them in his dialogue "Timaios", where he describes the Pythagorean Cosmology. Here they are defined on the basis of their looks and symmetrical properties. Because the dodecahedron is the body being closest to the divine perfection, namely the sphere, it is equal to Universe and the spiritual dimension. The basic particles for the four archetypal elements are: The tetrahedron is fire, the octahedron and icosahedron are air and water, respectively. These three types of particles may flow into one another as they are built from the same basic unit, the triangle. The last particle which cannot change its state is earth, which is therefore the cube and something very special due to its square polygons.

Based on Plato, Kepler has in "Harmonices Mundi" (1618) tried to explain and link the movements of the planets and harmonies in music by considering how these bodies can be built into each other. Leonardo da Vinci has taken an interest in them, and he has for example drawn them as illustrations for Luca Pacioli's "De Divina Proportione" (1509). Modern geometers have found apparently inexhaustible sources of still new polyhedra and connections between them. All is based on these five, the definitely most simple spatial bodies with plane facets.

Now it turns out that these bodies contain so far unknown connections between the two most fundamental types of structure, the lattice and the plate structure.

Some of the five polyhedra get stable and others get unstable if designed as pure lattice structures, while the unstable structures get stable and vice-versa if designed as plate structures[1], although there is one exception as shown later.

A lattice structure is geometrically based on nodal points connected with bars as spacers. The bars are only subjected to axial forces, kept in equilibrium in the nodal points.

If models (Fig. 4) form the five polyhedra are made as pure lattice structures—with bars along the edges of the body and nodes in the vertices—it is found that the polyhedra where the bars form triangles only, are stable (the tetrahedron, octahedron and icosahedron), while the rest becomes unstable.

The situation turns out quite differently if the polyhedra are made as plate structures.

If the five are made up of polygons of thin cardboard interconnected by tape along the edges, and the vertices are cut off in order to prevent any structural action by the vertices, the test will show that three of the polyhedra become stable, namely the cube and the dodecahedron, which were unstable as lattice structures, and the tetrahedron, which is stable in both cases, —not surprisingly called the Platonic "Master solid". The remaining two polyhedra become unstable.

It is typical for the stable plate polyhedra that geometrically they have all got 3-way vertices.

Fig. 1   A vertical row of plates from a sea urchin, separated into single plates. The 3-way connection pattern is typical.
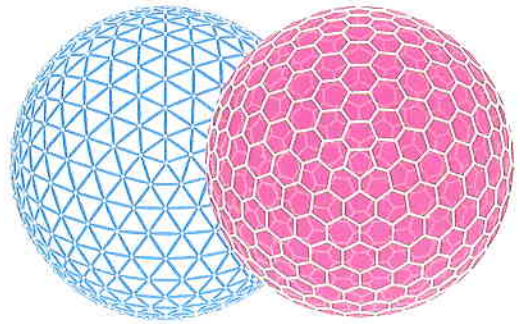

Fig. 2   Multi-facetted dual lattice and plate polyhedra of the icosa- and dodecahedron family. Graphics Burvad-Copenhagen.
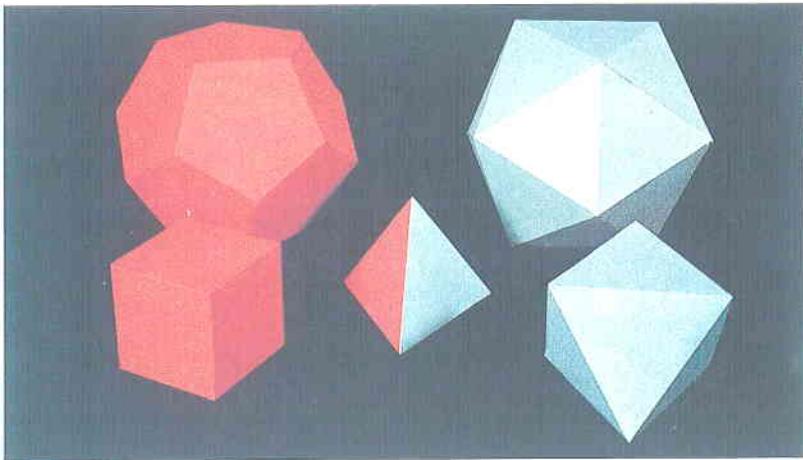

Fig. 3   The five Platonic bodies: The cube and the dodecahedron to the left, the octahedron and the icosahedron to the right, and the tetrahedron in the centre.
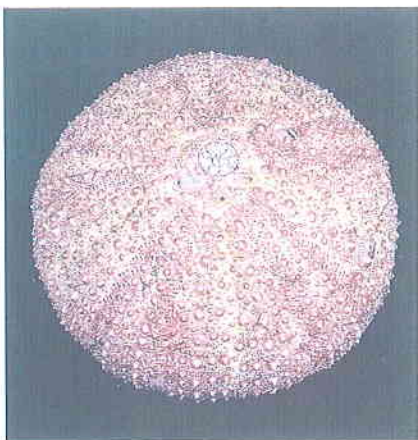

Fig. 8   Sea urchin seen from above. The upper pole is filled up with small plates.
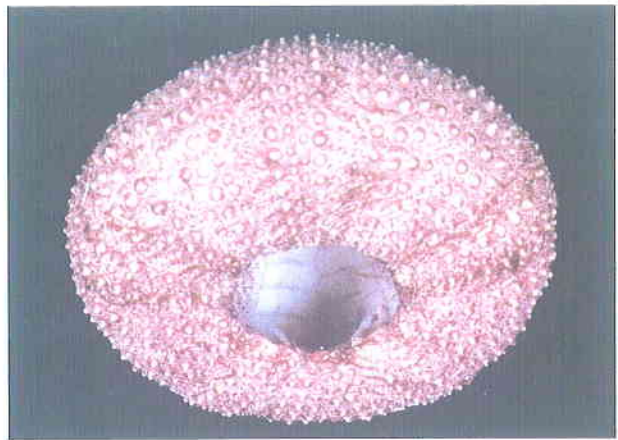

Fig. 9   Sea urchin seen from below. The stabilizing strong united frame around the mouth parts is clearly seen. Note the 3-way vertexed pattern between the plates on the inside of the test.
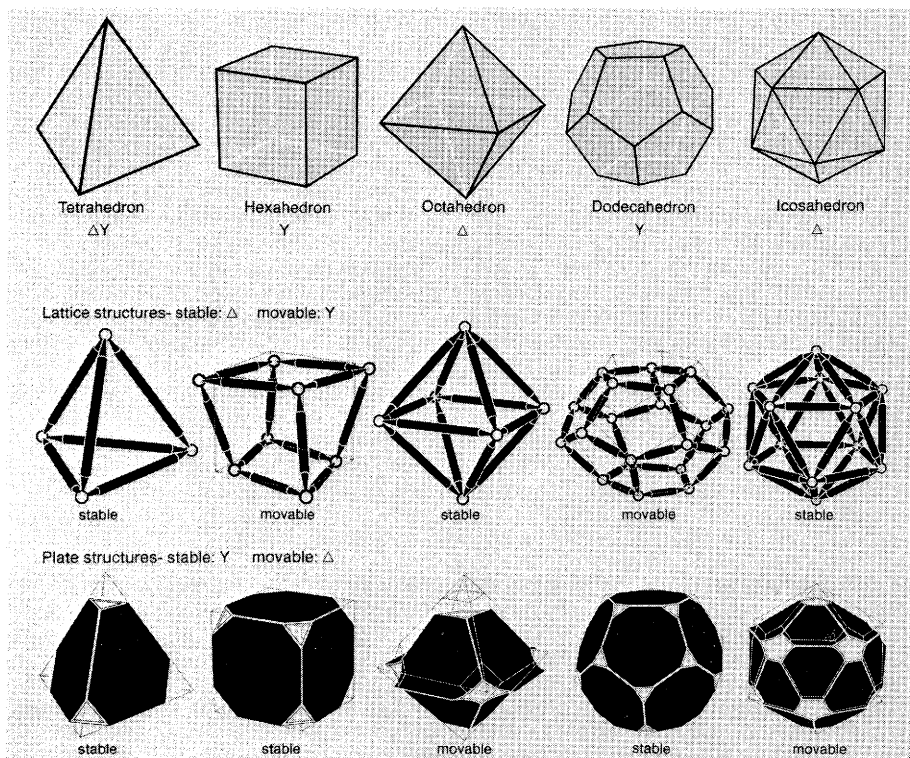
Fig. 4　The five Platonic polyhedra evaluated as pure lattice and pure plate structures, respectively. Graphics Burvad-Copenhagen.
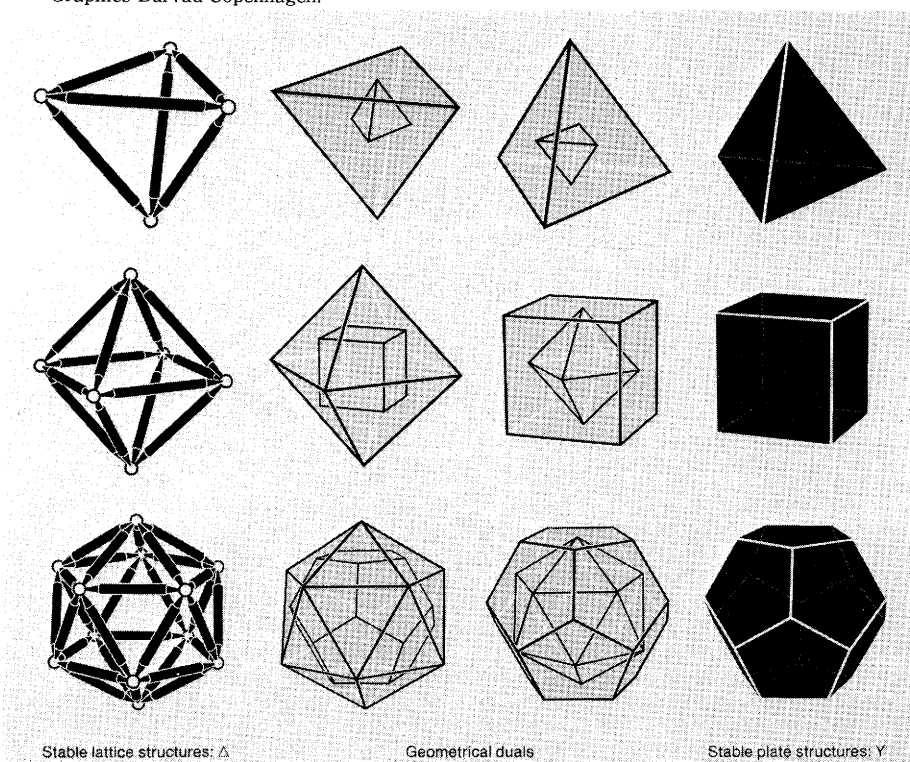

Fig. 5　The five Platonic polyhedra reduced to three basically different types, each with a stable lattice and plate version. Graphics Burvad-Copenhagen.

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All the stable versions have in common, that they are only "just" stable or statically determined, i.e. no active part of the structure can be removed without the structure getting unstable[1].

The correlation of stability just described fits perfectly with the well-known geometrical dualism of the Platonic polyhedra. If vertices are considered as plane facets and vice-versa, the cube will produce the octahedron and the dodecahedron will produce the icosahedron—and vice-versa, while the tetrahedron as master solid produces itself ! (Fig. 5)

As also shown in fig. 5 the five stable versions can be regarded as three basically different polyhedra, each with a stable lattice and a stable plate version[3].

These standard polyhedra are very convincing as physical models, but they are only examples of principles. Luckily the results of these tests can be generalized, so that all polyhedra (with a few tricky exceptions) with only triangular facets are all just stable as only lattice structures, while all polyhedra with only 3-way vertices are all just stable as only plate structures.

ADVANTAGES OF BOTH TYPES OF STRUCTURES

The lattice and the plate structures are of quite different "nature". The lattice structure concentrates its forces in the bars and the nodes, and therefore it is evident to build this kind of structure from strong materials and with very efficient joints. Steel is an appropriate and popular material for such lattice structures.

In the lattice structure the mesh between the bars is open while the plate structure is completely closed. The plate type distributes the forces all over the plate surface and transfers the forces evenly along the lines of support. Therefore, less strong materials and less efficient joints are appropriate.

Even though the plate structure is by "nature" closed, it is of course possible to create the necessary openings for doors, windows etc. if certain rules are observed. It obviously invites for the use of plane structural elements of limited strength e.g. plywood, precast concrete and may be even glass, glued along the edges.

But just as well as lots of excellent small wooden lattice structures i.e. trusses and girders exist, steel will also be an appropriate material for plate struc-

tures, especially for large spans and heavy loadings[9].

Apart from being used for resisting horizontal wind, earthquake etc. the plate has, contrary to the lattice, only been used exceptionally in contemporary buildings. The reason is not that the plate structure is an inferior or unsuitable construction principle—on the contrary—but the knowledge of its special properties has been sparse.

It is even not necessary to change the traditional shaping of our buildings for profitable use of the plate principle in the main structure. A view of a roof-scape of traditional North European buildings (Fig. 6) verifies the frequent use of the 3-way vertex, i.e. a form concept where plate-effect of facades and roofs, when taken as structurally active surfaces—as polyhedra—is latent[8].

Of course it is required that the planes are rigid in their own plane and that the shear forces can be transferred along the edges, but often these requirements are only insignificant appendices to the existing construction tradition. However it becomes more exciting if the geometrical design is made on the basis of knowledge of the plate principles, i.e. in order to emphasize the particularities and special appearance of the plate principle. Only very few of such works have been done so far.

THE SEA URCHIN AS A GENIUS OF ENGINEERING

The calcite test of the sea urchin is a stable as well as an efficient structure, with the ability to inspire man for future plate structures[3].

The test is made up of two types of plates, which are positioned in five double rows, running in vertical bands between the upper and lower pole. For some types of sea urchins the two plate types are very different in size, while they are nearly equal for others. In both cases the test is stable, but with the experience from Plato's pólyhedra it is easier to analyse the stability if the two are of the same size.

As the single plates may be regarded as plane and as all vertices are 3-branched, the requirements for purely plate-stabilized structures are accomplished with (Fig. 1).

At the lower pole (Fig. 9) the plates meet five united strong calcareous beams, called the "perignathic girdle", forming a structurally closed but geometrically open plane frame functioning just as
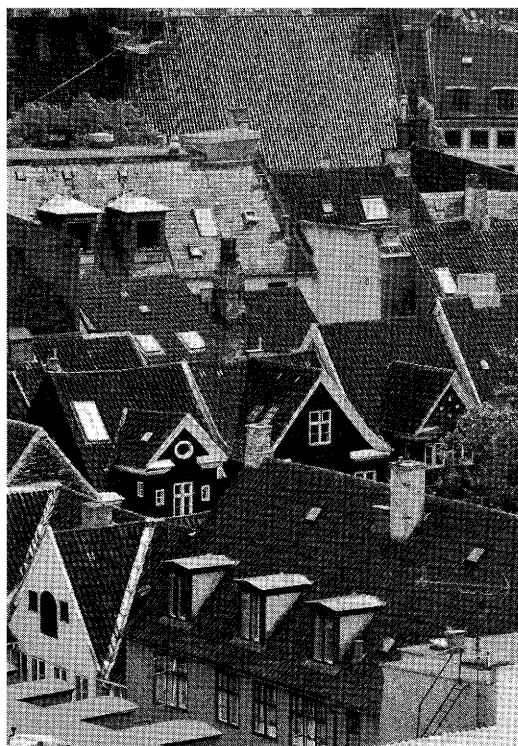
Fig. 6　Roof-scape in traditional North European build-
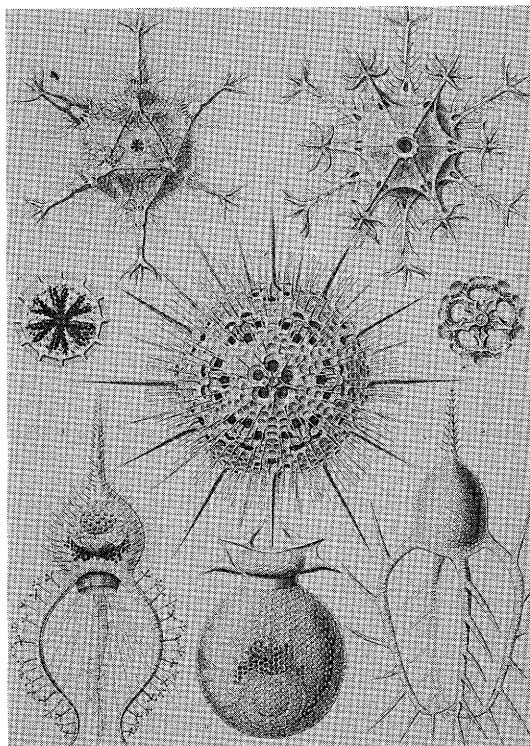ings showing lots of 3-way vertices, synonymous
with possible plate action.

Fig. 7　Graphical plate with radiolaria from "Kunstfor-
men der Natur" by the biologist Ernst Haeckel,
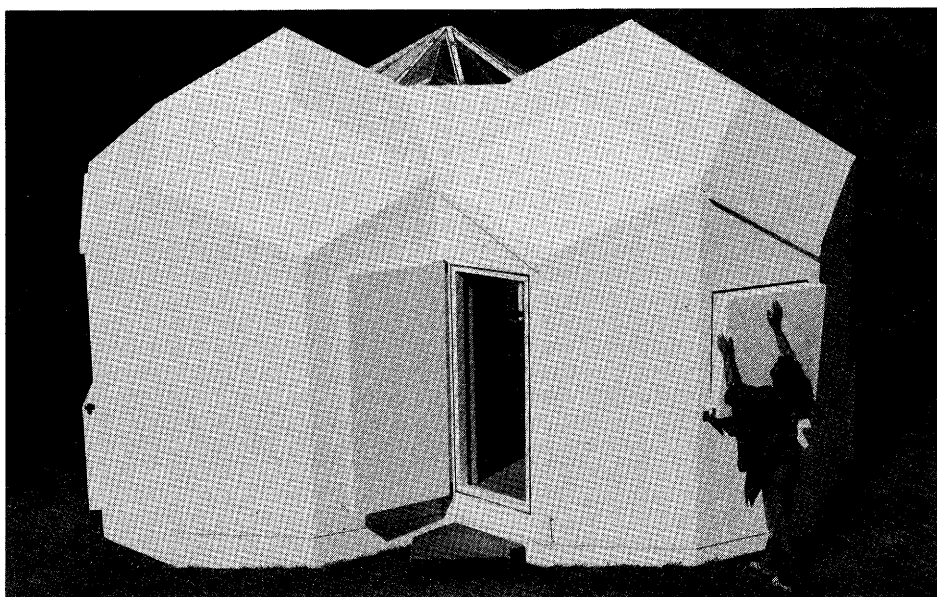Germany 1924.

Fig. 10　Interconnected domes acting as a combination between plate and lattice action. Exhibited in
Denmark 1977 and designed in collaboration between teachers and students from the Royal
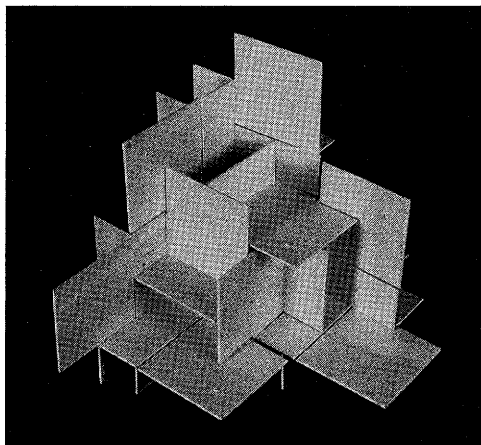Academy of Copenhagen.

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Fig. 11   Model of a house based on plate action as a
combination of identical plate elements. Design
K. Feilberg Hansen, Copenhagen.

well as a closed plate. This girdle is the basis for the
strong and highly deleveped chewing apparatus,
called "Aristotle's Lantern"

At the upper pole (Fig. 8) the rows of plates meet
the five strong and thick genital plates, together
forming a plane plate with a central hole, filled up
with small plates tied together by soft tissue.

Including the structurally intricate poles, the sea
urchin is seen to comply with all the geometrical
requirements for a stable pure plate-stabilized closed
polyhedron. At the same time the joining of the single
plates is solved as a toothing for perfect transmission
of shear forces without losing stability during the
growth of the animal.

Even though the single plates are not perfectly
plane and even though the statical function of the
polar parts is complicated, the test of the sea urchin
is still a very fine example of a highly developed pure
plate structure of the polyhedron type, made by
nature.

Until now it seems that the plate type of structures
is hardly used for buildings, and when it is used, it is
in a rather primitive way, while they seem to be very
common in biological structures.

In this paradox there is an inspiration for design of
man-made buildings, containers and other structures
based on surfaces, and to exploit the plate principle
for other advantageous purposses.

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