STRUCTURAL VISUALIZATION IN ARCHITECTURE

by

THOMAS DWIGHT JACOB

B. Arch., Kansas State University, 1965

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF ARCHITECTURE

College of Architecture and Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

Approved by:

Eugene Thorson

Major Professor

ACKNOWLEDGEMENTS

I gratefully acknowledge the advice and encouragement given me during the preparation of this thesis by Professor I. Eugene Thorson.

Appreciation is further extended to my committee members Professor G. Alden Krider and Professor Charles E. Parks, and to Dean Emil C. Fischer, Committee Chairman.

TABLE OF CONTENTS

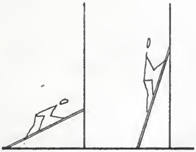
CHAPTER 1

INTRODUCTION

The importance of the structural revolution on contemporary architecture is a much debated question. No matter what argument one makes there remains one obvious fact: the architect cannot get by with a knowledge of structures which is inferior to the knowledge of the structural engineer. Likewise, engineering and the mental make-up produced by engineering training do not suffice to create architecture. This is specialization. The architect needs the specialization of the engineer to carry out the structural schemes required by the architectural themes of today, but the architect must have an understanding of structural concepts in order to transform the concepts into real objects. His understanding must be deep enough to think through the physical origins, mathematical theorems and experimental data that belong to structural analysis.

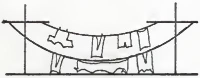
This thesis provides a visual understanding into the working characteristics of the various structural systems without the use of quantitative methods.

The premise that beginning students in architecture should have to wait until they are exposed to structures through the slow process of mathematical analysis does not allow the student to realize the structural content of architecture. This gives rise to the question, "How well can the essentials of structural action be understood by a person untrained in the mathematical and physical sciences?" This understanding is possible only if a clear distinction is made between basic structural concepts and a thorough knowledge of structural analysis.



LADDER PLACEMENT REQUIRES INTUITIVE STRUCTURAL KNOWLEDGE TO KEEP IT FROM FALLING DOWN

After establishing the basic structural principles, one does not have to be a specialist to understand them on a purely physical basis. In our daily experiences we encounter various structural principles. It is easy to utilize these experiences, to systematize knowledge, and to reach an understanding of how and why contemporary structures work. While the layman will be awed by this inquiry, the architect will find it a necessity to keep pace in his profession (26).



COMMON STRUCTURAL PROBLEM THAT CAN BE SOLVED INTUITIVELY

THE TENT MUST BE ANCHORED SO IT WILL NOT BLOW AWAY

A purely intuitive approach used to introduce structural concepts cannot be expected to lead to a qualitative knowledge in structures. Since interest in a field is usually aroused by prior exposure, a qualitative knowledge should often be a prerequisite to quantitative analysis.

The presentation of the material in this thesis will be by visual diagrams that show the working motions of the systems. The student should not be content to accept the material as a governing code of architectural structures, but rather,the material should be used as a guide for the understanding of structures.

It is not possible to use graphic presentations without supplementing them with an additional written description of the system. As a system grows or deviates from the original scheme, it will always take with it some of the original characteristics. No matter how complicated the system may become, the "basics" are still present. If one trains himself to see through the cover into the skeleton for the simple origins of the system, he should be able to more readily understand new principles.

To undertake a work on structures without making some reference to architectural design is difficult, so the last chapter will be devoted to a discussion of the interrelationship between structural form and architectural form. This subject will be presented through the arguments that are raised concerning these various relationships. The integration of structural form and architectural form will also be investigated and discussed.

ORGANIZATION OF THE TOPICS

In order to gain a better understanding of the material contained in this thesis, it is necessary to explain the organization. Continuity and simplicity from section to section is of utmost importance. Each structural system is laid out under the following topics: Structural Concept, which is a written description of the system and its relationship to nature; Structural Geometry and Stresses, which is a graphic presentation of the primary form, and the visual action of the stresses working in the system; Structural Feasibility, which is the best use for the system, and the capabilities of the system to enclose space; and finally, Structural Variations, which are examples of the various forms the system may take. These variations will be, for the most part, visual, but they will be supplemented by any written description which might be needed for clarification.

In addition, a consistent set of graphical symbols has been adopted to further maintain continuity between sections. These symbols are shown here without a definition of their meaning merely to acquaint the reader with them. It should be noted, while these symbols will not change in visual representation, they may vary in size to correspond to changing magnitudes.

LIVE LOAD SMALL LIVE LOAD

WIND LOAD SMALL WIND LOAD

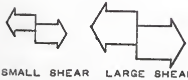
IMPACT LOAD

LIVE DEAD IMPACT

GRAPHIC SYMBOLS FOR LOADS

COMPRESSION TENSION

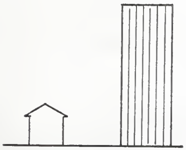
MOMENTS



SMALL SHEAR STRESS LARGE SHEAR STRESS

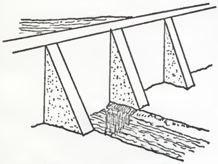
CHAPTER II

THE PHYSICAL PROPERTIES OF STRUCTURES



ENCLOSING STRUCTURES

STRUCTURES BETWEEN POINTS



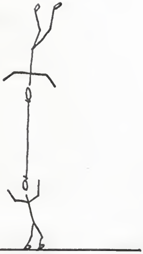
RETAINING STRUCTURES

The following statements will be used in this thesis to define what constitutes a structure; its purpose and function. Structures are always built for a definite purpose. This fact is one of the essential differences between structural form and sculpture; there is no structure for structure's sake (26).

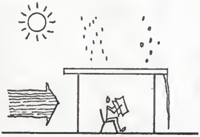
Architectural structures define and enclose a space in order to make it functional. Their usefulness stems generally from the separation of the defined space from the weather, but this may not require complete enclosure of the space. A stadium is an example of this type enclosure (26). Other types of structures may be built to connect two points, or to withstand the action of natural forces.

The structure resists the pull of gravity on the building materials and on the masses which the building carries: such as occupants, furniture, storage and machines; and it transmits such forces to the base supports.

Structural design is basically a process whereby a balance is made between the imposed forces on a building and the materials that resist



THE PURPOSE OF STRUCTURAL DESIGN IS TO BALANCE LOADS



STRUCTURES SERVE AS SHELTER FOR MAN

these forces. Creative structural design must be intimately associated with architectural design itself (35).

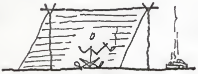
The structure, be it large or small, must be stable, lasting, and satisfy the needs for which it was built, and it too must achieve the maximum result with the minimum means. These conditions can be found, to an extent, in all construction from the mud hut to the most magnificant building.

The primary function of an architectural structure is to enclose and protect a given volume of space from the natural elements of wind, rain and snow, from changes in temperature and from noise. A spanning structure provides passageways for the movement of persons and vehicles. Floors, staircases, ramps, bridges and viaducts are used to fulfill this function. To resist the lateral thrust of earth, water, and other fluids, retaining structures are required. Specifically, every structure has a resisting function to fulfill.

HISTORICAL

THE CAVE WAS MAN'S FIRST TYPE OF SHELTER

Man has always had a need for and an interest in structures. At first man needed structures for protection and shelter. The two simplest forms of human habitation were the cave and the tent, which are extremes within the range of structural expression. The cave is a natural structural mass which encloses the inhabitants within the body of the earth. Man had but to discover the cave to acquire its protection. On the other hand, the tent was a structure of a frame members which formed a skeleton that was then covered with hide or leaves to form the protection. After obtaining shelter for himself, man later built public buildings for government and religious needs. As man began to transport himself from place to place the need for bridges arose.



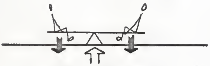
THE LEAN-TO SHELTER WAS MADE FROM A POST AND BEAM SYSTEM

There were always specific men in charge of the design of the structures of a community. These men were usually the community leaders, and those of high intellect and responsibility. Even though they did not have a knowledge of material behavior and characteristics, they based their profession on "rules of thumb" which they developed with respect given to proper proportion (6).

STRUCTURAL PRINCIPLES

There are certain structural principles on which all structural resistance is based. An attempt to create a structure without a knowledge of these principles would be extremely difficult.

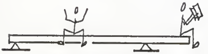
Irrespective of the type of analysis employed, these fundamental principles, which are based on the physical laws of nature, are invariant and must be met. These principles may be categorized into four different, but interconnected, fundamental concepts which are present in every structure. It is necessary for the structure to resist the efforts produced by the addition of these physical concepts, which are equilibrium, loading, stress and deformation.



FOR EQUILIBRIUM THE LOADS MUST BALANCE

EQUILIBRIUM

The first basic principle that has been foundation for structural design, one which cannot be neglected by one designing a structure, is equilibrium. Equilibrium is required to guarantee that a building, or any of its parts, will not move. Intuitively, this says for a body or structure to be in equilibrium, there must be as much force pushing in one direction as there is pulling or pushing it in the opposite direction (26).



THE LOAD BETWEEN THE SUPPORTS BALANCES THE LOAD AT THE END OF THE BEAM

IF THE LEFT LOAD IS REMOVED, THE BEAM WILL ROTATE ABOUT THE RIGHT SUPPORT

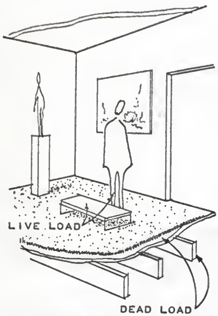
FOR EQUILIBRIUM, THE BEAM MUST BE TIED TO THE LEFT SUPPORT

Simple equilibrium principles apply to all structures. These principles are considered to be the laws of statics. First, to guarantee equilibrium in one direction, the external forces are balanced by the equal and opposite internal forces of the structural system. Second, to have equilibrium against rotation, external forces which try to make a structural member rotate about a point must be counteracted by the internal physical strength of the member at the point of rotation.

LOADS

All structures, by the simple fact of their existence, are submitted to, and must resist a variety of loads which act upon the individual structural members. A knowledge of the types of loads which act upon the structural system is essential since forces are created by subjecting the structural members to loading. These forces cause stresses and strains in the elements of the materials which compose the structure, and their magnitude determines whether or not the structure will hold together or separate. Separation of the elements will mean failure of the structure.

Types of loads can be divided into gravity loads, horizontal or lateral loads, and dynamic loads.



VARIOUS LOADS FOUND IN EVERY STRUCTURE

Gravity loads are those which act in a vertical direction due to the earth's central gravitational pull. Under this catagory are found the dead loads. Dead loads are constant and fixed in position. The self-weight of the structural elements and the weight of the superimposed components, such as the roof, floor and walls are dead loads.

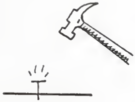
Live loads are also considered to be gravity loads, however they are of uncertain nature because they are variable and movable. Included under live loads are humans and animals, movable machines and fixtures, partitions and other non-structural elements such as rain, snow and ice. These loads can be determined mathematically and experimentally (11).

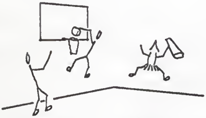

WIND FORCE ON A TREE

Horizontal loads are the loads most usually overlooked in structural analysis. Wind is the most common horizontal load. Because of the variability of winds, and the complexity of the aerodynamic effects on a building, precis wind forces are difficult, if not impossible, to determine accurately.

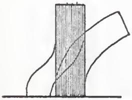

WIND FORCE ON BODY

Loads that change rapidly, or loads that are applied suddenly, are called dynamic loads. It is essential that this type of load be clearly


DYNAMIC LOAD


CONTINUOUS DYNAMIC LOADS ACT ON THE FLOOR

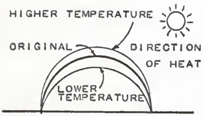

EARTHQUAKE EFFECTS ON A STRUCTURE CAN BE VISUALIZED BY IMAGINING A DISH OF SHAKING JELLO


EARTHQUAKE MOTIONS ON A STRUCTURE

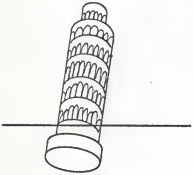
understood because they can be exceptionally dangerous if ignored. The importance of dynamic loading is the fact that when a dynamic load is applied instantly to a structural member the resulting stresses in the member will be much greater than if the same load were applied slowly to the member (26).

An earthquake is a dynamic load that acts mainly in a lateral direction. It is possible to analyze the effects of an earthquake by approximating it as a static load. Seismic (earthquake) load tables of probable intensity of earthquake magnitudes for geographical zones have been made to help reduce much of the guess work involved in designing structures to withstand earthquake forces.

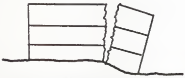
Another way to determine the effects of earthquakes on a structure is to consider their dynamic quality. This method offers a more accurate analysis of actual behavior in structural members under earthquake loading through the "feeling" of the forces exerted by the earthquake on the structure. To visualize this, imagine the structure as being seized by a giant hand at the foundation and shaken vigorously back and forth. If you can conceive of the building holding



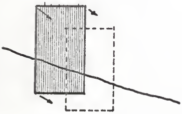
EFFECTS OF THERMAL MOVEMENT IN A DOME



RESULT OF UNEVEN EARTH SETTLEMENT



UNEVEN EARTH SETTLEMENT



SLIDING BETWEEN STRUCTURE AND THE EARTH

together, your design is essentially correct (11).

All of the loads that have been considered so far are those which are visible or can be felt. However there are loads which can cause large and dangerous forces on a structure even though they are invisible. One such load is thermal expansion and contraction. Whenever a structure must withstand large temperature changes, it is necessary to make the structure flexible in order to accommodate such changes. In essence, this is one case where the structural members resist the forces of a loading condition by moving with the load rather than by remaining fixed in position (26).

Other types of "invisible" loads which must be studied when considering structural design are earth pressure, hydrostatic pressure, and friction. Primarily, the upward push of the earth is passive and fixed. The only requirement is that the earth resist forces coming from the building mass. Occasionally, due to the moisture characteristics, the soil will push up actively against the foundation of the building resulting in hazardous, uneven earth settlements (35).

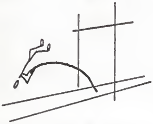
Friction forces are developed whenever there is sliding, or the tendency to slide, between two objects. In structure, large sliding friction forces are often developed between the foundation and the surrounding soil.

STRESSES

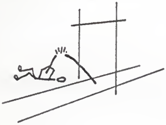
To measure the strength of a structural system, it is necessary to analyze the simple stresses which may be found in the structural elements. Conventionally stresses are divided into those which act parallel to the axis of the structural member, and those stresses which act perpendicular to the axis of the member. Also, there may be combinations of the two types of stresses acting on the member.

COMPRESSION IN NATURE

BUCKLING IN A STIOK



BUCKLING IN A POLE´



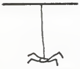
CRITICAL BUCKLING

Parallel or axial stresses are of two types. One of these, compression, occurs when the particles of a material are pushed one against the other. Shortening of the material is typical of compression. Because of this shortening effect, a slender structural element may reach a point, if loads are applied indefinately, that instead of just shortening, the element will buckle out and break. Whenever there is a choice between different paths, a physical stress will follow the "easiest" path through the structural member. Confronted with the choice of buckling or shortening, the member will choose to shorten for relatively small loading conditions, and to buckle out for relatively large loads. Buckling is very common in slender structural members.

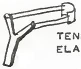
Tension is a second type of axial stress and it tends to pull apart the particles of a material. In contrast to compression, the members elongate in tension instead of shorten, and they may also decrease in cross-sectional area. A tension member is not subject to buckling, thus making it a much more efficient structural member than a compression member.

In shear stress, the particles of the material will slide past each other. This sliding takes place in both the longitudinal and transverse sections of the structural member. Torsion is a shear stress in a member that is produced by twisting the member (26).

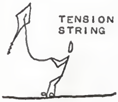
Bending stress is a combination of tension and compression acting in different fibers of the same structural element. The fundamental characteristic of bending is that a load, applied normal to the axis of the member, is transmitted through the member at right angles to the applied load. The most satisfactory structural member able to resist bending is one which is constructed of a material that has equal strength in tension and compression (26).



TENSION IN NATURE



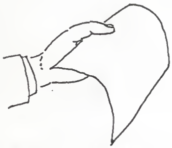
TENSION IN ELASTIC



TENSION IN STRING

SHEAR TORSION

BENDING IN DIVING BOARD



BENDING IN A SHEET OF PAPER

DEFORMATION

DEFORMATION DUE TO MATERIAL FLOW

DEFORMATION IN A LEAF

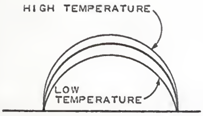
BENDING IS DEFORMATION IN A BEAM

Structural members deform whenever they are loaded. Deformation in compressive members is characterized by shortening of the member and increased cross-sectional area. In tensile members deformation is the lengthening of the member and the reduction of the member's cross-sectional area.

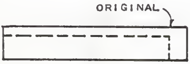
Basically, deformation is the deviation of a structural member from its original axis in the transverse or longitudinal direction. This deviation is measured normal to the original axis from the deformation axis. Even though this deviation may only be infinitesimal in size, it greatly influences structural behavior.

If there is too much deformation, the structure's functional usefulness could be destroyed. It is not uncommon for excessive deformation in one component of a structure to trigger failure or total collapse in another component, because other structural members required to support the loads that are shifted to them from the deformed members may not be strong enough to carry the additional load.

Deformation may be caused by other conditions than external forces. Expansion or contraction due to temperature changes is one of these conditions. Other deformations are shrinkage in moisture-absorbing materials, such as concrete and timber, because additional moisture in these materials decreases their resisting structural properties. Concrete and plastics also change shape, which is called "creep," as they increase in age. This is a natural characteristic of these materials that should be considered during the design.



DEFORMATION IN A DOME



SHRINKAGE IN TIMBER DUE TO MOISTURE REMOVAL

MATERIALS

Any discussion of structural design cannot be complete without presenting the capabilities of the materials which may be used to build a structure. Structural materials can be categorized into four primary groups: masonry, timber, metals and concrete.

MASONRY

Masonry includes the following types: dry masonry, stone masonry, mud masonry, adobe, brick masonry and concrete masonry. Dry masonry, now of only archaeological significance, was the forerunner of all stone masonry. It involved constructing with stone and rock by laying them in such a manner as to enclose space without cutting the material or using any type of bonding material between the joints. Stone masonry is massive in character with high resistance to compression and very little resistance to tension because the mortar joints required to bond the stones cannot resist tension.

Bricks are considered to be the first material created by man from the elements of earth, air, water and fire. Since bricks may be manufactured in a variety of sizes and weights they have a wider range of application than other masonry materials.

To summarize, structures of masonry materials, either natural or manufactured, resist compression well, but are weak in tension. Masonry materials also require massive elements if they are used in a load bearing capacity.

TIMBER

Timber is a cellular material produced in nature with its structural potential ready for use, and it does not require the complex manufacturing processes needed by other materials (19). Because it is a natural material, the durability of timber is limited. Prismatic and straight workable pieces of greater length than width are common structural elements in timber.

Timber strength varies in different species. However, all species have an equal capacity to resist tension or compression. Through the process of laminating small, thin timber pieces together, greater freedom of shape and strength is added to timber structural elements. Timber can now be treated in order to protect it from fire and deterioration.

METALS

Metals, like timber, are nearly as strong in compression as they are in tension. Cast iron, which preceded steel, is a material with high compressive resistance. In general the tensile and compressive strengths of metals exceed those of the classical materials - stone and wood (30).

Steel is a very valuable structural metal because of its great elasticity. A disadvantage in steel construction is that steel will weaken if it is left exposed to extreme heat or weathering conditions. Therefore, it is necessary to wrap steel members in some type of material to satisfy fire and safety regulations. Some new types of steel can be left exposed and allowed to weather, thus they are more economical than steels which require protection.

Molded and forged steels are not considered to be structural materials. They are used to advantage only in such auxilary or local elements as pivot pins and roller bearings. Stainless steel is not normally considered a structural material because of its expense and difficult fabrication requirements.

CONCRETE

Concrete is a man-made material that has changable properties. For the first few weeks after being poured, concrete is generally weak, but after about a month, it matures to approximately full strength and continues to gain additional strength thereafter. This strength can be varied by changing the properties of the basic ingredients of concrete which are cement, water, fine sand and course-grained aggregates of sand and stone.

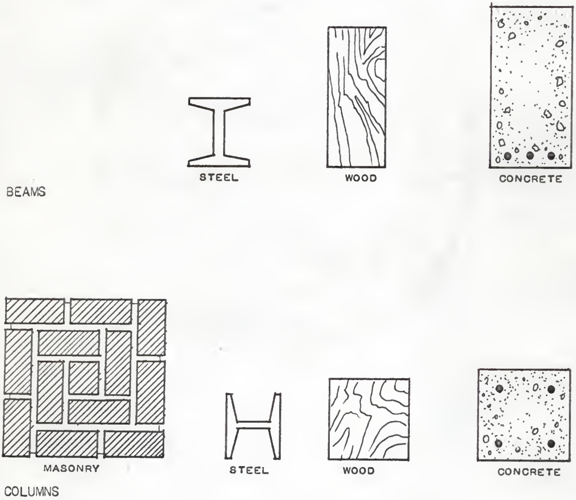
Concrete is an extremely strong material when used in compression. Reinforced concrete makes use of a strong tensile material (usually steel) to increase concrete's tension strength. From a technical stand point, reinforced concrete is a nearly perfect material because it presents two fundamental characteristics which differentiate it from all other building materials: (1) it is produced in a semi-fluid state and therefore can be molded into any form, and (2) it has continuity which, because of the monolithic nature of construction, hold together the various parts of the structure (20).

Prestressed concrete is reinforced concrete that is compressed before loading so that loading only reduces the amount of compression, rather than increase tension. Prestressing can be done in two basically different ways: (1) by pre-tensioning, in which reinforcement is stressed before the concrete is poured, and (2) by post-tensioning, in which the concrete, sufficiently hardened, is stressed by tensioned wires or cables that have adequate anchorage in concrete. Prestressing allows for an even greater use of reinforced concrete in construction due to the fact that greater spans are possible without increasing the size of the structural members (30).

ADDITIONAL MATERIALS

In addition to the four basic structural materials, structural plastics are gaining wide usage. Some of the qualities of plastics are high impact resistance, easy maintainance, aesthetic appeal through shape, colorability, and various textural possibilities. However, plastics are expensive, burn easily and are not as strong as other building materials (28).

It is not possible to design the same structure from different materials and achieve equal stability. The choice of structural material is dependent on many factors among which are availability, cost, ease and suitability of construction, and strength. Also important are such factors as the material's resistance to weather, fire and corrosion; the shapes which material may take; and color and textural qualities which are important if the material is exposed to weathering. To conclude, it might be said that the physical properties of a material not only limit the structural design, but in many cases, it may dictate the design.



RELATIVE CROSS-SECTIONAL AREAS OF MATERIALS REQUIRED TO CARRY EQUAL LOADS OVER EQUAL LENGTHS

CHAPTER III

THE STRUCTURAL SYSTEMS

There are three basic elements of building which are available to man and nature. These elements can be expressed by a rock, as a solid body, an egg as a stressed surface, and the tree trunk as a slender member (1). These three types fulfill the primary function of a structure - to collect loads and transfer them to the earth.

The manner and form in which the loads are collected and transferred are many. Nature builds her structures in such a way that the internal forces act in the direction of least resistance. In man-made structures, the "easiest" path utilizes the geometry of the architectural form to transmit the imposed forces.

The simplest structural form is a straight bar that transmits a constant force between two points. The extent to which the structure deviates from a straight line increases the complexity of structural analysis. Therefore, to simplify complex structures, it is necessary to investigate the geometry of the structural form and determine the common characteristics it has with a simple structural system.

MASS

Structures which gain their strength from members which are totally compressive are termed mass structures. The pull of gravity keeps the members aligned, and their weight helps maintain their position. The bearing wall is the most common mass structure.

ROCK FORMATIONS DEPICT MASS STRUCTURES IN NATURE

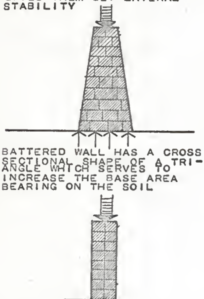
BEARING WALL - STRUCTURAL CONCEPT

The bearing wall distributes loads gradually through a vertical, or near vertical continuous mass to the earth.

THE PYRAMIDS ARE MASS STRUCTURES THAT ARE CONSTRUCTED WITH A SQUARE BASE AND TRIANGULAR FACES WHICH GIVES THEM GET LATERAL STABILITY

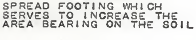
BEARING WALL - STRUCTURAL GEOMETRY AND STRESS

If the compressive stress in a mass structure remains constant, the cross-sectional area must increase as the load increases, thus the wall must become thicker toward the base. The resulting shape of the wall section resembles a triangle and is called a battered wall.

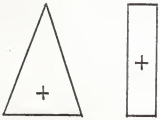


BATTERED WALL HAS A CROSS-SECTIONAL SHAPE OF A TRIANGLE WHICH SERVES TO INCREASE THE BASE AREA BEARING ON THE SOIL

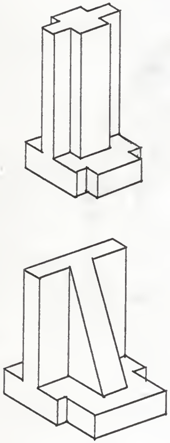
If the wall is penetrated by an opening the structural continuity is disrupted, the stress will not increase uniformly throughout the wall, and the loads on the soil will not be uniform (3). Lateral stability or the tendency to tip over, is the biggest problem facing bearing walls. It can be solved by either using stronger compressive



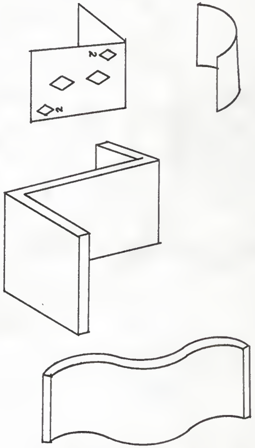
TRADITIONAL MASONRY ON SPREAD FOOTING WHICH SERVES TO INCREASE THE AREA BEARING ON THE SOIL materials, or in the case of weaker materials, by using buttresses. Buttresses are structural elements which increase stability by the triangulation of a portion of the wall. This method requires more material than is necessary to sustain the loads. Another way to increase the stability is by the geometry of the system of walls, this gives stability by interaction of adjoining walls (3).



THE TRIANGLE OFFERS MORE STABILITY TO LATERAL LOADS BECAUSE IT HAS A LOWER CENTER OF GRAVITY



BY INCREASING THE AREA UNDER CONCENTRATED LOADS, OR ADDING MATERIAL TO THE FACE OF THE WALL, LATERAL STABILITY IS INCREASED

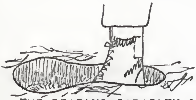


DIFFERENT ARRANGEMENTS OF THE WALL GEOMETRY WILL ALSO INCREASE THE LATERAL STABILITY OF THE BEARING WALL

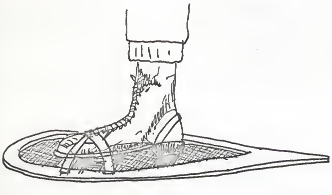
BEARING WALL - STRUCTURAL FEASIBILITY

Presently the masonry wall and the reinforced concrete wall are the most common of mass structures. Both of these materials are limited in height due to their instability. Masonry walls become very unstable if they are built higher than twelve feet, unless the thickness of the wall is increased. In concrete, as the wall increases in height, the economy is lost, due to the fact that areas required at the base becomes impractical. If more reinforcement is added to the concrete it is possible to reduce the cross-sectional area of the wall. If the bearing wall is limited to heights of one or two stories, then the system is one of the most economical of the structural systems.

A WOMAN'S HIGH HEEL SHOE DISTRIBUTES THE WEIGHT OF THE WEARER OVER AN EXTREMELY SMALL AREA, THEREFORE IT MUST HAVE HIGH COMPRESSIVE STRENGTH

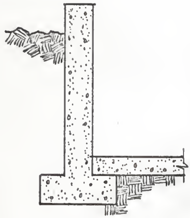


THE BEARING CAPACITY OF SNOW IS VERY WEAK, THEREFORE IT GIVES NO RESISTANCE TO A PERSON WHO TRIES TO WALK ACROSS IT



THE SNOW SHOE USES THE PRINCIPLE OF INCREASING THE AREA AT THE BASE OF A COMPRESSION MEMBER TO SPREAD THE SUPPORT LOAD

FOUNDATION WALL - STRUCTURAL VARIATION

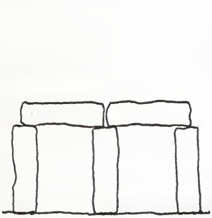


TYPICAL FOUNDATION WALL ENCLOSES SPACE ON ONE SIDE AND RESISTS EARTH PRESSURE ON THE OTHER SIDE

The most common use of the mass structure can be seen in reinforced concrete foundation walls used below the surface of the earth. These walls not only support the structure above the surface, but they also serve to retain the earth's pressure which act laterally on the wall.

POST AND BEAM

The post and beam is a structural system which distributes loads to supports through a linear arrangement of horizontal and vertical members. The vertical members are referred to as posts or columns, and they resist compressive forces. The horizontal members are referred to as joists, beams or girders, and these members resist bending and shear stresses.



ANCIENT BUILDING MADE USE OF THE POST AND BEAM SYSTEM, BUT WERE LIMITED TO THE PHYSICAL SIZES OF AVAILABLE MATERIALS

COLUMNS - STRUCTURAL CONCEPT

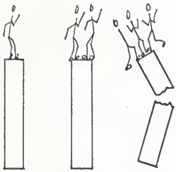
Columns are quite common in nature. Examples are human legs, tree trunks and flower stems. The function of the column is to transmit a compressive force along a straight path in the direction of the member (3). The top of the column supports a load, and the base of the column transmits and distributes the loads applied at the top of the column over the supporting soil.

THE TREE TRUNK IS A NATURAL POST

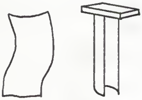
A LOAD APPLIED TO THE TOP OF A POST IS TRANSMITTED TO THE BASE OF THE POST BY DIRECT COMPRESSION

COLUMNS - STRUCTURAL GEOMETRY AND STRESSES

Columns resist applied loads by compression if the loads remain below a certain critical value. At this critical load level and beyond, the column may start to deform laterally. This is the buckling phenomenon which was discussed under Structural Principles. The column will continue

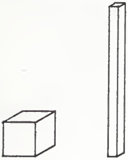


POSTS WILL SUSTAIN LOADS BY DIRECT COMPRESSION UNTIL A CERTAIN CRITICAL VALUE IS REACHED, THEN THEY WILL SNAP OUT LATERALLY



A SHEET OF PAPER CANNOT SUPPORT ITSELF ON EDGE UNLESS IT IS GIVEN SHAPE, SUCH AS A TUBE, THEN IT IS CAPABLE OF SUPPORTING LOADS MUCH GREATER THAN ITS WEIGHT

THE BEST COLUMN SHAPES ARE THE CIRCLE, SQUARE, AND THE H-FORM



SHORT COLUMNS DO NOT BUCKLE, BUT APPEAR VERY MASSIVE, WHILE THE TALLER, SLENDER COLUMN WILL TEND TO BUCKLE VERY EASILY

to buckle until failure occurs as the column snaps out laterally.

COLUMNS - STRUCTURAL FEASIBILITY

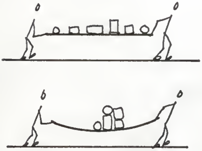
Since the column's resistance to buckling is dependent on the bending strength of the column, long columns should be designed in part as a beam. Hollow, circular shaped columns provide the greatest strength against buckling. Short, thick columns are so massive that buckling is not a problem, but they are generally impractical due to their size. Likewise, long, slender columns are impractical because their critical buckling load is so low (35).

BEAMS - STRUCTURAL CONCEPT

THE TRUNK OF A TREE WHEN UPRIGHT ACTS AS A COLUMN, BUT WHEN LAID FLAT IT ACTS AS A BEAM

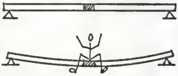
The beam is probably the oldest of all structural members. Beams are used to transfer vertical loads horizontally to supports.

BEAMS - STRUCTURAL GEOMETRY AND STRESS



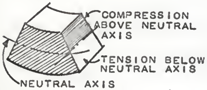
THE BEAM LOADED UNIFORMLY HAS LESS DEFORMATION THAN THE ONE LOADED AT ONE POINT

The cross section of a beam is usually deeper in the direction of loading and narrower in its width. A beam is said to be simply supported when it is supported at both ends; when it is free to rotate, or when it is free to expand or contract in the longitudinal direction. Bending and shear are the critical stresses present in a beam.



A SIMPLE BEAM HAS MAXIMUM DEFLECTION AT THE CENTER OF THE SPAN

An obvious way of improving beam efficiency requires shifting the supports toward the center of the beam, whenever it is feasible, because this will reduce the bending stresses at midspan.



STRESSES IN A GIVEN CROSS-SECTION OF THE SIMPLE BEAM CHANGES FROM COMPRESSION IN THE TOP TO TENSION IN THE BOTTOM

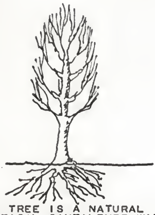
BEAMS - STRUCTURAL VARIATION

CANTILEVER

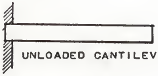
The cantilever beam might be considered as a beam supported rigidly at only one end. This rigid attachment is required to keep the beam in position (11).

BY LOADING MANY SHEETS OF PAPER IT IS POSSIBLE TO SEE THE TOP SHEETS SHORTEN (COMPRESSION) AND THE BOTTOM SHEETS APPEAR TO STRETCH OUT (TENSION)

The bending stresses and deflections of a cantilever depend on the location of the loads. The largest shear stresses occur at the root or

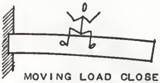


THE TREE IS A NATURAL VERTICAL CANTILEVER WITH THE ROOT SYSTEM ACTING TO RESIST THE LOADS APPLIED ABOVE GROUND



UNLOADED CANTILEVER

LOADED CANTILEVER DEFORMS MAXIMUM AT END



MOVING LOAD CLOSER TO FIXED-END REDUCES DEFLECTION UNDER SAME LOAD

THINNER BEAM HAS GREATER DEFLECTION UNDER SAME LOAD

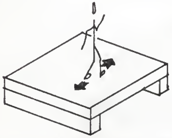
THE DEFORMATION OF A CANTILEVER IS CRITICAL AND CAN BE VARIED AND CONTROLLED BY REVERSING THE CROSS-SECTION OF THE MEMBER, OR APPLYING THE LOADS AT DIFFERENT POINTS

fixed end of the cantilever beam. The bending stresses increase in magnitude as the load moves away from the fixed end with the greatest bending stress occurring at the free end of the cantilever.

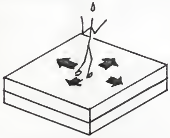
In comparison to a cantilever beam, a simple beam, equal in length to a cantilever beam, is capable of supporting a load four times greater than the cantilever beam (35).

SLABS

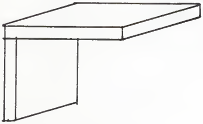
A RELATIVELY LARGE, FLAT STONE IS A NATURAL SLAB



THE ONE WAY SLAB DISTRIBUTES VERTICAL LOADS IN TWO HORIZONTAL DIRECTIONS TO SUPPORTS



THE TWO WAY SLAB DISTRIBUTES LOADS IN FOUR HORIZONTAL DIRECTIONS TO SUPPORTS



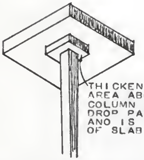
THE ONE EDGE CANTILEVER SLAB IS SUPPORTED ONLY ALONG ONE OF ITS FOUR EDGES

A slab may be thought of as a thin, wide beam which distributes loads in one or more directions, within a single plane, to edge supports. As true of a beam, the forces developed within a slab are primarily bending and shear. The common application of a slab is to span between beams. Slabs are usually of reinforced concrete, but they can be metal, plywood or masonry. Concrete slab thicknesses of three to eight inches are possible for spans of five to twenty-five feet.

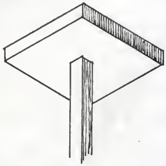
The one way slab is a slab which is supported principally on only two of its four edges. The supports are usually beams or girders, but may be walls. A two-way slab is one supported on all four edges. The slab with a two way span is superior to that with a one way span, both in regard to load bearing capacity and cost. Other types of slab supports are along one edge, two adjacent edges, three edges, or by a point support which is a four-way cantilever (1).

FLAT SLAB AND PLATES

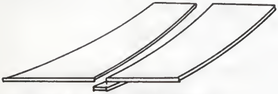
A flat slab is constant in depth, except for a thickening in the region around the supports. This thickening is called the drop panel. If the drop panel is omitted, the flat slab then becomes a flat plate, a type of slab with uniform thickness. The flat slab and flat plate have a length and width which is much greater than its thickness (11).



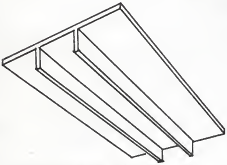
THE FOUR WAY CANTILEVER IS SUPPORTED ONLY AT ONE POINT



THE FLAT PLATE IS A SLAB WITHOUT DROP PANELS AT THE SUPPORTS

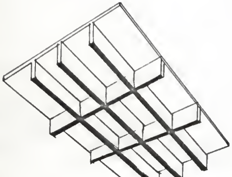


PLATES ACT AS A SERIES OF INDEPENDENT PARALLEL BEAMS ACTING IN TWO DIRECTIONS PLUS TWISTING ACTION



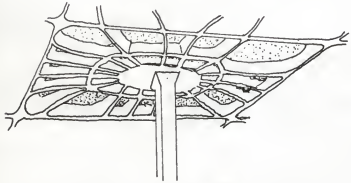
RIBBED PLATES MAKE USE OF RIBS TO INCREASE THE STIFFNESS OF THE PLATE BY RELOCATING THE NEUTRAL AXIS

WAFFLE SLAB



THE WAFFLE SLAB OBTAINS EXTRA STRENGTH BY THE ADDITION OF RIBS IN TWO DIRECTIONS

The waffle slab is a two-way slab or flat slab made up of a double system of narrow ribs or joists, usually at right angles to each other, forming a pattern of waffle like coffers. A variation of the waffle slab is one in which concrete ribs and reinforcing steel are placed only where they are needed to resist concentrations of internal forces. These internal forces follow paths called isostatic lines. The resulting pattern is an expression of the internal load distributions of the slab (35).



THE MOST EFFICIENT TYPE OF WAFFLE SLAB IS ONE IN WHICH THE RIBS FOLLOW THE NATURAL STRESS PATHS IN THE SLAB (ISOSTATIC PATHS)

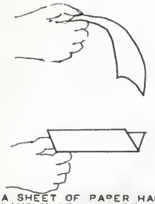
FOLDED PLATES

As pointed out in waffle slabs, the efficiency of slabs can be increased by stiffening them with ribs. Another method of achieving extra strength from a slab is by folding it. A sheet of paper held along one side cannot support its own weight because of thickness it does not give sufficient resistance to the bending stresses. Folding the paper sheet relocates the center of gravity, which in turn increases the strength of the system (26).

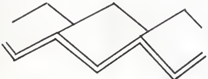
The folded plate is essentially a modified beam. However, folded plates have much greater load carrying and spanning capacities than beams.

Folded plates may be given a variety of cross-sectional shapes. The basic shapes are the V, Z, and modified W. Because the folds do not have to be always longitudinal, polygonal and circular folded plates may be used to cover circular areas (4). It is also possible to use folded plates as vertical walls to resist both vertical and horizontal loads.

By allowing for folded slab action, the building materials, timber, metal and reinforced concrete result in very expressive structural forms. Folded plate structures can be constructed from thin, flat prismatic members. This



A SHEET OF PAPER HANGS LIMPLY IF HELD BY THE EDGE UNLESS IT IS CREASED, THEN IT FORMS A RIGID SHAPE CAPABLE OF SUPPORTING LOADS

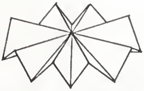


THE FOLDED PLATE CAN BE EXTENDED IN EITHER DIRECTION TO COVER GREATER AREAS

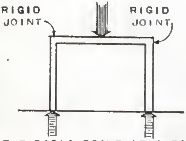
A SERIES OF PLATES LYING FLAT CARRIES A CERTAIN LOAD

IF THE SAME PLATES ARE FOLDED THE LOADING CAPACITY IS INCREASED

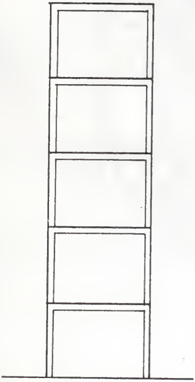
AN INCREASE IN THE FOLD ANGLE INCREASES THE LOAD CAPACITY EVEN MORE



POLYGONAL FOLOED PLATE



THE BASIC FRAME IS A POST AND BEAM WITH RIOGIO CONNECTIONS WHICH CANNOT ROTATE



THE BASIC FRAME SHAPE CAN BE STACKEO TO GREAT HEIGHT, THUS RESULTING IN THE HIGH-RISE STRUCTURE

increases the economy of the system.

FRAMES

The action of the post and beam system changes substantially if a connection is developed that ties the beam and the posts together so they act as a single unit. This new structure, the simple or single-bay rigid frame, behaves monolithically and is stronger against both vertical and horizontal loads. Stacking of this system gives rise to contemporary high rise structures.

TRIANGULATION

SIMPLY BEAM TRANSMITS LOADS TO SUPPORTS

THE CENTERED OF THE BEAM HAS THE GREATEST STRESS WITH THE ENDS REQUIRING LESS MATERIAL

BY REPLACING THE SHAPE WITH SHORT MEMBERS, WHICH ARE PINNED TOGETHER, FORMS THE BASIC TRUSS WHICH GAINS STRENGTH FROM THE TRIANGULATION OF THE MEMBERS

Consider as an example a standard rectangular beam. If such a beam were acted on by a uniform load, only the two points at the center of the beam would be stressed to the material's design capabilities. The rest of the beam would be stressed far below that value, thus making full use of only a fraction of the total capacity of the beam's material. The beam may be reshaped to carry this same load but fully utilizing a much greater percentage of its material. The portions of the beam now carrying the full design stresses are shown in heavy lines. The second beam thus utilized appreciably less material than the first beam, yet does the same job. Further material economy may be gained by piercing the beam at the right places. This is the concept of triangulation where every solid segment is designed to carry its share of the load to the full design stress capabilities of the material (35).

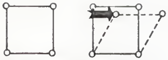
TRUSS - STRUCTURAL CONCEPT

A truss is a structural element assembled from thin prismatic members in a pattern of triangles or other rigid configurations which are considered to be in the same plane (11). A truss is loaded only at the points where two or more members intersect and are uniformly stressed in only tension or compression.

TRUSS - STRUCTURAL GEOMETRY AND STRESS

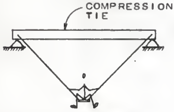
The most desirable design for trusses is one that has relatively strong bars arranged in a series of successive triangles of approximately equal sides and with angles between forty-five and sixty degrees (30).

The bars of a truss are joined by being riveted, bolted or welded to a "gusset plate" at their point of intersection (26). At any joint the truss bars are assumed to be stressed in either pure tension or pure compression. It is customary to permit one end or support of a truss to slide in order to accommodate expansion and contraction of the truss. Because the tension members in the truss are more efficient than the compression members (the compression member might buckle), it is desirable to make the truss form using as few compression members as possible. However, since an all tension frame is impossible under normal gravity loading, there must always be at least one compression member in any truss system.

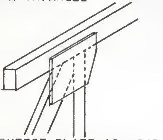


THE SQUARE OFFERS NO RESISTANCE TO ROTATION WHEN LOADED

THE TRIANGLE IS THE SIMPLEST FORM POSSIBLE TO RESIST ROTATION WHEN LOADED

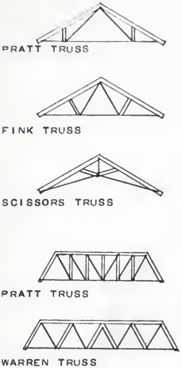


IF A WIRE IS LOADED, THRUST DEVELOPS AT THE ENDS, AND A COMPRESSION MEMBER IS USED TO COUNTERACT THE THRUST - THE FORM IS A TRIANGLE



A GUEEST PLATE IS USED TO TIE ALL THE MEMBERS TOGETHER AT A JOINT

THE VIERENDEEL TRUSS IS FORMED BY HORIZONTAL AND VERTICAL MEMBERS, THERE IS NO TRIANGULATION IN THE TRUSS



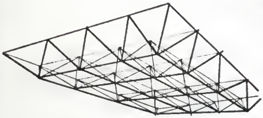
VARIOUS TRUSS SHAPES
═══ COMPRESSIVE MEMBERS
─── TENSION MEMBERS

TRUSS - STRUCTURAL FEASIBILITY

A truss may take many forms, so in any particular situation the form must be selected so as to best fulfill the function of transmitting the imposed forces to the desired destinations. Aesthetics and space requirements may also dictate the shape of the truss. Spans of several hundred feet are possible with truss frames, giving them much greater capabilities than simple beams. Although plane trusses are not as popular today as they were in the nineteen-hundreds, at the beginning of the structural steel era, trusses are still essential components of large structures (3).

TRUSS - STRUCTURAL VARIATIONS

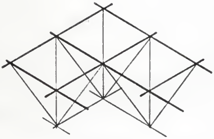
SPACE FRAMES



THE SPACE FRAME APPEARS AS A THREE-DIMENSIONAL TRUSS

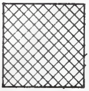
In general, the term "space frame" is used to designate any structural system in which members lying in different intersecting planes are linked together in such a way that if any one member is loaded and stressed, all members of the system are stressed. In this thesis the term "space structure" shall be used to describe the above condition. Space frames are those space structures made from three-dimensional trusses. Space frames are stiffer and shallower than a system of parallel, planer trusses because there are more truss bars to share in resisting the forces.

The depth of a planer truss with horizontal upper and lower chords is of the order of one-tenth the span, whereas, space frames may have a depth as small as one-twentieth or one-thirtieth the span (26).

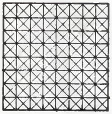


THE TRUSSED SPACE FRAME IS FORMED BY SHORT MEMBERS TIED TOGETHER INTO EQUILATERAL PYRAMIDS

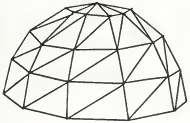
GRID PLAN



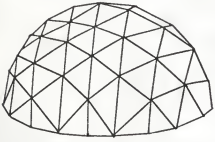
DIAGONAL PLAN



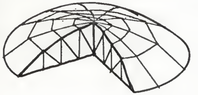
THE SPACE FRAME PLAN IS CREATED BY PLACING A GRID PLAN OVER A DIAGONAL PLAN AND THEN GIVING IT DEPTH FOR THE THIRD DIMENSION



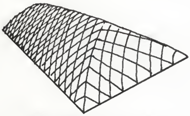
THE SCHWEDLER DOME IS A SPACE FRAME OF SHORT STRAIGHT MEMBERS PLACED LATERALLY AND DIAGONALLY



THE GEODESIC DOME IS ALSO FORMED BY STRAIGHT MEMBERS IN A DIAMOND PATTERN



THE RADIAL TRUSS SPACE STRUCTURE IS TIED TOGETHER AT THE TOP AND THE BOTTOM SO THAT ALL MEMBERS ARE STRESSED WHEN LOADED AT ANY POINT



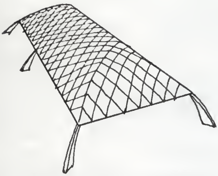
THE LAMELLA IS A SPACE STRUCTURE FORMED BY TWO SETS OF PARALLEL ARCHES THAT SKEWED IN RELATION TO EACH OTHER

SPACE FRAME DOMES

If a given area, to be covered, is circular and the spanning structure has the shape of a dome, it is possible to subdivide the dome surface into a number of triangles or other regular polygons through the use of short hinged bars. The dome then becomes an exceptionally light structure which permits the spanning of large distances. The critical stresses in this type of structure are created at the joints, thus making the joint the most important structural element in the dome.

LAMELLA

The lamella type roof is a space structure made up of a series of parallel arches, skewed with respect to the sides of a rectangular area, which are intersected by another series of skewed arches. The interaction of the intersecting arches produces a very efficient structural system. This curved space structure is extremely versatile and it may take the form of a segment of a cylinder, parabola, sphere, curve or even a hyperbolic paraboloid (19). The most efficient lamella structure is square in plan, since in this case the arches near the corners have small spans



LAMELLA STRUCTURE RAISED ON EXTENDED ARCHES

and are very rigid. Lamella structures are dependent on their ability to resist horizontal thrust, both laterally and longitudinally. If the members are rigidly connected in the roof plane, the structure will maintain its own shape, and there will be no lateral thrust to be resisted.

CURVATURE

Structures in which strength is obtained by shaping the materials according to the loads that they must carry are called form-resistant structures and are usually curved in shape. The load carrying capacity is obtained not by increasing the amount of material used, but by giving it proper form. Imagine a sheet of paper held in the hand, it bends limply and cannot support its own weight. If this paper is pinched and given a slight upward curvature, it is capable of supporting its own weight and even some additional load. The upward curvature increases the stiffness and the load carrying capacity of the paper (26).

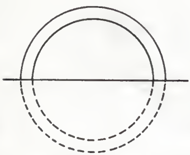
A SHEET OF PAPER HANGS LIMPLY WHEN HELD BY THE EDGE

IF THE PAPER IS GIVEN A SLIGHT UPWARD CURVATURE IT IS CAPABLE OF SUPPORTING LOADS

ARCH - STRUCTURAL CONCEPT

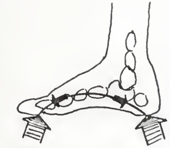
The arch is the simplest of the curved forms. An arch is a structural member with an upward curved axis that distributes loads to support through a curvilinear form within a single plane.

Man-made arches can be traced back through many centuries to before early Roman days when it was discovered that curved arches made of adjoining stones could span many times the distance of straight stone or wooden beams, even if the stones in the arch were not bonded together (35).



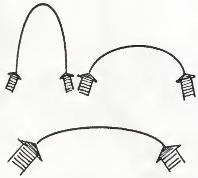
THE ARCH FORM HAS A CURVED AXIS THAT FORMS A CLOSED LOOP OR RING IF IT IS ALLOWED TO CONTINUE IN A CURVED PATH

THE FIRST ARCHES WERE OF STONE WEDGES THAT WERE LAID TOGETHER UNTIL THEY CLOSED



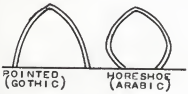
THE BONE STRUCTURE OF THE FOOT IS AN ARCH FORM

THE ARCH TRANSMITS COMPRESSIVE STRESSES ALONG A CURVED PATH (ARCH AXIS) TO SUPPORTS



THE STEEPER ARCH HAS LESS HORIZONTAL THRUST THAN THE FLATER SHAPED ARCH

ELLIPTICAL (ROMAN)



POINTED (GOTHIC) HORESHOE (ARABIC)

VARIOUS ARCH FORMS

Even though man has been in contact with and impressed by the arch form, he was not aware of its resistant capacity. In nature the arch can be found in the arch of the foot and in the cage of the human body.

ARCH - STRUCTURAL GEOMETRY AND STRESS

The arch can take a variety of shapes and span large or small distances. From the standpoint of stressing, the arch is very similar to a column because the prevailing stress is compression. The most critical stresses are found in the horizontal thrust produced at the arch supports. It is therefore essential that the foundations and anchorage must be capable of resisting this thrust.

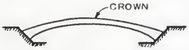
A uniform load on a parabolic arch produces practically no bending if the supports are rigid and do not permit horizontal displacement. If the load is changed to a concentrated position, substantial bending develops in the arch. This loading condition should be avoided in order to get maximum efficiency from the arch system.

Present day arches are of three basic types: the monolithic arch, the two-hinged arch, and the three hinged arch. The monolithic arch is designed and constructed as one continuous member with both ends rigidly connected to supports. This type must be able to resist bending forces throughout the span and at the supports. The two-hinged arch is constructed of one continuous member with pins or hinges at both ends to allow rotation. Loading variations which may cause the crown of the arch to rise or fall will not produce any bending moment at the base. This arch is thicker at the crown because there is a moment at the crown.

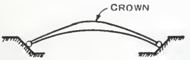
The three hinged arch is constructed of two members which are hinged at the base and at the crown. These hinges allow the arch to "breathe" easily from the load stresses by permitting the arch segments to rotate freely at each pin. Bending stresses are completely eliminated at these three hinged points. This type of arch has found wide use in laminated timber construction. It is easier to fabricate and transport than the two-hinged arch because it may be broken down into sections (3).

ARCH - STRUCTURAL FEASIBILITY

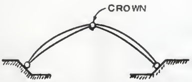
The arch is a very efficient way of spanning between two points without the need of any interior supports. The arch form produces very dramatic structures, and it has found wide



THE MONOLITHIC ARCH IS A CONTINUOUS FORM WITH THE ENDS RIDGIDLY TIED TO THE SUPPORTS



THE TWO HINGE ARCH IS A CONTINUOUS MEMBER WITH HINGES AT THE ENDS WHICH ALLOW IT TO ROTATE AT THE SUPPORTS



THE THREE HINGED ARCH IS FORMED FROM TWO SEGMENTS WITH HINGES AT BOTH THE ENDS AND AT THE CROWN


A VARIATION OF THE THREE HINGED ARCH APPEARS TO BE SHAPED AS A FRAME


CONTEMPORARY ARCH OF STAINLESS STEEL THAT HAS A TRIANGULAR CROSS SECTION

application in buildings in which large, clear spans are desired.

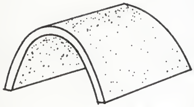
ARCH - STRUCTURAL VARIATIONS

VAULTS

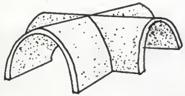
The vault is one of the older structural systems in building, with the first type being the cylindrical vault. The vault is useful for covering rectangular spaces without requiring interior supports. The vault can be a single element across the width of the area to be covered, or in several parallel rows.

A vault may be considered as a series of independent arches assembled together. As is true of the arch, the stresses in a vault are primarily compressive. The supporting elements at the vault base must be large enough to counteract the horizontal thrust. It is also necessary to avoid any shearing forces that tend to displace the supporting elements at the base of the vault.

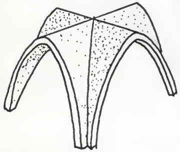
The vault is not presently constructed from masonry materials as it was in the past, however, some of the present shell forms are similar to vaults in shape (30).



THE BASIC VAULT MAY BE THOUGHT OF AS AN INFINITE NUMBER OF ARCHES PLACED SIDE BY SIDE



THE GROINED VAULT IS FORMED BY THE INTERSECTION OF TWO HEMISPHERICAL VAULTS



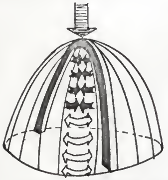
THE RIBBED VAULT IS A VARIATION OF THE GROINED VAULT THAT TRANSMITS THE LOADS TO FOUR POINTS

LAYING VAULTS SIDE BY SIDE HELPS TO REDUCE THE HORIZONTAL THRUST

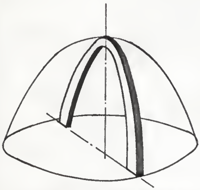
DOMES

A dome can be defined as an arch rotated about a vertical axis that passes through the arch crown, or highest point. Therefore, the dome is simply a three dimensional expression of the arch. The dome shape presents a continuous curved geometric form without corners or abrupt changes in surface direction. The dome encloses a maximum volume of space with a minimum of surface area, and it does not require interior supports, it is light in weight, strong and resistant against loading, and economical.

THE SKULL IS A NATURAL DOME CAPABLE OF SUSTAINING THE FORCE OF CONCENTRATED LOADS



THE STRESSES IN A DOME ARE COMPRESSIVE NEAR THE TOP AND TENSILE AT THE BASE

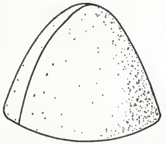


THE DOME IS CREATED BY REVOLVING THE ARCH ABOUT A VERTICAL PIVOT POINT

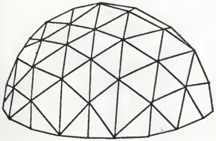
Examples of the dome in nature can best be shown in the skull. The skull can resist loads applied from any direction. It is a structurally stable shape, and it is able to resist bending caused by concentrated loads, but it is more resistant to uniform loads (3).

When loaded the dome produces lateral thrust around the base which can be resisted by horizontal forces from the ground or foundation, or by a tension ring around the base. An opening made in the top of a dome would require a compression ring for reinforcement.

Elliptical domes are described by half an ellipse rotating around a vertical axis. The



THE PARABOLIC ARCH HAS A STEEPER CURVATURE AND THEREFORE LESS THRUST AT THE BASE WHICH GIVES IT ADVANTAGE OVER OTHER SHAPES



THE GEODESTIC DOME IS FORMED BY SHORT MEMBERS PLACED IN A GEOMETRIC PATTERN TO FORM A CURVED SHAPE

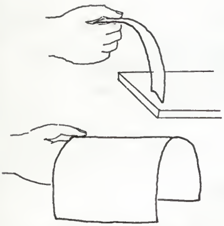
action of an elliptical dome is not as efficient as the action of a spherical dome because the top of the dome is flatter. This reduction in curvature introduces larger stresses at the base. The parabolic dome has a sharper curvature at its top, and it has structural advantages because the horizontal thrust is reduced by its greater height (26). A geodestic dome is one which is constructed of a pattern of surface divisions that are always a function of an entire sphere. These divisions are based on the regular and semiregular polyhedia and their components, but most typically they are based on the geometry of the icosahedion (11).

SHELLS - STRUCTURAL CONCEPT

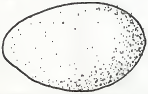
The shell is a structure formed by singly or doubly curved surface, the thickness of which is small in comparison with the surface area. From this there emerges two fundamental assumptions of shell statics: a shell is not flat, but curved, and it is thin.

By holding a sheet of paper along one edge and lifting it from a horizontal surface, the paper hangs limply from the points of support because it has practically no strength when cantilevered. By rolling the sheet into a half circle and holding it along one edge it is not only able to cantilever, but it will also support additional loads (26). This arc shape is a basic shell.

One of the most common shell forms in nature is the egg. Strength of the egg is gained from the doubly curved surface which has a ratio of shell thickness to length of one to two-hundred and thirty. Other natural shells are nuts and sea shells. Many of nature's shells make use of thickened edges and corrugations for strength and stability. This is a property which man makes use of in designing structural shells (3).

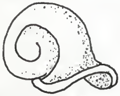


IF A SHEET OF PAPER IS ALLOWED TO HANG FREELY FROM A POINT SUPPORT IT GIVES A STRUCTURAL SHAPE OF THIN CROSS SECTION AND GREAT LOAD CARRYING CAPACITY



THE EGG IS A NATURAL SHELL FORM WITH A GREAT THICKNESS TO SURFACE AREA RATIO

THE NUT SHELL IS ANOTHER NATURAL SHELL THAT HAS A THICKENED EDGE TO HELP RESIST THE THRUST



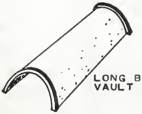
THE SEA SHELL IS A NATURAL SHELL THAT GAINS STABILITY THROUGH ITS SHAPE

SHELLS - STRUCTURAL GEOMETRY & STRESS

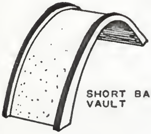
The loaded shell structure distributes loads in many directions within the plane of the shell's surface. The applied loads induce compression, tension, and shearing stresses. The stresses in the shell are uniform throughout the thickness. The shell has internal stresses, which are called membrane stresses, that tend to twist the shell surface.


THE STRESSES IN A SHELL ARE TRANSMITTED ALONG THE SHELL SURFACE IN MANY DIRECTIONS TO THE SUPPORTS

There are two broad categories of shell shapes. These are singly curved shell form, and doubly curved shell form. Singly curved shells have a normal cross section which is a straight line. Typical of this type is the long and short barrel vault. This type of shell can span like a beam along the length of the barrel, and it is a completely self-contained structural element. The shell vault differs from the arch vault of non-tensile materials, because it transmits loads in more than one direction of the surface curvature, and does not require continuous support along its edges as do arch vaults. This can be shown by trying to support a sheet of paper in a horizontal position along two parallel edges. The result is considerable deflection, and if the paper is not thick enough, it will slip and fall



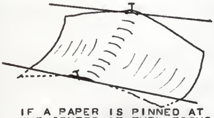
THE BARREL VAULT IS A SINGLY CURVED SHELL



between the supports. However, if the sheet is supported only on the two middle points of two opposite edges the unsupported edges will move downward and assume a shell form structure. The shell vault lends itself to repetition, since it normally permits the division of an area into a number of oblong bays (19).

A SHEET OF PAPER SUPPORTED ALONG TWO EDGES, BUT NOT TIED, DROOPS INTO A SINGLY CURVED SHELL

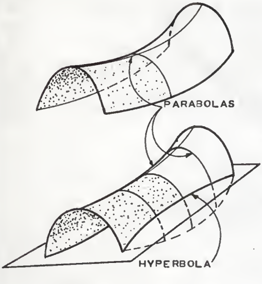
The doubly curved, or "arch segmental shell," has a surface which is curved twice, once in each the longitudinal direction and transverse direction. The double curvature results in a shell of increased natural stiffness. In doubly curved shells the dead weight of the structure is the most critical load.



IF A PAPER IS PINNED AT THE CENTER IT THEN FORMS A DOUBLY CURVED SHELL

SHELLS - STRUCTURAL FEASIBILITY

Shells are a spectacular type of structure that provide an efficient and economical means of covering an area. Shells may be constructed of metal, timber, reinforced concrete or plastic. Reinforced concrete is the most versatile for shell construction.

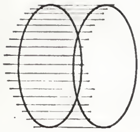


HYPERBOLIC PARABOLOID

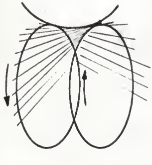
SHELL - STRUCTURAL VARIATIONS

HYPERBOLOID

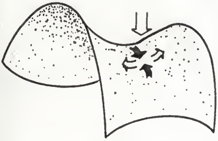
The hyperbolic paraboloid is a doubly curved shell which has as its dominating feature a



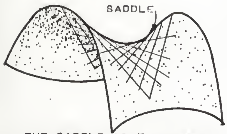
HYPERBOIDS CAN BE CREATED BY IMAGINING THE SIDES OF A CYLINDER BEING FORMED BY THREADS



IF THE ENDS OF THE CYLINDER ARE ROTATED IN OPPOSITE DIRECTIONS THE RESULT IS A DOUBLY CURVED SURFACE FORMED BY STRAIGHT LINES



THE BASIC HYPERBOLIC PARABOLOID



THE SADDLE IS THE FLATTER PORTION OF THE HYPERBOLIC PARABOLOID WHICH HAS ZERO CURVATURE IN TWO DIRECTIONS

surface which is generated by the use of a straight line. A simple explanation of this revolution can be shown by imagining the walls of a circular cylinder being replaced with threads. If the two ends of the cylinder are twisted in opposite directions the system of threads will form a three-dimensionally curved surface made up of straight lines. This curved surface is a hyperbolic cross-section (26).

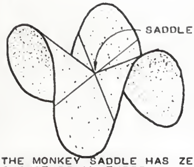
The geometry of this system lends itself to timber construction, because it can be formed from straight members. Reinforced concrete is also a good material for use in hyperbolic paraboloids when a monolithic structure is desired. Also the problem of edge connections are eliminated in concrete construction.

Two commonly used variations of the hyperbolic paraboloid shell are the saddle and the umbrella shapes. Umbrella shapes may be used in a conventional, inverted, edge supported or point supported manner. Saddle hyperbolas have, generally, two directions of zero curvature at some point on their surface. Zero curvature is the point where two straight lines on the surface of the hyperbola intersect. The monkey saddle is a surface with no curvature in three directions.

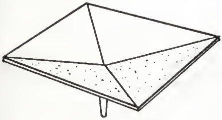
The name comes from the theory that a monkey can straddle the surface and have its legs, and tail down on the surface (27). A hyperbolic surface with more than three lines of zero curvature has a scalloped appearance.

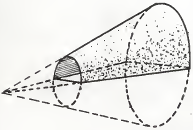
SHELLS OF REVOLUTION

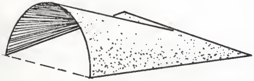
Shells of revolution are another type of doubly curved shell structures. These forms are generated by rotating a curved line about a fixed axis. The dome is a shell of revolution, and like the traditional dome, it exerts continuous thrust at the base. The thin shell dome is much lighter in construction than the arch dome, and it is capable of spanning larger areas with considerably less material than the arch dome.



THE MONKEY SADDLE HAS ZERO CURVATURE IN THREE DIRECTIONS

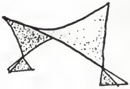

THE UMBRELLA HYPERBOLIC PARABOLOID IS SQUARE IN PLAN AND POINT SUPPORTED


CONICAL SECTOR
SHELL OF REVOLUTION

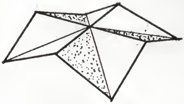

CONOID SHELL HAS ONE CURVED END AND ONE STRAIGHT LINE END

VARIATIONS OF SHELL SHAPES

DOME WITH POINT SUPPORT



HYPERBOLIC PARABOLOID



INVERTED UMBRELLA

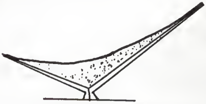
DOMED ARCHES

INTERSECTING HYPERBOLIC PARABOLOIDS

DOUBLY CURVED ARCH

MONKEY SADDLE WITH POINTED EDGES

RIBBED SHELL VAULTS

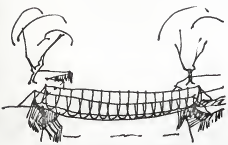


HYPERBOLIC PARABOLOID, NON-SYMMETRICAL

SUSPENSION

A suspension structure is one which distributes loads by tension stressed cables in a one plane system, and by tension stressed membranes in a two plane system. The three major principles of suspension structures are: (1) most materials have considerably greater limits in tension than in compression, (2) tension members are stable, whereas compression members have a tendency to buckle, and (3) a tension membrane may be utilized in a manner that makes use of the thrust produced around the membrane edges to stabilize both the membrane and all other structural members of the system (30).

The idea of suspension is not new to structural design. Ancient vine and bamboo bridges of Asia made use of the cable as the predominant load carrying member. This type of suspension bridge is a "plane system" because it spans between two points that lie in the same vertical plane. Recently the idea of suspension construction has extended into roof structures, and the term "suspended roof" is used to describe the result. However, this does not accurately describe the type of suspension present. The suspended roof uses families of cables which are stressed in



ANCIENT SUSPENSION BRIDGES OF VINE WERE SUSPENSION STRUCTURES

THE CAVE MAN USEO SUSPENSION PRINCIPLES FOR HIS CLOTHING

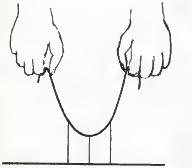
CONTEMPORARY TENT ORESSES ARE SUSPENOEO FROM THE SHOULDERS mutually opposed directions, but lie in the same plane. The result is a system with a curved surface that has three dimensional stability.

SUSPENSION - STRUCTURAL GEOMETRY AND STRESS

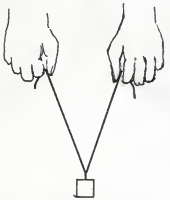
The common elements in any suspension system are the tower or arch, the main suspension members, the anchorage, and the stiffening required to prevent vibration and flutter of the structure (11). These elements can be shown by the following example. Hold the ends of a string and let it hang freely. The only load that the string carries is its own weight. Because it is light, the string will tend to oscillate, or "flutter," under the action of the wind. This flutter can be avoided by placing a load, which corresponds to the roofing material of the building, on the string, or by stabilizing the string with other strings which are anchored to the floor (26).

After the weight is attached, the string will assume a shape in which all internal forces are purely tensile. If the hands are joined, there will be no thrust at the ends of the string, but as the hands are moved apart, an increasing thrust is developed and the string sag is also decreased. It can be shown that the tensile stress is inversely proportional to the sag, i.e., halving

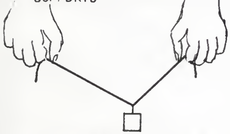
A STRING HANGING FREELY HAS NO RESISTANCE TO FLUTTER, AND IT IS NOT STRESSED



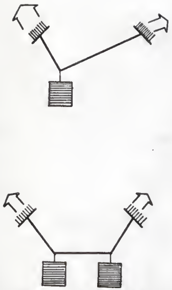
FLUTTER CAN BE ELIMINATED IF THE STRING IS TIED TO THE FLOOR



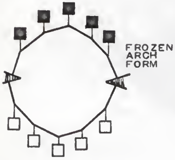
IF A LOAD IS APPLIED TO THE STRING, TENSILE STRESSES DEVELOP, IN ADDITION TO THRUST AT THE SUPPORTS



THRUST CAN BE REDUCED BY MOVING THE SUPPORTS APART



THRUST CAN VARY AT THE SUPPORTS DEPENDING ON THE LOCATION OF THE LOAO



IF THE LOADED STRING, CONTAINING ONLY TENSILE STRESS, COULD BE FROZEN, THE FORM MAY BE INVERTED AND THE RESULT WOULD BE AN ARCH HAVING ONLY COMPRESSIVE STRESS

the sag doubles the tension in the string and also the thrust at the supports. If the string were frozen in shape and inverted, the tensile forces are changed to compression and the arch form is produced. This example can also apply to membrane structures by using a net in place of a string. The loaded net assumes a shape in which all stresses are tensile. If the net were frozen in shape and inverted, it would produce a shell form having compressive stresses. The use of nets would simplify the development of shells, not only in form, but also in the ideal attachment for the edge conditions (24).

SUSPENSION - STRUCTURAL VARIATIONS

The possibilities of spanning great distances with suspension structures suggests several ways in which the system could be adapted for enclosing space. Suspension systems could be used with other structural systems to roof an area, or they may be used as the entire exterior surface of the structure. In no other type of construction does the form flow so spontaneously from the structural principle, and also offer economical construction.

CABLES

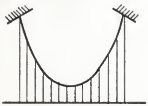
The steel cable is the most economical means known for spanning large areas. The lightness of the cable greatly reduces the dead weight of the structure, and for spans of several hundred feet, no other system is so structurally efficient.

In a cable system, since large sags increase cable length but reduce tensile forces in the cable, a small cross-section is needed in the cable. Smaller sags have shorter cable lengths, greater tensile forces, and require larger cable cross-sections.

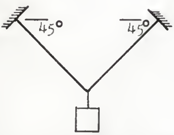
The limitations in the application of cables stem directly from their adaptability to changing loads. Cables are unstable, and stability is one of the basic requirements of a structural system. Vibration is the destructive force in a cable system. There is no buckling in tension cables, but if the resonant frequency of the cable material is reached, vibration can occur and the structure destroyed. It is possible to dampen the cables (tie them down) sufficiently during erection so dynamic instability is not allowed to develop, thus reducing the risk of flutter in the structure (26).

CATENARY

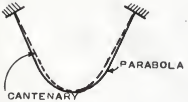
The basic difference between a cable and a cantenary is one of shape. The cantenary form



IF THE STRING IS LOADED UNIFORMLY, THE SHAPE IS PARABOLIC - THIS IS THE BASIC CABLE FORM



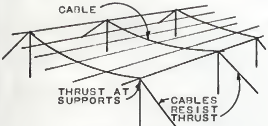
IF THE STRING IS LOADED BY A CONCENTRATED LOAD THE SHAPE OF THE CABLE IS A TRIANGLE WITH AN ANGLE OF 45 FORMED BETWEEN THE SUPPORTS AND THE STRING



THE CANTENARY IS THE SHAPE ASSUMED BY A CABLE UNDER ITS OWN WEIGHT, AND IT DIFFERS FROM THE PARABOLA SLIGHTLY

CANTENARY

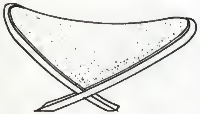
is the shape taken by a cable, of constant cross-section, under its own weight. The optimal sag for the cantenary is about one-third the span. A cable carrying its own weight (the dead load) and a load uniformly distributed horizontally assumes a shape that is intermediate between a cantenary and a parabola.



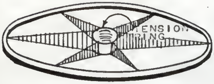
THE TENSIONED FRAME IS FORMED BY STRETCHING CABLES BETWEEN SUPPORTS AND COUNTERACTING THE THRUST AT THE SUPPORTS IN SOME MANNER

TENSIONED FRAME

A notable example of a tension structure is the tension frame which is built by means of radial tension elements and a tension and compression ring. This system may be thought of as a bicycle wheel. The spokes are tensed between the hub, which is a tension ring, and the outside rim. This type of structure has high "locked-in" stresses which are stable against both radial and transverse loads. The tension frame is practically free of flutter because of the high tension stress in the cables makes them more stable than if they were freehanging (26).



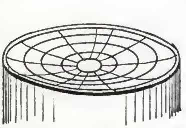
CABLE ROOF WITH SADDLE SHAPE AND THRUST RESISTED BY INTERSECTING ARCHES



THE BICYCLE-WHEEL ROOF

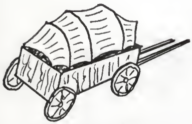
MEMBRANE STRUCTURES

Membranes are of special importance in a discussion of structural form, since the form of a membrane is itself the structure. A structural membrane is a sheet of material so thin that, for

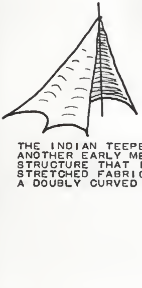


PRESTRESSED CABLE ROOF IS A VARIATION OF THE BICYCLE WHEEL HAVING ONLY ONE SET OF CABLES

SOAP FILM CONFINED TO A FRAME DEVELOPS A SUSPENDED SHAPE WITH ALL STRESSES BEING TENSION



THE COVERED WAGON WAS A MEMBRANE STRUCTURE CONSISTING OF FABRIC STRETCHED OVER FRAMES UNTIL ONLY TENSION WAS PRESENT



THE INDIAN TEEPEE WAS ANOTHER EARLY MEMBRANE STRUCTURE THAT IS A STRETCHED FABRIC FORMING A DOUBLY CURVED SURFACE

all practical purposes, it cannot resist compression, bending or shear, but it can resist tension. The system requires support from a compression ring, arches or ribs, otherwise the membrane cannot be properly stressed.

Soap films are used to study the action of membranes because, within a given frame, they will assume strength by tension with the minimum surface. From these soap films it can be shown that the load carrying action of a membrane is due to its curved shape. Because the membrane has a pure tension surface, the system acts essentially as a network of cables. When the load changes, the shape of the membrane also changes and adapts the curvature needed to carry the new load. Membranes must also be stabilized against flutter (39).

Tents are membrane structures consisting of stressed fabric. If they are to resist flutter, the tent panels, when stressed, must be curved in two mutually opposed directions. In order for doubly curved surfaces to be developed in a fabric, the panels must be cut in such a manner that they are able to assume a double curvature after stressing. The basic hyperbolic paraboloid is a convenient shape for tent construction (27).

The rain umbrella is an example of a prestressed membrane with locked in stresses. The curved ribs, pushed out and supported by the compressive struts connected to the stick, put tension in the cloth, and give it a shape suited to resisting tension stresses.

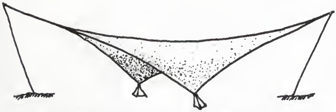
TENSIONED MEMBRANES ARE PRESENT IN THE UMBRELLA

Pretensioned membranes are stiffer and more stable than the other types of membranes. They do not flutter or move as easily under variable loads. Membranes can be prestressed by internal pressure alone, or by ribs (26).

THE CRITICAL PRESENCE OF UP-LIFTING FORCES FROM BELOW THE FRAME REQUIRES THAT THE MEMBRANE BE TIED DOWN IN SOME MANNER

Membrane roofs can be built of cloth, metal, or concrete. Metal membrane are well adapted to carrying loads by tensile stresses, but are seldom an economic structure. Concrete may be reinforced or prestressed to make it more suitable for the development of tensile stresses. Fabric is perhaps the best material for membrane systems, but its durability is very low in comparison to other materials.

MEMBRANES MAY BE TENSIONED BY TYING DOWN THE EDGES AND PUSHING UP FROM BENEATH AS IN THE TENT



MEMBRANES MAY BE STRETCHED IN SUCH A WAY THAT THEY TAKE A DOUBLY CURVED SURFACE

PNEUMATICS

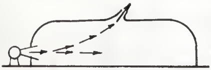
A pneumatic structural system is one which distributes loads to supports through air-pressurized membranes. The "bubble" skin under unilateral pressure is a useful method of obtaining new shapes. These air structures have as their main attraction the ability to enclose large areas quickly and cheaply.

PNEUMATICS - STRUCTURAL CONCEPT

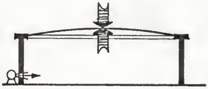
There are few examples of pure pneumatic structural systems in nature. A soap bubble is a unique example that is formed, by unequal pressures, into a spherically shaped membrane. This sphere develops uniform tensile pressure throughout its surface, and thus produces an efficient pneumatic system. If the pressure differential becomes too great and the tensile capacity of the film is exceeded, the sphere will rupture. A mechanical system is required to maintain a pressure differential in a pneumatic structure. Air locks provide access into the enclosed membrane. The structure will fail if the membrane is punctured; however, if the pressure is slow, the collapse is gradual, rather than sudden (3).

THE SOAP BUBBLE DEPICTS A PNEUMATIC STRUCTURE THAT REQUIRES EQUAL PRESSURES EXTERNALLY AND INTERNALLY

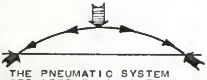
THE PNEUMATIC STRUCTURE IS PRESSURIZED INTERNALLY BY MECHANICAL METHODS



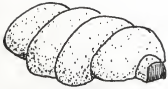
IF THE MEMBRANE IS PUNCTURED, THEN THE SYSTEM FAILS



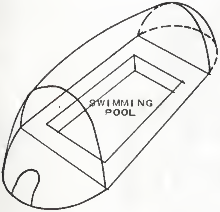
IT IS POSSIBLE TO HAVE A PNEUMATIC SYSTEM THAT DOES NOT FORM THE ENTIRE STRUCTURE, BUT IS SUPPORTED IN SOME MANNER



THE PNEUMATIC SYSTEM REQUIRES EQUAL INTERNAL AND EXTERNAL PRESSURES TO STRESS THE SURFACE MEMBRANE, WHICH TRANSMITS THE FORCES TO THE SUPPORTS



CABLE RESTRAINED MEMBRANE IS A PNEUMATIC STRUCTURE



TYPICAL USAGE OF A PNEUMATIC STRUCTURE IS FOR A TEMPORARY COVERING

PNEUMATICS - STRUCTURAL GEOMETRY AND STRESS

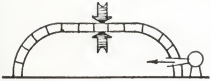
The pneumatic system develops its stability through the difference in pressure between the exterior and the interior of the structure. A slight pressure differential will support the relatively light weight membrane material. This system distributes tensile forces through membranes to anchors around the edges. A combination of nets and membranes may be used for long span structures. Lateral stability of the pneumatic system is dependent upon the systems geometry and supporting system.

PNEUMATICS - STRUCTURAL FEASIBILITY

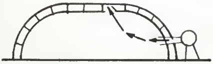
A pneumatic system is usually a prefabricated unit which can be rapidly erected, and which is capable of spanning three to four hundred feet. However, pneumatic structures should be considered to meet only limited requirements such as; portability, for exhibits, theaters, emergency hospitals and temporary shelters; demountability, especially for seasonal use, such as shelters for out-of-season sports; and limited life, this type of structure has a very short life expectancy.

PNEUMATICS - STRUCTURAL VARIATION

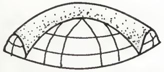
The inflatable roof is a structure which follows pneumatic criteria. This system makes use of a dual wall cellular roof or a double diaphragm that is filled with air. It will enclose a large area without interior supports and may easily be demounted. A typical use of this structure is to cover an indoor-outdoor swimming pool (3).



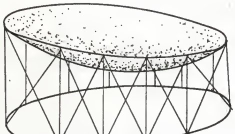
CROSS-SECTION THROUGH A BALLOON STRUCTURE



IF ONE SIDE OF THE MEMBRANE IN THE BALLOON STRUCTURE WERE PUNCTURED IT WILL NOT COLLAPSE AS THE SINGLE MEMBRANE



THE IGLOO BALLOON IS A VARIATION OF A PNEUMATIC STRUCTURE THAT HAS A ROOF OF TWO MEMBRANES WHICH ARE PRESSURIZED



THE BALLOON SYSTEM IS ONLY A ROOFING STRUCTURE AND IS INDEPENDENT OF THE FRAME

CHAPTER IV

SUMMARY AND CONCLUSION

From the preceding discussions of the various structural systems available, one is led to believe that if the designer can conceive the form, structural engineering techniques can make it stand. However, the designer must have a technical knowledge of structure not only to discover the forms, but also to shape them, and finally to relate them to a particular field of design. Pure intuition alone does not justify form.

In relation to architecture, the architect must have a knowledge of the qualitative principles of architecture and the quantitative values of structural principles. It is this knowledge that results in the forms of endless variety and in turn justifies them. In simple terms, the architect must speak the language of the structuralist, just as the structuralist needs to have an understanding of design forms, what they are, and what they do.

Architecture is differentiated from engineering, and nearly all other branches of design, by the fact that the architect has only one given element, the earth, from which he must conceive a result. The scope of structure, however, is bound up with the degree to which it satisfies the ultimate purpose of architecture, namely, the enclosing of space. There can be no question of wanting to build a shell in the form of a hyperbolic paraboloid, or a rotational surface, but simply a conception of space and form evolving from the essence of the problem to be solved, and the problem of deciding what structural means are appropriate for giving shape to the building - "form follows function." It is creative imagination which is capable of joining the parts together into a whole and giving it clear expression.

Structural form is chiefly concerned with the disposition of elements to meet the action of forces which try to disrupt the equilibrium of the structure, or simply, structural form refers to the parts of a building that keep it from falling down. The materials of the structural members are what resist the forces. In general, the simplest and most economical structure is one that brings the imposed forces down to earth in the shortest possible manner.

Structural form is not tied to any narrow trend in contemporary architecture. Its principles are deeper. Structural principles can be found in the architecture of the past, and they have now spread through time without being confined to any particular "school or period or architectural design." It is impossible to argue away the fact that structural form is an essential element of contemporary architecture. It is a real thing serving a real purpose, not a pseudo structure that has frequently appeared, and has discredited architecture of the past.

It is foolish to say that good construction alone is enough to constitute architecture. Structural form is a means of architectural expression of our time. It comes from a definite conception of the design process that recognizes natural order as basic law. In order for structural form to become a principle of all contemporary architecture, a better understanding of the technical reasoning and insight into its principles is required. The reason for this is that structural form is an area where the activities of architecture and engineering must be integrated. If an integration is not realized, the result will be either mere form or mere structure. Only by communication, a common goal, and collaboration in the solution of the common problems can the best solution be found.

An architect should not be content to design without a clear understanding of the structural principles that his design will entail. The minimum goal any architect should have is to at least provide as good and practical a building as the best which has yet been built. This can not be done by giving a design to a structural designer and asking him to "fill-in" the structure, which has so often been the practice in the past. With the technical advancements of the modern era, architecture is not relient on materials as applied decoration to provide aesthetic contrast to a solid structural frame. Now materials are available which allow the architect to create, like nature, an honest relationship between architectural form and structural form. It is now possible for the form to suggest an expression of the functional structure. The architect with talent will make use of this new technology and improve on it. The architect with more than talent will find new forms which are so appropriate to their purpose and so well related in their spaces that human experience is enriched and enhanced.

LIST OF REFERENCES

A. BOOKS

1. Angerer, Fred. Surface Structures in Building. New York: Reinhold Publishing Corporation, 1961.

2. Billington, David J. Thin Shell Concrete Structures. New York: McGraw-Hill Book Company, 1965.

3. Corkill, Philip A., Hormer L. Puderbaugh, and Keith H. Sawyers. Structure and Architectural Design. Iowa City: Sernoll, Inc., 1965.

4. Faber, Colin. Candela/The Shell Builder. New York: Reinhold Publishing Corporation, 1963.

5. Feininger, Andreas. The Anatomy of Nature. New York: Crown Publishers, Inc., 1956.

6. Firmage, D. Allan. Fundamental Theory of Structures. New York: John Wiley and Sons, Inc., 1963.

7. Fischer, Robert E. (ed.). Architectural Engineering - New Structures. New York: McGraw-Hill Book Company, 1964.

8. Fletcher, Sir Banister. A History of Architecture. New York: Charles Scribner's Sons, 1961.

9. Haas, A. M. Design of Thin Concrete Shells. New York: John Wiley & Sons, Inc., 1967.

10. Hertel, Heinrich. Structure, Form and Movement. New York: Reinhold Publishing Corporation, 1966.

11. Howard, H. Seymour. Structure; An Architect's Approach. New York: McGraw-Hill Book Company, 1966.

12. Joedicks, Jurgen (ed.). Shell Architecture. New York: Reinhold Publishing Corporation, 1963.

13. Kepes, Gyorgy (ed.). Structure in Art and in Science. New York: George Braziller, 1965.

14. Kranz, Stewart and Robert Fisher. The Design Continuum. New York: Reinhold Publishing Corporation, 1965.

15. Leontovich, Valerian. Frames and Arches. New York: McGraw-Hill Book Company, 1959.

16. Licklider, Heath. Architectural Scale. New York: George Braziller, Inc., 1966.

17. Makowski, Z. S. Steel Space Structures. London: Michael Joseph, 1965.

18. Marks, Robert W. The Dymaxion World of Buckminster Fuller. New York: Reinhold Publishing Corporation, 1960.

19. Michaels, Leonard. Contemporary Structure in Architecture. New York: Reinhold Publishing Corporation, 1950.

20. Nervi, Pier Luigi. Aesthetics and Technology in Building. Cambridge, Massachusetts: Harvard University Press, 1965.

21. Nervi, Pier Luigi. Structures. New York: F. W. Dodge Corporation, 1956.

22. Pye, David. The Nature of Design. New York: Reinhold Publishing Corporation, 1964.

23. Otto, Frei. Das Hangende Dach. Berlin: Im Dau Welt, 1954.

24. Rosenthal, H. Werner. Structural Decisions. London: Chapman & Hall Ltd., 1962.

25. Saarinen, Aline B. (ed.). Eero Saarinen on His Work. New Haven: Yale University Press, 1962.

26. Salvadori, Mario and Robert Heller. Structure in Architecture. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1963.

27. Siegel, Curt. Structure and Form in Modern Architecture. New York: Reinhold Publishing Corporation, 1962.

28. Skeist, Irving (ed.). Plastics in Building. New York: Reinhold Publishing Corporation, 1966.

29. Temko, Allan. Eero Saarinen. New York: George Braziller, Inc., 1962.

30. Torroja, Eduardo. Philosophy of Structures. Berkley and Los Angles: University of California Press, 1958.

31. Torroja, Eduardo. The Structures of Eduardo Torroja. New York: F. W. Dodge Corporation, 1958.

32. Wachsmann, Konrad. The Turning Point of Building. New York: Reinhold Publishing Corporation, 1961.

33. Wellman, B. Leignton. Technical Descriptive Geometry. New York: McGraw-Hill Book Company, 1948.

34. Wulff, John (ed.). The Structure and Properties of Materials. New York: John Wiley and Sons, 1966.

35. Zuk, William. Concepts of Structure. New York: Reinhold Publishing Corporation, 1963.

B. PERIODICALS

36. Bandel, Hannskari. "The Shell as Backbone," Architectural and Engineering News, 5:16-17, April, 1963.

37. Halperin, D.A. "Structural Form in Design," American Institute of Architects Journal, 27:33-35, January, 1957.

38. Le Messurier, William J. "Structure," Progressive Architecture. XLVI (June, 1965), 178-183.

39. Lessing, L. "Suspension Structures," Architectural Forum, 107:134-141, December, 1957.

40. Medlin, Richard D. "Prestressed Membrane Tension Structures," Progressive Architecture, XLVI (August, 1965) 162-167.

41. Nervi, Pier Luigi. "Place of Structure in Architecture," Architectural Record, 120:189-191, January, 1956.

42. Puderbaugh, Hormer L. "Nature's Structurees," Architectural and Engineering News, 8:54-58, September, 1966.

STRUCTURAL VISUALIZATION IN ARCHITECTURE

by

THOMAS DWIGHT JACOB

B. Arch., Kansas State University, 1965

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF ARCHITECTURE

College of Architecture and Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

STRUCTURAL VISUALIZATION IN ARCHITECTURE

Structure has evolved in importance from a mere necessity to one of primary statements in architectural design. Like nature's structures, architectural structures display a built-in program of growth and development which provides for an infinite variety of forms. This thesis presents the various structural systems available for architectural application in a visual form that can be understood by those who are not trained in the technical aspects of structures.

The primary concern of any structural system is that of collecting the externally imposed loads and equating them internally through structural elements in the most direct manner until the earth absorbs the total force of the loads and the structure. The internal stresses which may be present in a structural member to achieve equilibrium are compression, tension, shear, bending and torsion. In general, the four basic structural materials are masonry, timber, metal and concrete. These materials vary in individual ability to resist stress.

It is possible to resolve the most complicated structural form into one of five structural systems for the purpose of investigation. The mass system is based on the concept that all members bear directly on one another, and the system is held together by compressive stresses from member to member. The post and beam structural system transmits vertical loads through a horizontal member (the beam) to the supports (the post or column), which in turn directs the load, by compression, to the earth. Bending stresses in the beam and buckling stresses in the column are critical in this system. Form-resistant structural systems conduct imposed forces along a fixed curved or triangulated axis to supports by tension or compression. Suspension structures are stressed in tension and are characterized by a curved form. A pneumatic structure is created through the stressing of a membrane by pressurizing it by mechanical means until the membrane is in tension.

The advancements of technology in structures have brought about an era in which the construction of any conceivable form is possible. The architect, normally, does not have the technical ability to analyze these forms in structural terms. For this technical analysis the architect relies on the structural engineer. However, the architect now expects the engineer to possess qualitative knowledge of design forms in addition to quantitative structural knowledge. This new relationship requires the architect and the structural engineer to strive for a better understanding of their respective professions. Such a collaboration of talent results in a better solution for the problem of bridging and enclosing space.

The basis for this thesis is that the beginning student in architecture will find it easier to understand the physical limitations of architectural structural systems when the systems are presented in a visual form. Structural communication through visual graphics does not require a knowledge of the quantitative sciences associated with structural analysis.