A KINEMATIC INTERPRETATION OF THE CONSTRUCTION PROCESS

by

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ABSTRACT

On-site construction costs are very significant to project costs, as a result, the present trend is to fabricate larger components to simplify erection. This approach is however limited by the capacity of the transportation network and by constraints placed on erection. Instead of fabricating ever larger components it is possible to develop better adapted and more versatile construction machines, or to fully integrate the building components to the erecting mechanisms. The latter approach which finds its extreme expression in self-erecting structures forms the subject of this investigation. The objective is to present a framework of concepts and alternatives by which the potential of this approach can be more fully realized and better understood.

The conceptual framework for this investigation was taken from "Kinematic Geometry" a branch of Dynamics generally associated with machine design. We draw from it only its most elemental concepts, these provide the looking glass, the interpretation.

The main body consists of three parts. The first two follow the order of construction: first a mechanism is built, and then, by adding constraints, a structure consolidates, while the third discusses different relations and degrees of collaboration between the builder and that which is being built.

We believe that, from the perspective here presented, not only is it possible to reformulate many of the problems of construction, but also, as a consequence, the approach to design, allowing for the synthesis of new solutions.

Thesis Supervisor: Waclaw Zalewski
Title: Professor of Structures

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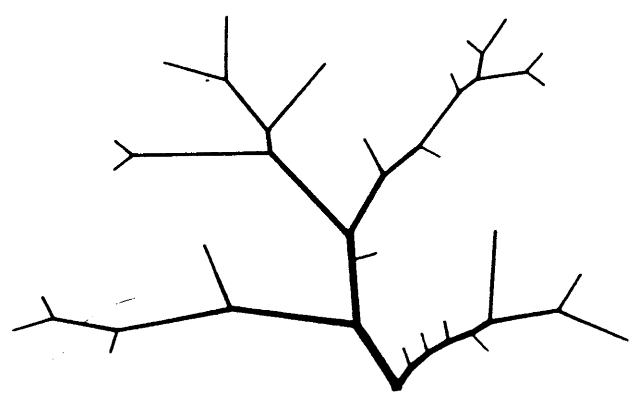
I also want to thank M.I.T. for the opportunity, and the Department of Architecture for the environment.

a mi Tita y al Joaquin que me llevan en la aventura, a mis padres y hermanos por su apoyo y paciencia, y a Catarina las horas y lunas.



The Builder

in a universe of wood, vast beyond imagination, lives a very tiny creature, a tree they say.

Legend

TABLE OF CONTENTS

FOREWORD

This work attempts to generalize certain ideas and findings originally motivated by the study of self-erecting structures, and their potential as an alternative to the high cost of on-site operations, and the current trend to increase the size of the components shipped. Soon in this investigation, it became apparent that the inherent capability of such structures to control their motion, was present in even the most traditional construction practice the difference being more a matter of degree than of kind. This recognition, redirected our effort from the study of particular extreme cases to the study of the general characteristics or properties which conveyed to the components of a building, and for that matter to any machine the capability to control motion. This path leads not to specific solutions, it is geared towards the expansion in the range of applications of an approach to construction for which we found no better name than "kinematic".

Bibliographical note:
all numbers in parenthesis are bibliographical references. With the exception of the introduction and conclusion, figures are labeled with numbers that are called by the text, if letters also appear in the call the figure must be read left to right and top to bottom.

INTRODUCTION

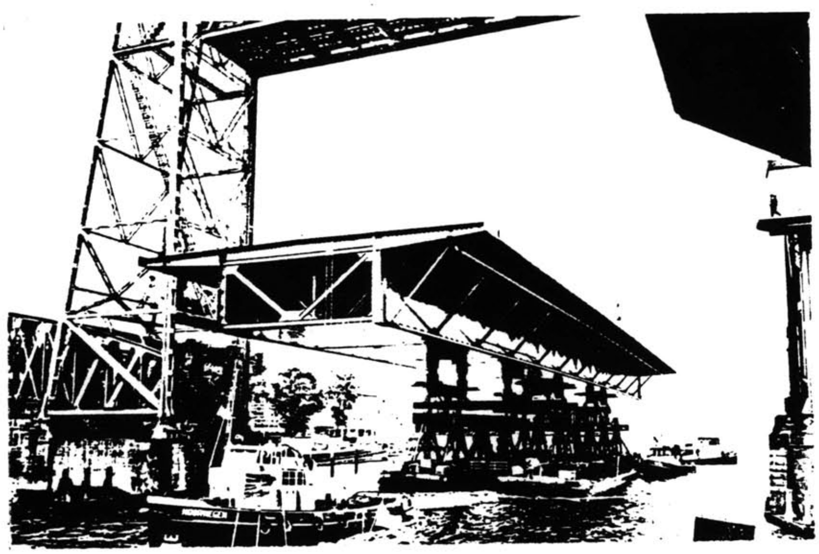
On site fabrication and erection costs are very significant to project cost estimates, as a result the present trend is to fabricate components as large as possible for simplified erection. In this manner, larger portions of the building are assembled in the shop eliminating the need to assemble many small units in dangerously exposed positions, and facilitating the adherence to precise shape.

In bridge construction for example, whatever the difference between present erection methods, there is an obvious trend to install ever larger structural parts. Only a few years ago it was the general practice to use pieces weighting 12-25 tons each, whereas nowadays erectors prefer to install complex box sections weighting some 80-180 tons each.

The trend to increase the size of the components shipped to the site, is however confronted by hard limitations imposed by the capacity of the transportation network, and the constraints placed on erection.

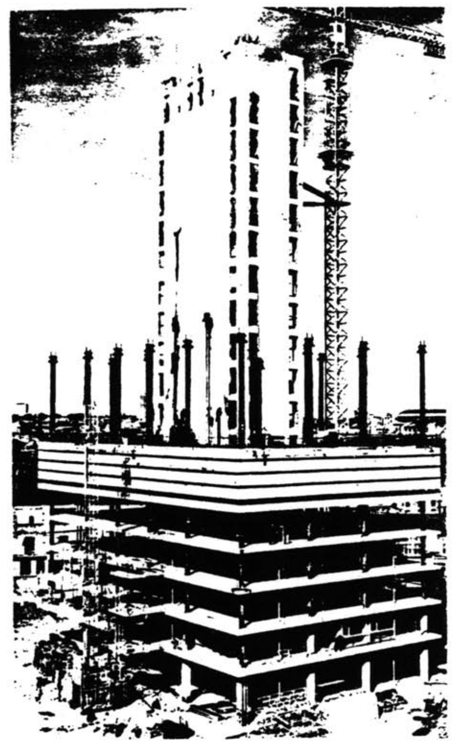
The transfer of building materials from the mine and factory to the construction site, is generally done by land, here the size rather than the weight of the cargo determines whether it can travel through the network, and since roads represent a major investment in infrastructure, we can only in the long run expect important changes in its handling capacity.

Other mediums, like water transportation can manage much larger components than those handled by the system of roads. However we are here limited to those originating ports and destinations on the river banks and on the sea shore, from these the supply of material inland must be carried out by land. Inevitably if an object is to travel through a network of pipes, it will have to be small enough to get through the smallest slit in it.

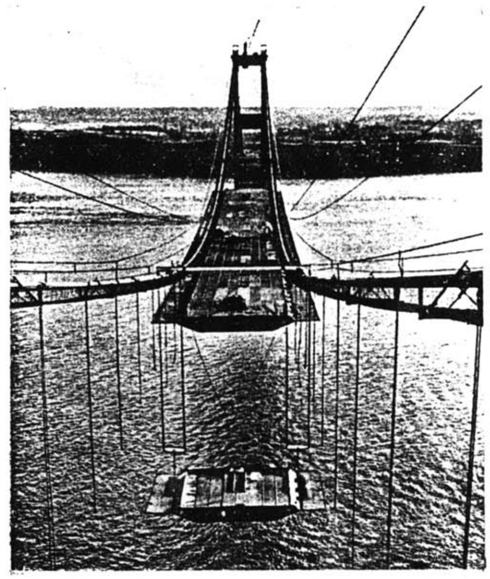


When large components reach the site, still remains the problem of handling and erecting larger parts. Constraints placed on erection are those caused by the topography of the site, its limited capabilities to support the maneuvers of the lifting equipment, the very availability of this equipment, access to the site, working space etc.. Such constraints in many instances determine the feasibility of the project to the extent, that nowadays an economic optimum is hardly possible if the method of erection and the available equipment is not known at the time of drafting the design.

As an alternative to the high cost of on-site operations, in the context of transportation and erection constraints, construction methods have developed expanding the performance of the building components by fully incorporating them to the process of construction, like in split tower erection, where floor units wheinghing as much as 710 tons are successively lifted up to form a series of floors, or push-up construction where the structure is assembled at ground level and pushed up by jacks, or slip forming techniques, where the structure is used to guide the motion of the traveling formwork.



In bridge construction where the severity of conditions probably taxes the ingenuity of the builder to the outmost, construction has also developed in this direction, with launching, which also seems to be in line with the trend towards mounting superheavy pieces, the bridge girder is here so to speak moved from the pre-assembly site continuously into its ultimate position, or in suspension bridges, were deck units weighting as much as 120 tons are lifted into place by a system very similar to a rope way or a cable car.



These methods have in common the concentration of most of the building activity in a single work area (whether moving or fixed), this concentration considerably simplifies the movement of men, machines and material during construction. When the work area is further weather enclosed on-site conditions become very much like those at the factory.

This simplification of on-site operations is achieved extending the performance of the building components, increasing both: their capacity to be self-supporting which eliminates the need to mount the usual crust of roaming temporary structures, and their self-erecting capabilities, that eliminate the need for equipment and the nature and number of the inputs required for construction at the site.

The capacity of the incomplete structure to support itself as well as the passage of material through it, and the added hardware by which self-erecting capabilities are increased, adds up to a transfer of functions and costs from equipment and on site labour, to the permanent elements of the building. Rather than a method this transfer can be characterized as a strategy or an approach to construction.

Self-supporting and self-erecting capabilities are from the point of view of analysis distinguishable functions, furthermore one does not preclude the other. The purpose of this investigation is to concentrate on the latter, that is, on the incorporation of a constructive or erecting function in the building components.

The capacity of of the building components to guide the motion by which a building is put in place, is evidenced clearly in those construction methods developed as an alternative to unusually constrained conditions, However not so clearly, this capacity is nevertheless present in even the most traditional practice of construction, the fact that here they generally go unnoticed, is due to a lack of the proper optics which can scan them out.

The driving force and main objective of this work, is to present a conceptual framework by which to analyze and model the construction process in another light. We are here concerned with concepts and not with particular methods, these are only used as illustration.

The material here presented is organized into sections that are incorporated to constitute three parts, which are followed by an overall conclusion. To frame the central ideas, we set up a system of light houses (so to speak) along the way in the form of subheadings that subdivide each section, and in order to keep constantly in view the thread which ties the main body together brief summaries preceed each Part.

In Part I, "Mechanisms", we begin characterizing the construction process as resulting from two operations: the motion of material or components, and the subsequent consolidation of a structure, in the remainder of this Part we are concerned with the problem of motion while consolidation is taken up in Part II. The notion of constrained motion, path building, and other elementary concepts of Kinematic Geometry are also introduced.

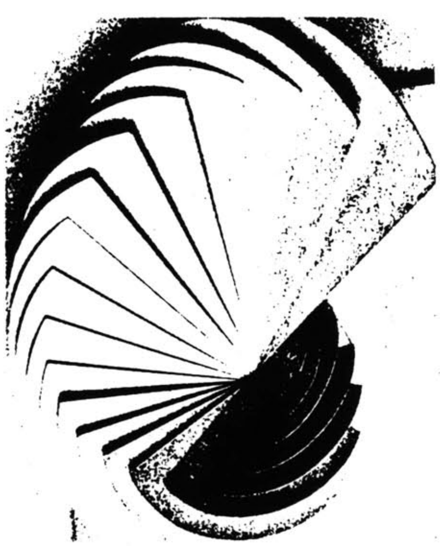
The material of Part I is further generalized in Part II, "Structures from Mechanisms", here we attempt to model the process of construction as a gradual reduction in the number of degrees of freedom inherent in a bundle of material from which the future structure is to arise. The application of this formulation to tension and compression structures is then discussed making use of the concept of stability, and finally we take up the problem of structural consolidation.

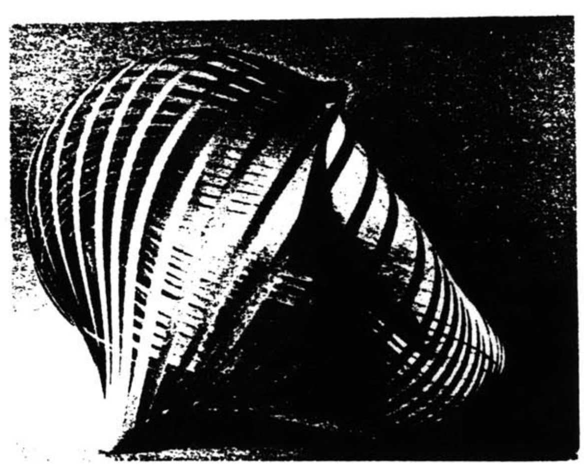
In Part III, "Tool & Work Piece", we partition the construction process in terms of the entities involved: the builder and the building, and an effort is made to identify the different nature and degree of their involvement in the process. Also discussed are: "Self-erecting structures", were the work-piece is indistinguishable from the machine, and "hybrids" were the work piece is coupled to the construction equipment.

briefly stated; in Part I, we study the construction of mechanisms from an otherwise dismembered bundle of material, in Part II, we turn this mechanism into a structure, and in Part III, we distinguish types and degrees of collaboration between the components and or carcass of a structure and the construction equipment. The wider implications brought about by the incorporation of self-erecting capacities, are left for the conclusion.

The illustrations where drawn from current or proposed construction practices, as well as from other related fields like crane construction and convertible roofs, some of these could have been used to illustrate several concepts, nevertheless, a wider exposure was preferred using the chance to concentrate under a single title otherwise scattered information. Analogies with living organisms are also established, not as an attempt to imitate nature, which rests upon an altogether mistaken idea, but in order to illustrate the generality of certain concepts.

There is nothing new in the ideas here discussed, these are largely taken from "Kinematic Geometry" a branch of Dynamics also known as the "Science of Pure Mechanism" (19), which provided the necessary conceptual framework for this investigation. Our only contribution, if any, is to have applied some of its elementary concepts to the analysis and interpretation of the construction process.





It is our believe, that from the perspective here presented, not only is it possible to reformulate many of the problems of construction, but also of design, opening the road to the synthesis of new solutions.

PART I

"MECHANISMS"

Construction consists basically of two operations: one involving motion, the other the freezing of motion. Movement of material during construction is in no sense arbitrary, a physical path must exist to connect the origin with the destination of its travel, building this path is what concerns us here. The science providing the necessary conceptual framework is "Kinematic Geometry", a branch of Dynamics generally associated with machine design, we take from it only its most elementary notions, these serve to lay the foundations for subsequent parts.

The examples used here to illustrate concepts, reveal to a degree a contribution of the building components in the provision of a path to channelize, either their own motion or the movement of subsequent material, however we leave the discussion of this participation for Part III, while the problem of consolidation is taken up in Part II.

1 CONSTRUCTION, MOTION & KINEMATICS

2 PATH BUILDING

3 ANALYSIS & SYNTHESIS

1 CONSTRUCTION, MOTION & KINEMATICS

CONSTRUCTION & MOTION

Giving a material its required form results from the combination of three possibilities: adding or joining, substracting or removing, and forming or deforming. Although the bulk of man made construction and the traditional view of building has been one of simple accretion (stone is put on stone, brick on brick, steel on steel, and so forth until the final form takes shape), a building like a piece of sculpture can be brought about either by adding, substracting or moulding clay or whatever material.

What characterizes construction, is not whether material has been removed, added or balanced to zero, but rather if it has moved at all. Motion by itself is not the complete story, a building must last, using our analogy; the clay must consolidate or dry.

We have then, two basic operations in construction: one involving movement, the other the prevention of motion, here we deal with the first, while the latter is taken up in Part II.

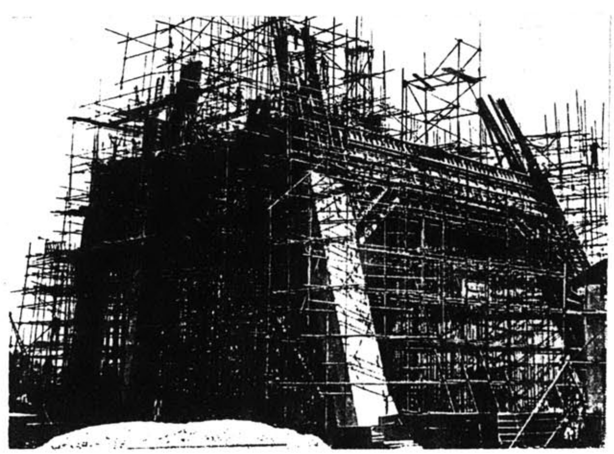
At the time of construction, material moves at two different scales, we can distinguish microscopic from macroscopic motion; the first is due to the action of molecular forces as in the making of a drop or a splash the movement of the particles of matter lies for the most part within molecular range, while in the latter, we have to deal with transference of portions of matter from widely distant places. Of microscopic movement we have a purely statistical knowledge, and can be brought about only evoking mechanisms within the material like the arching of a bow, or the freezing of water to obtain ice, while macroscopic motion occurs at a scale directly accessible to men and machines like the building of a wall of bricks, or the turning of a screw. It is this latter scale of motion that is of interest here, reference to the first will be made only inasmuch as it reflects in a macroscopic change.

KINEMATICS

In construction the movement of material is in no sense left to chance, whatever the origin there is a definite destination, and a suitable path must be found or built to guide and support this motion.

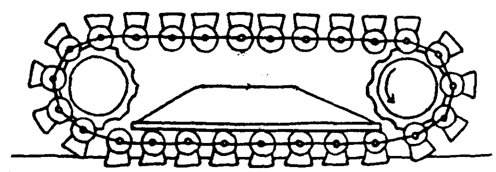
A path connects two terminals: origin and destination. In a typical building under construction several thousands of such paths must be provided, however it is rare to find their traits in the finished structure, because (like with the antler, which once mature sheds the highly vascular tissue involved in bringing materials to the actively growing apex), the supply lines by which material is delivered and incorporated to the permanent structure, are detached and removed from the site once construction is finished (fig. 1).

1



Cranes are path builders of a more elusive kind, even if the building is under construction, it is possible to find no evidence of delivery corridors, in this sense, cranes are very much like caterpillars in that they install the road with the front wheel and remove it with the rear (fig. 2).

2



A path must be given a suitable form and resistance if it is to support the required motion. "Kinematic Geometry" or as it was first called by Reuleaux (19) the "Science of Pure Mechanism" deals with the problems of "form" and motion, while resistance, forces and motion are treated in Kinetics (another branch of Dynamics).

Not only because of its relative simplicity does Kinematic Geometry present a good starting point in this investigation, but also, because the problem of magnitude of forces, momentum etc., can not, in this context, be disembodied from a formal proposal, we are then starting from the beginning.

The most important concept in Kinematic Geometry is the notion of constrained motion, and as will become clear, a path cannot so well be said to consist of elements as of pairs of elements; these constitute the kernel of kinematic chains and mechanisms, by which even the most elaborate paths can be constructed and motions obtained.

2 PATH BUILDING

KINEMATIC PAIR

We assume, in the following discussion, that those parts of a mechanism transmitting the forces by which the moving points are caused to limit their motions, are bodies of suitable resistant capacity, possessing complete rigidity, and for the moment will pay no attention to their size.

In order that any moving body A (fig. 3), of a given form may remain continually in contact with a stationary one B, we must give to the latter a special form, this form can be found if the body A be caused to take up consecutively the series of positions which it is intended to occupy relative to B, thus determining the envelop of A. This relationship will also be found to be reciprocal, since A can also be said to envelop B.

3

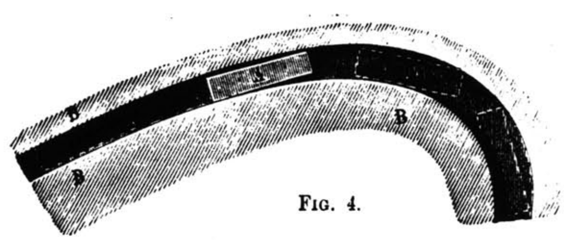


FIG. 4.

Many such reciprocal envelopes can be constructed; in all cases at least two bodies correspond in being envelopes of each other. Such a pair of elements constitute a "kinematic pair", its elements carry the envelopes required for the motion which the bodies in contact must have, and by these, all motions other than the ones desired in the mechanism are prevented.

Kinematic pairs can be classified into lower and higher pairs: in lower pairs one element not only forms an envelope for the other, but encloses it, that is, the forms of the objects are geometrically identical one being solid or full the other hollow or open, in a higher pair the elements do not enclose each other, but nevertheless, restrain each others motion in a unique way (fig. 4).

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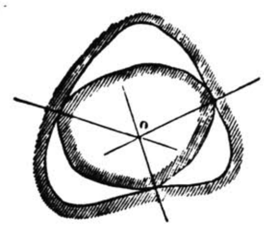


Lower pairs have certain practical advantages over higher pairs:

1) applied loads are spread over a larger area, enabling lower pairs to be more heavily loaded and wear resistant.
2) all of them, except the screw pair, derive directly from circles and straight lines, these geometrical forms can be embodied in precise manufacturing processes.
3) when a profile closed lower pair is worn out, or when its bearing surface is failing, we should be able to detect any slackness fairly easily.

For these reasons, Kinematics has developed in the direction of using mechanisms with lower pairs.

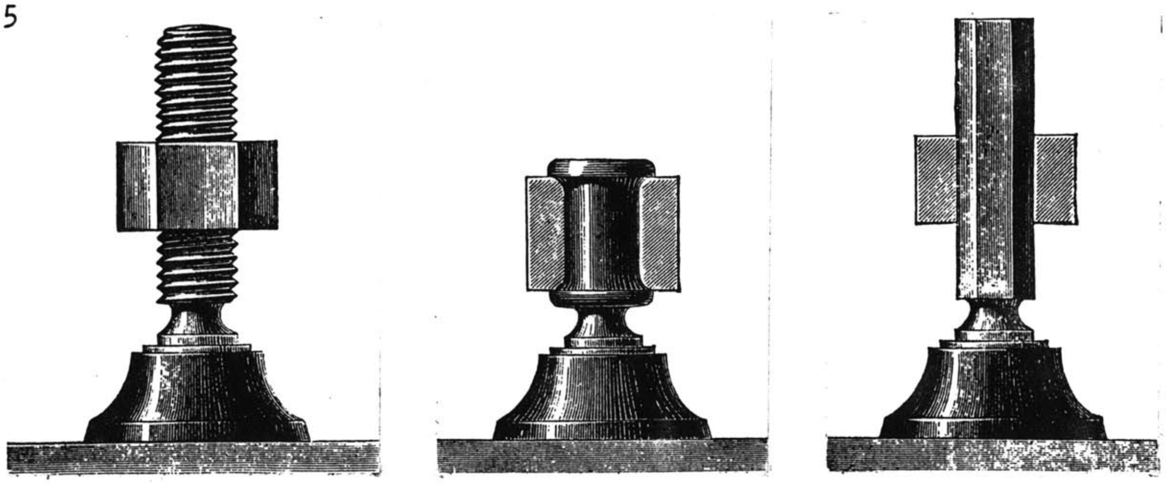
Since lower pairs have continuous surface contact, they can only be built from surfaces with constant curvature. The three most important lower pairs are:

1) the common screw and nut or twisting pair (fig. 5a).

2) the hollow solid of revolution or turning pair (fig. 5b).

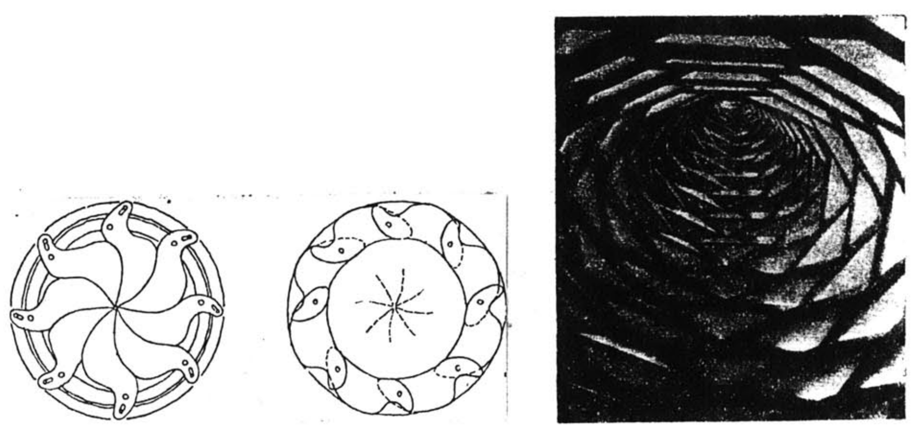
3) the full and open prism or sliding pair (fig. 5c).

5



By increasing the pitch angle of a screw to 90′, its axis becomes a straight line and we have the sliding pair, if on the other hand we decrease its pitch angle to 0′, we obtain a circle and we have a turning pair. Thus, the motion of the screw pair is the most general of the three since it includes as limiting cases the sliding and turning pairs. The break down of the helical motion of the screw pair into a translation motion and a rotation is evidenced in fig. 6b, which shows an interior model of a proposal for the Theme Pavillions, Expo '67, Cite du Havre, diaphragms in cameras also depict sliding and turning motion (fig. 6a), only here the axis of rotation is perpendicular to the sliding axis.

6

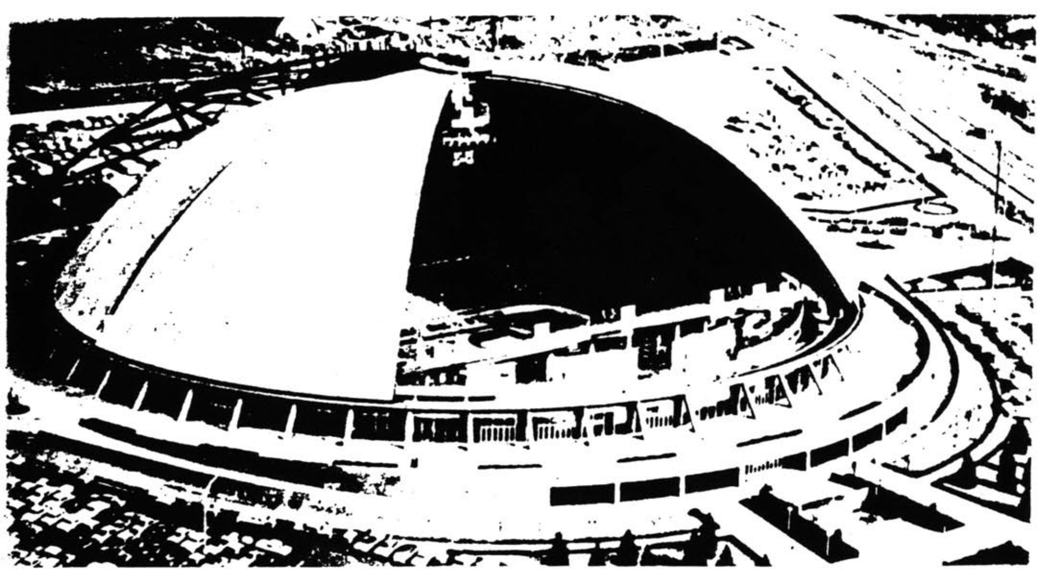


An example of twisting motion is given in the model for a self-erecting Folding shelter proposed by Synergetics (fig. 7); here triangular panels are laid out flat and are hoisted up the central mast by a twisting motion of the top square panel.

7

Fig. 8 is an example of a turning pair; the Pittsburgh Auditorium designed by Mitchell & Ritchey built in 1961, illustrates how a single turning pair can be used to enclose space if its elements are curved in a plane parallel to the axis of rotation.

8



Push-up methods and slip forming techniques, as well as climbing and traveling cranes and erecting equipment, are based on sliding motion; the erection by a slewing crane of the Danube Bridge, Hainburg, illustrates this (fig. 9).

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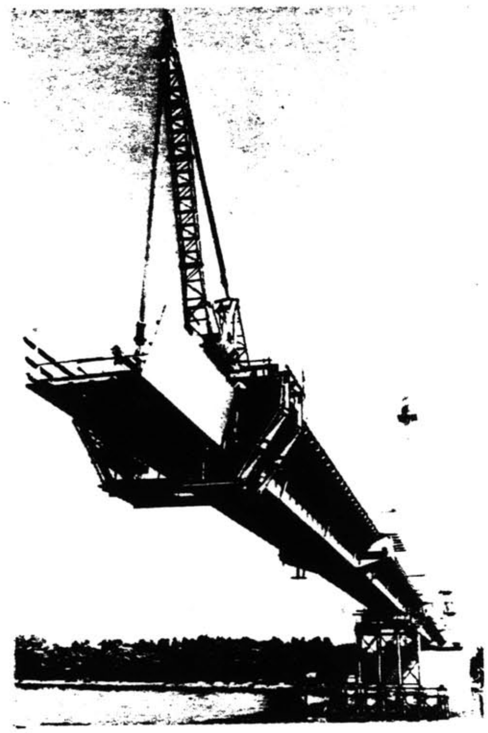

KINEMATIC CHAIN

A link is the force resistant connection of two or more elements which belong to different pairs. If several pairs are connected in such a way that each element of each pair is joined to one element of another pair, the whole will now form a linkage returning upon itself like an endless chain, this combination we call a "kinematic chain"; every link in this chain consists of two elements, so that the chain has as many links as it contains pairs, a simple hanging cable (fig. 10), is an example of a kinematic chain (note the inclusion of the link representing the earth).

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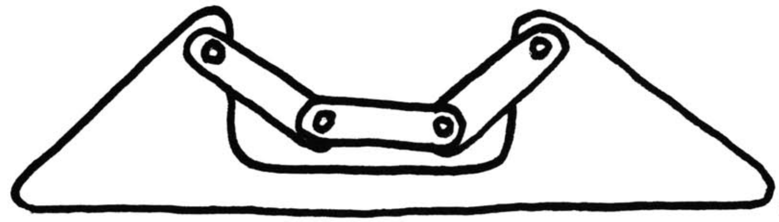
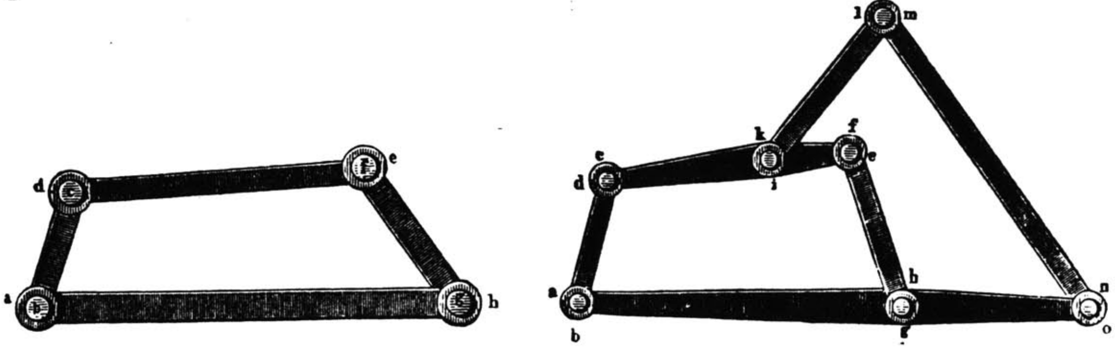


By adding elements of new pairs, a chain can be extended to form "compound chains", like the project for a weekend house by R. Holzapfel (fig. 11). The construction of compound chains, allows the possibility of obtaining motions according to more and more complex laws procuring an infinite number of different forms of motion.

11

If a kinematic chain be so arranged that every alteration in the position of a link relatively to the one next to it, is accompanied by an alteration in the position of every other link relatively to the first, then such a chain becomes a "constrained chain"; fig. 12a, shows a simple constrained chain, while fig. 12b, shows a compound one.

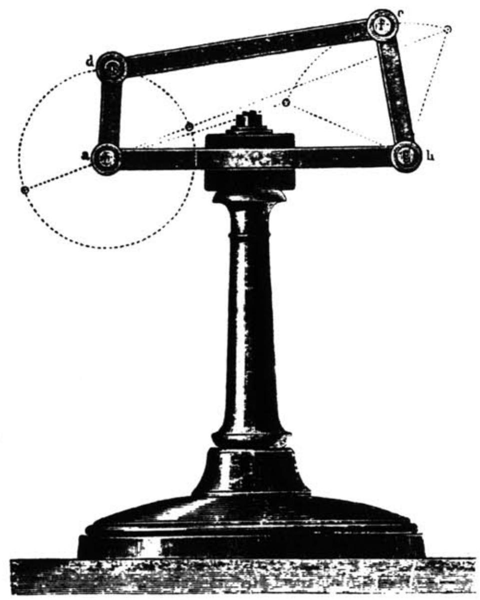
12



MECHANISMS

In itself, a constrained chain does not postulate a definite absolute motion, to obtain this, a method similar to the one adopted with pairs of elements must be used, namely, to fix in position one link of the chain relatively to the portion of surrounding space assumed to be stationary, the relative motion of the links then becomes absolute. A constrained chain having one of its links fixed is called a "mechanism" or train (fig. 13).

13



Mechanisms can be classified into:

1) planar: links move in planes that remain parallel to each other, the axis of turning pivots also remain parallel to each other (fig. 13).
2) Spherical: the pivot axes intersect in a point, the motion of the links takes place on the surfaces of concentric spheres whose center is the point of intersection of the pivot axes; fig. 14, shows one such mechanism proposed by Synergetics, wherein a compact form can be expanded by the spin translation motion of its rigid panels.

3) Spatial: here some or all the links are free to move in three dimensions (fig. 15).

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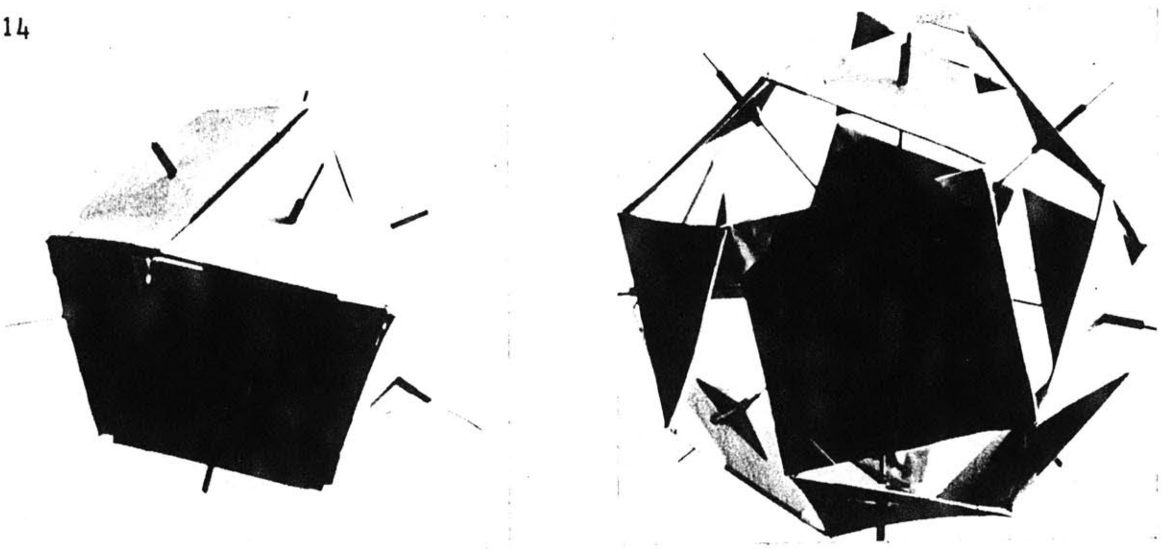
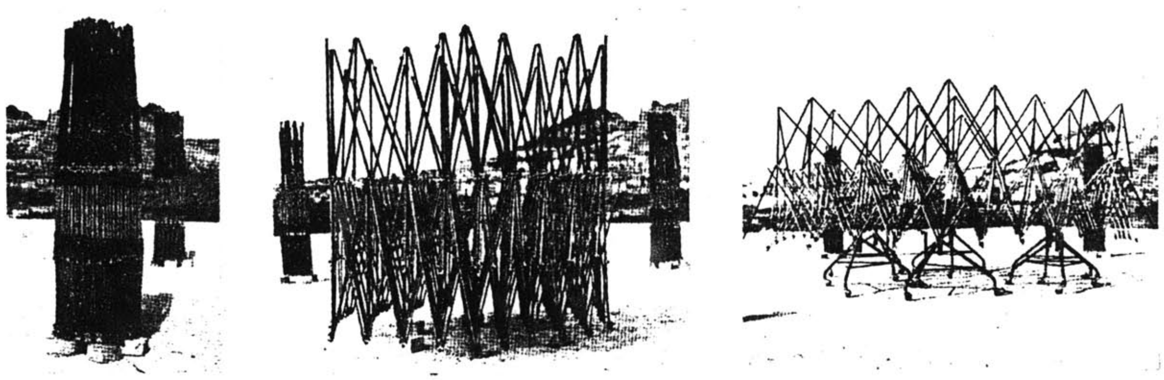


Fig. 15, shows a three dimensional mechanism developed by Emilio Perez Pineiro, the structure consists of a system of rods pivotally connected to each other by couplings, the mechanism can unfold over a three dimensional space and then close up forming a compact bundle of rods, each rod has three couplings, two of them at the ends and a third at an intermediate point. The position of the couplings defines the curvature of the structure, end couplings are connected permanently by flexible ties of predetermined lengths which control the geometry of the expanded surface.

15



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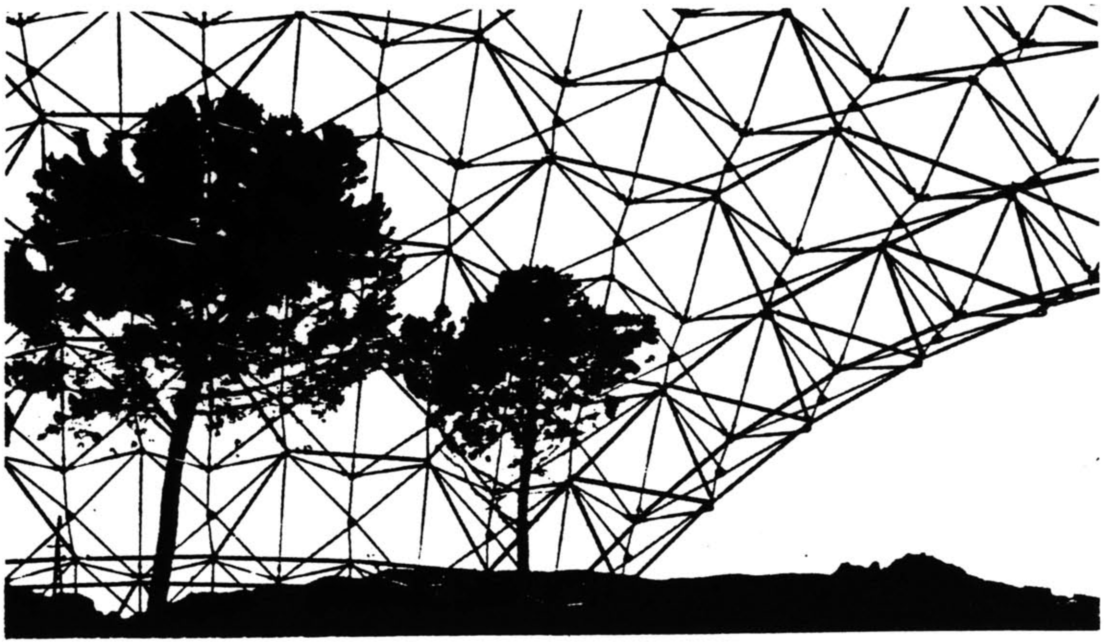


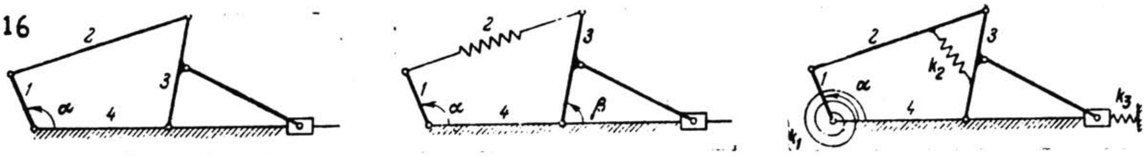
STORAGE MECHANISMS

We now relax our initial assumption of complete rigidity of the elements, to consider another class of mechanism, namely, storage mechanisms with elastic components. this class of mechanism is characterized because part of the energy is not immediately transmitted but stored and later returned to the system.

It is important to distinguish between mechanisms with elastic connections and mechanisms with elastic links. A mechanism with elastic connections does not impose any additional limits on the mobility or constrained motion of the mechanism, while an elastic link allows relative motion between the ends which it connects (it can be replaced by a pair of rigid links connected in series), with a corresponding alteration in the mobility of the mechanism.

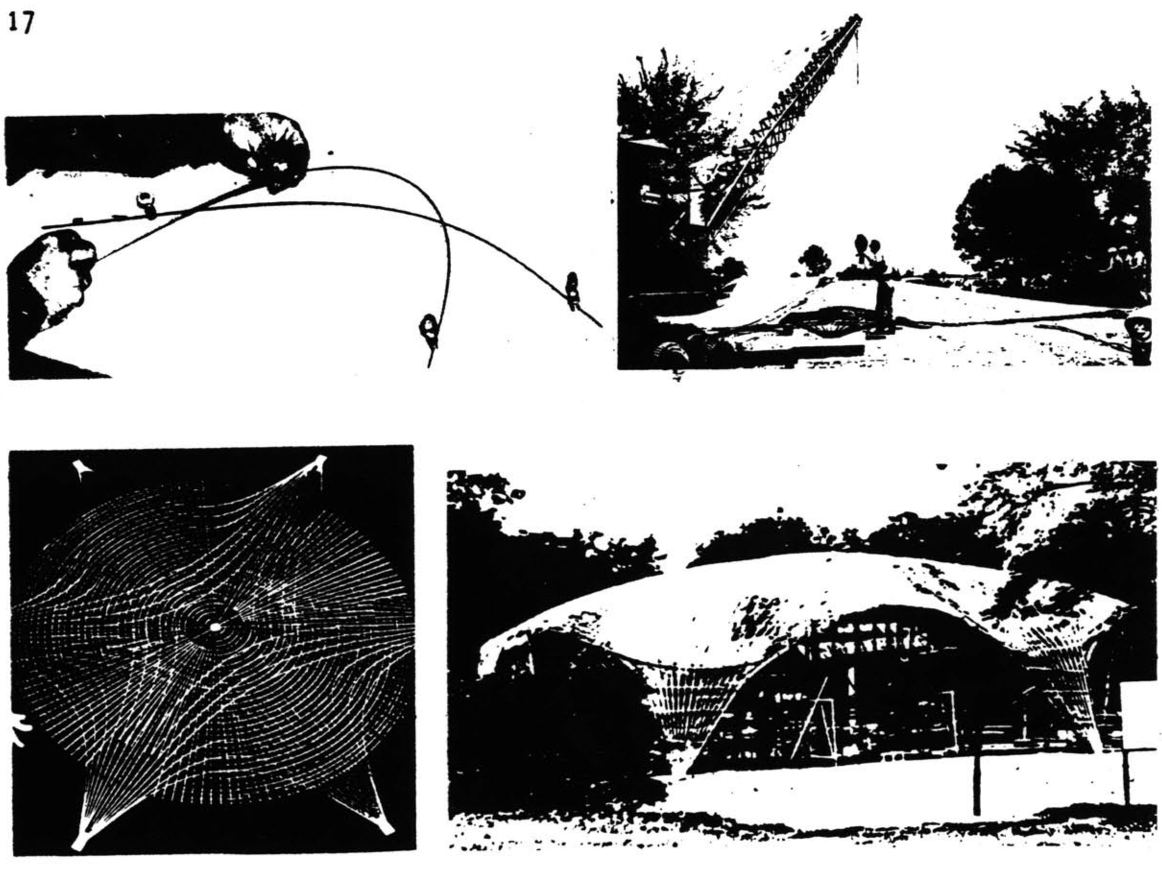
Fig. 16a, shows a plain six component mechanism while fig. 16b, shows the same mechanism with additional elastic connections k1, k2 and k3, these do not form part of the kinematic loop of the mechanism they are supplementary components. A mechanism with an elastic link is shown in fig. 16c, here the spring whether it be in tension or compression, alters the mobility of the mechanism and its constrained motion.

16



The lift shape method for the construction of thin shell structures, makes use of a mechanism with elastic links (fig. 17). Here the process stems from the observation that when compressive forces are applied to the ends of a straight bar, it will bow acquiering a predictable parabolic curve so long as the stresses induced in bowing do not exceed the yield strength of the material.

17

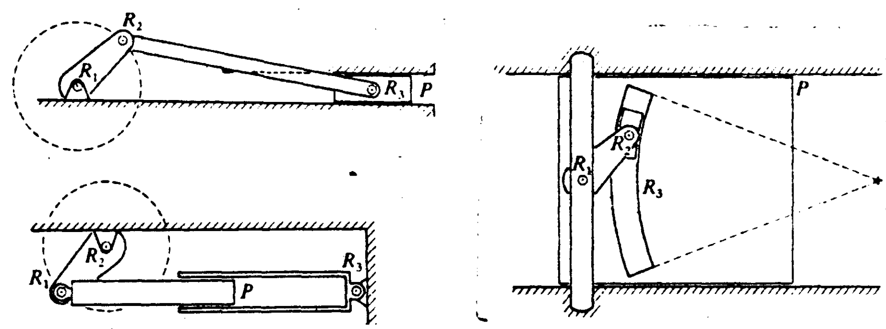


3 ANALYSIS & SYNTHESIS

ANALYSIS

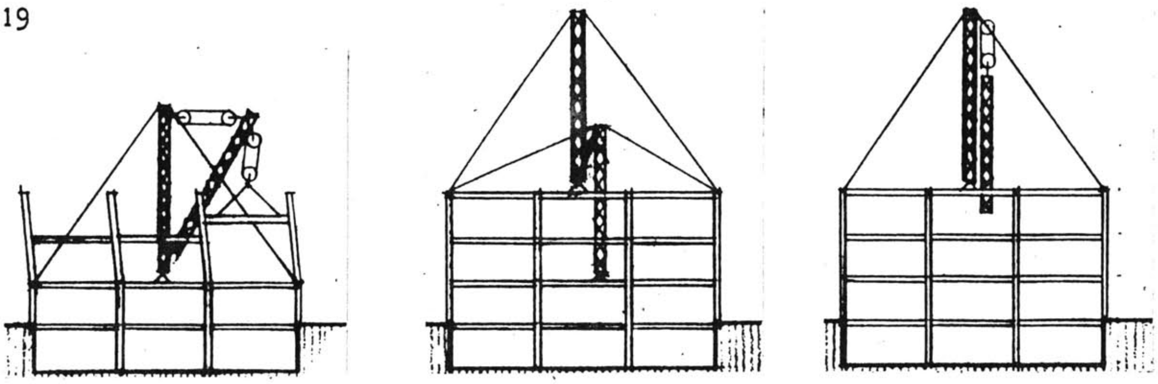
It was Reuleaux who first showed in all its simplicity how a single kinematic chain made of members connected by pairs, could serve to explain the essential structural similarity between mechanisms which appear quite distinct from one another. The similarities are revealed when we rid a piece of hardware of all unnecessary detail, and then examine its elemental structure; for instance, a pair can be expanded in diameter or lateral extent to enclose within the periphery of its elements the elements of a neighbouring pair, fig. 18a shows how the elements of its sliding pair P can be expanded to enclose two rotary pairs R1,R2 (fig. 18c).

18



A definite motion can be obtained from a given kinematic pair if one of its elements is fixed and the other moved. If we exchange the fixed with the movable element we speak of the "inversion" of a pair, the inversion of lower pairs causes no alteration in the motion belonging to them. The inversion of a pair belonging to a mechanism, produces a different set of motions with respect to the surrounding space, while the structure of the mechanism is unaltered; for example, the slider crank linkage of fig. 18a, is best known with the sliding pair fixed in the base, when the linkage is inverted some other member is fixed, fig. 18b shows one of three possible inversions the coupler now being taken as a fixed base. In construction, traveling and climbing equipment very often use the inversion of a pair as means of locomotion; for instance, the derrick in fig. 19, as the building is erected by inversion raises itself to the top of the next tier.

19



In the analysis of a mechanism, it is often possible to reduce a kinematic chain removing one of its links and substituting it by a suitable pairing between the two links which it connected. In this way the motion of a particular link can be obtained without requiring at the same time to use the motions of any other of its links (fig. 20).

20

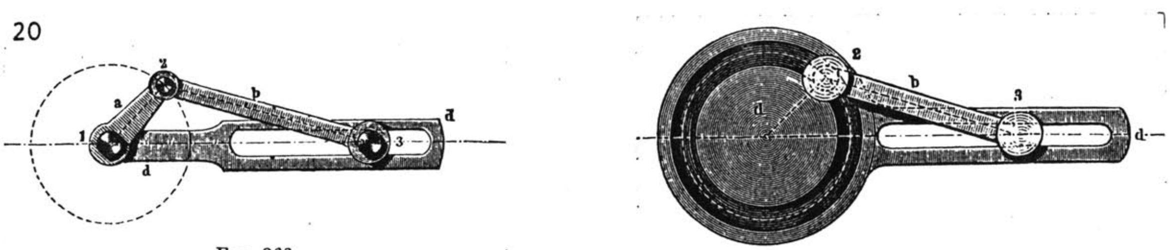


Fig. 268

SYNTHESIS

Kinematic analysis studies the nature of the constrained motions obtained by the use of given combinations of elements, pairs, links, or chains. The province of kinematic synthesis is the reversed operation, that is, the determination of the pairs, chains or mechanisms necessary to produce the required motion.

The synthesis or creation of a new mechanism, is a more difficult task than its analysis, its province being that of invention. Reuleaux quotes from Gothe:

> "Everything we call invention, discovery in the higher sense, is the ultimate outcome of the original perception of some truth, which, long perfected in quiet, leads at length suddenly and unexpectedly to productive recognition." (19)

In spite of great efforts by kinematicians to rationalize the process of geometrical synthesis, many imponderables are left unresolved, many choices remain open, each one calling for careful judgement to weigh its advantages and disadvantages. Nevertheless, Kinematic synthesis presupposes an acquaintance with analysis.

> "Essentially invention is nothing other than induction, a continual seeking down and thereafter analyzing of the possible solutions which present themselves by analogy."(19)

Although pencil and paper are useful tools in the modeling of mechanisms, physical models are much more illuminating, and to a degree, indispensable for the synthesis of new mechanisms.

Planar mechanism are the easiest to model and can be built from readily available materials and simple tools (fig. 21a), here the basic link stock is cardboard, thumbtacks are used for turning connections between links; riding in a straight slot, a thumbtack functions also as crosshead. Spatial mechanisms are the most difficult to design, when motion in three dimensions is required, the designer must never loose sight altogether of the goal of inherent balance and simple structural design. Physical spatial models require more of a shop and stiffer materials than the construction of planar models; fig. 21b shows a model of a spatial mechanism whose links are connected only by turning pairs, it was made from sheet metal strips suitably twisted and connected by metal eyelets, the axes of the turning pairs has been emphasized by soldering wires into the eyelets.

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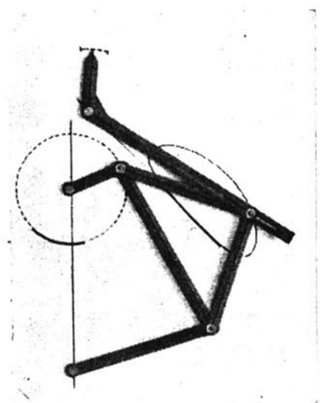
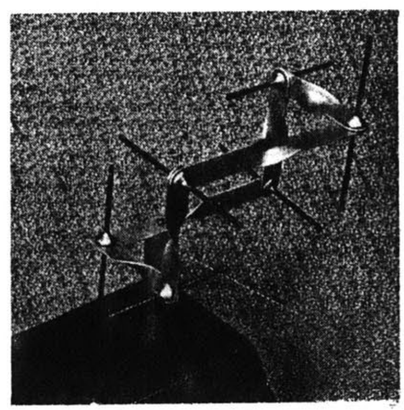




PART II

"STRUCTURES FROM MECHANISMS"

A structure is but a special type of mechanism that can be distinguished from the number of its degrees of freedom. Since we generally build by adding or joining, a structure can be said to arise from a constrained mechanism. First a mechanism is built, and then by adding constraints it consolidates into a structure. The number of constraints required, is equivalent to the number of construction operations or inputs of the building team. The number of inputs will depend on: the degrees of freedom, on whether the structure being built is tension or compression loaded, and on the nature of the force field in which it is submerged. Such are the main ideas here discussed, these extend and generalize the concepts introduced in Part I.

1 DEGREES OF FREEDOM

2 STABILITY, TENSION & COMPRESSION

3 CONSOLIDATION

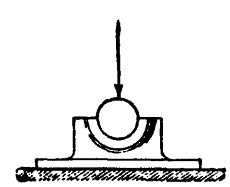
1 DEGREES OF FREEDOM

CLOSING FORCE

In Part I, we dealt with constrained mechanisms; when any point in the mechanism was moved in a prescribed way all the other points on the mechanism had a uniquely determined motion. Such mechanisms were built with kinematic pairs of elements where the reciprocal restraint of the two elements was complete. Under certain circumstances however, this condition may be relaxed when precautions are taken to prevent the possibility of sensible forces having certain directions ever affecting the pair. This done, it is no longer necessary to make the pair entirely self closed, bodily envelopment being no longer essential for restraint in those directions.

To prevent the disturbing action of sensible forces acting in any given direction upon an element, we allow another sensible force to act upon it continuously and make the direction of this force opposite to, and its magnitude not less than those of the former. Such pairs of elements requiring a closing force are incomplete in themselves; their usefulness depends upon the application of the closing force (fig. 1).

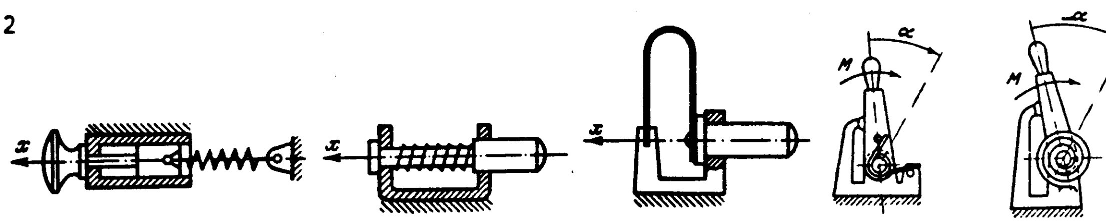
1



We then have another important classification of kinematic pairs into "open" and "closed" pairs: in a closed pair, one element completely surrounds the other so that it is held in place in all possible positions, open pairs on the other hand maintain their relative positions only when the elements are prevented from separating by external means.

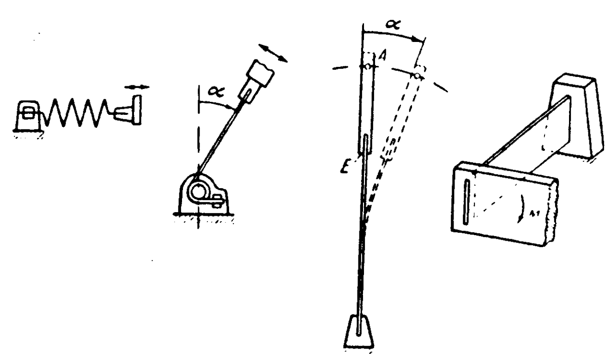
Spring elements, in the form of elastic couplings are well adapted to close open pairs; fig. 2, shows three examples of sliding pairs and two rotation pairs with elastic couplings: a) the elastic element operates in tension, b) the elastic coupling operates in compression, c) the elastic element operates in bending, d) the elastic element is a helical spring, and e) the elastic element is a spiral spring.

2



It is important to distinguish elastic couplings from elastic joints, the former only close the kinematic pair without altering the nature of the relative motion of its elements, while an elastic joint determines not only the force interaction of the elements, but also, the nature of the relative motion of these elements. Four examples of elastic joints are shown in fig. 3.

3



The construction of an elastic joint is simpler than the construction of an elastic coupling, with these it is possible to achieve relative mobility without free play, at the same time the accuracy of the relative displacements of the elastic joint is much lower than the accuracy obtainable with a plain kinematic couple.

HARDWARE VS. INPUTS

The incompleteness possessed by certain pairs of elements which we have now found means of rendering harmless, occurs also in many kinematic chains, and here similar means can be employed to neutralize it.

It is possible then to build mechanisms which under certain conditions will behave as constrained mechanisms, and under others will disengage or have undefined motion. Since we are here interested in constrained motion, there is evidently a trade-off between the completeness of the internal hardware in a mechanism and the number of external forces or inputs required to obtain the specified motion, this relationship is formalized in the concept "degrees of freedom" of a mechanism.

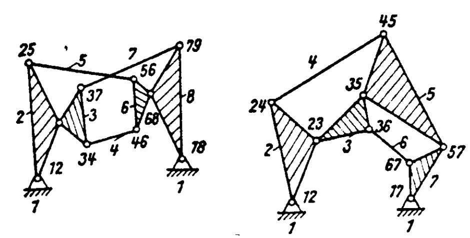
The number of degrees of freedom in a mechanism determines how many inputs a mechanism must have in order to fulfill a useful engineering purpose. One degree of freedom denotes constrained motion, when there are two degrees of freedom, then two independent motions must be introduced at two different points in the mechanism.

The number of degrees of freedom is independent of the dimensions of the links; it is determined only by the number of links and the number and types of pairs in the mechanism. In a planar mechanism, each movable link not connected to any other link, contributes 3 degrees of freedom, since it can have translatory motion in two perpendicular directions as well as rotational motion about any point. each lower pair connecting two links substracts two degrees of freedom, and each higher pair connecting two links substracts one degree of freedom. Thus in a planar mechanism with N links including the fixed link, G lower pairs, and H higher pairs the number of degrees of freedom F is given by the following expression:

$F=3(N-1)-2G-H$

Fig. 4a and 4b show the application of the above equation to mechanisms with turning pairs, fig. 4a has N=7 links and G=9 joints and therefore has zero degrees of freedom; thus it is an immovable mechanism or a static structure. fig. 4b has N=8 and G=10 and therefore has one degree of freedom and is a constrained mechanism.

4



From the above formulation whether it be erection or consolidation, the construction process takes place by a continuous reduction in the number of degrees of freedom inherent in an originally dismembered bundle of components, first, in order to allow for a unique motion by which the final configuration is attained, and later, in order to prevent the occurrence of even this motion.

Since the elements of a mechanism possess a certain mass and are not perfectly rigid, the actual number of inputs required from the building team, will not in general be equal to the degrees of freedom of the mechanism from which the structure is being derived, due consideration must be given to the type of structure being built, whether in tension or compression, and to the nature of the field of force in which it is submerged.

2 STABILITY, TENSION & COMPRESSION

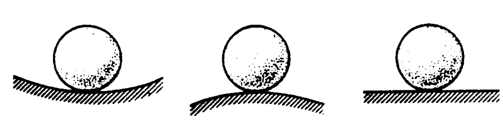
The number of inputs required in the construction of a structure loaded under compression, are in general more numerous than those required to built its counterpart under tension, the main reason being the inherent instability of the former.

STABILITY

A system is said to be in a state of stable equilibrium if, for all possible geometrically admissible small displacements from the equilibrium configuration, restoring forces arise which tend to accelerate the system back towards the equilibrium position.

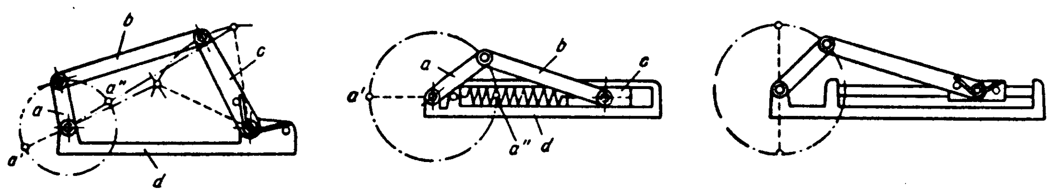
In terms of energy, an equilibrium state can be said to be stable, unstable, or neutral according to whether the potential energy is a minimum or a maximum or exhibits a point of inflection. Equilibrium is stable (fig. 5a), if a slight displacement from the equilibrium position results in an increase of potential energy and a corresponding tendency to reduce this energy by returning to the former position. Equilibrium is unstable (fig. 5b), if a slight displacement results in a decrease of potential energy and a corresponding tendency to reduce this energy still further by additional movement away from the equilibrium position. In the case of neutral equilibrium (fig. 5c), a slight displacement causes neither a tendency to return to nor a tendency to move away from the equilibrium position.

5



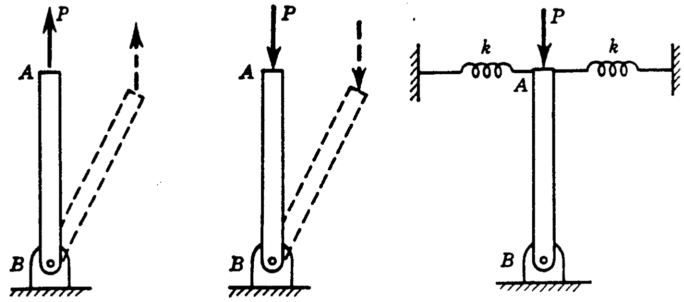
When springs are used to reduce the degrees of freedom of a mechanism, these impart to it properties characteristic of oscillatory systems; for example, fig. 6a shows a crank shaft connecting rod mechanism with a spring loaded slide, it is not difficult to see that the position a′ is a position of unstable equilibrium, when disturbed from this position, the mechanism does not return to it but moves to the position of stable equilibrium. The same effect of stability can be achieved whether the spring element is introduced between a moving and a stationary component (fig. 6b), or between two moving components (fig. 6c).

6



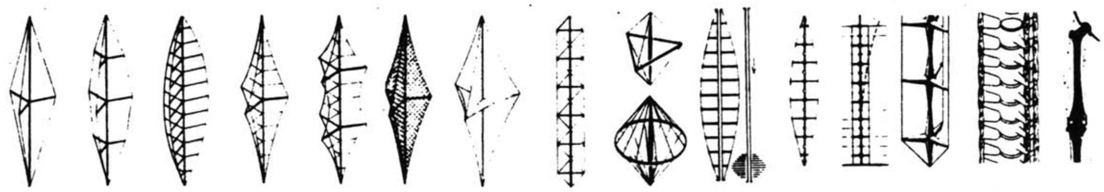
The difference in terms of stability between a tension and a compression structure can be seen in fig. 7. If the applied force P remains vertical it is easy to see that a small rotation of the bar will give rise to a restoring torque in fig. 7a, and an upsetting torque in fig. 7b. Thus the bar will be stable for a tensile load and unstable for a compressive load. The instability of the latter can be eliminated by adding lateral restraints as guy wires or springs (fig. 7c).

7



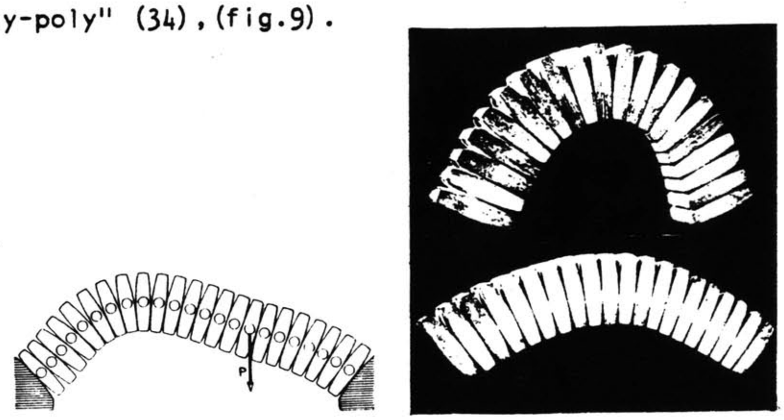
The instability of a compression bar with an intermediate articulation is present in continuous slender bars due to buckling, and similar ways of achieving stability with intermediate elastic supports can be used. Some examples are shown in fig. 8, where the elastic intermediate supports take the form of: short braced struts, a combination of struts and tensile elements, and a system of cable networks or membranes.

8



Instead of bracing by external elements, it is possible to render stable a compressed structure increasing its thickness or bulk. By so doing, material not in contact or understressed in normal loading conditions is brought into action as a result of an external destabalizing force. Such mechanism is inherent in brick arches where the voussoirs are evenly stressed under the work load, when an external force disturbs this equilibrium state, rolling motions of the voussoirs one with respect to the other will occur changing the internal distribution of stress; if rolling does not reach either the intrados or extrados edge, the arch will assume another stable configuration. This principle is some times referred to as "the roly-poly" (34), (fig.9).

9



TENSION STRUCTURES

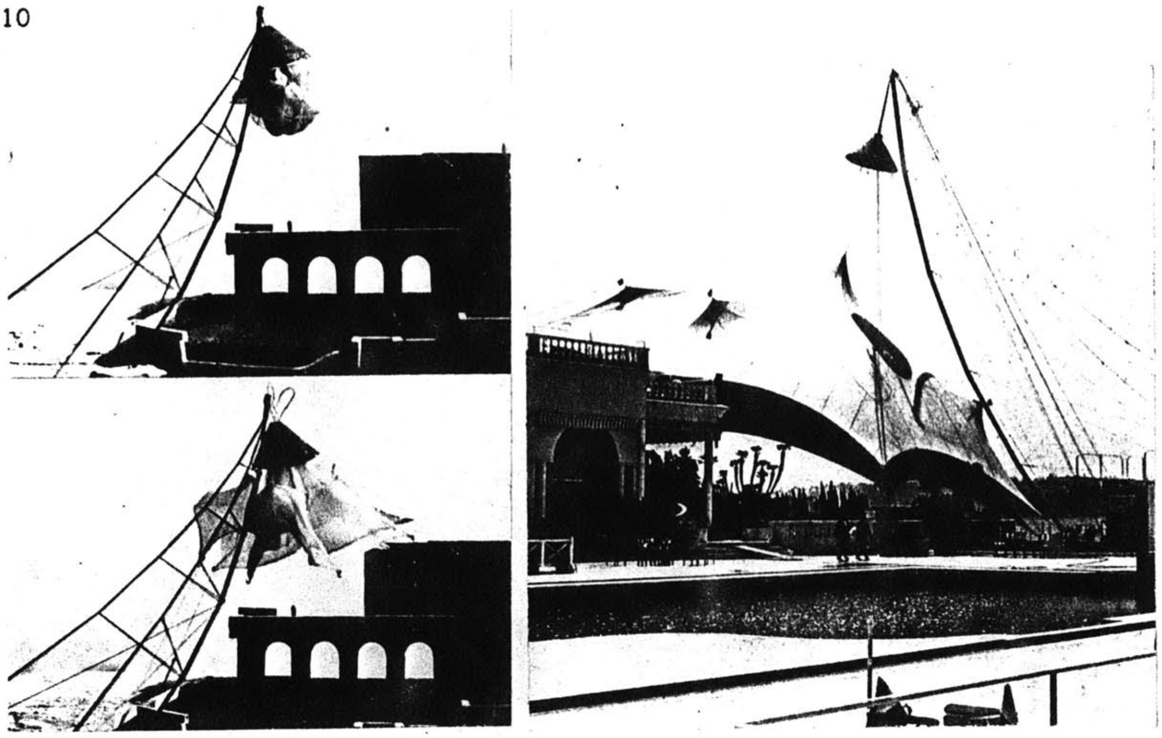
Given the instability of compression structures there is no clear demarcation between these and those loaded in bending. With tension structures there is no danger of buckling, thus, tension loaded structures are not subject to such complicated states of stress as occurs in bending, this applies in particular when the tension loaded component is capable of taking only tension, like when a cable or a flexible membrane is used.

The flexibility of the materials used in tension loaded structures refers to their capacity to adopt different shapes without cuts and joints, and ideally without storage of energy, that is, motion is not accompanied by plastic or elastic deformations.

A surface element possessing ideal flexibility is sometimes called "inextensible membrane", it is assumed to be completely compliant in bending, and admitting no strain in the tangential direction. A membrane having such characteristics can be modeled as a kinematic chain or unconstrained mechanism, possessing an infinite number of degrees of freedom, derived from its equally numerous links (microscopic) and rotation pairs.

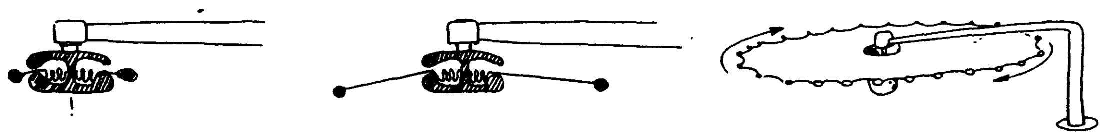
The degrees of freedom inherent in flexible material makes it possible to manufacture large continuous portions and indeed complete tension structures at the factory, which can then be folded in a number of ways for transportation to the site. Such a system can be turned into a constrained mechanism and eventually a structure with few inputs, given the force closing effect which the mass of each of its elements provide under the influence of the gravitational pull of the earth. The project for an open air theater Masque de Fer, France, by R. Taillibert '65, illustrates how a flexible membrane can be erected to become a tension structure with relatively few inputs (fig. 10).

10



In the case of tension structures built with flexible material the basic erecting agent is then the field of force, when the nature of this field is altered, different forms can be derived from the unconstrained mechanism inherent in the material. In the last century for example, attempts were made to tension nets with rotating weights (fig. 11), in the resting position the membrane is centrally bunched at the hub from which it spins out during rotation, in this system sometimes referred to as a "centrifugal umbrella", the centrifugal force takes over the function of the umbrella ribs. Pneumatic structures are better known examples of structures erected by the provision of a field of force.

11

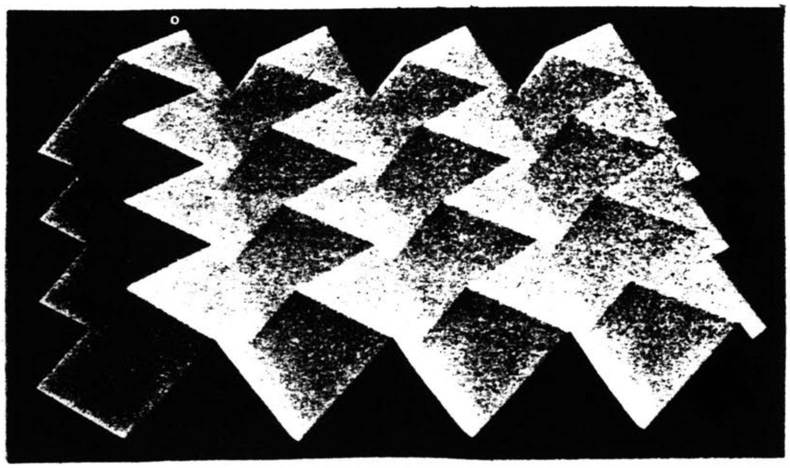


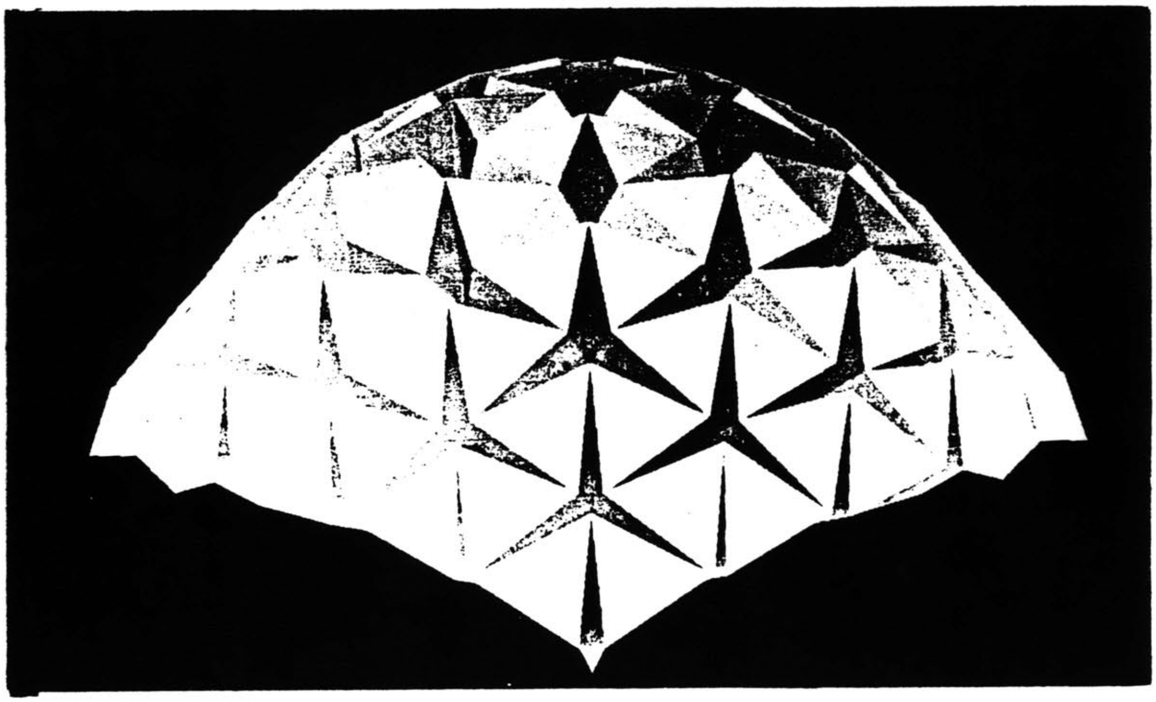
However advantageous a tension structure might be (in terms of simplicity of erection), in general, structures loaded purely in tension without compression members constitute exceptional cases, when for example the carrying cables are anchored to natural high points such as rocks or hillsides. With structures loaded mainly in tension it again and again becomes apparent that the material used in the compression members constitutes a very substantial proportion of the total quantity. Another significant feature of tension structures is that they cannot be "designed" in the conventional sense, as there are no flexurally rigid elements, while shell construction permits a certain amount of freedom of shape.

COMPRESSION STRUCTURES

Several methods have been proposed for the construction of structures subject to compression and bending which can be manufactured at the factory and folded for transportation to the site. The structure is shipped as a continuous kinematic chain, which can be derived from the ideal inextensible membrane by taking only a subset of its total degrees of freedom. Kinematic folded plate systems as they are sometimes called are built in this way with rigid panels as links of hardwared rotation pairs, or from a single sheet of material subject to plastic deformations along the ridges. Fig. 12 shows a proposal for a space structure and a dome derived from two kinematic folded plate systems.

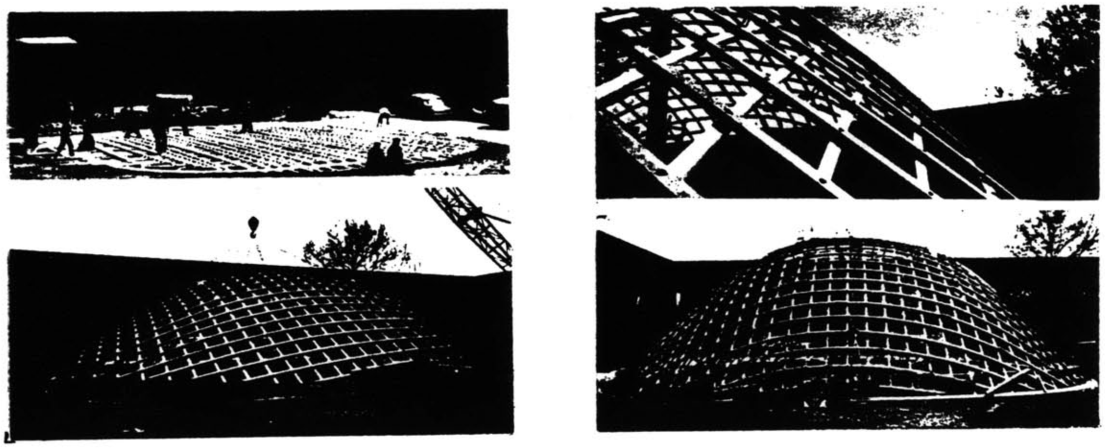
12





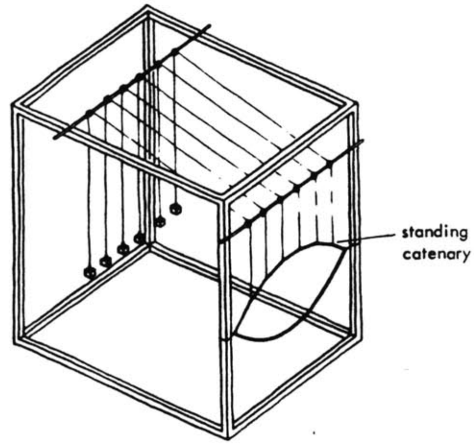
Lattice domes, are derived from the spatial deformation of originally plane flexible membranes (fig. 13), here, the mechanism is further constrained by the allowance of only turning pairs with rotation axis perpendicular to the plane of the originally flat membrane, motion in the direction perpendicular to this plane is brought about by the elastic deformation of the material . Lattice domes can be built from flexurally rigid latticeworks of round steel bars, aluminium tubes, sheet metal, plastic sections or wooden strips. Since the joints can rotate it is possible to collapse the lattice diagonally into a narrow bundle of strips side by side and transport them in one piece.

13



Shells under compression are also built as tension structures, either by temporarily overwhelming the downward pull of gravity with ballast or dead weights (fig. 14), or by turning upside-down after consolidation a structure shaped under tension forces. By Aquatexture techniques, compression shells can be built without subjecting the structure to a reversal in the type of forces which act upon it, stability is here attained neutralizing the field of force of gravity, since the mechanism is submerged in water.

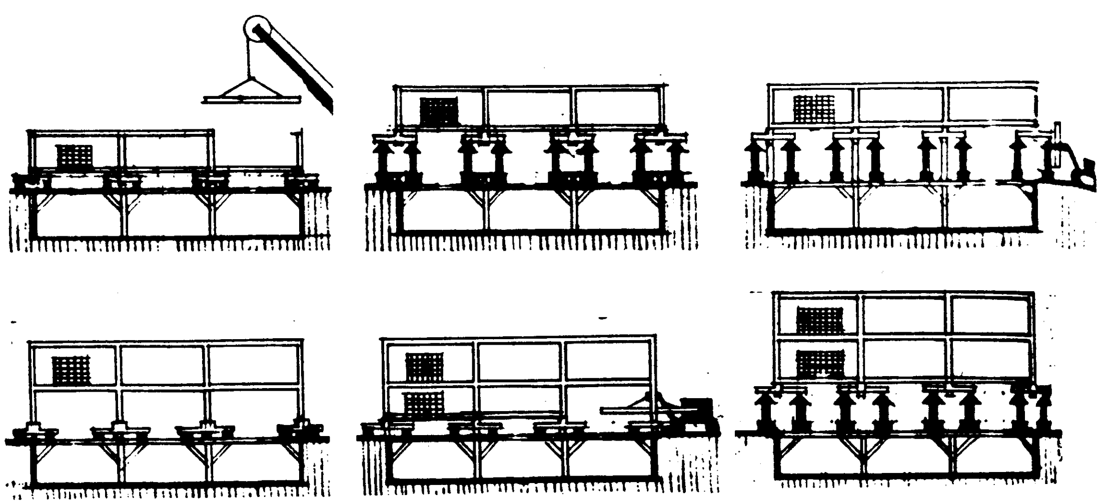
14



Every additional degree of freedom introduced in the structure allowing it to adopt a compact configuration for transportation, will have far more implications (in terms of the number of inputs required) if the structure is to be loaded under compression.

An alternative approach to the construction of structures subject to bending moments or compressive forces, is to assemble a mechanism from the components of the future structure at a convenient location in the construction site, from which it can then be launched to its permanent position, the advantage being that here no additional degrees of freedom will be required for transportation. Push-up methods used in the construction of medium and high rise buildings illustrates this latter approach (fig. 15), the mechanism is assembled within a narrow band near ground level from which the building is literally pumped up to its final position.

15



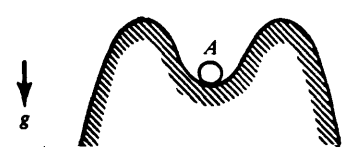
3 CONSOLIDATION

In the previous sections we modeled the construction process as a gradual and continuous reduction in the number of degrees of freedom inherent in the initially dismembered components of the future structure. We have also suggested that essentially there is but one degree of freedom separating the stages of erection and consolidation; ideally, the erection stage can be modeled as the process by which a constrained mechanism or unique path is built, with the expenditure of some energy the components of the future structure are then set in motion, and travel through the path so built to be positioned in what is to be their permanent configuration. Consolidation is the closing of this path, once the last resort for motion vanishes, a statically determined structure has consolidated. Consolidation can be brought about either by adding energy or links to a mechanism.

ENERGY

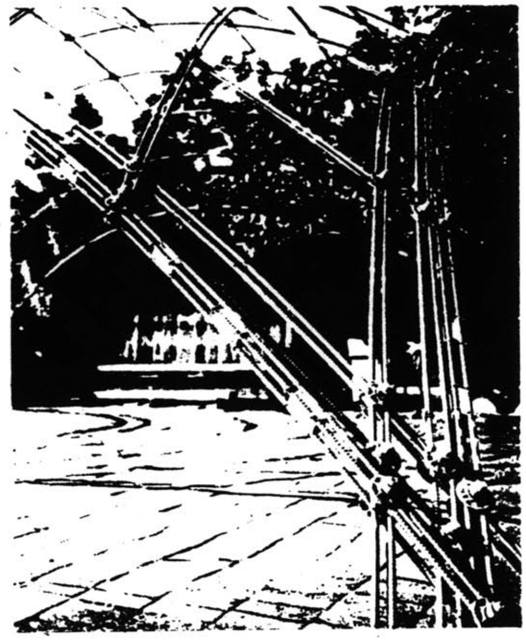
Consolidation by energy inputs can be modeled as the positioning of the mechanism in the bottom of an energy dish (fig. 16). Here the energy barrier must first be overwhelmed in order for motion to occur.

16



Consolidation by addition of energy can be a reversible process if for example the energy is stored in spring elements, or irreversible if some energy is dissipated. The simplest method of giving a lattice dome its final rigidity (fig. 17) illustrates energy inputs accompanied by energy loss through heat, since the bolts fix the joints of the dome by friction.

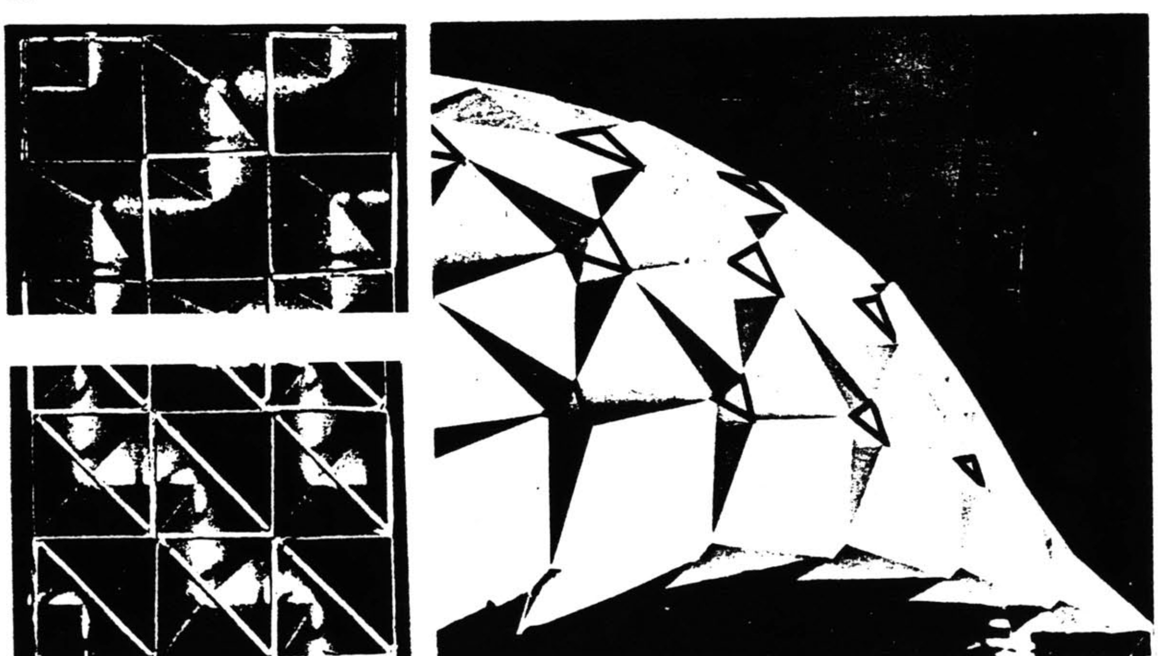
17



LINKS

Consolidation by addition of links to a mechanism is illustrated in fig. 18, here a complete set of constraining links is added to fix two kinematic folded plate systems in order to consolidate a spatial structure and a dome.

18



It is important to clarify that strictly speaking a structure is never entirely deprived of motion, all structures are in a perpetual state of oscillation, this is specially evident in the case of for example pneumatic structures which are constantly alternating free fall with up-lift motion. What is actually sought in consolidation is to reduce this motion to within certain narrow limits. In this sense, the ideas here presented must be considered but simplifications made in the pursuit of clarity.

PART III

"TOOL & WORK PIECE"

In Part II, we established the trade-off between the completeness of the hardware in a mechanism, and the number of external inputs required, the degrees of freedom in a mechanism formalized this relation, and its implications with respect to tension and compression structures were discussed. In this discussion, no effort was made to identify with a single entity the various external inputs, nor to disentangle what parts or portions of the mechanism belonged to the building agent, and how much of it, was due to the actual components of the future structure, that is, no explicit mention was made of what remains and what is removed once construction concludes.

The material presented here derives from a different partitioning of the construction process, not in terms of internal hardware and external inputs, but in terms of the entities involved: builder and building, and the degree and nature of their collaboration.

1 ORGANISMS, ARTIFACTS & MACHINES

2 SELF-ERECTING STRUCTURES

3 HYBRIDS

1 ORGANISMS, ARTIFACTS & MACHINES

ORGANISMS & ARTIFACTS

The building and the builder are not always clearly identifiable entities, the possibility of establishing such a separation will distinguish (in terms of construction) a building or an artifact from a living organism, this can be seen if we compare the construction process from which they arise.

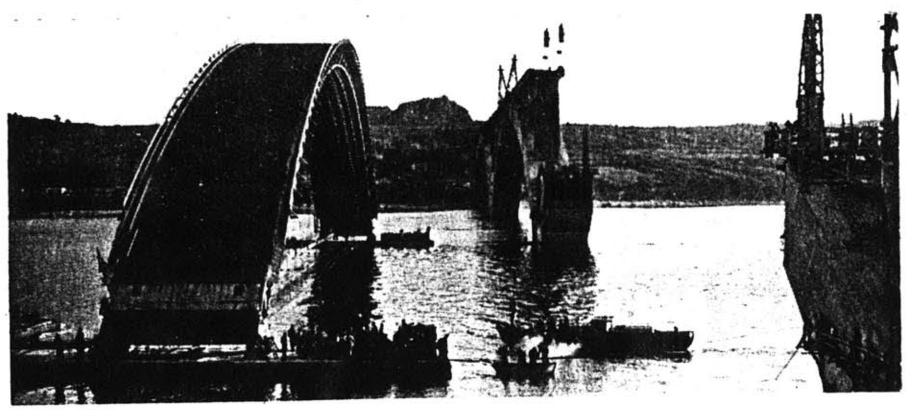
There are three major constructive processes involved in the progressive development of an organism: growth, morphogenetic movement and differentiation.

Growth involves an increase of living material, and by adding certain quantities of new material at specific places a new shape is created, to use an old analogy, it is like the art of the sculptor, and in this case the sculptor creates his statue solely by adding material. There are many instances among living things where masses of protoplasm move from one region to another during development, and by so doing mould the shape of the organism, this is called morphogenetic movement, the sculptor here starts with a block of soft clay, and by kneading and modeling it pushes the clay about to form the shape of his desires without ever adding any new material. The term differentiation is applied to qualitative differences between cells, tissues and organs, in terms of our analogy, the various regions of the statue would become transformed from clay into other materials of different chemical, composition.

Organisms then, have methods analogous to those used by man in the construction of buildings and artifacts, the only and fundamental difference, is that in organisms there is no sculptor, the cells themselves do the moving and like pygmalion they bring their Galatea to life (13). With organisms the builder is indistinguishable from the building itself, while with artifacts the builder is a separate entity external to it.

Clearly evident when construction is taking place (fig. 1), the externality of the builder will also be fingerprinted in the macroscopic structure of the finished product, since it results from the application of forces exterior to the object itself. Once complete this macroscopic structure attests, not to inner forces of cohesion between atoms and molecules constituting its material, but to the external forces that have shaped it.

1



The above applies whether the artifact is a paleolithic hatchet, a bridge, or a spacecraft, and whether it is built by man or by other living organisms, be it a honeycomb a beavers dam, and even horns and shells which though belonging to the living are in no sense alive, they are by products of the animal; they consist of formed material, their growth is not of their own doing, but comes of living cells beneath them or around, they accumulate rather than grow (24).

> "The structure of a living being, results from a totally different process, in that it owes almost nothing to the action of outside forces, but everything, from its overall shape down to its tiniest detail, to morphogenetic interactions within the object itself. It is thus a structure giving proof of an autonomous determinism: precise, rigorous, implying a virtually total "freedom" with respect to outside agents or conditions, which are capable, to be sure of impending this development, but not of governing or guiding it.
> The organism is a self constructing machine. Its macroscopic structure is not imposed upon it by outside forces. It shapes itself autonomously by dint of constructive internal interactions. spontaneous structuration ought rather to be considered a mechanism." (13)

MACHINES

Any artifact owes its macroscopic structure to the action of external forces, of tools which impose shape upon matter. It is the sculptor's chisel that elicits the form of aphrodite from the block of marble; as for the goddess herself, she was born of sea foam (13).

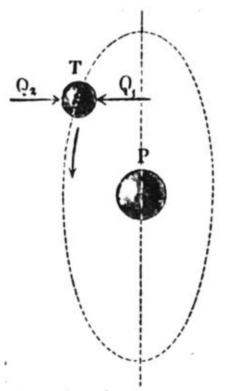
Since our main interest is not with the construction of living organisms, we leave for the moment the problem of spontaneous structuration (and the goddess rising from the sea foam), concentrating instead here and in the remainder of this section, on the relationship between the sculptor's chisel and the block of marble, or in more general terms the building machine and the work piece.

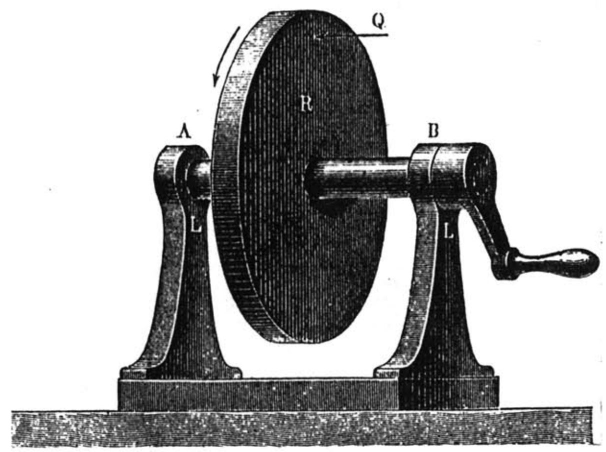
Reuleaux defines a machine as a combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motions (19).

The difference between a machine and any of the force and motion distributors of nature, lies in that in the latter the external measurable mechanical forces are opposed by similar external forces, while in the machine, there are opposed to all external forces others concealed in the interior of the bodies forming the system, and appearing there, and acting in exactly the required manner, in consequence of the action of the external forces. To illustrate this Reuleaux presents the following example:
Suppose that a satellite T (fig. 2) by whatever cause so moves about the planet P that it describes a circle about the center of P. So long as the conditions remain unaltered the motion continues the same, so soon as an external force Q begins to act on one side of T, T alters its path. In the machine the case is quite different, in order that points of the wheel R may move in circles let it be fixed upon a rigid shaft, if now the wheel be set in motion by some suitable handle, every point in it beyond its axis describes a circle. If any disturbing force act sideways upon the wheel no alteration of the circular motion occurs.

With the wheel the action of the forces is exactly the same as with the case of the satellite, however with the satellite, all external forces are independent of each other, while with the wheel, the action of an external force becomes at once the cause of the opposite action of a molecular force.

2





A machine is but a special purpose mechanism, it is built to do work on something, evidently the work piece, in this sense it is sometimes defined as that which connects the source of energy with the work done.

FORM & PLACE CHANGING MACHINES

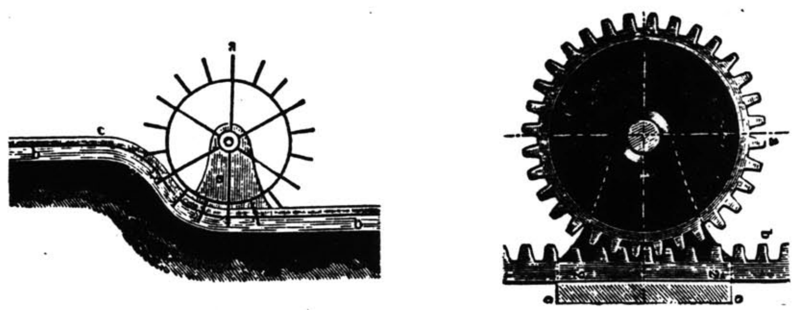
Machines can be divided in two great classes according to the purpose for which they are used, namely, form and place changing machines.

In form changing machines motion is used to alter the shape of the work piece, in place changing machines to alter its position. The nature of both alterations being fixed by the form of the chain, both result in the motion of bodies in given paths, and the alteration perhaps simultaneous of their shape, both being forms in which the machine has compelled the natural forces to do work.

A characteristic of form changing machines, is that always a kinematic pair is established between the "tool" (a part of the machine) and the work piece, which also becomes a kinematic link in the chain. The tool changes the original form of the work piece into that of the envelope corresponding to the motion in the pair employed. A kinematic chain is then not broken at the tool or the working point, but continues through it, it is not the end of the chain, but only a point in it having special importance with respect to the object of the machine.

Besides the tool, other parts of a machine having special importance like the receiver or the transmitter of energy are also kinematically indistinguishable from any other link in the chain. Taking the water wheel for instance (fig. 3), its buckets are kinematically paired with the water, and this again with its canal, or when a living mechanism is chained to a machine (like when a workman applying both hands to turn a crank chains in a very complex manner his limbs to that of the mechanism). In both these cases, wherever we decide to draw the line, the receptor is unquestionably a link in the kinematic chain.

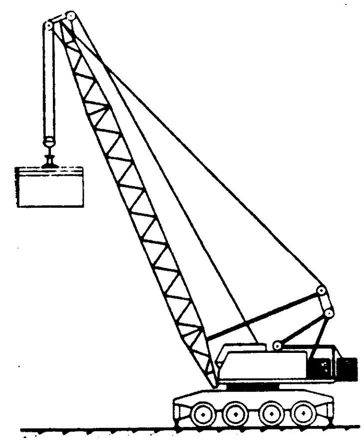
3



The form changing action which occurs between the tool and the work piece then, differs in degree and not in kind from the action taking place between the elements of every other pair in the machine. The coupling tool work piece, characteristic of form changing machines will be further discussed in the section on "Hybrid" construction methods.

With place changing machines the kinematic coupling machine work piece is not characteristic. The action of a simple crane (fig. 4), is a good example of a place changing machine which does work basically on the mass of the cargo, the shape of which is but of little importance.

4



Like with form changing machines, it is possible to have incomplete place changing machines kinematically paired with the cargo, and requiring it, as the closing link of an otherwise open chain. Place changing machines can also do work on the mass of their own components, these form the subject of the following section on "Self Erecting Structures".

2 SELF-ERECTING STRUCTURES

NATURE

A self-erecting structure can be characterized as a place changing machine, built to do work on the mass of its own components changing their relative position, here, as with the construction of living organisms we have difficulties identifying the machine from the work piece, and hence, self-erecting structures seem possessed of certain animistic qualities. There is, nevertheless a fundamental difference: while in a self-erecting structure the predetermined expanded structure is brought about by the hardware inherent in the initial form, in organisms

> "No performed and complete structure preexisted anywhere; but the architectural plan for it was present in its very constituents. It can therefore come into being spontaneously and autonomously, without outside help and without the injection of additional information. The necessary information was present, but unexpressed in the constituents. The epigenetic building of a structure is not a creation; it is a revelation.
>
> At each stage more highly ordered structures and new functions appear which, resulting from spontaneous interactions between products of the preceding stages, reveal successively, like a blossoming firework, the latent potentialities of previous levels". (13)

TWO STATE MECHANISM

The mechanism of a self-erecting structure is generally conceived having in mind two states: in one the mechanism adopts a compact configuration, in the other it attains a stable expanded one. A self-erecting structure changes its attitude or position (like the spiral coil of the elephants trunk or the chamaleon's tail) rather than its form, and because it is erected by simply driving the mechanism through a half cycle defined by its two limiting states, we speak here of deployment rather than construction.

The capability of the mechanism to adopt a compact configuration is generally used to allow for easy of transportation. When the mechanism is built at the construction site its compact configuration is used in order to concentrate the construction activity at a single convenient location.

CONNECTION TO THE SITE

We can classify self-erecting structures according to whether or not all of its links move during deployment, that is, if there is a kinematic pairing or a fixed connection to the site.

The mechanism developed by Emilio Perez Pineiro fig. I-14, partly reproduced in fig. 5, is kinematically paired to the terrain by a set of rollers, here all the links move during deployment.

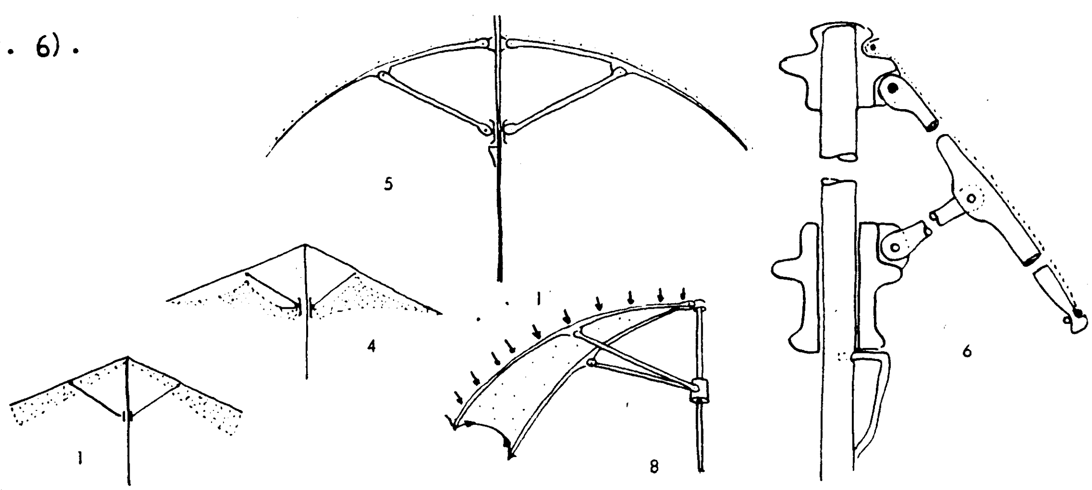
5

While rolling on a plane surface is the most common type of kinematic connection to the site, it is also possible to incorporate the irregularities of the terrain (like a hill or a valley) in the mechanism, the self-erecting structure would then become simpler and in itself incomplete, since the site would provide the completing or closing links.

To illustrate a fix connection to the site, we use here the mechanism of the common umbrella, its simple and precise can be considered the archetype of self-erecting structures, since it is beyond doubt the most successful of its kind.

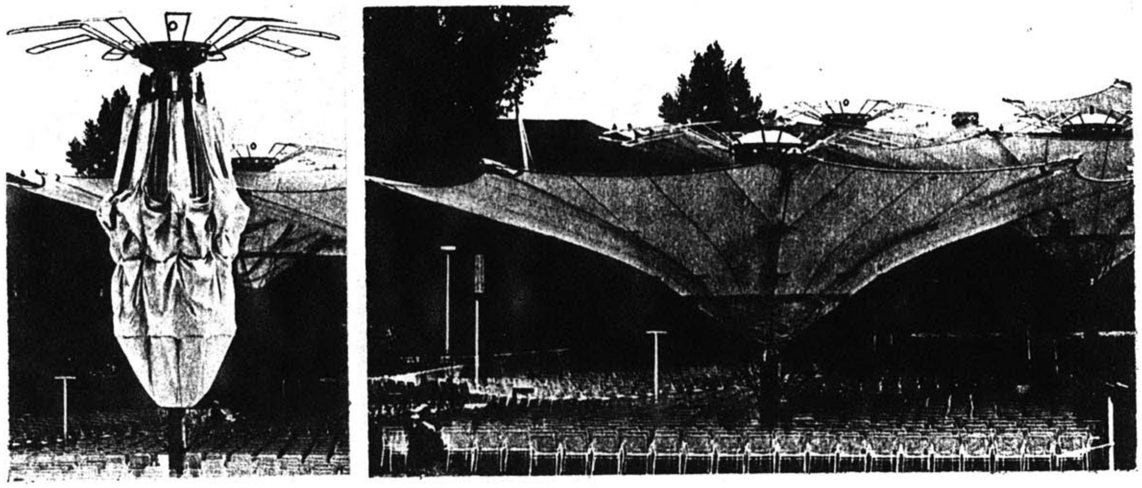
In all its many varieties whether covered with paper or cloth, the supporting membrane, the ribs, the rods and the middle pole form a structural unity. An umbrella frame consists of: rigid ribs between which the membrane is attached, rods which support the ribs against the middle pole and a sliding ring which guides the rods up and down along the middle pole. The membrane can hang freely between the roof ribs or be attached below the frame, in the most common umbrellas the membrane is attached to the roof ribs and is evenly tensioned during deployment (fig. 6).

6



Successful as the umbrella mechanism might be, it is generally economically feasible in spans of up to 25 m., due largely to the strong forces in the cantilever arm; fig. 7 shows 17 m. diameter inverted umbrellas used in the National Garden Show, Cologne, West Germany.

7

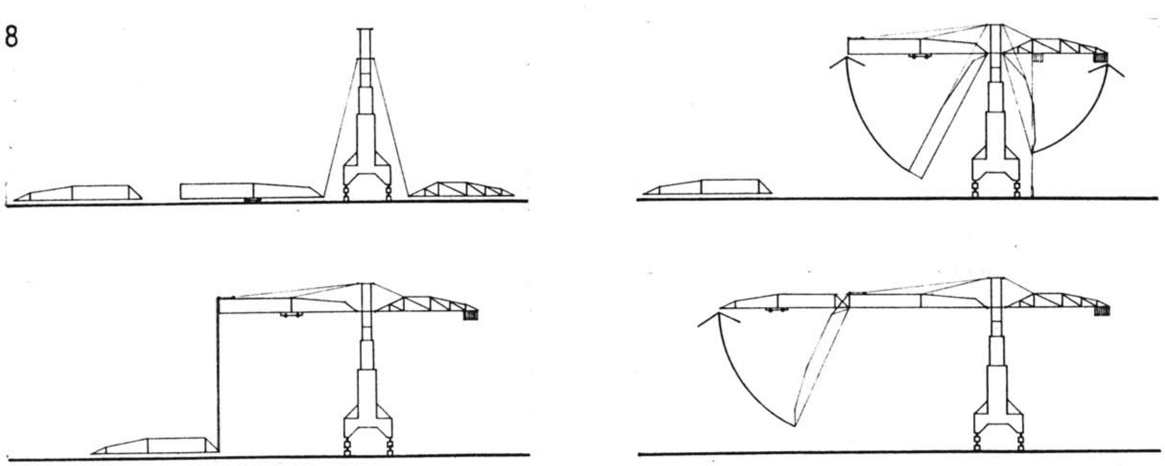


ENERGY

The power source which delivers the energy required to deploy the mechanism can be in motion (common umbrella) or stationary.

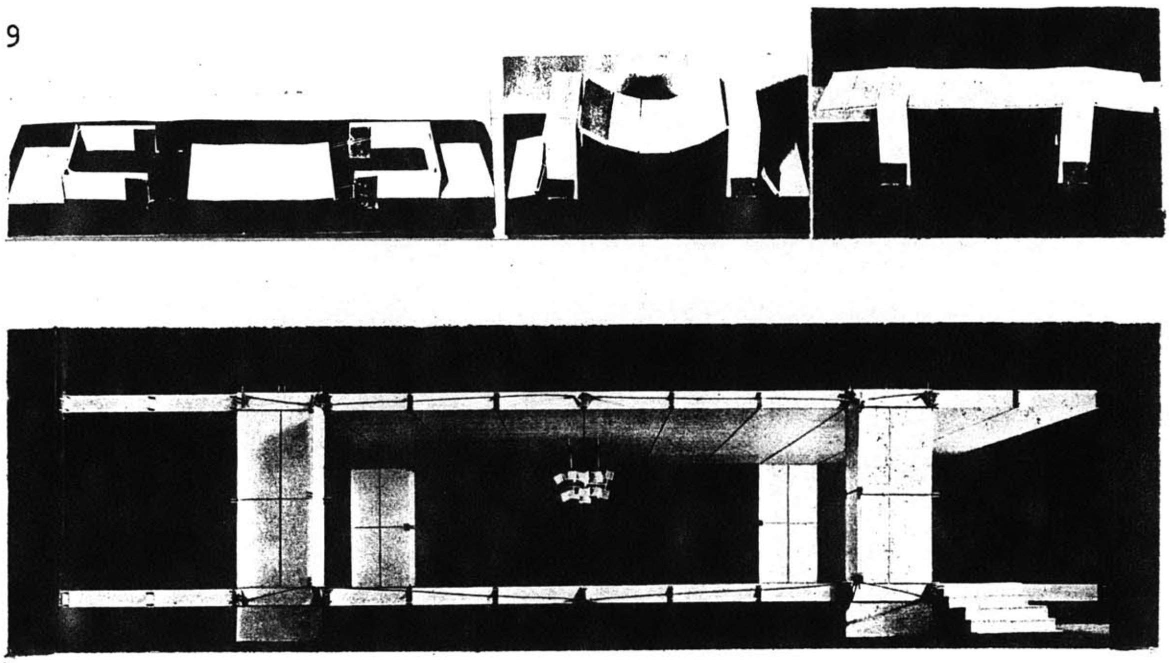
When the source is stationary, power is generally transmitted through a system of pulleys, rings or slides which in themselves possess no driving power, like in the partial self erecting sequence of a Richier tower crane (fig. 8).

8



The student project at the University of Virginia (fig. 9a), shows another self-erecting structure which uses cables threaded through the units when laid out flat, the ends of the cables pass beneath the supporting positions, when the strands are pulled the entire structure follows a predetermined erection sequence resulting in a post-tension system. Making use of a similar principle a full scale model was developed by a group of students at the International Student Academy, Salzburg, '58, and is shown in fig. 9b.

9

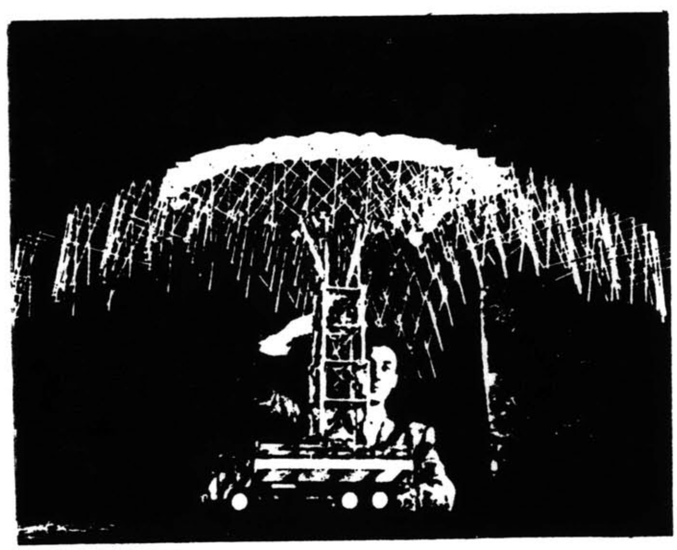


The transmission of energy through large portions of the mechanism can be avoided if the medium surrounding it, is used instead as the vehicle for energy transport. Analogous to certain motions occurring in plants, the response of a mechanism here can be characterized either as a "tropism" or an "isotropism".

A tropism is the bending or turning of a plant or one of its parts in response to directional stimulus; for example, if we apply heat on one side of a steel bar it will always bend away from the heat source, and hence can be called a tropism. If on the other hand heat is applied uniformly on a "shape memory alloy" (shape memory alloys are nickel titanium alloys that are capable of returning to their original shape no matter how they are distorted or bent(15)), we would have the phenomenon of isotropism.

The use of multiple energy sources is an alternative to either power transmission through the mechanism or through its surroundings. Self-erecting masts and antennas which use springs for deployment have been developed by companies as Astro Research, General Electric and General Dynamics. Instead of multiple elastic energy sources, it is possible to deploy a mechanism by means of the potential energy stored throughout the mass of the mechanism by virtue of its relative position. The scissor lattice dome (fig. 10), developed by Emilio Perez Pineiro illustrates this; here the lattice acquires potential energy as it is lifted by the telescopic mast, this energy is then used in its deployment, like a cascade the lattice expands as it drops.

10



TEMPLATES & DELIVERY SYSTEMS

A self-erecting structure, is much more than a simple structure. While a structure is generally conceived having only one configuration in mind, (very much like the fancier who does not care how the chicks look while embryos and during growth, as long as they acquire the proper form at maturity) self-erecting structures must satisfy a continuum of states, and all the necessary hardware must be present, fully pact in the initial form.

The added cost of a self-erecting structure must then be amortize by repetitive use or cyclical deployment. Only but the most ephemeral of structures, or under the most extreme circumstances (when for example speed of erection is essential, or when field equipment is unavailable), can we expect to obtain a return on the investment through a single deployment.

Temporary and emergency shelters are the most widely spread application of self-erecting structures, however it is also possible to use them as pieces of equipment in the construction of permanent structures, either as "templates", or as specialized cranes or "delivery systems" which could simultaneously put in place a complex configuration from numerous building components.

The rubber mould (fig. 11) used by Eliot Noyes and Associates in the construction of a reinforced concrete shell illustrates an application of self-erecting structures as templates. Since we have no example of a self-erecting structure used like a specialized crane, we instead discuss briefly some of the implications of this idea.

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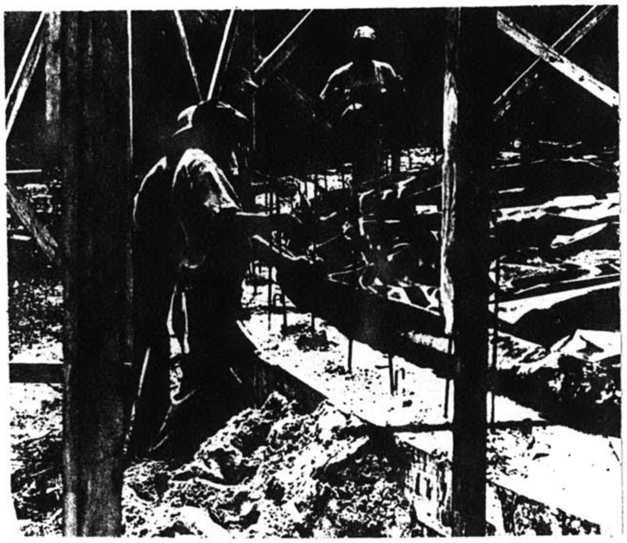
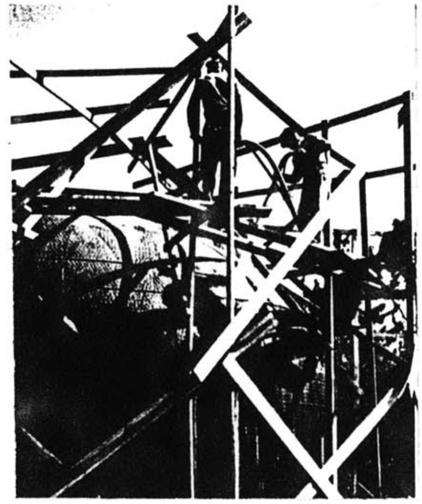
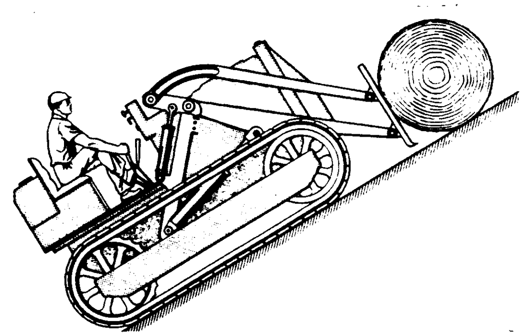




With traditional methods of construction, very complex buildings can be erected from a dismembered bundle of material with the use of rather few and simple tools. This is possible, because construction is carried out a step at a time; tools are arranged in order to perform the necessary work, then are disengaged and rearranged for the next operation, and so on and so forth. The provision of a sequence of instructions plus an interpreter that can translate these into hardware is then a substitute for more complex machinery. If instead of simple tools we use a single but sophisticated piece of equipment, like a self-erecting structure, the same building could be erected with no interpreter and no sequence of instructions, since the delivery system would have integrated them in its hardware.

The same amount of work would have been done on the building, whether simple tools or a complex delivery system is used, however with the former additional energy is required in order to operate the interpreter. In fig. 12 we model this idea; here, the circular mass represents the material or building components which must be lifted and placed during erection, the slope of the inclined plane is analogous to the amount of equipment simultaneously in use, while the energy required to operate the interpreter would here be proportional to the energy lost by friction. Using this model a self-erecting structure would be very close to the vertical plane.

12



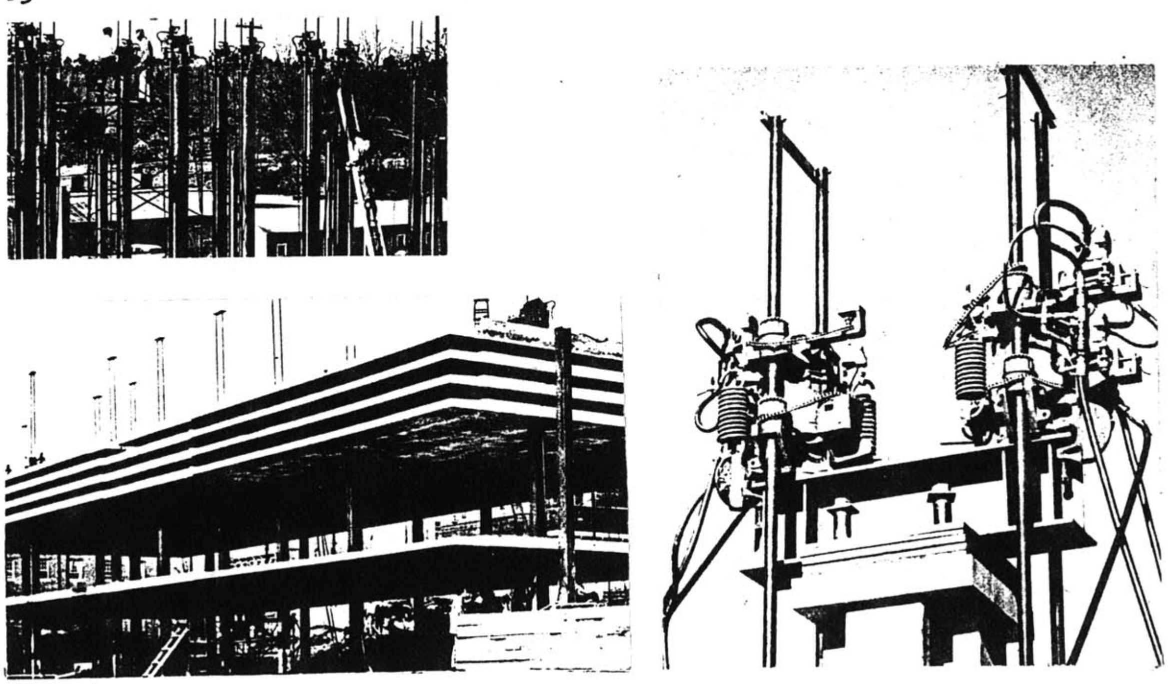
Evidently, though more energy consuming, construction with simple tools has the advantage of greater flexibility, indeed a basically infinite variety of artifacts can be derived from them, as the equipment becomes more specialized this flexibility is gradually lost. The feasibility of using a self-erecting structure as a delivery system in construction, will then, to a large extent depend on the identification of those structures or portions of them which are repetitive and in constant demand.

3 HYBRIDS

In this section we discuss and illustrate construction methods which involve a kinematic coupling between the building agent, and that which is being built.

We are here not interested in identifying or discussing mechanismal qualities in the work piece itself, these we believe are better treated in the context of self-erecting structures; for instance, in the push-slab method (fig. 13), the elements of the building are kinematically paired to each other but no such coupling exists between these and the lifting devices, in other words, erection does not result from any definite motion at their interface. Our concern here is precisely with construction methods which involve a kinematic interface or coupling between the machine and the work piece, for this reason methods such as push-slab will not be here discussed.

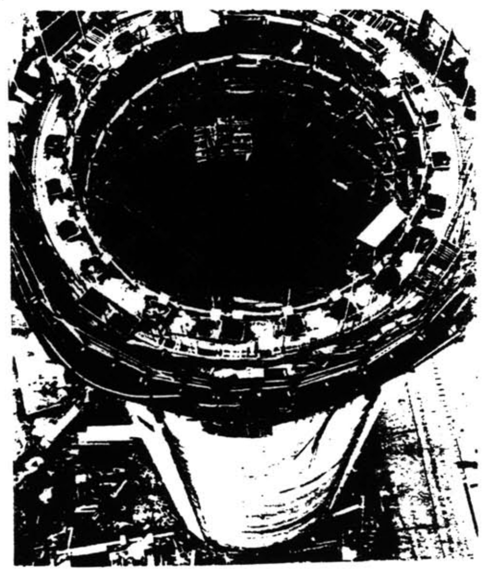
13



CLOSED PAIRS

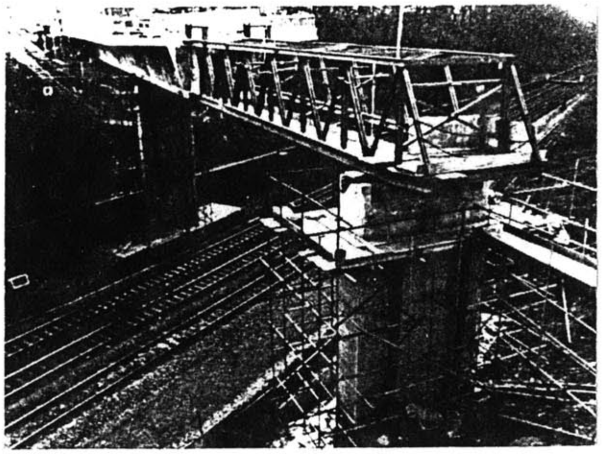
Since the kinematic coupling tool work piece is a characteristic of form changing machines, it seems only natural to begin our discussion with slip form construction given its similarity to an extrusion process (fig. 14). Here plastic concrete is placed or pumped into the forms which act as continuously moving dies to shape the concrete. The rate of movement of the forms is regulated so that the forms leave the concrete after it is strong enough to retain its shape while supporting its own weight, and move along the structure to the next section to be concreted, working deck, concrete supply hoppers and finishers platforms or scaffolding are attached to and carried by the moving formwork.

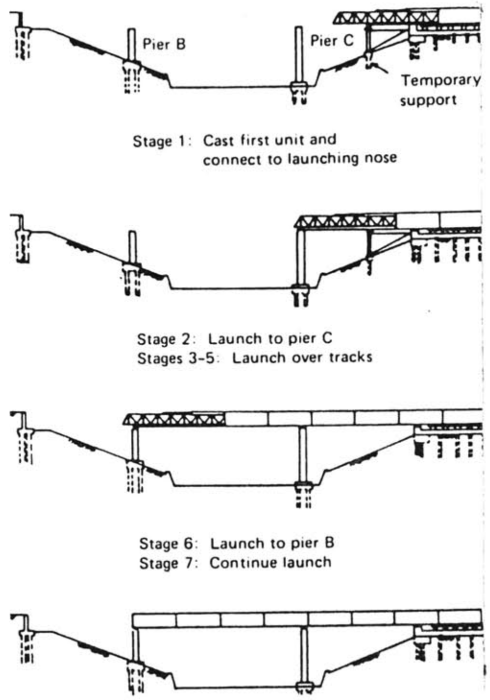
14



When slip forms are used, construction activity takes place at localized regions similar to plant development where growth is located in regions called meristems. Generally the most active meristematic regions in plants are the apex and the shoot areas; the construction of the silo in fig. 14 is analogous to apex growth, while the launching sequence of the Shepherds House Bridge (fig. 15), is similar to shoot growth.

15





A leaf of grass grows from meristematic activity at the shoot, in this case the growing leaf is enclosed within a sleeve of a more mature and rigid leaf, its purpose being not only to form, but also to protect the yet tender material of the new leaf, which otherwise would collapse under the strong bending moments at its base. Stresses derived from localized growth are not only felt at or near the area of activity but throughout the piece, sometimes becoming critical at the opposite end of the line; for instance, in fig. 15, a launching nose made out of steel trusses is attached to the end diaphragm of the concrete bridge, in order to minimize the large cantilever moments in the front part of the structure being launched from pier to pier.

Returning from this digression into the structural implications of growth, slip forming and incremental launching can be modeled from the point of view of kinematics as consisting of a single closed lower pair, one of its elements belonging to the tool, the other provided by the work piece. A lower pair (Part I), limits the relative motion of its elements to basically: rotation, translation and helicoidal motion. Hence, the possible forms derived from these are rather simple and few, since they are restricted to a constancy of curvature (fig. 16). The question of shoot and apex growth or location of construction activity, can be explained in terms of the inversion of the pair: if the tool is fixed we have shoot activity, and if the work piece is fixed construction takes place at the apex.

16

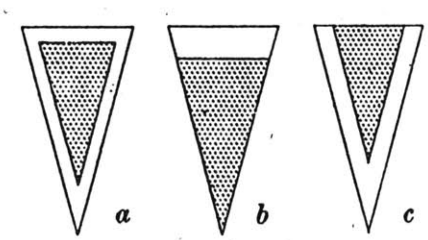
OPEN PAIRS

More complex forms can be obtained with open lower pairs, here the tool or builder has surface contact with the work piece but there is no surface enclosure. Many living organisms which experience but little morphogenetic development (no change of form), are in this way coupled to their constructions (like the nautilus shell), the forms derived from these pairs are subject to a constancy in the change of curvature, and the material added is sometimes referred to as a "gnomon" (fig. 17):

> "There are certain things, says Aristotle, which suffer
> no alteration save of magnitude when they grow. Thus if

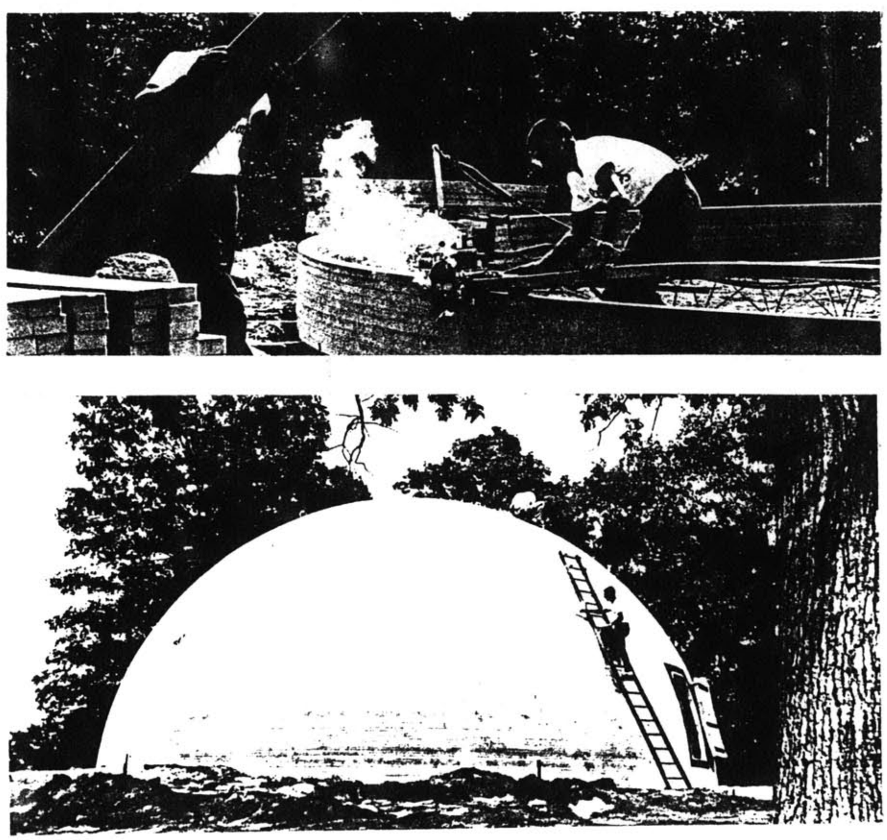
we add to a square an L-shaped portion, shaped like a carpenter's square, the resulting figure is still a square. The portion which we have so added, with this singular result, is called in Greek a "gnomon"". (24)

17



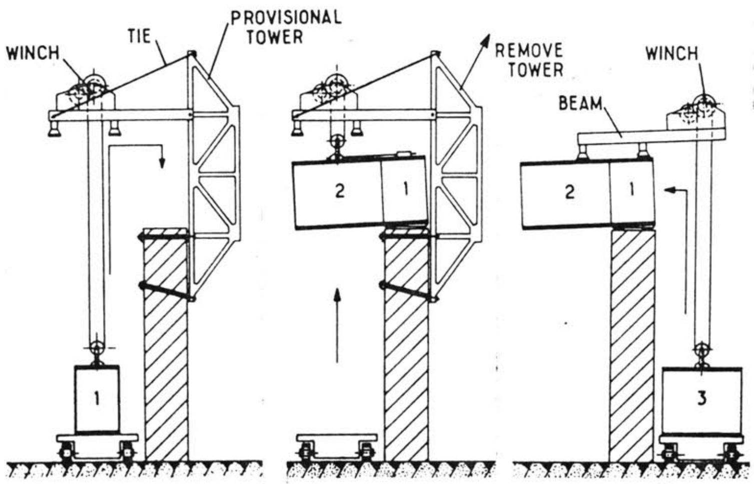
The method for the construction of shells out of polystyrene blocks (fig.18), developed by Prof. Paraskevopoulos at the University of Michigan, shows a form derived from the constantly changing curvature of the pair formed by the laying machine and the strips of material already installed.

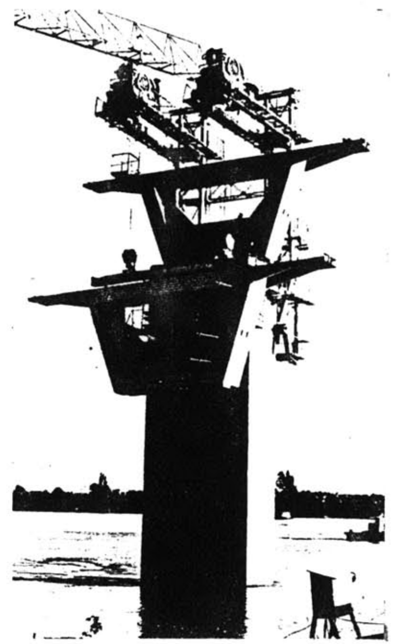
18



As the form of the building grows in complexity, the equipment if it is to be continuously paired to it, will correspondingly increase in versatility and sophistication; some recent improvements in erecting equipment, combine the capabilities of travellers and climbers, and are equipped to perform 90' turns, the beam and winch method used in the placing of the precast segments for the Saint Andr'e Cubzac Bridge (fig. 19) illustrates this.

19





As the form becomes less ruled or more complex, the coupling tool work piece tends to go from closed to open and from lower to higher pairs, increasing the number of external inputs or on-site operations required to close the chain and produce the required motion.

CONCLUSION

Using the carcass of a building or its components as part of the erecting equipment, be it a single element of a kinematic pair, or a complete self-erecting structure, implies a shift in the allocation of resources, and a shift in the approach to design.

The shift in allocation of resources, amounts to their transfer from on-site equipment and labor, to the permanent elements of a building, which would have integrated them. The consequent increase in the cost of the components stems on the one hand from the higher cost of development, and on the other, from the added cost of material and hardware.

In terms of engineering much more will be required because of the greater sophistication of the building as well as the more controlled method of construction. While the necessary know-how exists, it is however dispersed in a variety of fields, and their assimilation under a single concerted effort, will evidently require more time and money than would be necessary to develop more conventional methods of construction.

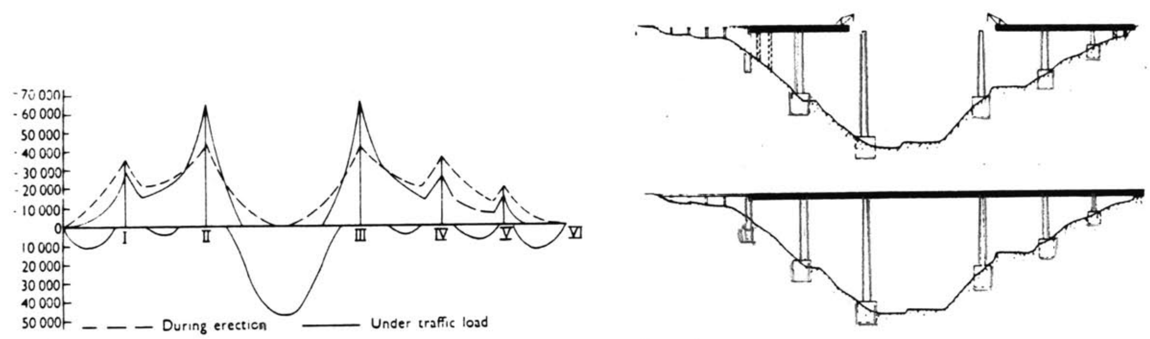
For instance, In the field of convertible roofs which partakes of many of the technical problems posed here, only very few construction systems over large spans have been developed to the point where they could be realized, developmental times in this field are still very long, the know-how from crane construction, control technology and lift mechanism construction, is but gradually being incorporated to the design of movable membranes (which is probably the most difficult field in light weight construction), to the extent that ten years of preparation were necessary to develop the basically new system of centrally bunched membrane construction (fig. II-10).

Besides the added cost of development, an increase in the cost of the material and hardware of the components almost inevitably follows from their wider performance range, not only must they satisfy a single set of requirements as part of a complete structure but a whole spectrum of circumstances taking place during construction, and in which they would actively be involved.

Structural implications are probably the most important single consideration in terms of the added cost of material, since the components of the building will be subjected during construction to loading conditions very different to the loads they would experience as a part of the finished structure.

Always, it is essential to ensure that the components of the incomplete structure will be strong enough to bear all the loads acting upon them throughout the intermediate stages of construction, this is true no matter what construction method is employed, but very special attention must be given to those units which must be hoisted, jacked, or if themselves are to serve as transport vehicle for other components and equipment.

In the lift-slab method for instance, the inertial bending stresses due to the jacking-up of the slabs could easily exceed the stresses expected after construction is completed, hence, additional reinforcement must be provided which otherwise would be superfluous under the final loading conditions. Another example of erection loads controlling the dimensioning of the structural components is shown in the next figure, where the erection procedure of the Sill bridge is shown as well as the moment curves during erection and under traffic load.



A problem resulting from this integration of several functions in a single building component, is that full optimization is generally not possible, although the value of having such integrated functions may well be worth the disadvantages incurred in not having optimized specialized facilities.

Evidently the added cost of the components must be balanced against the savings in on-site equipment and labour, however, the transfer of costs brought about by the transfer of constructive functions to the building components, will also have a wider and more difficult to asses impact on the organization of the construction firm, and the composition of the labour force, since a much higher percentage of construction workers would then be involved in manufacturing operations; in the case of self-erecting buildings a couple of men operating field machines one or two days is all that would be needed to erect a building now taking thousands of man hours, the bulk of the work being done at the factory.

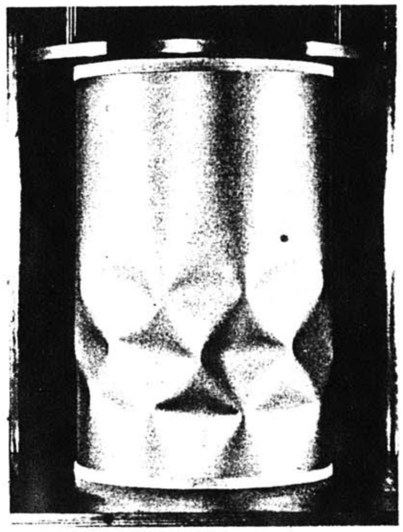
The realization that the structure of a building can arise from the freezing of a sequence of motions, and not as usual from a single apparently spontaneous event, presupposes doing away with a baggage of preconceptions, and an altogether different approach to design.

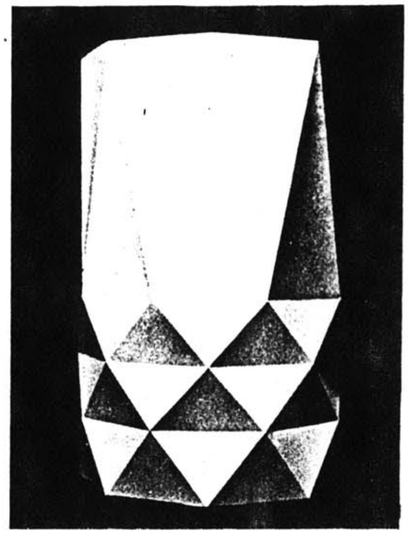
If the design effort is to be at all successful in this endeavour, it must take of from the dynamics of the construction process and not from the predetermined forms and structures conventionally conceived as static spontaneous events.

Preconceptions are sometimes so deeply rooted that they are almost indistinguishable from the very act of construction; like the post and beam method put together precisely in this order, first the post then the beam, it took thousands of years for man to realize that he could first install the beam and only later the column, and now many buildings are in this top-down order built.

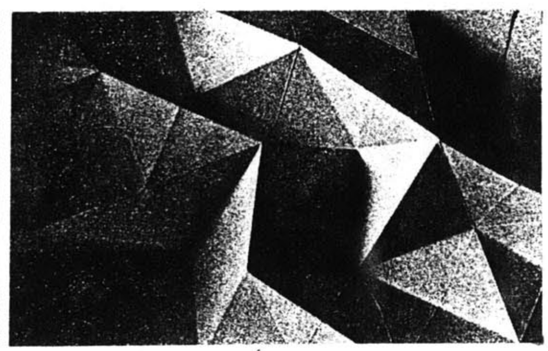
It is a principle, that architecture must be in accord with the order of construction, and if a new idea is to see the light, another one will become a memory. Stone columns of ancient Egypt were decorated to imitate their wood ancestors , the memory of a lost forest was frozen in a layer of stone, but had no place whatsoever in stone construction.

New ideas are not necessarily conceived as a logical conclusion of a certain rational analysis. A fresh new approach is brought about in many instances by an awareness to, and observation of previously disregarded phenomena; K. Miura (38) mentions that his discoveries of folded plate shells came from an accidental or chance recognition of an analogy between the folding pattern of a paper cylinder, and the post-buckling wrinkles of a very thin cylinder subject to axial loading.





In another instance also from the field of kinematic folded plate systems, R. Resch (38) notes that a main source of inspiration in his research derived from the study of the random folding pattern of a simple wadded up piece of paper, the kind people usually discard.



The incorporation of the building components to the construction mechanisms, also has implications in terms of the external aspect of a building, the added information that the traits of the process would convey, could considerably enhance the expressive possibilities of the final configuration, revealing (if not concealed) not only the nature of its static equilibrium, but also the fingerprint of the motion by which it was generated.

The intention of this work was to present a conceptual framework, to convey an approach to construction. It is hoped that like the splinter of an iceberg the material here discussed can hint at a vast area of largely unknown potential:

> "To travel deliberately in the right direction is possible only to those who see and are within the boundaries of what is known and understood.
> New roads into the unknown are the prerequisite for extending the boundaries of knowledge.
> Such roads cannot in themselves always be the right ones. Progress without mistakes is extremely rare, an exception, like an absolutely correct prediction.
> Scientific work in new territory calls for courage coupled with a sense of responsibility the courage to dare to make mistakes, the constant verification of practicability, and the ever watchful readiness to apply corrections, which relate not only to the direction of progress but also to the appraisal, from the newly gained vantage point, of what has already been attained."(21)

To recognize the possibility of literally weaving or threading a building or letting it free fall into place like a cascade, whether it is implemented or not, we believe changes the perspective from which new territory can be devised in the every day.

LIST OF ILLUSTRATIONS

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