Synthesis of Form, Structure and Material

Design for a Form-Optimized Lightweight Membrane Construction

Generative

Edgar Sach

Associate Professor, College of Architecture & Design, The University of Tennessee
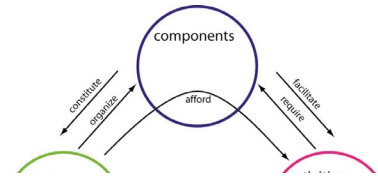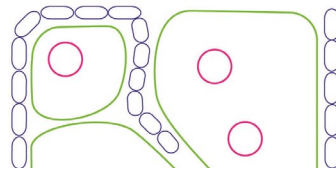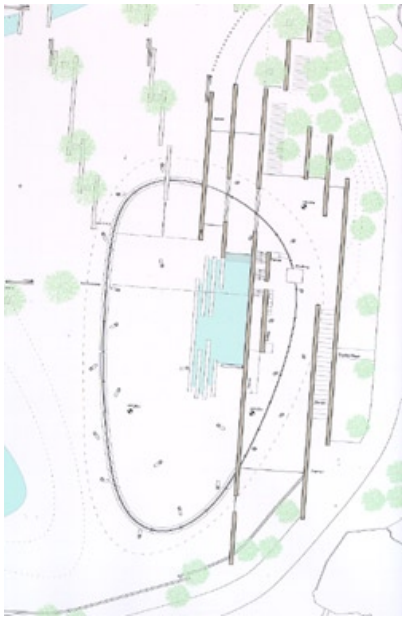
Material

Optimization

THE DESIGN FOR THE COLOGNE ELEPHANT HOUSE IS THE LIGHTWEIGHT, MEMBRANE CONSTRUCTION OF A TRANSPARENT "ROOF CLOUD" OVER A FREE PLAN GEOMETRY. This was made possible through the use of a new form-optimization method for structural calculations (SLang)[1] and the use of ETFE Fluoropolymer sheeting for the roof material.

Spaceframe

Structure

1 Introduction

"What is light-weight construction?" One of the many possible definitions is "optimizing the loading capacity of the construction without consideration of additional loading" or, somewhat more theoretically stated, the optimization of the path of the forces towards the reduction of the constructed volume. Light-weight construction and form-optimization are the critical themes in the construction technology of today.

The development of light-weight construction can be traced far back into human development. Machinery, transportation technology and ingenious constructions have been going through dynamic development since the Renaissance. The beginning of the 19th century was the first time that the constructions of engineers began to have an impact on architecture. This change in architectural vision occurred parallel to a broader understanding in the sciences, the development of new materials, industrial processes, and new thought created by the industrial age. Complex engineering works and the development of new structural systems presented architects with a new constructive intelligence.

Already in the early 1900's, new biotechnical discoveries began to enter the technical world of construction through the work of the biologist Heackel. Other examples of light-weight construction and the use of new materials from this time are the greenhouses of England such as Bicton Gardens. Yet the biggest innovations in lightweight construction came through developments in flight up towards the end of the 19th century. Balloons, dirigibles, and flying machines generated ideas of new forms and construction methods that quickly found their way into the new architecture. Intelligent construction and the machine aesthetic became the catchwords for the 'engineered architecture' and the basis for the early modern architecture.

The accelerated development of computer-supported materials research and structural analysis gives architects new possibilities for designing structures. This paper proposes seeing lightweight construction and form-optimization in a new light through its application to a specialized construction.

2 The Architectural Design: Competition for the Cologne Elephant House

The Cologne Zoo wanted to conduct an experiment:

The elephants, recently removed from their natural habitat, should be kept in an environment as similar to their own as possible. Rather than building a new elephant house, the zoo would like to build a new environment.

2.1 THE CONCEPT

- Trees – clouds – sun – earth – stones – water
- Interior and exterior spaces blend together into a spatial and functional continuity. Seemingly by chance, the shadows cast by a cloud creates a space on the hills, walls and ground.

2.2 THE IMAGE—THE ACCESSIBLE LANDSCAPE

- A cloud seems to hover over the trees, a rough cliff face, a soft ridge holds them in place—elephants move past.
- A man-made ridge creates a backdrop, an outlook; a terraced cliff-face interpreted as parallel walls blend interior and exterior space. Tree trunks and columns stand in front of and behind the façade with no organizing grid. Above all this, a transparent roof is suspended as a bent spatial framework. The visitor occupies various raised levels behind the green walls.

2.3 TRANSPARENCY

The transparent roof gives the visitor the impression that they are under the open sky. Roof structure, columns, trees, and elephants cast shadows on the inside of the building, creat-
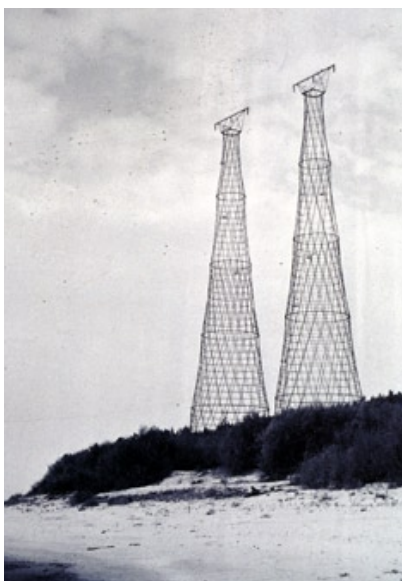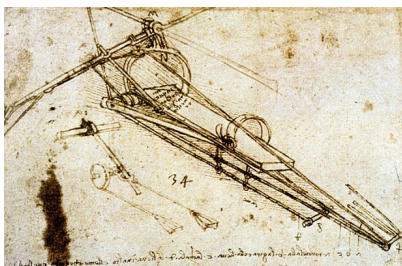

FIGURE 1. (TOP LEFT) ROOF PLAN

FIGURE 2. (TOP RIGHT) CROSS SECTION ELEPHANT HOUSE, COLOGNE.

FIGURE 3. LEONARDO DA VINCI, FLYING MACHINE
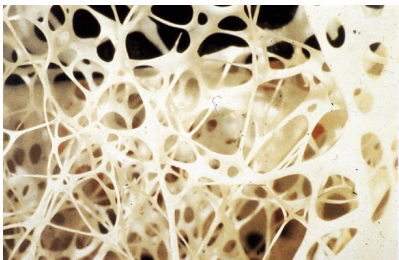
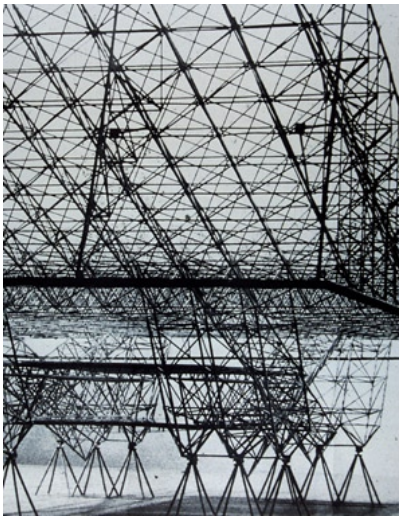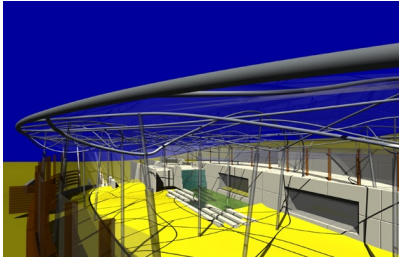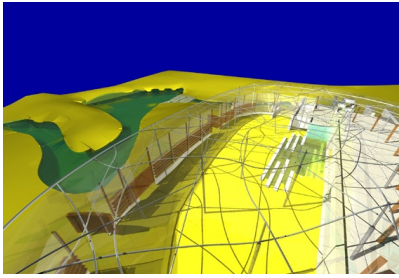**FIGURE 4.** RADIOTOWER, VLADIMIR SUCHOW 1853–1939

ing a dynamic image that allows changes in season and time to become apparent on the building's interior.

3 Primary Structural System

3.1 EVOLUTION OF A STRUCTURE—STRUCTURAL OPTIMIZATION

Caterpillar Cocoon and Spatial Framework

The design concept was to develop a structural system optimized as an irregular spatial structure over a free plan, a symbiosis of an insect cocoon[2], bionics[3], and a spatial framework[4] in the form of a 'roof cloud'.

The automated development of an optimized structure, as opposed to conventional design methods, allows one to deal directly with forces as required. The creation of the structural design is thus analogous to the growth of organic structures on the grounds of structural-mechanical regulations. Important parameters were the minimization of stress at the middle of the fields, and the optimization of the load bearing elements in their scale and dimension.

3.2 DESIGN PROCESS AND STRUCTURAL SYSTEM

The requirements of the new roof construction came from the idea of a balanced, flowing, weightless form. The image of a cloud is given form through the new structural framework. This natural image would not have been possible with a conventional structural framework, a cantilevered roof construction, or a cable-stayed system. This structural system does not seek an individuated solution; instead, it proposes a new universal system that affords the greatest design flexibility.

3.3 STEPS IN THE DESIGN OF THE STRUCTURAL SYSTEM:

Design Parameters:

- Unconstrained form of the roof-line
- Long-span capabilities
- Three-dimensionality of the roof construction to create the image of a cloud
- Wave-like development of the 'roof cloud'
- Freedom of column placement beneath the roof (allusions to a forest)
- Angled columns to create the necessary stiffness

Steps in the development:

Schematic Design

1. Mechanical analysis of a volumetric finite element model
2. Three-dimensional stress analysis using Finite-Element-Method [SLang] Structural Language
3. Spatial stress analysis and visualization of stress trajectories[5] (force paths) within the volumetric model
4. Redevelopment of the finite element model based upon the direction and magnitude of the primary stress trajectories
5. Visualization of the primary spans creates the starting point for the design as resulting from a three-dimensional, optimized structure.

Design

1. After analyzing the primary stresses, the curved tubes of the spatial framework were oriented precisely along the stress trajectories and a finite-element-model of the spatial framework was created.
2. Finite Element[6] re-analysis of the spatial framework model for deformation, swinging and deflection.

The result of this structural evolution is an extremely light-weight optimized structure based on the parameters of the column positioning within the free plan geometry.

2.1 STRUCTURAL OPTIMIZATION

In principle, there are multiple possibilities for structural optimization. One possibility is the one presented here, where span-trajectories are made continuous (volumetric model) to eliminate the elements that carry less weight while subdividing the remaining ones. Continuous, self-intersecting structures are thus created. Each step of structural adaptation

FIGURE 7. COMPUTER MODEL ROOF EDGE

FIGURE 8. COMPUTER MODEL ROOF

FIGURE 9. KONRAD WACHSMANNN, PROTOTYPE AIRPLANE HANGAR

FIGURE 10. BONE TISSUE 'SPONGIOSA'

optimizes the entire system, and at every stage of the development the safety of the total construction is ensured.

Another possibility of structural optimization takes natural constructions as an example. Similar to nature itself, computer-generated genetic algorithms can be calculated using stated goals to achieve global optimization—the search strategy is, like in nature, goal-oriented. Using algorithms, mechanical selection, mutation and recombination improves generationally with a fixed parameter size and quality.

The basis for the optimization is a vast array of possible solutions (population), where every solution (individual) is defined through a particular parameter (chromosome). The individuals within a generation are in competition with one another (selection), in other words, the value (fitness) of the individual is what allows the survival of the parameter (gene) until the next generation. The results of this computer-supported process are automatically generated and optimized.

3 Secondary Structure: Fluoropolymer Sheeting Pillow

As a result of the complex geometry and dynamic qualities of the roof structure, the roofing material chosen was a triple-layered transparent pneumatic membrane construction made of fluoropolymer sheeting [Ethylene-Tetra-Fluoro-Ethylene]. Glass, or other stiff transparent materials, could not be used because of the material qualities (limited spanning capabilities, weight, aesthetic qualities). The criteria for the use of fluoropolymer sheeting were as follows:

- Approximately 96% transparency. In the proposed triple-layered system, only 10% of light rays are lost to the interior space. The degree of light transmission necessary for plants and animals is far better than that of glass.
- Extremely low surface weight of approximately 0.15 kg/qm in a material thickness of 0.2mm (1% Glass)
- High degree of pliability and flexibility
- Self-cleaning through application of anti-adhesive film
- Weather protected and slow-aging (manufacturer quotes a lifespan of over 20 years)

Economical outlook

- K-Value of only 2.2 W/qmK for the triple-layered membrane. The creation of water droplets can be halted through an anti-condensation application.
- High temperature resistance up to 150 degrees, 180 degrees for short periods of time
- Fire resistance B1 according to DIN 4102, minimal fire loading
- 100% recyclable
- Simple connections through hot-seam pressing and linear clips.

The pneumatic fluoropolymer sheeting pillows are filled with clean, dry air through flexible, sealable tubes that run along the steel elements. The air pressure of the films is approximately 300 Pa. The inflation level of the pillows is computer-controlled, dependent on the external forces from wind and snow. Minor damage to the membrane can be compensated for through an alteration in the level of inflation. The connections to the steel and glass façade must be able to withstand the large deformations of the roof, and are for this reason planned as pneumatic duct-shaped pillows. The steel and glass façade itself is self-supporting and structurally not connected to the roof construction.

4 Ecological Concept

The energy concept is designed to incorporate the natural resources of wind and sun, minimizing the need for complicated technical systems through natural means. The triple-layered membrane roof is an active component in this system, acting as an adaptable collector surface that can react to the changing parameters of light and temperature.

Four different conditions are the basis for the planning:

4.1 SUMMER DAY

The increased heat gain is expelled from the building through extensive cross-ventilation.
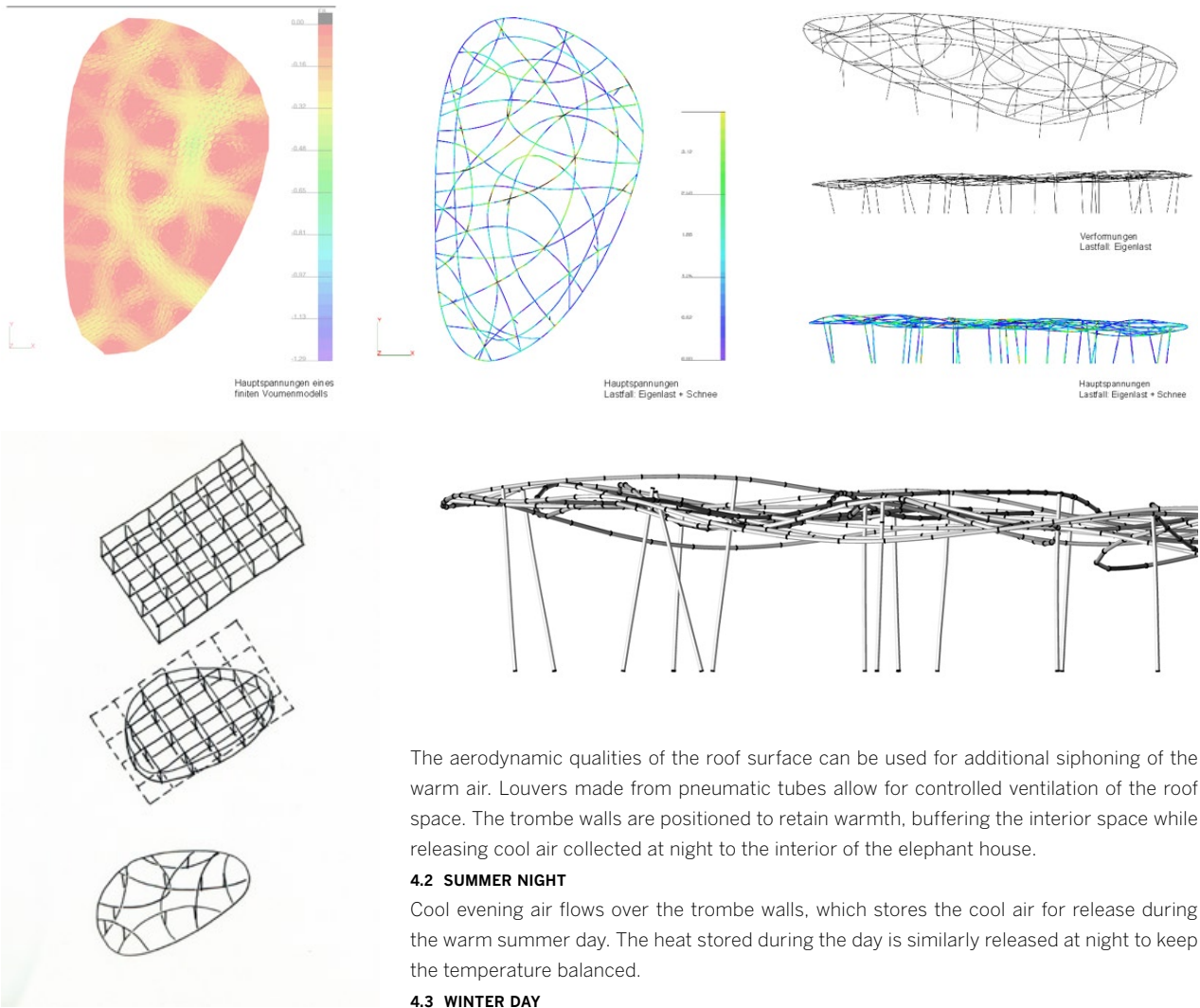
Hauptspannungen eines
finiten Voumenmodells

Hauptspannungen
Lastfall: Eigenlast + Schnee

Verformungen
Lastfall: Eigenlast

Hauptspannungen
Lastfall: Eigenlast + Schnee

The aerodynamic qualities of the roof surface can be used for additional siphoning of the warm air. Louvers made from pneumatic tubes allow for controlled ventilation of the roof space. The trombe walls are positioned to retain warmth, buffering the interior space while releasing cool air collected at night to the interior of the elephant house.

4.2 SUMMER NIGHT

Cool evening air flows over the trombe walls, which stores the cool air for release during the warm summer day. The heat stored during the day is similarly released at night to keep the temperature balanced.

4.3 WINTER DAY

With this roof system the collection of solar heat is possible even on cloudy winter days. Through the siphoning and transmission of fresh air through the roof construction, the roof can be used to pre-heat the fresh air. The k-value is made extremely low, reducing unhealthy drafts of cold air. The amount of fresh air can be regulated with simple air technologies. The solar heat collected by the transparent surface makes k-values of < 0 possible (energy gain).

4.4 WINTER NIGHT

The ventilation functions similarly to that of the winter day. The trombe wall, having absorbed extra warmth during the day and given it up at night, can receive supplemental warmth under extremely cold conditions. In this way, the walls become low-temperature radiators; a heat pump (earth) is proposed as an energy source. The large storage capacity and surface dimension create a balanced interior climate.

5 Summary and Outlook

The combination of a form-optimized structural system with an extremely light and flexible material creates an extremely low ratio of steel per square meter. Naturally, tent or cable systems are still lighter, yet the construction system presented here becomes an additional possibility in the realm of optimized structural systems. Still remaining to be discussed is the possibility of using new materials for the structural system.

5.1 NEW MATERIALS IN THE STRUCTURAL SYSTEM

For about the last ten years, there has been an increase in the use of composite fiber materials made from glass, carbon, or aramide fibers (ex. Kevlar) in architectural applications.
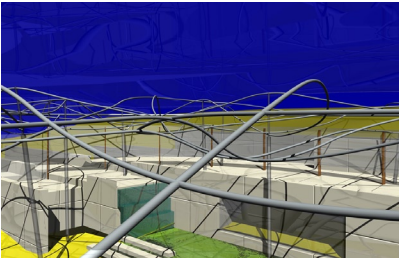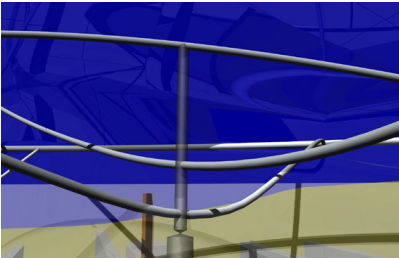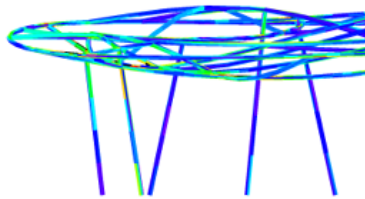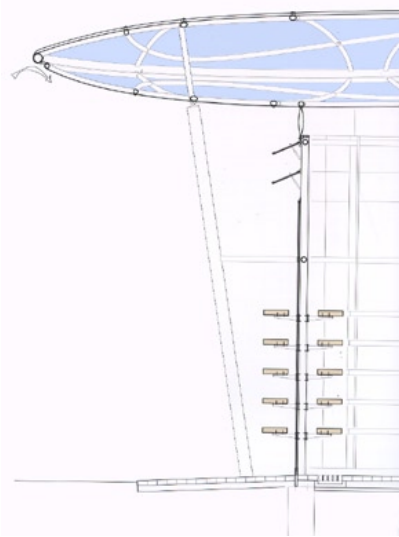
FIGURE 12. SKETCH: ORTHOGONALLY GRIDED SPACE STRUCTURE AND NON GRIDED SPACE STRUCTURE

FIGURE 13. SPATIAL STRESS ANALYSIS WITHIN THE VOLUMETRIC FINITE ELEMENT MODEL AND VISUALIZATION OF STRESS TRAJECTORIES

FIGURE 14. ELEVATION FINITE ELEMENT MODEL

The benefits from these fiber-reinforced plastics are in their increased stability, minimal weight, and resistance to corrosion. Compared to steel, whose length of failure is 24 km, the fiber-reinforced materials have failure lengths of up to 180km at a material weight that is ¼ that of steel. This is in addition to qualities of increased stability, better resistance to corrosion and aging, as well as limited expansion and contraction.

Unexplored uses for composite fibers would be not only the replacement of conventional materials like steel, aluminum or wood, but also uses particular to the new material. Especially in the case of structurally optimized building elements and systems, entirely new design possibilities are available.

Unlike steel, an isotropic material whose structural capabilities and mechanical properties are equivalent in all directions, composite fibers are an-isotropic. This means that, like wood, the mechanical properties are decidedly different along their length than along their breadth. The controlled directionality of the fibers allows composite fibers to react extremely well to specific directional requirements. New production methods from the textile industry[7] allow carbon fibers to be made into a variety of three-dimensional building elements using modified weaving and braiding machinery. The weaving and braiding allows the highly complicated shapes and sandwich panels to be formed from one piece. In this way, the fibers can be given the precise directionality required by the loading trajectory. This material and form optimization process has already been in use since the 19th century in the biological sciences[8] and is similar to Spongiest[9] structures in bones. These so-called bone beams are always directed along the path of the greatest tension or compression, in other words along the trajectory of the force.

The idea of material and weight distribution according to the specific requirements means that material will only be placed where it is necessary according to the amounts required by structural statics and dynamics. It opens a new dimension in the field of material and structural optimization. Even a new technology of optimized connections of building elements can be developed from the adhesives used for plastics and aluminum in the airplane industry.

5.2 SMART MATERIALS AND SMART MATERIAL SYSTEMS

A look into the future of lightweight structures shows that 'smart materials' have a wealth of unexplored possibilities. These 'adaptive' materials of one or more components are able to adapt themselves to particular external requirements, for they do not have fixed properties. They actively respond to external changes such as temperature, radiation, loading or electrical current. Of particular interest is the reversibility of changes in property. These materials are similar to adaptable, self-repairing structures in nature that can identify a failure and react accordingly. Shape-memory alloys of nickel-titanium, form-variable piezo-electric or electro-viscous fluids are already in use in the airplane and space industries.

Principles of Intelligent Structures:
*   Actuators and Motors that act like muscles
*   Sensors that serve as a nervous and memory system
*   Communication and calculation networks that are representative of the brain and vertebrae

Actuators[10]

As a result of a change in temperature or in their electromagnetic field, they can vary their shape, stiffness, position, oscillation frequency, or other mechanical characteristics.

Differences between the most important actuators:
*   Shape-memory alloys
*   Piezoelectric[11] ceramics
*   Magnetostrictive[12] materials
*   Electrical and magnetic rheological[13] fluids

5.3 SHAPE-MEMORY ALLOYS

Shape-memory alloys (Nickel-Titanium alloys) can return to their original shape after deformation through a temperature change. In this way they can accept forces and deformations of up to 8% over their capacity, thereafter returning to their original state. Shape-memory alloys embedded in composite materials, such as nitinol wire, can actively alter
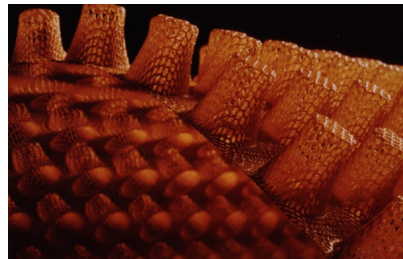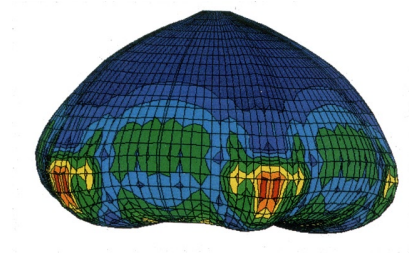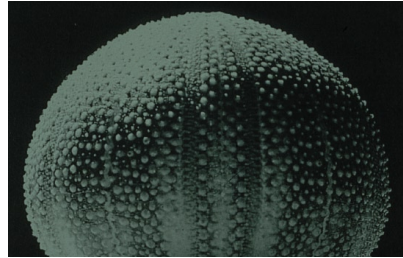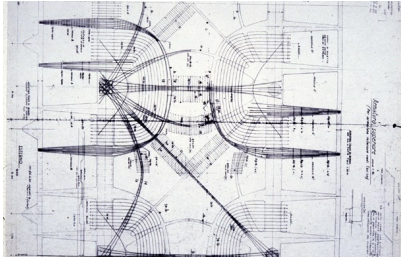

FIGURE 15. DETAIL ROOF / FASSADE

FIGURE 16. FE MODEL

FIGURE 17. COMPUTERMODEL

FIGURE 18. COMPUTERMODEL

their oscillation qualities by shifting their internal frequency to eliminate resonance result-ing from external vibrations—something that, in the past, has caused failures in bridges. Reinforced concrete construction could contain sensors that identify cracks in the con-crete or corrosion in the steel reinforcement. Additionally, internal shape-memory alloys can resist internal stresses that arise over time.

5.4 CONSTRUCTIVE PHILOSOPHY AND INTELLIGENT MATERIALS: SELF-ORGANIZATION AS THE DEFINING PRINCIPLE OF NATURE

At its best, intelligent materials will influence the entire philosophy of construction. Engi-neers will no longer ensure safety through quantity of material and cost. Simple structural analysis will no longer suffice; instead, self-organizing structures will define the new con-struction principles.

The concept of self-organization is not new; it is a defining principle of nature. It defines things as simple as a raindrop or as complex as living cell—simply a result of physical laws or directives that are implicit in the material itself.[14]

The defining principle of self-organization is a process by which atoms, molecules, mo-lecular structures and constructive elements create ordered and functional entities. Man-kind may conceive of them or get them started, but once started they move forward ac-cording to their own internal plan, searching for an energy conscious form that develops into a system whose shape and function is directly keyed into the elements of their make up.
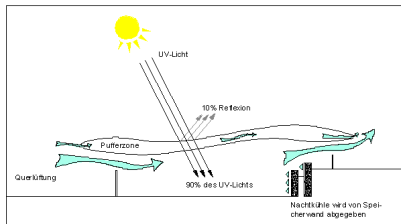
In the future, the materials engineer will develop constructions out of self-structuring materials that consciously use the principles of self-organization, creating not only materi-als with brand new properties but also inspiring architects to define their constructions in a more intelligent way.
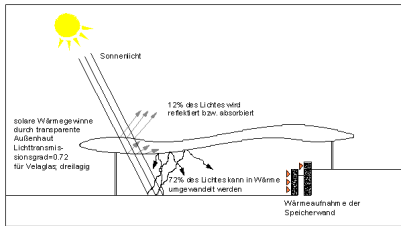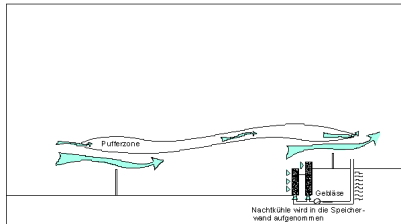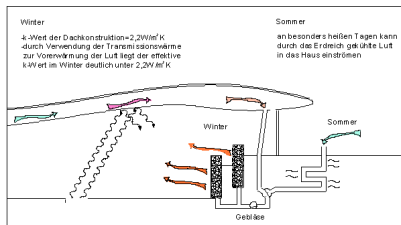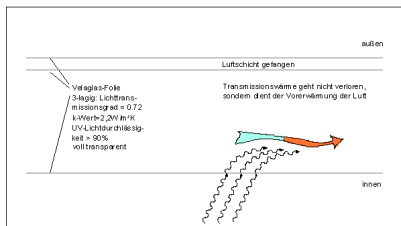
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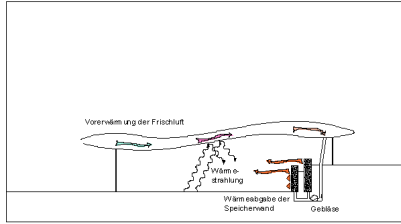
Winter Nacht

Sommer Tag

Sommer Nacht

Belüftungskonzept

Dachsystem

6 Acknowledgements

7 Endnotes

1. SLang [The Structural Language] was developed at the Institute for Structural Mechanics at the Bauhaus-Universität Weimar. The SLang software package uses the Finite-Element Method as well as probability calculations to model stochastic loading along with physical and geometric improbabilities.Shell-like protective casings around an insect pupa or egg sac (ex. spiders, beetles, and worms), made from woven silk and tissue.

2. Bionics deals with the systematic and technical application of constructive, procedural, and developmental principles of biological systems. The spectrum of applications encompasses nearly all technical disciplines and defines the areas of Constructive Bionics, Procedural Bionics, and Information Bionics.

3. Spatial frameworks are systems that operate on the arranged interaction between singular tension and compression members. In this case, the positioning of the elements is a result of the direction of external forces and the size of the vector forces in the elements.

4. Trajectories are the directions of the primary spans in massive structures; they are defined by external forces and internal loads.

5. The finite-element-method is a procedure used to solve structural-mechanical calculations with precedence given to the three-dimensionality of the system. As a result, the construction is broken into discreet elements—Finite Elements (FE)—such as columns, beams, plates, shells, etc. characterized by the individual connections (discreet points) where they are combined with one another.

6. Developed at the RWTH Aachen

7. K. Culmann, Sir J. Herschel

8. Frame-like bone structure

9. Basic output element of a control switch, that can be used as changeable resistance in mass and energy flows.

10. Piezoelectricity is the generation of electricity or of electric polarity in dielectric crystals subjected to mechanical stress, or the generation of stress in such crystals subjected to an applied voltage.

11. Magnetostrictive materials are similar to piezoelectrical materials, but they react to magnetic fields instead of electrical ones.

12. Electrical and magnetic rheological fluids contain small elements (micrometers-1/1000 of a millimeter-in size) that create chains in electrical and magnetic fields within milliseconds, increasing the material viscosity.

13. An example of technical uses of self-organization already in use is the production of float glass.