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Structure in Architectural Design

by

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"SHOW ME YOUR ART
AND I WILL
SHOW YOU YOUR SCIENCE"*

St. James

*W. R. Lethaby, Form in Civilization, p. 123.
It is the opinion of the author, that architecture today is schismatic in its expression and in the manner in which we view it. The predominating opposing factions are "structure" in the engineers' sense of the term and "esthetics and design" in the artists' and architects' applications of the terms. The thesis maintained herein is, that "structure" and "design" being part of the same thing, architecture, are necessarily related, and as such, their simultaneous consideration should be reflected in the final product. The following dissertation attempts, primarily through the use of examples and the extraction of principles, to illustrate how the consideration of "structure and design" is or can be so reflected as an integrated entity in architecture.
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THE PROBLEM
The Beauty of the Past

The remains of the Parthenon stand today as an example of a historical masterpiece in architecture. For generations scholars have marvelled at her refined proportions; have measured and remeasured her; and have formulated and advanced theories in an effort to discover the secrets of her "beauty." The classic beauty that this "objet d'art" symbolizes has been little short of gigantic in its influence throughout history. This influence had its manifestations in the Roman era, in turn, the period of the Renaissance, and planted itself, no less firmly, as late as the end of the 19th century in this country. The impact of the Parthenon's mode of beauty is clearly visible even today, particularly in many of our governmental edifices and public buildings.

Yet, the architectural practitioners of the present generation would think of no more proposing a "Parthenon" than they would an Egyptian pyramid. Such a building is simply out of place with our present day society! Why? Has the appearance of this structure undergone some mysterious change within the confines of the history text, or is it that we are just less concerned today with proportion and esthetics in general? Obviously, both points are unsound. A change has taken place however, not in the object viewed, but in its judges and the basis by which they judge. Let
us say that the scale of human values has imposed new esthetic criteria. It is the firm belief of the writer that the rapid advancement of technology has been among the principal causes in shifting the scale of values in architecture.

These rapid technological advancements figuratively pulled the pins out from under the classic esthetes. Hand in hand with technological progress came new expressions in art. The Cubism of the Picassos; the Purism of Ozenfants and Le Corbusiers; the Neo-plasticism of the Van Doesburgs and Mondrians; all caused the architect to take stock of his position. The sensitivity of these movements to their ecology provided architecture with a badly needed stimulus. Not only was there a direct influence in building design, but also a restatement and clarification of the basics of design in art. Lines, planes, colors, textures, space and other elements were discussed in reference to position, measurement, transition, and in reference to the resultant attributes of rhythm, harmony, proportion, balance, etc. In short, the "abstract" or "non-objective" quality of the new art forms reawakened consideration of the basic components of art in terms of the elements, principles, and attributes of design.

Though the imagination becomes a source of infinite and
Many similarities can be found in these buildings so long as discussion is confined to the aesthetic measuring criteria such as proportion, line, mass, etc. In other words there exists the common ground of elements, principles, and attributes of design. Both these buildings may be beautiful in their own right in terms of these criteria. But obviously, both buildings are so different that they appear incongruous on the same page. They are separated by time and ecology and the technology & the change in values that they imply.
Measuring Criteria in Design

differing combinations and relationships of the basic design components just stated, these components in themselves remain relatively stable throughout the passage of time; i.e., the concepts of line, space, harmony, proportion, etc. are constant measuring criteria even though their relationships differ. The components form the common ground on which Parthenon and Saarinen's M.I.T. auditorium may meet and be called beautiful in the same breath ..., and herein lies the danger in modern architecture! We may be stimulated by the beauty of both structures, yet obviously they differ radically. It is when the factors of time and ecology enter into consideration that the mutual relationship is decidedly severed.

Technology as an Additional Unit of Design

Commensurate and analogous to the connotations of time and ecology is the idea of the dynamic in present day technology. The implied inter-relationship is a complex one, and though important, is not directly relevant to the purpose of this text. Suffice it to say, that the idea of science or technology imposes considerations above and beyond the basic design components described. The "danger in modern architecture" implied a moment ago refers to the misapprehension of considering design in architecture, with due respect to the purpose of the building, important merely as a pleasant relationship of the aforementioned elements,
principles, and attributes of design. If we fail to recognize or attempt to de-emphasize the technological separation between past and present in our meaning of design we become invariably guilty of conceiving contemporary Parthenons; contemporary in the sense that the conceptions are formulated in the present day; Parthenonic in the sense that the major value as an architectural work is a visual relationship.

The danger is further magnified when interpretations of artists such as Mondrian are treated as entities in architectural design. The artistic conceptions in themselves are products of their time and as such are not necessarily permanent as units of measure in architectural design. It appears sounder then, to attempt to investigate the causes of a work of art, rather than to accept the developed result as an entity in establishing esthetic criteria. Investigations of such a nature will generally reveal the keen awareness of the artist to his environment and the influence of technology upon it. In any case, esthetics in architecture cannot be irrespective to the momentousness of our technology as another motivating factor in good design.

An exact measure of the degree to which technology shapes our thinking and feeling is difficult to define. It is axiomatic, however, that the physical execution of an
the influence of contemporary painters

Contemporary painters have helped to clarify the measuring criteria in "esthetic" design in terms of line, plane, color, proportion, etc. However, literal interpretations of painter's works do not necessarily mean good design in architecture. Further investigation into painting will generally reveal an artist's awareness of his time and ecology. We can profit more through attempting to understand what the artist is trying to do.

The Memorial in the Milan Cemetery (right) by architects Rogers, Peresutti, and Belgioioso reflects the strong influence of the painter, Mondrian.
idea can be no less intuitive, original, or imaginative than the works and forms permitted by modern technique. Consequently, the designer's product is generally shaped by the prevailing level of technology. Eero Saarinen, for example, did not invent reinforced concrete or shell construction. But, familiarity with these processes inspired his M.I.T. Auditorium. On the other hand, the technical basis itself would not have produced this structure. To a new rationalization of a specific problem, Saarinen added the architect's sense of the esthetic to produce something more than just a functional building.1

Moholy-Nagy implies a similar train of thought in his famous comparison of the wooden and plastic handles.2 A wooden handle, generally cylindrical in shape, is expressive of the process of machine lathe production. Whereas, the plastic handle was so formed as to provide recessions which would comfortably receive the contour of the fingers and palm of the hand. A simple conception such as this, illustrates the designer's sensitivity to the nature of the material he is employing. The idea that the plastic can be

2Lisslo Moholy-Nagy, Vision in Motion, p. 35.
easily molded to any desired shape is clearly conveyed in
the final product. Certainly, the plastic could have been
molded to imitate the easily formed wooden handle. But, the
designer's awareness of the problem, his intuitive feeling,
and a technological process enabled him to produce a much
more efficient form and one as readily pleasant to the
senses.

A meaning of design which does not consider the material
of which it is to be shaped, or the process that shapes it,
becomes near fantasy in architecture. Often, the accusation
is made, that acquisition and concern of technical skills im¬
pedes the "imaginative" powers of the designer. Though it
may be possible to "imagine and create" on but a thread of
material reality, this writer violently disagrees with any
opinion which infers that knowledge of technique or skills
decreases the expressive powers of the individual. On the
contrary, the increase of such knowledge may act as a more
purposeful stimulus, in which the conceived form takes ad¬
vantage of the natural assets of the material and the proc¬
esses that shape it.

The advancement and importance of technology is a factor
of such magnitude that architecture can no longer be impar¬
tially defined as just a fine art. It is also a science of
building! The problem in architecture arises when we treat
the art of building, and the science of building, as having individual essence, when in reality they are opposite sides of the same looking glass. We cannot talk about building and then in the same breath sever the product as science or art. As far as architecture is concerned, there is a marriage between art and science in which neither partner can achieve independence. "The best art is founded on the best science in every given matter."¹

Danger of Dual Standards

Should we elect to disrupt the art-science relationship, art, in the sense of physical manifestations of the esthetic, becomes the work of the "artist"; technology by itself, the work of the scientist or engineer. Generally speaking, it is the "artist" who has passed judgement on our architecture in the past, and culturally, these have been the predominating views by which we have reached our standards in architecture. The technologist has also passed judgement on another set of standards. From the viewpoint of architecture as an integrated art and science of building, either position implies a schizophrenia between design and technology. Consequently, either set of standards by themselves, as basis of judgement in architecture, is unrealistic. A

The Basic Problem

building may meet the requirements of the basic components of design as imposed by the artist, yet in terms of its time, be unsound architecture. An extreme would be to consider the example of the Parthenon or the ruins of the Maya in our present environment. Conversely, a building may have all the conveniences of air-conditioning, lighting, and generally be an efficient technological machine, yet it can still be an accumulation of cliches or ideas which have no relationship. The resultant feeling is one of apparent indifference, lacking in artistic integration, and devoid of any emotional impact, whatsoever!

If we can agree that design and technology are aspects of the same thing in architecture, and are at the same time relative to each other, the problem then, is not whether the esthetic principles of the artist or the "rationality" of the engineer should dominate; but how can we achieve an integrated whole in which the marriage of art and science becomes a harmonious relationship? The second, and more difficult, phase of the same problem is to attempt to discover what is meant by a "harmonious relationship."

Some of the pitfalls of the predominance of the artistic point have been briefly sketched. (The exaggeration in some of the illustrations is conceded, but such tactics have been generally employed to more clearly illustrate the
author's point of view through use of similes, rather than by a much more difficult literal attack). Similarly, an overstressing or mistreatment of the technological factor may lead to extravagance and resultant disharmony in the final product. Often times, new technical acquisitions may cause the feeling of a naive pleasure, and we must be on constant guard that their possibilities do not carry us away into insensitive channels. The expressiveness in the charm of new materials and the general exhibition of technical novelties, does not insure harmony in design. Divorced from the idea of technology and from the rules of reason, the result must appeal to the senses and emotions alone by the final form and its interrelations.

In recognizing the difficulties above, we can easily become sympathetic to the complexity of simply defining "what constitutes and how we achieve a harmonious relationship in the marriage of art and science in architecture." The magnitude of the problem is so enormous, that by necessity we will limit our consideration merely to a portion of it, and to that phase of technology which is called "structure."

Structure was elected to represent the science factor in exploring the art-science relationship since it is the consideration of that segment of architecture which permits the transformation of drafting board conceptions to reality.
It is the term applied to that constituent of building designed to support weight and transmit stress. Obviously, structure must take physical form and is the largest visible elemental factor that present day thought has classified under the jurisdiction of science. Without it, architecture does not exist. The remainder of the discussion will therefore confine itself essentially to the integration or inter-relation of structure and design; an attempt to demonstrate an opinion as to what constitutes a harmonious relationship; some of the methods contemplated in achieving such a relationship; and some of the resulting difficulties that are imposed.
FUTURE IN THE PAST
It is inevitable that we become a part of our past. No matter how individualistic the architect would believe himself to be, there appears no escape from the influence of the past or the actions of contemporaries. Retrospection appears logical then, in reorientating ourselves in terms of our present position concerning the structure-design relationship.

There exists in the recorded history of architecture, dating back as far as the time of ancient Greece, evidence of the "nature" of man's work to be a product of much of what has gone on before. It is generally an established opinion, that the Doric Order of classic times was a derivation of the timber construction produced in the infancy of Greek culture. The Mycenaens and Minoans, who represented the earlier part of this culture, are thought to have executed much of their architectural work in timber. As time progressed, stone and wood were employed simultaneously in the same structure. Finally at the height of the glory that was Greece, stone reigned supreme as the architectural medium of expression. However, the carry over of appearances, peculiar to the earlier wood renditions, was plainly marked in the stone translations of the Doric temples. The triglyphs of the frieze appeared to substitute for what were formerly exposed ends of the large timber beams. The mutules
or blocks under the cornice of the cornice apparently replaced the projecting ends of the sloping wood rafters. There were, in addition, other features which could have been easily synonymous with the initial wood versions.

Though we may pursue numerous similar examples, even to points earlier in the historical calendar, one example should suffice to illustrate the interactive influence in the character of building. Though this characteristic may be a necessary function of the evolution in architecture, it can as easily act as a repressive force in this same evolutionary process. The distinction seems to hinge on the manner in which this past influence will cause us to react. We may imitate blindly, or we may use our heritage as a stepping stone to something further. The distinction is often much more subtle than this and as such becomes difficult to differentiate.

Architects and designers in general, recognize the dampening of emotions in discovering wood painted to imitate marble, plastics decorated to imitate wood, and anything camouflaged to appear as something it really is not. The process is one of deceit. In fact, it is an outright lie! The objection seems to stem from an assumption that there are specific materials or processes best suited to a particular function and certainly the limits of our present level
Danger of Imitation

The Sin in Architecture

of technology and power of logic substantiate this belief.

In the light of pure imitation, the above concept is easily visualized. Carrying the concept one step further to processes and to relationships in our technology and time, a clear vantage point becomes difficult to reach. But, once the debris is cleared away, the problem remains essentially the same. By and large, we rediscover steel and concrete imitating the stone construction of the past. In the case of concrete, for example, a plastic material that can be molded and formed into inexhaustible varieties of shapes beyond the imagination of any one man, finds its principal utility in architecture in imitating or paralleling the fashion of the Greek. Surely, there must be other applications more suited to the inherent nature of the material than the "inelastic" rigid construction of the Post and Beam.

But the sin in architecture is not that our methods or forms resemble the past, for we will justify numerous circumstances in which post and beam will best serve conditions imposed by the problem on hand. The objection centers around the premise that tradition must necessarily, or more often than not, dictate the solution. On the contrary, the belief is that there exists within the framework of the conditions imposed by the problem, suggested solutions outside of the realm of the prevailing tradition, more applicable to
plasticity in building

Guggenheim Museum for exhibit of non-objective paintings designed by Architect Frank Lloyd Wright illustrates that expression of the plastic nature of modern technological materials need not merely be confined to sculpture, automobiles etc. Truly this is a monolithic structure, with an unbroken floor surface which stretches in a continuous spiral from subterranean theater to glass bubble roof. The structure designed for reinforced concrete will be nearly indestructible by forces of shock, such as quake, bombing, etc. The plasticity of the structure is further emphasized by the continuous ribbons of glass which follow the structural spiral admitting daylight to all portions of the exhibit gallery. "Why keep on building costly windows and doors? Why not smooth plastic surfaces?" asks Wright.....and "Why stack up buildings. Why not pull them out—like a spring?.....WHY NOT ?????
the character of the materials and techniques afforded or made possible by the existing level of technology.

Had the aping of tradition been an inherent characteristic in the nature of man, the unity of the Gothic culture could never have been expressed in its architecture. Here, the same basic material employed by the Greek was put together in another fashion peculiar to its own society and methods of craftsmanship. The result in the Gothic cathedrals was one of emotional-dynamia and economy of form rarely equalled in our time. It was impossible to separate design from structure. Every piece of stone acting in compression, contributed with its neighbor to form an integral whole. It appeared that every available energy inherent in the material was utilized to maximum advantage in creating this economy of form in structure. Though no energy had been misplaced or squandered to create a dishonest emotional effect, the final product seemed to be a visible manifestation of energy. The eye was not stopped by rigid limits, but was drawn from point to point along the lines of the structure so that they seemed to flow in a life-like manner through the space they enclosed.

During the later part of the 19th century in the United States, demands were imposed by a rapidly expanding industrial and mechanized society for multistory, commercial
The Gothic Culture departed from the Post and Lintel system of the ancient Greek, to create a dynamic architecture in its cathedrals. Each stone was utilized to its most efficient capacity of weight transfer; each stone was as important to the structure, as the next. The result was an economy of form for the material employed. No energy appeared to have been squandered or wasted to create "emotional effect" - yet the structure appeared to be alive in its display of energy and movement. There was no separation of the design element from the structural. Right - Cathedral of Charles, France.

The technology of the present day provides us with materials that differ from the stones used in ancient and medieval times. Our materials can be molded into innumerable shapes such as the thermo-plastic sculpture by Moholy-Nagy (Right) yet...

...we continue to use materials capable of the forms illustrated, in the manner of the ancient. So, we continue to build story upon story, with the Post and Lintel system of long ago as the predominant form of construction.
buildings, structurally and economically feasible. The answer was an exploitation of new materials, repeating the theme of post and lintel, to create a skeleton frame which has persisted with us to date as the predominating and sometimes almost unquestioned system of construction. Urban congestion had fostered the development of the frame and the architects of Louis Sullivan's time could do little but accept it as their heritage.¹

Though Sullivan did not question the frame itself, he was, in a fashion, concerned with honesty of emotional effect such as discussed in the previous paragraph. This concern of Sullivan's has come down to us in the phrase "morality in architecture." Among the many connotations of "morality in architecture" was an implication of what we have termed an integration of structure and design. For example, the design of the Carson, Pirie, Scott Store in Chicago (1899-1904) was not in spite of the frame. It was a part of it! The frame was not in contradiction to the design. It was synonymous with it.

In the final expression, spandrels and piers were reduced to a minimum width and the remainder of the space

The Lister Building, Chicago, 1889, conceived by Architect-Engineer William Le Baron Jenny represents the first building of pure skeleton type. Though an early example, its purity of expression made it a much superior building than some of the pretentious confused ideas that were to follow. The problem was solved in its own right and did not rely on tradition to express its statement.

Louis Sullivan and the "Chicago School" were to take on and refine Jenny's expression. They were concerned that their expression too, would be honest reflections of the construction method. Structure and Design were fused into a single entity. Not until the past few decades has the "moral" of the Chicago School been heeded by architects and designers.
between the framing members was occupied by unbroken glazing. The result of the repetitive pattern of the large window areas, contrasted to the directional neutrality of the frame, was an expression of steel construction unexcelled in its directness of statement. It has been only during the second quarter of this immediate century, in which, the large unbroken glazed areas employed by Sullivan, have been recognized as a logical outgrowth of present day construction techniques.

The real estate man's desire for a unit divisible into, large and small, well lighted offices, plus the requirements and potentialities of steel construction, (as they were realized at the time) determined the fundamental skyscraper frames. Engineer William Le Baron Jenny was the first to integrate the system into a design. The movement called the Chicago School, of which Sullivan and his sympathetic contemporaries were a part, refined Jenny's conception and gave it distinctive character. It appeared that the United States was well on the way to an integrated architecture reflective of its enormous technical progress and pioneering spirit. The movement was, however, destined to suffer an unglorious death. The impact of the classical elegance of the Chicago Fair in 1893 was too insistent an obstacle to be surmounted.
The strange anachronisms that soon followed were prompted by the New York architects and their clients. In the desire to be impressive, big business became a willing victim of the Classic influences proposed by the gullible architect. The unity and clarity of the Chicago School was lost among structures ridiculously decorated with Classic colonades below and Bramantesque detail above. The contradiction between the delicate steel frame and the applied classic facade, progressed even to the point of including pseudo-gothic. It was not until 1931 that N. Y. began to show signs, in the McGraw-Hill building by Hood, of emerging from the depths of confusion.

At the same time that Sullivan's Carson, Pirie, Scott Store was taking form as the culminant of the Chicago School in the United States, the Galerie des Machines of the International Exhibition of 1839, in Paris, was culminating another movement spearheaded by the Parisian engineer, Gustave Eiffel. While the Chicago School was achieving an integration of structure and design, principally through accepting and expressing the frame, the architect Dutert, operating under a different set of conditions, went beyond the frame in further exploitation of the potentialities inherent in the basic structural material. Never before had a space enclosure bridged such a span (150 meters) devoid of
columnar obstructions. Twenty trusses constituted the skeleton of the building. The huge glass walls, which enclosed its sides and ends, acted as a thin transparent membrane affecting a union of inner and outer space.

But the confusion of the esthetic, caused by the innovation of technological processes and materials was severe. Criticism was leveled at the lack of filling material between the members of the trusses, the lightness of the girders, and the reversal of usual proportions. Where traditional static feelings, with regard to rational relations of support and load, expected to find solidity and weight, they found attenuation and absence of dimension. A central pivotal pin divided the truss, overhead, at midpoint. Moving downward, the truss became lighter until, at its base, it scarcely appeared to make contact with the ground. Moving back upward, the truss appeared to gain in weight and power. The disruption of the standards, emanating from the stone architecture of the barrel vault, was too extreme for the established esthetists. The axe of tradition fell, as it did on the Chicago School, to sever the lessons of the Galerie des Machines from the world for a number of decades.

disruption of esthetics


The Galerie des Machines was the largest unobstructed clear span structure ever erected at that time. Span 377 ft. Conceived by Architect Dutert and Engineer Gallandm.

Paralleling the movement of the Chicago School in the U.S. was a European movement, chief proponent of which was Gustave Eiffel. The Galerie des Machines symbolized the culmination of this movement. It was a direct contradiction however to the established ethics of the classic mind: Attenuation and lightness replaced mass and solidity.
Robert Maillart was an artist in the fullest sense of the word. He collaborated, for many years, with architect Hans Kruck in Zurich, who has pointed out Maillart's regard for esthetic expression in Max Bill's biography. Maillart was not only concerned with meaning, he was concerned as strongly with feeling! He was willing to recognize the basic materials of his technology, not to imitate tradition, but to learn from her and hence, attempt to utilize the inherent characteristics of the material in question. We may best attempt to express Maillart's feeling in his own words.

1Max Bill, Robert Maillart, p. 9.
The Individual Character of Reinforced Concrete

Reinforced concrete does not grow like wood, it is not rolled like steel and has no joints as masonry. It is most easily compared with cast-iron as a material cast in forms, and perhaps we can learn something directly from the slowly discovered cast-iron forms regarding the avoidance of rigidity in form by a fluid continuity between the members that serve different functions. The condition of this beautiful continuity is the conception of the structure as a whole. The automobile and aircraft constructors have attained this in the highest degree, while it is an exception for the reinforced concrete constructors to perceive this. It is not only the feeling for beauty which makes desirable the conception of the whole primary to that of the single elements. Seeing the structure as a whole nearly always brings economical advantage as well.

Though the architect may consider himself divorced from the field of bridge building, he cannot afford to overlook or dismiss the principals of Maillart. Certainly, Giedion as one of the earliest introducers of Maillart's artistry, did not, on his treatise of Maillart in "Space, Time, and Architecture", present his views merely from the point of bridge construction. Conditions of bridge design, in the architectural sense of the word, are very simple. The object of the problem is to permit traffic to move from one side of an obstruction to the other. The manner in which the problem was solved, however, resulted in an integration of structural and esthetic requirement to rival and surpass the Gothic economy of form.

1Max Bill, Robert Maillart, p. 15.

2Sigfried Giedion, Space, Time and Architecture, p. 371.
Undoubtedly, Maillart could have fallen into the traditional system of the arbitrary masonry arch form for his bridge constructions and easily have done an excellent job of calculation in the customary manner (that same manner employed, as a rule, to this day). His desire to achieve a more truthful and beautiful expression of the material employed caused him to cast aside the manner of tradition.

He says,

"Here (in the bridge) for the most part the arch, derived from the masonry form, is still the main feature whether it be reduced into flanges or hollowed out into flanges it remains basically the same. Upon this, steel or wood structures are "set up", and it is always preferable to reinforced columns dressed to resemble masonry walls. The traffic-way rests on pillars and columns. It is known from numerous experiments that the most exact calculations for the design of the arch no longer prove to be correct, and because the stresses occurring in the arch are smaller than designed for, one is satisfied without further investigation that this overestimation corresponds to the increased loading of the superstructure.

These heterogeneous structures assembled from forms stolen from the language of older materials cannot possibly give any aesthetic satisfaction. They are also less economical than any type of structure between and above the abutments, that is considered as a whole, and is constructed in the most practical and appropriate way. Only then can a clear construction evolve with the minimum waste of material.

The engineer should then free himself from the forms dictated by the tradition of the older building materials, so that in complete freedom and by conceiving the problem as a whole, it would be possible to use the material to its ultimate. Perhaps then we would also arrive at a new style as in automobile and aircraft construction, as beautiful, and in the same way determined by the nature of the material. Then perhaps taste will begin to be rectified, so that the public judge the traditional form of reinforced concrete bridges in the same way as they judge the automobiles of the turn of the century whose prototype was still the
Maillart's rejection of customary methods of calculation was not based on feeling alone, but also on a profound knowledge of the nature of materials. It is both beyond the scope of this thesis and the capabilities of the author to discuss, in exactitude, the technical methods and views of Maillart. However, we may comprehend and sum up the highlights of his invaluable teachings so as to point to the direction of his thoughts and emotions. The method of calculation of a rectangular reinforced concrete beam, for instance, is dependent on Hooke's Law i.e., "within the elastic limit, strain is proportional to the stress that produced it", and a "constant quantity" called "n" (which really becomes a variable after a certain point). The calculations resulting from these postulates are, at best, close approximations since they in no way reflect the actual behavior of the section under all conditions. The adherence to the resultant method of computation is largely one of mathematical expediency and admittedly, so, even in the eyes of the engineering profession. Codes, based on these "accepted" methods of computation, push structural design one step further beyond the reality of the actual behavior of materials by encouraging a high factor of

1Max Bill, Robert Maillart, p. 15.
safety, cynically but perhaps more honestly called the ignorance factor, in the design stresses of materials employed.

The genius of Robert Maillart, in its burning desire to more closely approximate and beautifully express the true characteristics of reinforced concrete, developed methods of design combining both processes of experiment and calculation. These methods of attack were directed not to the ancient beam and column form, but elementally to the flat slab, which in Maillart's hands more fully realized the potentialities of reinforced concrete both in terms of structure and in terms of esthetic design.

The Tavanasa Bridge constructed by Maillart, as early as 1905, was as shocking to tradition as was the Galerie des Machines fifteen years earlier. Instead of the accepted series of heavy static-like arches of masonry form, the Bridge leaped the Tavanasa in a single arched reinforced concrete slab, to which was fused the horizontal slab of the platform and was articulated by a series of vertical slab stiffeners. The structures following were to express the same directness of purpose, the same boldness, the same sculptural and plastic beauty of the Tavanasa. Sifgried Giedion expresses his feelings as follows:

"It is easier for the constructor to find a convincing solution than the artist, because physical factors dictate its conditions. All the same, there is something altogether out
maillart’s bridges

Schwonbach Bridge, considered one of Maillart’s finest executed in the elemental flat slab, is an example of material economy and aesthetic rhythm.

Bridge over the river Thur near Felsegg, Switzerland is a refinement of the 3 hinged box type arches which are merged into the roadway slab to span 236 ft.

Typical of Maillart’s bridges are the type shown above, an example of which is the Schwandbach Bridge composed of road slab and single arch slab stiffened by vertical structural slabs to form a single unit.

Another version of typical Maillart construction is the union of road slab and arch slab eliminating the vertical structural members and refining the grace of structural economy. New term takes into consideration bending moments induced in flat slab arch.
of the ordinary in the way Maillart succeeds both in expressing and in sublimating the breadth of a chasm left between two walls of rock (i.e., in his Salginatobd-Brucke, 1929-1930). His shapely bridges spring out of shapeless crags with serene inevitability of Greek temples. The lithe, elastic resilience with which they leap there chasms, the attenuation of their dimensions, merges into the coordinated rhythms or arch, platform, and the upended slabs between them.  

Giedion also attributes the likeness of the forms independently arrived at by Maillart and the same absolute forms employed by Picasso as the "mirror of a higher reality in terms of development." While the modern painter was concerned with plastic organization of forms suggested by lines, planes, and colors on a flat surface, so Maillart was concerned with a similarity of organization. True, the line or the plane of the artist was not his medium of expression; yet the slab, in an analogous fashion and as a basic element of construction, suggests a parallelism of view.

We may find it difficult to agree whether Maillart was engineer or artist. Perhaps the difficulty in claiming him is that he at least both and likely more than both. Max Bill is interested in him from the sculptor's viewpoint, Paul Weidlinger from the engineers viewpoint, and Sigfried

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Maillart's Proximity to Modern Painting

Maillart, Engineer or Artist?

1Sigfried Giedion, Space, Time and Architecture, p. 379.
2Ibid., p. 380.
a higher reality

Bridge over the Thur River, Saint-Gall, Switzerland, 1933 by Robert Maillart. The "columns" or supports have been derived essentially from technical premises.

Oil painting by Picasso, "L'Adesienne," 1911-12.

Are the half-geometric, half-organic plastic images painted by Picasso mere accident in their resemblance of absolute terms to those of Maillart's bridges? Author and critic, Sigfried Giedion, thinks that the mechanical shapes and the shapes evolved by art, as demonstrated by these two men, are the "mirror of a higher reality rank, in terms of development." A parallelism exists in the methods of painting and construction. It is the medium of expression that differs.

Bridge over the river Arve, near Geneva, 1937, by Robert Maillart. "Columns" here are shaped to conform exactly to structural requirements for transmitting linear distributed bending moments and shear.
Giedion sees his meaning in Architecture.¹

The Concrete Exhibit at the Zurich Exhibition of 1939 (a year prior to Maillart's death) had little to say to a war-worried world. Thirteen years later engineers still ponder over the daring of the $2\frac{1}{2}$ thick shell of the arch which reaches the height of 50 ft. The emotional impact of the shell alone may not be enough, in itself, to hold the attention of the artist for long. However, when the shell becomes a part of a symphony of arched and straight planes varying in size and direction, contrasting in their lightness and delicacy to the massiveness of the classic-like sculpture, and becoming a rhythmical movement in three dimensions, the constructed feeling has passed out of the realm of engineering. Though the purpose of this structure was a simple one, and represents, perhaps, the closest Maillart came to a complete building, the architectural implications are there for those who care to see. Ironically, it is the engineering complications which, at present, are holding back a fuller realization of Maillart's contributions. We will consider some of the implied complications briefly under another heading. Suffice it to say that his conceptions are different than those practiced in

¹Sigfried Giedion, *Space, Time and Architecture,*
The 2-inch thick, 50 ft high, shell of the Concrete Exhibit in the Zürich Exhibition was a technical achievement in relation to its time (1939) and continues to be so even today. Perhaps, in its naked form, the shell becomes but an engineering feat (Right). But in the hands of Maillart it becomes a work of art—a thorough integration of structure and design. Maillart has recognized the plastic nature of the building materials of his time. He has given his principles expression in the grace of economy of material and economy of form. This exhibit similarly demonstrates the monolithic character of the design and means of forming it.
Maillart's work may be broken down, for the sake of synthesis, into a system of flat and curved slabs. We must not lose sight, however, of the fact that these slabs were so juxtaposed so as to achieve an amazing counter-balance of all stresses and strains arising between them. The action of the structures cannot be understood in terms of the synthetic elemental breakdown of slabs. The forces at work are ones of action and interaction and hence "continuous." Understanding of Maillart's economy of form can only be attempted on the basis of recognizing the structure as a whole. On re-examination of the statements by Maillart as quoted on page 20, we shall discover his use of the phrases:
"fluid continuity between the members," and "condition of this beautiful continuity is the conception of the structure as a whole."¹

The principal of continuity (interation) is based on the monolithic nature of a material i.e., reinforced concrete, welded steel, plastics etc. Architect Eric Mendelssohn visualized the possibilities of the principle in terms of its application to architecture at the same time that Maillart was constructing his bridges. It is difficult for the author, however, to realize Mendelssohn's exact meaning when he undoubtedly, in thinking of the same principle, calls it "elastic continuity."

"The structural principal of elastic continuity is derived from Nature, its continuity of form made possible by the elastic nature of steel and reinforced concrete. Only in the last few years has this revolutionary principle of elasticity in steel and reinforced concrete been applied as the structural basis for a new architecture."²

The idea of the elastic behavior of materials was proposed as early as 1667 when Hooke published his discovery that "ut tensio sic vis," the extension is proportional to the force.³ Prevailing methods of engineering calculations are

¹Max Bill, Robert Maillart, p. 15.


Concept of Limit Design

Continuity as a Characteristic of Modern Materials

based on this same principle of Hooke's Law.

Perhaps Mendelssohn is really thinking of the idea of engineering term called "limit design" which is comparatively new and proposes to modify the elastic theory. Limit design considers that materials can yield sufficiently to bring unstressed parts of the structure into play and thereby permitting further utilization of the "reserve strength" not considered by Hooke's Law. Tests on continuous beams and portal frames have shown that bending movements redistribute themselves in the tendency to retard the collapse of the structure should any section become highly stressed.

Neither is the idea of continuity first demonstrated in our time. We can go back at least as far as the Baths of Caracalla in ancient Rome to demonstrate its application. However, as Mendelssohn may imply, the preponderance of plastic materials such as reinforced concrete and steel, made possible by our technology, has awakened a desire for a fuller utilization of their potentialities. The realization of such an ideal, as Maillart's works signify, lies in a fuller understanding, both by engineers and architects,


2 Eric De Maré, New Ways of Building, p. 37.
of this concept called continuity. But to achieve an understand-
ing to the degree of utilizing the principle with ease and within practical limits, is a strong challenge to our generation. The path is not an easy one to traverse. Many obstacles must be overcome before we can view a hangar by architect-engineer Nervi or a bridge by Maillart as a matter of course. In contrast to the tradition of skeleton construction, the idea of economy of material and form through continuity, opens up an opportunity for a greater integration of structure and design, of intellect and imagination.
Explicit details in the technical significance attached to the meaning of "economy of form" i.e., a maximum utilization of the stress potential of a material, are not necessary to our purpose. However, a review of a few basic concepts in mechanics may assist us to more readily "visualize" part of the significance attached to economy of form. Such a "visualization" may result in a greater appreciation of the smooth flowing lines in Maillart's Bridges which are synonymous with the "economical" use of materials and the accompanying eveness of stress distributions.

The typical suspension bridge is a simple but very clear example of economy of form. The steel suspension cables, gracefully sweeping from pier to pier, represent the curves of maximum material utilization. Since the nature of steel is such, that its greatest efficiency is realized when used in tension, the ideal situation would be to find a form, in which there would be no compressive stresses exercised, and therefore no bending. The condition of pure tension and hence of equilibrium (zero bending) may be demonstrated mathematically as describing the equation of a catenary when the steel cable is supporting only its own weight. Its weight, of course, is uniformly distributed along the arc length of the cable.

Similarly, as demonstrated by the mathematical proof on
the following page, a theoretically weightless cable carrying a uniform load horizontally, i.e., the platform of the suspension bridge, will describe the locus of a parabola. Since the cable does have weight, however, the final condition of pure tension is in a curve which lies somewhere between the catenary and the parabola. Though suspension bridges are usually called catenary types, the proportionally greater weight of the platform in combination with certain portions of the live load, cause most computation to be centered around the parabolic formulas.

The simplicity of this type of bridge and the form which it takes, not only satisfies our esthetic sense, but enhances it by appealing at the same time to the intellect. In spite of the apparent simplicity of concept, the suspension bridge is certainly a magnificent illustration of the integration of structure and design through economy of form. Though the idea of continuity may not be as vividly illustrated in terms of the text definitions, the elemental parts of the completed whole are in a state of action and interaction. No part of the structure is wasted energy for the sake of producing an effect.

We may go one step farther with the above concept when, instead of "pull", or tensile stress, is substituted a thrust or a compressive stress. As may be suspected, by
The condition of equilibrium will form a closed force triangle of the forces $T_1$, $T_2$, and $wL$ concurrent at point "A".

The locus of the curve described by the weightless cable may be derived in the manner shown below.

**MATHEMATICAL LOCUS:**

To equate conditions of force, employ theory of moments about point "A".

\[ \sum \text{clockwise moments} = \sum \text{counter-clockwise moments} \]

Lever arm ($y$) x force ($T_1$) = lever arm ($\frac{L}{2}$) x weight ($wL$)

\[ yT_1 = \frac{L}{2}wL \]

\[ 2Ly = wL^2 \]

The above equation is the general equation for the locus of a PARABOLA with origin at "o" and axis vertical.

By a similar method, it may be demonstrated that the locus of the curve of the suspension cable due to the weight of the cable only, will describe a mathematical CATENARY.

Since the cable of a suspension bridge does have weight and at the same time carries a uniform horizontal load in the platform, the true curve of the loaded cable falls between the limits described by a catenary and a parabola. Live and dead load considerations cause the actual cable to more closely approximate the parabola.
employing a reasoning process analogous to that for the suspension cable, the condition of pure compression will also be a parabola-catenary but inverted in relation to the curve of pure tension. Now, if concrete which derives its greatest strength in compression (nearly valueless when considered in tension) is substituted for steel, we have an economy of form for the specific characteristics of the material involved.

"Visualization" may be facilitated if we consider the same idea in a slightly different sense. Assume that two spheres of equal size and weight are anchored to a common base at a specific distance apart. In bridging this distance through the use of spheres identical to the anchored ones, their placement will automatically be such that points of contact will form a catenary curve. The resultant arch is one of pure compression and under a condition of equilibrium. If the arch is made to carry a uniform horizontal weight it will, as in the suspension cable, approach a parabolic curve dependent in its proximity upon the magnitude of the horizontal weight.

Though it is next to impossible to discern with the naked eye, whether a curve more closely approximates a catenary or a parabola, we can generalize for the sake of "visualization" to the arch shape. The generalization can also
be extended to associate the arch shape with an economy of material in utilization with respect to its maximum stress potentialities; the normal arch compressively, the inverted arch in tension.

There are many additional factors which must be investigated before the above concepts may be soundly employed in building. However, the generalization becomes adequate from the standpoint of permitting a clearer visual conception of the meaning of "economy of form." Perhaps we can now "see" that the beauty of Maillart is in view of, and equally satisfies, structural considerations. The whole represents a perfect fusion of design and structure.

This same generalization may be applied three dimensionally, or in part, to ideas already presented and to those that follow, with the intention of more easily "visualizing" the basic behavioral characteristics of the structures involved. For the sake of illustration, let us consider a typical rigid frame. Once conditions of dead and live load have been taken into account, we may infer from the concepts discussed, that there exists an ideal linear arch or line of pressures which corresponds to the modified catenary-parabola locus of material economy for these particular load conditions. Furthermore, since this ideal linear arch represents the form for zero bending, the further the shape
of the rigid frame departs from this arch, the greater the bending moments induced. Consequently, the sections of the frame will decrease or increase in depth in direct relation to the distance of their center line from the ideal pressure line or arch. Since the corners of the frame are farthest from the arch or pressure line, heavy haunches are required to counteract the heavily induced bending moments. The process of "visualization," therefore, in terms of the arch or pressure line generalization, is comparatively simple and technically sound.
San Francisco-Oakland Bay suspension bridge, with a maximum clear span of about 2326 ft. The tensile nature of steel is completely expressed in the suspension cable...its form is one of equilibrium.

The 867 ft span hingless arch of the bridge over the river Angerman at Sund, Sweden, is one of the longest existing concrete arches in the world. This too represents an "economy of form" in that the compressive nature of the concrete is expressed in the reverse of the parabola-catenary of the steel suspension cable.

Retired type of three hinged frame in riveted steel used in a garage at the Hague, Holland. Span about 80 ft.

The bending moment set up at any point in a three-hinged arch is governed by the extent to which the arch deviates from the ideal catenary-parabola passing through the hinges. Note in photograph of arch how the frame deepens in section as it deviates from the "pressure line."
FUTURE IN THE PRESENT
Nature offers an outstanding illustration of the possibilities of design-structure integration through the principles of continuity and economy of form. Even on the basis of our own standards, many of her designs are structurally and esthetically sounder than ours. Few are the building problems that our generation faces that Nature has not solved, either directly or indirectly, through principle. We may venture so far as to remark, that Nature can serve as an inspiration for our solutions provided we are properly equipped with the proper knowledge and insight to see and analyze her statements.

Modern technology can serve as a major source for acquiring this knowledge or insight, the basis of which, may figuratively serve as a vocabulary to better understand and employ Nature's principles to utilitarian-esthetic ends. Photo-elasticity, X-ray, testing machines, computers and many other analytical techniques aid in establishing a more workable analysis of stresses in materials and structural forms. The welded metals, molded plywoods, reinforced concrete, and other plastic media, peculiar or prevalent to our technology, serve as the means to realize the natural principles of continuity, economy of form, and their adaptations. The interrelation of technology to the interpretation of natural forms cannot be overemphasized. The idea of nature
as a teacher is not new, but without science, analysis was generally insufficient or incorrect, and often resulted in little more than artistic frustration when applied to architecture.

The recent war years gave impetus to the idea of employing technological materials to greater advantage. From the standpoint of conserving material, increasing production, and mechanical efficiency, mass and weight became extremely critical factors. Structurally, the consequence was one of simplification and efficiency in the use of material. Curiously enough, many of the forms produced closely resembled nature's solutions to physically similar problems either by intent or coincidence.

The concepts evolved in solving such problems have, in many cases, left the conventional engineering of pre-war days far behind. In fact, some of these concepts, such as the design procedure for shell construction, have been just recently reformulated for simpler use. Other concepts, typified by the idea of limit design previously discussed, are aiming at reformulation through discussion and experi-


From Morning Glories to Buildings

The directional aspect of these resultant concepts points to lighter structural systems, more efficient and more attractive structural forms, than known heretofore in the art and science of building.

Nature seems to be telling us that we are on the right track. At first glance it may appear factitious to compare natural forms to man-made designs. Closer, and more critical examination will reveal, however, that this is not so. There are very few who would dispute the inherent beauty of nature's flowers, regardless of individual aesthetic standards, yet engineer Fred Severud, in his analysis of the Morning Glory, discovers a form equally as efficient as it is beautiful. The simple graceful shape becomes integral with the construction of the flower in performing its function. The principles suggested have been adapted by Severud into the unique airplane hangar design illustrated. To prove that the idea is not purely hypothetical, a hangar following these same suggested principles has been actually constructed in Belgium, as well as


the tension ring principle

Cross section through Airplane Hangar Design by Engineer Fred M. Severud illustrates the potentialities possible in design and construction through employment of the shiel tension ring

Concrete Umbrella - Shell Construction

Aluminum Doors

Tension Rings

Hangar Space

Compression Ring

Motors

Tension Ring

Scale: 1" = 50'
an engine shed in Avignon, France. Frank Lloyd Wright, likewise, has demonstrated the application of these ideas in his design of the so called mushroom column employed in the Johnson's Wax Building at Racine, Wisconsin.\textsuperscript{2}

The columns and the hangars are rotational structures, the peripheries of which are banded by a steel tension ring. The steel ring emulates the tension ring provided by the curved lip of the Morning Glory. In nature, the purpose of the ring is to prevent disbanding everytime a bee alights the blossom. Transposed into terms of load and stress, the man-made structures are engineered to do the precisely same thing, i.e., to transmit stress 'safely under conditions of load.' Like its natural counterpart, Wright's famous column consists of a series of ribs and curved blades radiating from an inner throat, or compression ring, designed to absorb the forces tending to collapse it. The assembly, hollow in section, constitutes an inverted cantilever shell of great strength and remarkable structural unity. The beauty of Wright's design caused many skeptical engineers to label it as poetic. Tests on the column in 1933 demonstrated its

\textsuperscript{1}Leonard Michaels, \textit{Contemporary Structure in Architecture}, p. 68.

\textsuperscript{2}Ibid., p. 100.
structural efficiency however. How then, can we honestly separate the design of this column from its structural purpose and make-up? If we materially alter one, will we not affect the other?

While Wright uses the column as a means of support for glass and concrete roofs, architect, William Lescaze and engineer, Fred Severud arrange the hollow "Morning Glory" shells to constitute a complete roof structure. The columns and shells are precast. In assembly, the columns are so spaced as to allow the interstices between the columns to hold an inverted shell. The resulting design is very stable and of a high material economy. The shape approximates the pressure line and is in conformity with the bending moments induced in a continuous flat slab structure.

Applied on a larger scale, the Morning Glory principles can be utilized where it is desired to obtain large unobstructed or columnless areas. Wright demonstrates this again at Racine in the Johnson Wax Laboratory Tower,¹ and Severud more decidedly in his hangar design. The inverted cantilever of the cup can extend for an almost limitless length, while the throat of the Morning Glory form can be widened, roofed over, and used for office space. The

perimeter of the structure is columnless, and can lend itself to any door or panel arrangement.

Nature illustrates the integration of structure and design emphatically in her shell constructions. The fluted shell of the scallop combines a corrugated surface and compound curve to achieve relatively enormous strength and remarkable beauty. Considering its thickness, the shell's span is comparatively wide. Its purpose is to protect the sensitive inner of the marine animal from damage due to impact or weight. Until recently, our use of the corrugations illustrated in the fluted shell has been generally confined to surfacing materials such as glass, sheet metal, and asbestos. Increased research in the field of shell construction, however, has encouraged use of the corrugation principle in a more magnified sense. Standing examples are the barrel vaults of the canteen for May and Baker in England, and 20 ft. corrugated contilevered canopy for the Store Street Bus Station in Dublin.\(^1\) The columns are so placed so that a cross section through the roof or canopy is very similar to the cross sectional picture of the Lescase-Severud roof previously described. Therefore, such a

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section similarly follows the curve dictated by the moment diagram of a continuous flat slab allowing an extraordinarily thin shell.

The concepts of the fluted marine shell are most closely realized in the exhibition hall at Turin, Italy by architect Biscarotti di Ruffia and engineer Pier Nervi.\(^1\) The exhibition hall, as does the shell, utilizes the corrugated surface in a curved form to enclose a wide unobstructed space. The structure makes most efficient use of the concrete in compression, and at the same time, boasts an ingenious method of lighting the interior by inserting glass on the downslope of each corrugation. The continuity of the surface is further strengthened by reinforced concrete stiffening ribs following the crowns and hollows of the corrugations. In passing judgement on the Biscarotti-Nervi exhibition hall at Turin, it becomes difficult to see any validity to the claim that structural considerations dampen the imaginative spirit. In fact, we may go to the other extreme in stating the appreciation of the structural possibilities and practicabilities has led to an esthetically simulating work. There exists in the final result no significant dividing line.

\(^1\) Leonard Michaels, *Contemporary Structure in Architecture*, p. 115.
Nature illustrates the principle of corrugation and the compound curve particularly well in her marine specimens such as the sea shell. Right—the 2\(\frac{1}{4}\)" thick reinforced concrete canopy at the Dublin street bus station cantilevers an amazing 20 ft.

The 315 ft. wide exhibition hall at Torin, Italy, by Architect A. di Ruoff and Engineer A. Nervi is a continuous corrugated arch with longitudinal stiffening fins of precast concrete. Either sides of the corrugations are glass filled to admit light to the interior.

**SECTION**

Precast system of columns and caps rationalized by engineer Fred Severud for maximum economy. The section of the structure is reminiscent of the corrugated shell. It also has been likened to the "Morning Glory" tension ring structures.
between structure and design. One has led to the other, both are interdependent.

The protective shell extends through a wide range of nature's organisms and each type, with a lesson to impart. Engineers have learned, that the simple but handsome shape of the egg shell is also responsible for the remarkable strength of this form. Man-made designs have even gone one step further, and replaced the less suitable calciferous substance of the egg shell with technological materials more suited to the compound curves of stressed skin construction. Examples are the Horton-spheroid fuel tanks such as are located in Southern Texas. The tanks are constructed of stiffened sheet steel welded to form complete three-dimensional space-enclosing structures of 127 ft. diameter. The spatial entirety of these spheroids makes them independent of the ground as the final space enclosing plane.

Similar examples, but employing another material for the stressed skin, are the elliptical concrete shell domes developed by the engineering firm of Foster, Roberts and Schaefer Co. in collaboration with J. C. Taylor, architect. The domes form the Sewage Treatment Plant at Hibbing,

Leonard Michaels, Contemporary Structure in Architecture, p. 125.
The ISO ft. diameter, elliptical concrete shell domes perform the entire duty of space enclosure at the Hibbing Treatment Plant, Minnesota. The ground plane is the only additional space defining limit.

The 127 ft. diameter, welded sheet steel, Horton-spherical fuel tanks in Southern Texas are complete three-dimensional space enclosing structures independent of the ground as the initial space defining plane. Its strength is derived through the same compound curves and continuous nature demonstrated in the egg-shell.

The project for a concert conceived by Architect Amano Williams represents and ultimate example in the integration of structure and design. The structural shape has been developed from the requirements dictated by the consideration of vision and acoustics. It reflects an awareness of the plastic nature of the material of which it is to be formed and simultaneously a high regard for aesthetic principles.
Existence of Many Natural Examples

Minnesota. Though not as complete in spatial concept as the industrial spheroids described above, the monolith shells of the Hibbing Plant preform the entire duty of space enclosure in conjunction with the limiting ground plane, as well acting self-sufficient in terms of load transfer.

The egg shell principles are not limited to the uses described above. A canteen built for the assemblers of the Horton-Spheroids on a similar system demonstrates that the ideas are applicable to buildings housing human activity. An ultimate illustration may be found in the project for a concert hall by architect Amancio Williams.¹ The word ultimate is used here to indicate that the shape of this structure has been developed from the visual and acoustic requirements of the concrete hall and consequently is in complete integration with design considerations.

There exist countless other instructive illustrations in nature of integration between structure and design. The simple pad of the water lily (Victoria Regia) designed to float restfully upon the water is held in a flat plane by a system of rods and membranes in tension. This design principle has had important implications for metal construction.

¹Leonard Michaels, Contemporary Structure in Architecture, p. 125.
Paul Nelson's "Suspended House" on exhibit by the Museum of Modern Art is a lily pad adaptation in welded metal yielding a structure of tremendous resistance to conventional loads. The flexible structure of the jelly fish has been closely approximated by the patent of H.H. Stevens, New York engineer. His idea of an inflated air supported roof has been contemplated for the Baltimore Arena. The light and flexible, but strong and impervious, skin of the jelly fish is simulated by a modern material, such as aluminum or magnesium. The light weight allows a slight differential between outside and inside atmospheric pressure to carry the roof.

The fascinating design of the spider web, with its simplicity and remarkable efficiency, has attracted the attention of many engineers and architects alike. The tension principle of the web has proved successful in bridge design, and Buckminster Fuller has demonstrated, in his Dynexion House that suspension structures are also applicable to building design. The Transport Building of the Chicago Fair further substantiates the plausibility of the idea.

Examples, similar to those just mentioned, are close to limitless. All serve to illustrate the variety of ways in

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2 Ibid.
The simplicity and remarkable efficiency of the spider web has long attracted architects and engineers. Here, its principles are duplicated in the tension-suspension structure of the Transport Building of a Chicago fair.

The inflated sac of the jellyfish is light but strong, impervious but flexible. These are the same requirements for the collapsible roof of the Baltimore Arena proposed by engineer H. H. Stevens. A small pressure differential between outside and inside holds up the light magnesium or aluminum roof.

The Museum of Modern Art holds this welded metal structure executed by Paul Nelson. It is synonymous with the principles of a series of rods and membranes in tension, exhibited in Nature by the underside of a water lily pad.
in which nature may integrate structure with design, and how man may learn from her examples. A word of caution becomes necessary at this point however. Mere intuition is not sufficient to extract wisely from nature. To develop logically, analysis must be substantiated by scientific investigation and knowledge. The intention should be, not to mimic or simply imitate Nature's designs, but to utilize or investigate her principles. Nature's curves generally are an expression of the principle of structural continuity and economy of form; her appearance, a result of structure and design integration. It is in consideration of these and similar principles, that may lead us to better understand and achieve a similar beauty and efficiency in the field of architecture.
The reader may have, by this time, formulated an opinion that the principles advocated, and the position maintained herein, are antagonistic to the skeleton frame, as indeed, to a great degree they are. Of course, it is not possible, in all cases, to conveniently abandon the right angle or the straight line in favor of the curves predominant in nature, and the forms of material economy. Neither can we disagree, that because of man's physical nature, we most easily work and live on surfaces essentially flat and level. In many instances, contemporary values, such as cost of land, desire for concentration, etc., will even cause the superimposition of one such surface above another. Good design must and will consider these factors.

The greatest argument in favor of the skeleton frame from the designer's vantage point, is its flexibility; from the clients, its economy of cost. Both conceptions, if not properly considered, can be dangerous! If the designer misconstrues the meaning of flexibility to mean lack of concern for structure during design, the idea of economy of cost becomes merely a value relative to the final design form. The frame so considered, in many cases, merely becomes an expediency for the designer and hence lacks a true integration with the structure. On the other hand, we could gain a maximum economy by employing a grid system consisting
of typically efficient skeleton bays prescribed by the engineer. It does not appear necessary to press the idea that such a system is suited to a limited number of functions. Nor is it good design to force a function into a grid pattern. The point is: that the idea of cost is a factor relative to the degree of design-structure integration and to do justice to an architectural work, we can neither approach the process of design nor the structural considerations, as independent elements. There must exist, as near as physically possible, a simultaneity of thought between these related factors. But most important of all, we must not consider the "flexibility" or the "cost" arguments attributed to the skeleton frame as valid for all conditions and hence, unquestionably accept this system of construction as our standard.

Consider a typical 20' x 20' bay framed in steel. Designed for a 200 pound floor load, this bay actually requires 10 to 15 pounds of steel per square foot.\(^1\) This conventional skeletal bay first runs all loads in one direction to the beam, then switches to run the loads in another direction to the girder, and finally, transmits them at right

\(^1\)"Is This Tomorrow's Structure," *Architectural Forum*, (February, 1953), p. 150.
angles to the column. Most of the inherent supporting potential of the steel, therefore, is expended merely in a process of transfer. The idea becomes shocking when we realize, that the same size bay would but require three to five pounds of steel per square foot if designed in the manner of Architect-Engineer Nervi's spectacular concrete hangar roof.¹ Nervi's roof is essentially a three-dimensional application of the compressive arch principle previously discussed. Hence, the structure is one demonstrating the concept of economy of form.

Again the sceptre of economy of cost becomes the justification for the waste of steel in the frame as opposed to the material economy of the arch rib construction advocated by Nervi. The proposal is made, that it is cheaper to frame a bay with five or seven big wasteful members, than to frame it efficiently with the multiplicity of small members characteristic to the Nervi system. The critical jointing of these many members is part of the same objection.

The high cost of construction labor in the United States makes a structure, such as Nervi's, an expensive undertaking. In view of this consideration, perhaps, we can more

readily appreciate one of the principal causes of the more progressive advancement of architecture in foreign countries. We find the Nervi hangar first appearing in Europe (Rome, Italy) where the labor potential is proportionally greater and extremely cheaper. The comparative scarcity of resources makes economy of material a critical factor, where the apparent waste of material, in this country, makes the converse appear true.

This relationship of labor-material cost seems a logical consideration of the building process. The architect must not forget, however, that, this too, is a relative factor which fluctuates with time, locality, technological achievements, and the economic state of the nation etc. Conditions are never constant enough that the architect may take the labor-material relationship for granted. Even now the dollars and cents balance between small-member framing and large member framing is radically shifting due to the more efficient employment of steel welding. An example is the General Motors Technical Center which used its so-called "Zeppelin" trusses to get a stiffer frame at no extra cost.¹ Under these conditions, the Nervi construction system is

perfectly feasible provided that both architect and engineer are technically and professionally ready to handle it. Often times, code considerations, soil conditions, etc., will initiate additional, but valid, objections to a less traditional structure. But too often, the truth is that neither architect nor engineer are sufficiently informed to properly consider these newer concepts. What usually follows is a dissertation concerning cost (when in reality no one knows enough about the structure to make even a reasonable guess), or a cyclical accusation between architect and engineer which is very successful in frustrating both factions involved.

The writer will be the last to maintain that the cost element must be overlooked. On the contrary, the proposal is that cost investigation is seldom thorough enough. Even in such a thorough investigation as that conducted by the engineering firm of Ammann and Whitney in the cost of roofing the University of Wisconsin, Field House, the architect must remember, that the cost of a building does not end with the final construction price. A long range view will consider the cost of maintenance, fire insurance, etc., over

Comparative Cost Estimate of Methods of Building Field House, University of Wisconsin

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<tr>
<th>FRAMING TYPE</th>
<th>LAMINATED HEDS</th>
<th>WOOD BOWSTRING</th>
<th>ARCHED TRUSS</th>
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<th>ROLLED BEAM</th>
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UNIT COST (total per sq. ft) $3.04 $3.20 $7.62 $3.32 $2.94 $3.14
Unpredictability of "True" Cost

Even then the cost figure becomes, at best, a rough estimate of the true cost of the building. The first Johnson's Wax Building designed by Frank Lloyd Wright, took a number of more "expensive" liberties than those advocated by the more "economical" traditions of the day. It is hard to say how many dollars worth of advertising the Johnson Wax Company received due to the publicity received by this relatively "expensive" structure. Evidently, the Company must have been sufficiently pleased in order to commission Wright to repeat a similar "extravagance" at Racine, Wisconsin.

The principal element of the Racine buildings stands as a shining example of integration in structure and design beyond the skeleton frame. The Maillart-Mendelssohn principles of continuity, of economy of form, and of the plasticity of present day technological materials, are well illustrated. The structure permits design to more fully realize its intended function. This "expensive" structure also appears to be doing its share of advertising for the Johnson's Wax People. To summarize, let us say that the argument of "economy of cost" must be consistently reviewed with discretion before it is allowed to interfere with the advancement of new concepts in architecture.
Of all the concepts demonstrating the principles of continuity and economy of form through structural shape, that category of building, called shell construction, is the strongest contender against the bulwark of tradition. Even then, progress is painfully slow. The two-dimensional, elemental plane or slab of Maillart's bridges represents the stepping stone from which has evolved the three-dimensional concept of contemporary shell construction, pivoted consciously or unconsciously about Maillartian principles. Consider the concept of the compressive arch applied three-dimensionally, and we can begin to visualize how these thin shells can achieve such enormous clear spans, and simultaneously, exhibit such remarkable strength.

A word of warning is necessary at this point to emphatically state that the catenary-parabola arch principle is no more than an "assistance" to visualizing contemporary shell behavior. In using this guide of economy of form, we have been considering it the light of homogeneous materials acting purely in compression, or purely in tension. As such, we can get a fairly accurate picture of the action of forces in the homogeneous traditional vault of earlier periods in the historical calendar. We must also bear in mind that, even though concrete or steel are far from new in the building world, reinforced concrete is! Hence, in employing this
material, peculiar to our technology, we are utilizing a plastic, which in its most efficient usage, will resist both tensile and compressive forces to the full capable limits.

This results in behavioral characteristics, both in Maillart's bridges and in contemporary shell constructions, which are much more complex than just the simple linear arch concept applicable to homogenous sections. In fact the complexity is of such a degree, that at the present time, the average professional engineer does not know how, or has difficulty handling the involved concepts (let alone architects)! For example, in the contemporary shell, we now have a structure transmitting loads in the longitudinal direction i.e., parallel with the generating line, as well as in the transverse direction typical to the barrel vault.

The result is that, we are dealing with a structure in which there are an infinity of possible stress distributions for any given loading. In other words, the structure is statically indeterminate, meaning there exists no known mathematical systems capable of directly handling the imposed conditions; whereas, in the design of a simple beam, there is one definite theoretical distribution of stresses corresponding to a given loading condition and hence, analysis is a comparatively simple undertaking. So far, our discussion has been referring to shell designs of single curvature
Difficulties of Indeterminate Structures

shells i.e., corresponding to surfaces of cylinders of identical transverse section. We can see that the problem will become even more complex when we consider the indeterminateness of a shell of double curvature, such as the surface of a portion of a perfect or distorted sphere.

There are many objections voiced in technical circles against the indeterminate structure. Among them is the idea that, since loads are much more concentrated because of fewer supports, the structures become more sensitive to displacement of foundations, particularly in soils of light bearing capacity. Bending moments are directly influenced by such displacements and there exists a constant risk of overstressing. We also hear that a higher degree of workmanship is required and hence higher labor costs. Code conditions are so often accused of being the anti-progressive monster that we forget that technical men have the greatest percentage to say in shaping them.

The registered objections above have a high degree of validity. Certainly soil conditions, labor costs, code conditions are major considerations. But neither soil conditions nor labor costs are constant for each problem, and code conditions can be changed if sentiment against them is

1Eric De Mare, New Ways of Building, p. 85.
sufficiently strong and of a warranted nature. The writer feels that the truthful objection to the continuous or plastic structure is the complexity of analysis. For instance, the roof of the famed Broadcasting Center in Copenhagen, a shell of double curvature, occupied a team of four engineers for more than six months on the calculations.¹

But men must always function through a resisting medium to progress. Complex problems can be solved provided there exists a strong enough desire to solve them. Already modern ultra-rapid computing machines show promise to aid in the complexity of shell engineering. These machines not only are capable of unprecedented speeds but can also "memorize" and carry out complex operations without human supervision.² This does not mean that the architect and engineer must necessarily sit back to wait for the practicability of the machines in order to realize that advantages of shell construction. Of course, the process is not an easy one.

The American Society of Engineers after much time and thorough investigation, has recently published a manual for

¹Leonard Michaels, Contemporary Structures in Architecture, p. 122.

Advantages to Shell Structures

the purpose of encouraging engineers to use, or recognize
the feasibility of shell construction, by simplification of
the more cumbersome methods of calculation in the past.¹
The economy of form and material; the high resistance to
lateral forces - e.g., wind, earthquake, explosion blast,
etc.; are among the many attractive incentives furnished
the engineer.² To the architect, the shell becomes a mouldable medium to which he can give form in conjunction to the purpose of his building.

Appearance of Early Shell Structures in Europe

There are many examples of shell construction now standing, or in a proposal state, which are definitely a tribute to the pioneering spirit of both architect and engineer in their desire for integration of structure and design. Most of these examples represent work done with neither computers nor manuals, but, without a doubt, are expressive of an imagination backed by a sound scientific understanding. As we might suspect, the earliest examples of merit appear in Europe. Where the American architect and engineer would turn their heads from the complexity of designing an


²Eric De Mare, New Ways of Building, p. 85.
indeterminate structure, critical resources force the European to accept the challenge and employ his ingenuity. The process of design follows one of complex calculation and experiment. Even after methods of analysis have been proposed, they generally are too complex to be accepted in this country.

It is natural that one of the first applications of shell designs appears in Germany, where there was most concern about the theory of shell, in the work of Carl Zeiss in Jena, Germany.¹ The next notable example appears in Frankfurt in the form of a Market Hall. The great scale of this structure caused authorities to demand a model test before approving the construction.² In Madrid, Spain, two very notable examples are found in the Hippodrome or the Race Course Stands and in the Fronton Recoletos Hall. The Race Course Stands are shielded from the sun by a cantilevered roof composed of a series of curved hyperboloids. The Fronton Recoletos is composed of two, 3 1/8 inch thick, cylindrical shells, intersecting each other at right angles and enclosing


²Paul Eleck, Architect's Yearbook 2, p. 175.
Unfamiliarity of Shell Techniques in the United States

an area of 107 ft. by 180 ft.¹ A portion of the shell is replaced with an open trellis to provide light to the interior of the hall. Both structures were not only tested by models previous to erection, but also underwent rigorous full scale tests due to the repeated shelling of the Spanish Civil War. Holes as large as 6 ft. in diameter were torn into the Fronton Recoletos without disturbing the slability of the structure.

Since the 1920's when the Germans applied themselves to shell design, the process has come a long way and has proved itself in practice. Yes, in the United States, the techniques are neither widely known, nor widely practiced, though there exists a great opportunity to apply them economically in structures like assembly halls, auditoriums, terminals, hangars, garages, arenas, factories, gymnasiums, and many other types of single story structures generally where the problem is long span. Yes! We may go so far as to say, the process is even applicable to house construction. Architect Paul Fernandez and engineer Felix Candela, collaborated to produce some remarkable reinforced concrete shell houses in Mexico City. The buildings are a challenge to any architect’s imagination and to any engineer’s understanding of

¹Eric De Mare, *New Ways of Building*.
of materials.\textsuperscript{1} But in the United States, we continue to object on the grounds that we lack methods of simple analysis. If such is the case, then the problem is not one of collaboration between architect and engineer in order to achieve integration between structure and design, but emphatically, one of education for both factions involved!

There are, however, a relatively few examples which are worthy of merit in this country. The discouraging fact, however, is that the greatest percentage of structures have been engineered by the one single firm of Ammann and Whitney of New York. Any other ventures into the field of shell construction have been comparatively negligible. Among one of the most famous of these large span structures, is the 10,250 seat livestock coliseum of Montgomery, Alabama. The building is circular in nature, with seating following the inner circumference. It is surprising to note, that bidding favored the concrete version of alternate designs offered in steel and reinforced concrete. Speed of erection was also facilitated because of the selection.

Architects Edgerton and Edgerton were awarded the design for the Onondaga Memorial Auditorium of Syracuse, New York

\textsuperscript{1}Felix Candela, "Skew Shell Utilized in Unusual Roofs," \textit{Journal of the American Concrete Institute}, (March, 1953).
as a result of a competition. The design proposed a shell to cover the multipurpose sports area and auditorium. Engineers, Ammann and Whitney, fully integrated the structure with the purpose of the building to claim a 20 to 30 percent reduction of structural costs. Concrete supports were cantilevered over the seats to psychologically divide the spectator area from the activity area covered by the shell. The concrete cantilevers not only served to divide function, but simultaneously served a cost and structural purpose. As supports, they resisted the thrust of the shell, and at the same time, permitted a lower average roof height, which resulted in a lower cubage cost and a more humanized scale or proportion. The supports also served to reduce the clear span of shell required to roof over the auditorium, thereby resulting in a reduction factor for foundations and other supporting members. From the standpoint of integration, it appears, that the engineers operated imaginatively and efficiently to weld structure and function together.

In the writer's opinion, the Memorial, as an architectural work, suffers as soon as it leaves the auditorium proper. Then, there is a resort to conventional framing.

resulting in masses which appear incompatible with the main shell form. The feeling is one which leads the observer to believe, that the designers were either reluctant to express the quality of the main structure, or just did not know quite how to cope with it. A higher degree of integration is promised in the proposed Terminal Building for St. Louis' Municipal Airport by architects Hellmuth, Yamasaki, and Leinweber and engineer, Wm. C. E. Becker. The three pairs of intersecting cylindrical vaults are frankly expressed, and as a whole, form a stimulating composition.

More is known concerning the integration behind Saarinen's proposed M. I. T. Auditorium. The auditorium represents a more advanced and more complex system of shell construction, in that, it is dealing with double curvature. The inspiration seems to stem from the 160 ft. Domed Market Hall of Algeciras, Spain, which transmits forces to the ground through eight columns supports. Saarinen's dome is in the shape of spherical triangle, but eliminates columns by resting on the three corners of the triangle.

Ammann and Whitney are convinced that the auditorium design will be at least competitive in cost to more

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Precast concrete hangar near Rome, by Architect-Engineer, Nervi, spans an area of 135' x 340' with but six supports. Executed in steel, this type of construction would require but 3 to 5 pounds of steel, whereas a 20'x20' skeleton bay would require 10 to 16 pounds of steel to support a 200 pound load.

The long span, shell concrete, roof of the K.B. Tennis Hall in Copenhagen, Denmark not only represents an efficiency in use of material, but demonstrates the smooth flowing lines synonymous with economy of form in structure.

Proposed Terminal building for St. Louis Municipal Airport is roofed by pairs of intersecting shells of single curvature. It is the principle of the historical cross-vault applied to modern technological materials. Architects Hellmuth, Yamasaki & Leinweber. Structural Engineer, Wm. Becker.
Cost of M. I. T. Auditorium

This is an enlightening statement especially when one considers that the constancy of form work is at a minimum and hence encourages a high cost of labor. The cost of the shell is estimated at $60,000, with tile roof and buttress footings, the cost may rise to $100,000. This represents but a 2% cost of the total building! Hence, costs variations on the dome as high as 25%, will, but effect the total building cost by 2%. Cost per seat today in a small theatre is about $1,100. In Saarinen's auditorium the estimated cost is about $900 per seat.\(^2\) The shell offers another advantage in, that once it is constructed, the remainder of the enclosure is a rapid and simple operation. The transparent medium of our technology, glass, easily and efficiently walls up the voids between the corners of the triangle.

Bolt, Beranek, and Newman, M.I.T.'s famed acoustical experts, are equally convinced that the dome permits them to solve the auditorium's acoustical problem with ease and grace. Saarinen's concept of acoustics is opposed to the idea offered by Le Corbusier in his Leagues of Nations project, that acoustics should shape the building.


\(^2\)ibid.
The auditorium for the M.I.T. campus designed by Eero Saarinen & Associates is structurally integrated with a concrete + steel dome—a shell of double curvature. The dome represents 1/6 of a sphere, or triangular in plan and rests on each corner of the plan. The result is an excellent visual arrangement of seats. The dome, easily lends itself to an efficient acoustical treatment. The glass shell building exhibits an economy of form and a resulting graceful appearance similar to those found in the smooth flowing lines of today's aircraft. The completed structure, say engineers Ammann & Whitney will be competitive to other forms of construction. A prediction is made of cost at $900 per seat. Today's theaters average a cost of about $1200 per seat.
Saarinen's contention is that an ideal acoustical shape would generally be opposed to an ideal visual shape. As it is, the dome favors the vision of the spectator by its shape, but at the same time, allows an interesting and perfectly efficient acoustical treatment by suspending a partial, floating cloud ceiling from the dome. All considered, the M.I.T. Auditorium is a highly integrated work of design and structure, art, and science, which exhibits the grace in line and movement of today's aircraft, and is simultaneously conscious, with equal sensitivity, to its time and technology. It is a beacon light for the new generation of architects and engineers of this country.

The author by no means advocates, that we shall abandon all systems of construction in favor of the shell. Nor is it advocated, that the newer systems of construction must necessarily pivot about the idea of the spherical or cylindrical shell. The shell does, however, represent a most excellent symbol of principles, by which, we can achieve a greater integration of structure and design in terms of the potentialities of our time. The concept of economy of form and material, achieved by the plastic nature of materials peculiar to our technology, the principle of continuity, characteristic to the monolithic nature of the structure, are most clearly demonstrated in the shell.
Beyond the Shell

Livestock Pavilion of North Carolina

We do have the data to efficiently employ the shell as a component of our architecture. Its ultimate realization is dependent upon time and training, and the conviction, that it is worth while. The process will not be an easy one, and though we may consider that the shell in itself is primarily an engineering problem, the architect will have no small part to play in its application. He must be willing to understand the problems, difficulties, and methods of the engineer so, that there may ensue a creative, but intelligent, employment of his talents.

But why must we stop at shells? The principles advocated can be realized practically in an innumerable number of forms. The difficulty is, that no data is published for every conceivable type of structure, and hence, taxes the ingenuity of the architect, engineer, and builder alike. Again, in adherence to our principles, we must remember, that we are dealing with structures which are largely statically indeterminate. But this does not mean that they must be abandoned as impractical! As more difficult, as more time consuming, and as a challenge to the ingenuity of men—yes!

A tribute to that spirit, which has progressed beyond shell construction, is the Livestock Judging Pavilion of Raleigh, North Carolina. This exciting glimpse into the future was designed by architect Wm. H. Dietrick.
consulting with architect Matthew Nowicko. Severud, Elstad, and Krueger were the ingenious group of engineers who aided in making this dream a reality. As in Saarinen's auditorium, this building exhibits a beauty peculiar to the grace of economy of form and material. The structure is often compared in operation to a canvas topped camp stool with intersecting legs. The Pavilion, similarly, is formed by intersecting legs in the shape of two enormous parabolic arches of concrete, hinged at the point of interlock, and acting as compression rings for the suspended catenary roof. The steel roof, simulating the canvas top of the chair, is entirely in tension as are the cables that support it. Here we see the principle of the suspension bridge and the principles of Maillart's arched slabs in three dimensions.

The author does not unfairly wish to minimize the idea, that numerous difficulties were encountered in the problem. For instance, how to keep the roof from fluttering when the wind blew across the hollow surface, or how to support the arches on the abutments without inducing high bending moments, or how to prevent the spread footings from shifting horizontally, and many other additional problems. Each, however, was met and satisfactorily solved to produce commendable architectural work. The cost of the building, exclusive of land and seats, ran to a highly competitive
parabolic pavilion

Economy of form need not be confined to suspension cables, arches, and shells. The livestock Judging Pavilion at Raleigh, North Carolina typifies what can be achieved by structure-design integration. Overlapping and hinged concrete compression arches, supported by roof cables for an efficient utilization of materials. Conceived by Matthew Nowicki, Architect; Wm. Deitrick Engineers, Severud, Elstad & Krueger.

Right - Pavilion during construction stage showing the tension cables strung to the mammoth arches. A metal roof is to follow the curves initiated by the cables.
43 cents per cubic foot or $16.21 per sq. ft. The final cost figure was estimated at $1,600,000 which is closely compatible to the million - and - a - half dollar shell construction of the near, equal sized, Montgomery, Alabama, Coliseum. The structure is a standing proof, that structure and design can be integrated to the degree of losing individual identity, of being neither structure nor design, but a marriage called architecture.

Other possibilities in structures, illustrating the principles advocated herein, have been presented by such men as Buckminster Fuller, Fred Severud, and F. J. Samuely. The ideas presented are in the form of saddle shaped structures, hyperbolic paraboloids, oval trusses, etc. All center about a belief proposed by Maillart, that "the resistance function in reinforced concrete structures must rest mainly upon the election of an appropriate and preferably light form. The resistant function can be more safely attained in this manner than by means of exorbitant concrete masses." The present conceptions go one step further in not limiting Maillart's thought to reinforced concrete, but broaden the


category by speaking of "stressed skin," known in the engineering sense as membrane stresses. Considering the other objections, such as code, concentrated load, etc., the chief difficulty in the practical employment of these ideas, again centers around the high degree of indeterminancy.

Usually, the architects stock answer to the problem pivots about empirical methods. Though there is much merit to the idea, the architect must clearly realize, that it is impossible to predict the exact behavior of structure merely by experiment! Difficulties present themselves in the inability to exactly duplicate conditions of the final structure, and the change of conditions due to time. In concrete, for instance, the problem of "plastic flow", also called "time yield" or "creep", in effect, produces a volume change in the concrete through period of time, and causes a redistribution of bending moments. The challenge to the architect-to-be, then, is an attempt to appreciate the difficulty of the engineer, and attempt to work constructively with him.

Similarly, a challenge is extended to the position of the generation of engineers-to-be. If we agree that the structures in question are statically indeterminate, why must we look for solutions via conventional methods of statics? Is the rigorous method of present "rational" design in structure possible to meet these new demands?
Analysis is necessary, but certainly, the conventional methods of approach are not adequate. Even our so called "rational" methods are not necessarily in harmony with the actual behavior of the materials we employ.

The answer appears to lie somewhere between the empirical methods advocated by the architect and the rigid "rational" methods in the vocabulary of the average engineer. In spite of all the difficulties that may be implied, the opinion of the writer is that technology has afforded us the means to more clearly understand the behavior of present day building materials, and to predict their actions in a structure with a reasonable degree of efficiency. The major proviso is, the desire to do so and the conviction of its necessity.
The standards of the artist are not sufficient in themselves to judge the merit of an architectural work. Additional standards are imposed by the relation of a building to its time and technology. Hence "good" architecture then, must satisfy both the scientific and artistic considerations.

We see the tendency of men to imitate their past. The inevitable result is a failure in fully exploiting, to maximum advantage, the inherent characteristics of the materials afforded by the prevailing level of technology. Our technology has made possible plastic media, such as reinforced concrete, welded metals, steel, etc., yet their predominant usage is in the fashion of the archaic post and lintel system of the ancient Greeks. Men like Maillart have proven, that there are more efficient uses of present day materials than those dictated by tradition. His bridges are examples that science and art are not conflicting elements but partners in the process of building. He has integrated structure and design through expression of the economical material form of reinforced concrete by considering the monolithic character or the aspect "continuity" inherent in the nature of the material.

Nature appears to illustrate the same principles of continuity and can serve as an inspiration to men. We must not
however, attempt to imitate nature, but should try to understand her principles. Yet, by and large, we continue to imitate tradition on pretexts of economy of cost, code impositions, etc. Though these factors should be considered, they are variables that need not consistently, or unjustly, interfere with progress.

Among the most noteworthy departures from the conventional structural methods, is the field of shell construction. The principles symbolized by the shell are analogous to those of Maillart and indicative of our future in architecture. The plastic materials of our technology have been molded into a form of material economy which takes advantage of its "continuous" or monolithic nature. Shell construction has proven itself admirably, in versatility and strength, both abroad and in this country. The shell has similarly demonstrated that it is at least competitive in cost with other systems of construction despite the associated high labor costs. The greatest barrier to shell construction is the inability to cope with, or lack of knowledge concerning, methods of structural design. Workable information concerning the mechanics of shell design are available however, provided the architect and engineer are interested enough to pursue them.

The plasticity and economy of form through the
principle of continuity is not confined to shell structures. The marriage of structure and design permits innumerable combinations of form. The principle objection to these plastic forms is that they are statically indeterminate and hence, nearly impossible to analyze by conventional methods.

If, however, we choose to recognize the materials and techniques provided by our technology, and to employ them according to their own inherent natures rather than in the manner of tradition, we face a problem, not of collaboration, but of education! Structure and design are part of the same process of building. If they continue to be considered, taught, discussed, and thought of as entities, they will more often than not, be reflected as such in the architectural product.

It is impossible for a man in a life time to know all there is to art or all there is to science. Yet, from the architectural point of view, he must know enough of the general nature of both so that his buildings may reflect an awareness of the forces responsible for its creation.

In the past few years, there has been a serious attempt for the architect and the engineer to collaborate, but as a rule, collaboration too frequently never passes the point of compromise. The painful truth of the matter is, that the architect stands on one side of the building fence and the
engineer on the other. We cannot expect that each should know the other's field. We can however, expect a mutual appreciation of each position, to the degree, that we can work creatively together.

In the meantime, the architect must bear the burden of attempting to reconcile structure and design, art and science, in architecture. The incentive is the challenge of our time and technology; to utilize her techniques and the plastic nature of her materials; to utilize them efficiently and creatively; and to fuse intellect and feeling in bringing forth tomorrow's architecture.
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MISCELLANEOUS

