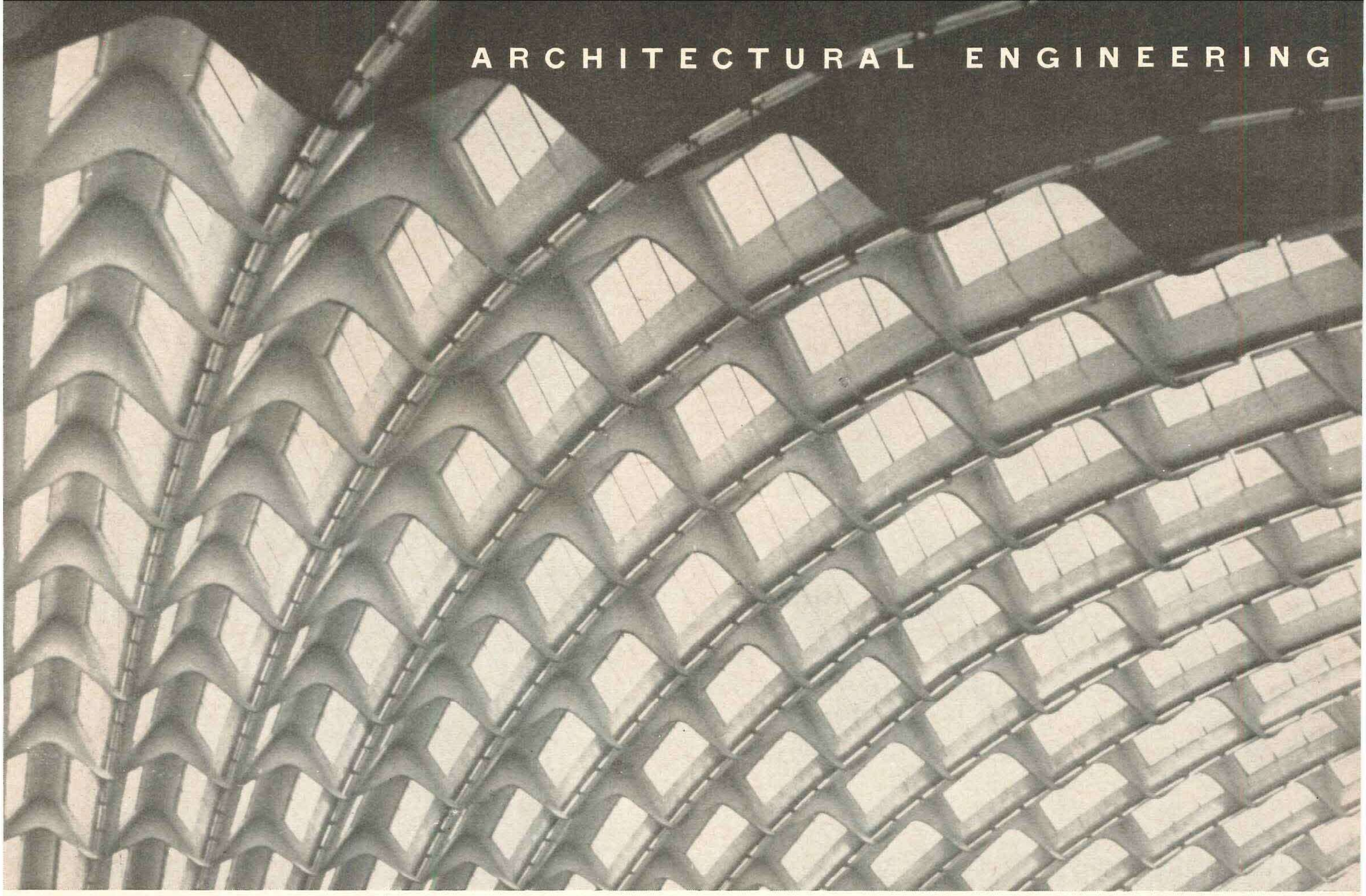


A PHILOSOPHY FOR BUILDING "CORRECTLY"

NERVI

Excerpts from Costruire Correttamente *by Pier Luigi Nervi. This book, translated by Giuseppina Salvadori and prefaced by Mario Salvadori, is to be published in July by F. W. Dodge Corporation.*

MANY DEBATES about architecture have been heard during the last decades and they continue today. But even if debates led to final conclusions, acceptable to the most severe critics, their practical results would be meager unless the client's judgment, the techniques and economics of building, and the academic preparation of the designer were adequate to the solution of the new architectural, structural and economic problems.

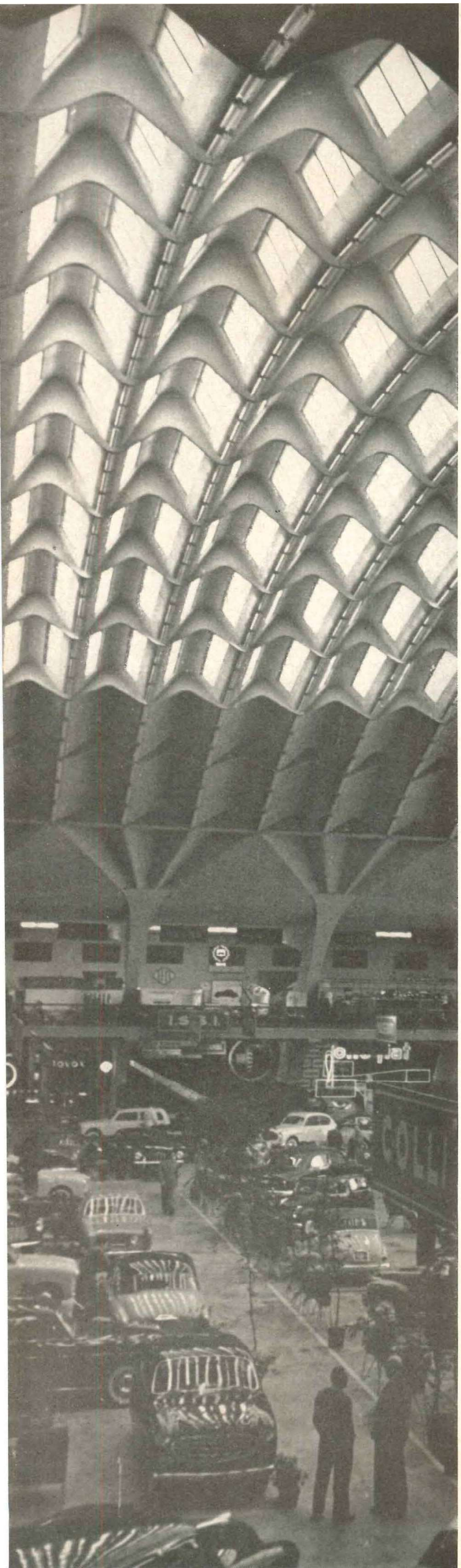
Similarly, the present dynamic development of theoretical research on reinforced concrete will not yield practical results unless we obtain a better knowledge of the actual behavior of this material and learn to relate more strictly the elements of structural intuition, mathematical calculation and construction procedure. Only a perfect synthesis of these factors can realize the unlimited technological and architectural potentialities of reinforced concrete structures.

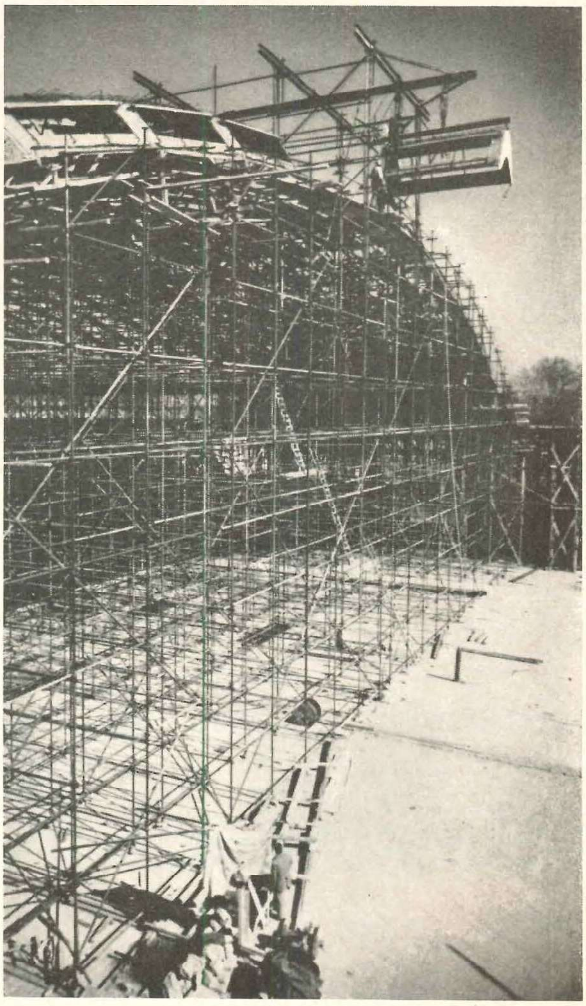
Construction gathers in a unique synthesis the elements of manual labor, industrial organization, scientific theory, esthetic sensibility, and great economic interests. Construction creates our physical environment, and thus exercises a silent but deep educational influence.

On the other hand, we all help to determine its characteristics and the direction of its development by passing judgments, by expressing preferences or dislikes, or by intervening directly in the construction process.

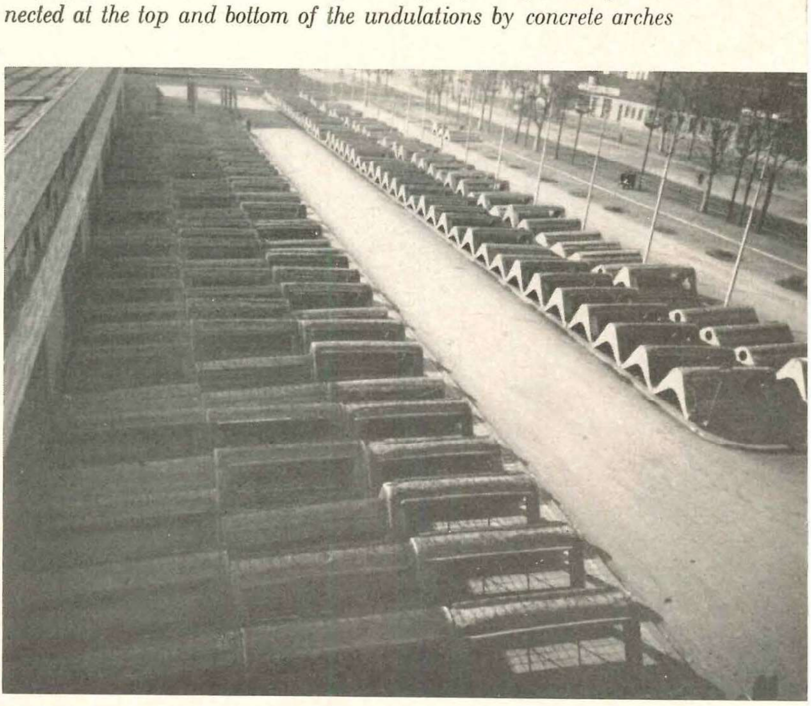
THE ROLE of the client is as important as it is difficult. In my long life as a designer and builder, I have seldom found clients capable of stating their problem clearly, of choosing the designer and his design wisely, or of accepting the responsibility for a daring structural or esthetic solution.

The designer, after a thorough study of the problem and under the impulse of his creativity, is naturally and understandably daring. The courageous decision of the client is to be admired much more, since it must be unemotional and must weigh, on one hand, his desire to build a structure in which he believes, but which will not necessarily be identified with him, and, on the other, his personal loss if it should fail. The client influences the architectural solution directly. Consciously or unconsciously, by defining the general outline of the structure, by choosing the designer, and by accepting or rejecting the designer's project, he becomes a decisive element of the architectural solution.



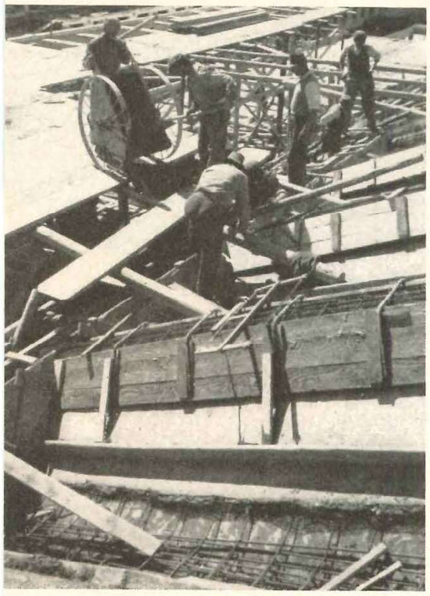


The whole structural concept and visual effect of the famed shell for the Turin Exposition Building were made possible through the utilization of a construction material developed by Nervi called Ferro-cemento. It consists of layers of fine wire mesh, and sometimes small bars, embedded in cement mortar to form prefabricated elements. For this shell they are only 1½-in. thick, and thus comparatively lightweight. They are connected at the top and bottom of the undulations by concrete arches



The average quality of the architecture of a nation is more influenced by the tendencies and the cultural level of the clients than by the knowledge and esthetic sensibility of its architects. Any hope that the modern architect, even if exceptionally capable, may win over the unsympathetic client is completely vain: in a coarse society the refined architect will be permanently unemployed.

THE ACADEMIC TRAINING of designers and builders presents a complex and difficult problem. Our universities lack tradition in the scientific approach to building because the theoretical study of structural and construction problems is only about a hundred years old. As far as an artistic approach is concerned, the revolutionary changes in the basic concepts of architectural esthetics, initiated at the beginning of our century and still in progress, have not given us clearly defined directives, even if they have succeeded in separating our problem from those of the Beaux-Arts academies.



All fields of knowledge play a role in the field of architecture and must find in it a balance capable of expressing values of an artistic, moral and social character which are neither easily definable nor commensurable. Moreover these values are, in a sense, absolute values that truly represent the essential characteristics of all construction — durability in time.

It is my belief that to express an esthetic feeling through the states of static equilibrium, the satisfaction of functional needs and technical and economic requirements — that is, by such a variety of knowledge — is much more difficult than to express any other kind of feeling by other intellectual means.

The loftiest and most difficult problems arise in architecture from the necessity of realizing a synthesis between opposing sets of factors: the harmony of form and the requirements of technology, the heat of inspiration and the coolness of scientific reason, the freedom of imagination and the iron laws of economy.

DO BUILDING PROBLEMS, even in their most technical aspects (for instance, stability) allow unique and impersonal solutions obtainable by the application of mathematical formulas? Or, on the contrary, can they be solved correctly only through a superior and purely intuitive re-elaboration of the mathematical results, because of the complexity of the inherent deficiency of our theoretical knowledge and, finally, the wide discrepancies between theoretical premises and physical reality?

In this re-elaboration lies the most promising means of penetrating the mysteries of the structural world.

Probably because I have failed to make myself clear, I have often been interpreted as trying to undervalue the results achieved by the mathematical theory of structures. I have thus been both championed and contradicted by people who did not understand my thoughts.

It would be absurd to deny the usefullness of that body of theorems, mathematical developments, and formulas known by the rather inaccurate name of "Theory of Structures." But we must also recognize that these theoretical results are a vague and approximate image of physical reality. We come nearer to this reality only by adding to the mathematical results the results of experiments, by observing the actual phenomena, by establishing a conceptual basis of these phenomena, and above all by understanding intuitively the static behavior of our works.

The fundamental assumption of the theory of structures is that structural materials are isotropic and perfectly elastic. But the most commonly used building materials, like masonry and concrete, are far from being isotropic and elastic.

Theory of structures considers our buildings being out of time, in a kind of eternal stability and invariability. The simple and commonplace fact that all structures decay and, after shorter or longer periods of time, become unstable, or at least show excessive displacements and amounts of damage, proves that this second assumption is also unrealistic.

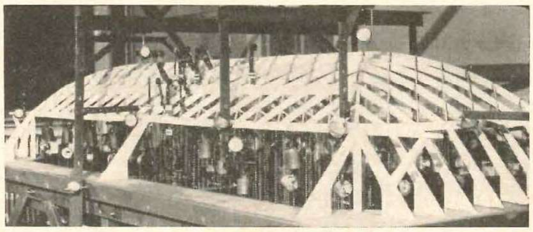
No soil is perfectly stable nor settles uniformly as time goes by. All building materials, but particularly masonry and concrete, flow viscously. The daily and seasonal temperature variations are irregularly distributed in the structure because of prevented displacements, and create stresses of unforeseeable magnitude and direction.

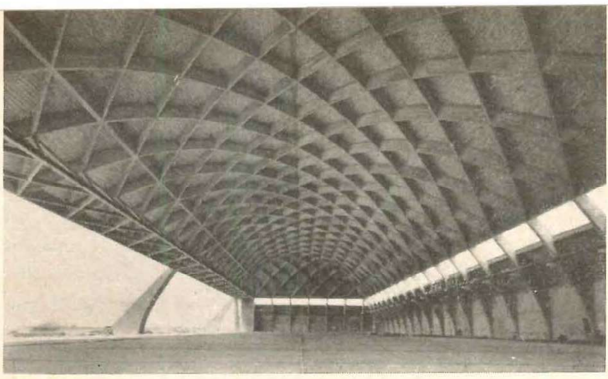
In other words, theory of structures may be compared to a physiology of perfect organisms which are permanently youthful and untouched by disease or functional deficiencies. The programs of our schools of engineering, from which the structural training of our architectural schools are derived, were set up during the second half of the past century. This was a period of great and justified enthusiasm for the developments of mathematical theory of elasticity which clarified the behavior of materials under load and allowed the analysis of statically indeterminate structures. As usual this enthusiasm impaired the objectivity of the engineer, who was led by his mental make-up to believe in the theory even when it was contradicted by facts.

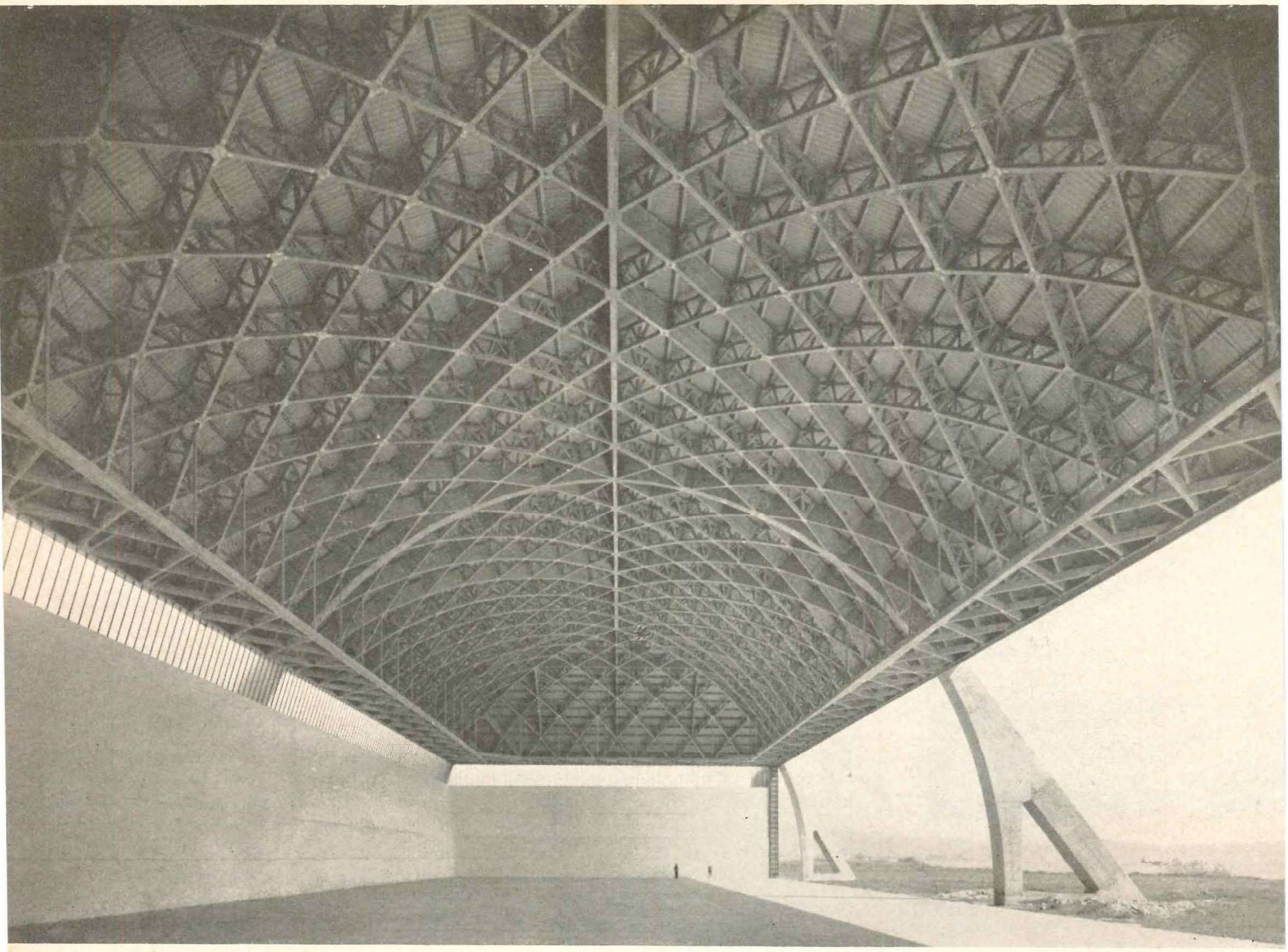
The pre-eminence given to mathematics in our schools of engineering, the purely analytical basis of the theory of elasticity, and its intrinsic difficulties, persuade the young student that there is limitless potency in theoretical calculations, and give him blind faith in their results. Under these conditions neither students nor teachers try to understand and to feel intuitively the physical reality of a structure, how it moves under load, and how the various elements of a statically indeterminate system react among themselves.

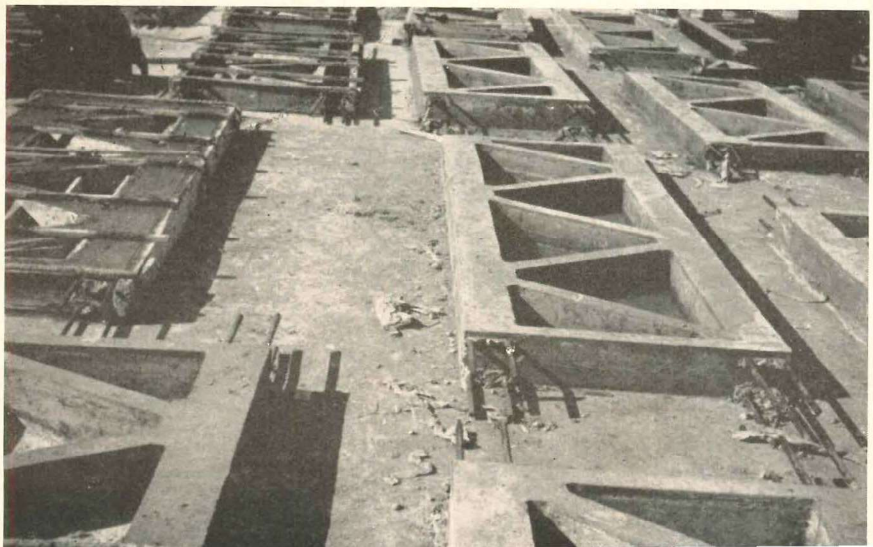
We cannot deny that the potentialities of mathematical methods are soon exhausted, even when their application is difficult and complex. Skin-resistant and highly indeterminate structures cannot be analyzed by mathematical theories, although these structures are extremely efficient from a technical, economical and architectural viewpoint.

The formative stage of a design, during which its main characteristics are defined and its qualities and faults are determined once and for all, cannot make use of structural theory and must resort to intuition and schematic simplifications. The essential part of the design of a building consists in conceiving and proportioning its structural system,









Model analysis in design and prefabricated components in construction are two basic elements in the building philosophy of Nervi. His hangars exemplify both. (There were six, all destroyed by war.) The first hangar, (top) built in 1935, was cast in place, and its design was based primarily on model analysis. A major improvement in later hangars was the use of prefabricated trusses to lighten the structure. Trusses were joined by welding of reinforcing bars and filling space with high-strength concrete in evaluating intuitively the dangerous thermal conditions and support settlements, in choosing materials and construction methods best adapted to the final purpose of the work and to its environment; and, finally, in seeking economy. When all these essential problems have been solved and the structure is thus completely defined, then and only then can we and should we apply the formulas of the mathematical theory of elasticity to specify with greater accuracy its load resisting elements.

The student lacking a thorough knowledge of structures considers an actual building essentially as a form. This attitude fosters solutions which are statically illogical and at times unrealizable, and starts an inner conflict between a desire for structural audacity and the incapacity of its realization, which is common to the great majority of designers today.

Unfortunately, although the present methods of stress analysis are extremely ingenious and one may hope that they will be refined in the near future, their efficiency in solving complicated statically indeterminate systems (particularly three-dimensional systems) is limited in comparison with the creative potentialities of the imaginative designer and the available construction methods. Some of the newer systems cannot be analyzed theoretically, and, therefore, their realization would be impossible without the practically limitless assistance offered by experimental stress analysis.

The only drawback to the experimental procedure is that the preparation of the model, its loading, and the reading of gauges are lengthy and costly operations. Whenever possible, it is therefore more convenient to use a theoretical approach and to limit the use of model analysis to structures of special technical and architectural importance.

What significance can we give, and what limits can we assign, to the word *art* in the field of construction? Can we consider as an artistic fact a structure or a building which is strictly defined by the laws of statics and dynamics, independent as they are of the human will and of our esthetic feelings? Are the parabolic profile of a great bridge, the catenary of a suspension bridge, the aerodynamic shape of an airplane to be considered artistic? Doesn't art require a freedom of form and of expression denied to all human products governed by physical laws? And how are we to establish how much freedom is necessary and sufficient to art?

I believe that art gives more than simple esthetic satisfaction. I think art is to be found in that indefinable quality of work to evoke in our minds the feelings and emotions experienced by the artist in the impetus of creation. If this emotional communication be the test of art, to define its characteristics is obviously impossible and to try to teach art would be negative and fruitless.

I believe, therefore, that the most effective artistic training should not go beyond those limits which in the field of literature are represented by grammar and syntax; that is, beyond the mastering of the means of expression. These means allow one to say what is to be said in correct, understandable, and formally satisfying sentences, or at least sentences which are not unpleasant.

The field of architecture presents the same situations. The real danger to architecture, today as always, is not represented by a simple, humble, and correct approach to its problems, but by an emphasis on rhetoric or by a decorative vacuum. These dangers are of a more fundamental character in architecture than in literature, since one cannot ignore an architectural failure, and one cannot forget the economical losses due to architectural rhetoric.

I believe, therefore, that the schools of architecture should above all teach structural correctness, which is identical with functional, technical, and economic truthfulness and is a necessary and sufficient condition of satisfactory esthetic results. The esthetic results achieved by these means usually suffice even if they do not reach superior heights of art.

I believe that even philosophers interested in esthetics find it difficult to explain the origin of our feelings toward forms which are dictated by the laws of statics or dynamics, since these laws are not intuitively understood, nor are they explainable by the experience of our ancestors. But there is no doubt that any product of high efficiency is always esthetically satisfying.

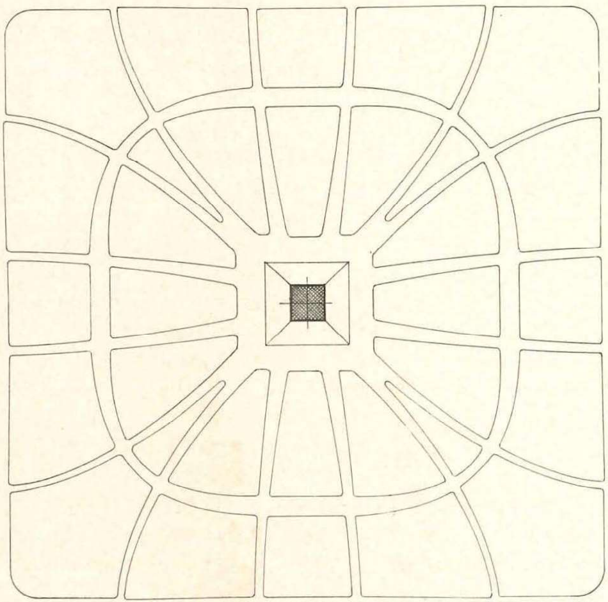
Reinforced concrete is truly the most interesting and fertile structural material available to mankind today because of its high compressive strength, its exceptional weather resistance, its constructional simplicity, and its relatively low cost.

As against these and many other positive qualities, reinforced concrete presents some hidden deficiencies and specific characteristics which make its structural behavior difficult, if not altogether impossible, to foresee exactly. Its high thermal sensitivity, its shrinkage, and above all its plasticity, shatter our hopes of investigating or knowing either before or after construction the real conditions of equilibrium of any statically indeterminate structure.

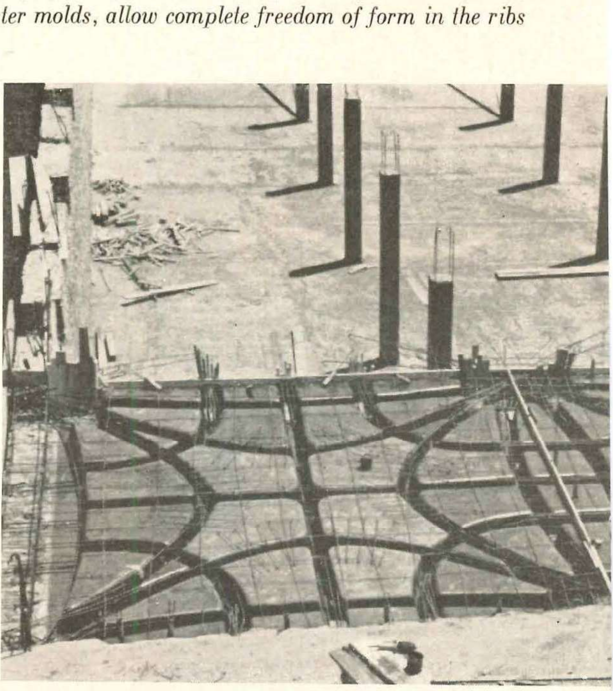
A few days after being poured, a concrete structure, particularly if it is complicated, is strained by internal forces that are independent of the external loads. These forces grow with the shrinkage of concrete and under the influence of thermal variations until the plastic flow of overstressed sections or the development of fine cracks brings about a sufficiently stable condition of equilibrium.

We must frankly confess that neither the designer nor the builder can be entirely satisfied with this final result. Even if the cracks, the excessive stresses, and the plastic flow are not considered dangerous, the solution is obtained at the cost of the structural continuity of the building — that same continuity which was the object of such complicated calculations.

Another factor of great importance to the success of a reinforced concrete structure is good formwork. The lowering of the forms of a concrete structure may well be compared to the critical moment of delivery. Whenever I have witnessed the lowering of the forms of a large structure constituting a single static system, I have noticed the impossibility of lowering all the forms simultaneously and have asked myself with deep anxiety whether the strains and the irregular conditions of loading to which the structure was subjected at the time would not induce stresses far above the allowable limits, or even above the breaking point. The adaptability of concrete structures to unforseen conditions and their capacity to over-



"The pattern of steel should always have an esthetic quality and give the impression of being a nervous system capable of bringing life to the dead mass of concrete." Amazingly, such a design condition may arise out of the structural requirements, as in the Gatti wool plant in Rome. Slab ribs are set along the isostatic lines of principal stress. These lines depend exclusively on the loading of the floor. Movable forms of Ferro-cemento, cast previously in plaster molds, allow complete freedom of form in the ribs



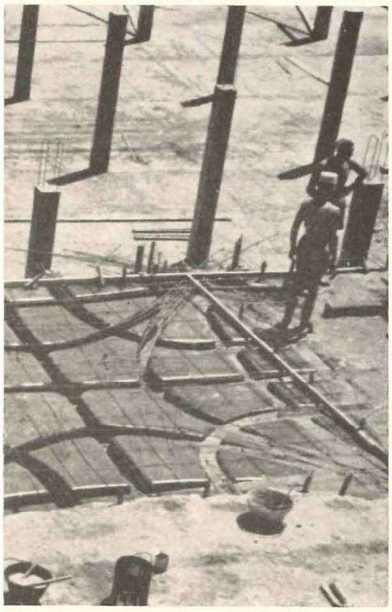
come temporary critical strains always fill me with wonder and admiration.

Although it is difficult to achieve an economical and permanent concrete structure which will remain youthful throughout the years, I shall make a few suggestions on how best to approach the goal.

My first and perhaps most fundamental suggestion is to create structures which are harmonious both in form and in the distribution of steel reinforcement. This quality, which may seem totally abstract and only esthetically important, has a deep correspondence with the physical reality of the structure. As I pointed out above, because of its inherent and unavoidable continuity, a concrete structure is an organism in which stresses spread from one element to another so that all together they withstand the internal or external forces menacing its stability. Almost always these forces are not only those considered as loads in the computations, but also those deriving from shrinkage, thermal variations, and yielding of the supports.

This complicated state of stress in the structure creates singular regions where stress concentrations are bound to arise as soon as the various elements are not well proportioned. Stress concentrations in turn are responsible for both capillary and large cracks. Hence, we must avoid all dimensional discontinuities between adjacent elements and substantial differences in the steel content of the sections of a member or adjacent members.

The steel reinforcement of a complicated structure should be so designed as to form in itself a stable structure capable qualitatively of sustaining the load. The added concrete should then be capable of implementing the equilibrium quantitatively, by connecting the steel bars and by absorbing compressive stresses. The pattern of steel should always have an esthetic quality and give the impression of being a nervous system capable of bringing life to the dead mass of concrete.



THE MOST SPECIFIC characteristic of concrete which usually determines its structural behavior and makes it so difficult to analyze, is the remarkable variability of its stress-strain ratio — that is, its imperfect elastic behavior.

In the first place the elastic modulus of concrete varies due to the problems inherent in mixing, placing and curing. Secondly, the elastic modulus changes due to plastic stresses and the strains or yielding under constant load (viscosity). The structural consequences of these two sets of causes are substantially different.

The first type of variability only gives trouble when it causes the elastic modulus of concrete to differ in two collaborating members of the same structure.

The changes in the elastic modulus due to the second set of causes, including the decrease of the modulus with stress, its increase under repeated loading, and its plastic flow under load, is of greater structural importance.

Due mainly to plastic flow, a concrete structure tries to adapt itself with admirable docility to our calculation schemes, which do not always represent the most logical and spontaneous answer to the requests of the forces at play, and it even tries to correct our deficiencies and errors. Sections and regions too highly stressed yield and channel some of their loads to other sections or regions which accept this additional task with a commendable spirit of collaboration within the limits of their own strength.

What are our present chances of understanding and of mastering such complicated phenomena? At present their qualitative and quantitative determination is out of our grasp. A designer bold enough purposely to increase or decrease the plasticity of certain concrete elements, contributing with others to the strength of the same structure, does not have quantitative data that can lead him to even roughly approximate results. In practice, the importance of this data would be fundamental. For example, by increasing the plasticity of certain parts of fixed arches the pressure resultant due to the dead load could be centered at all sections, thus resulting in great economy for these structures, in which live load is of minor importance.

THE FUNDAMENTAL IDEA behind the new reinforced concrete material Ferro-cemento which I have developed is the well known fact that concrete sustains large strains in the neighborhood of the reinforcement, and that the magnitude of the strains depends on the distribution and subdivision of the reinforcement throughout the mass of concrete. With this principle as a starting point, I asked myself what would be the behavior of thin slabs in which the proportion and subdivision of the reinforcement were increased to a maximum by surrounding layers of fine steel mesh, one on top of the other, with cement mortar.

The square mesh was made out of ductile steel wires 0.02 to 0.06 in. diameter, set 0.4 in. apart. The mortar was made of 0.6 to 0.75 lb of cement to the cubic foot of good quality sand. The slabs were very thin but extremely flexible, elastic, and strong.

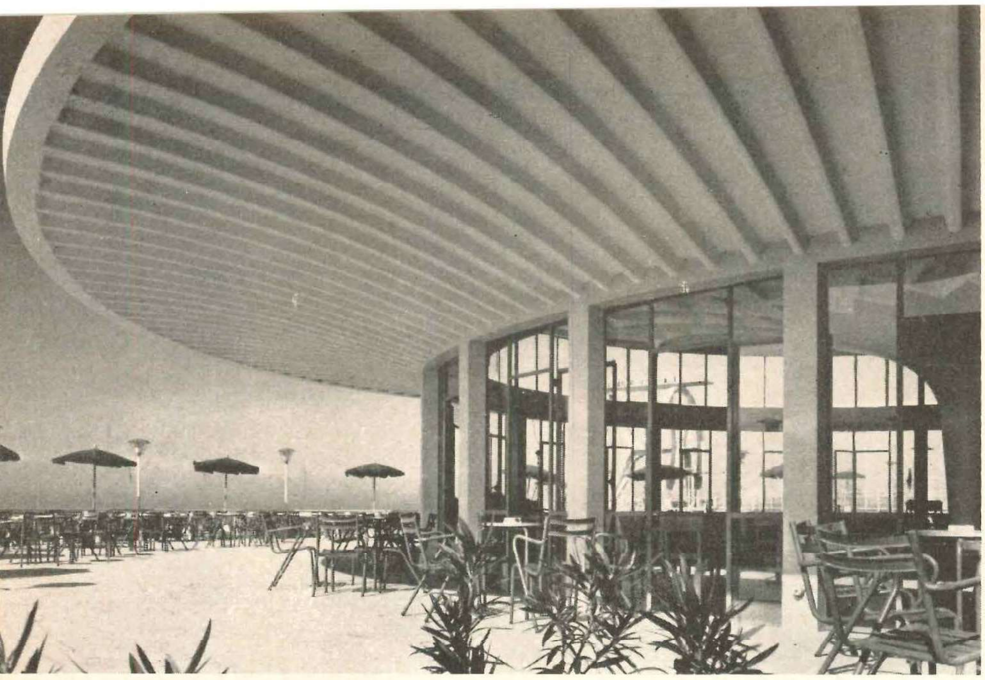
Later on, in order to increase the thickness and the strength of the slabs without using more than 10 to 12 layers of mesh, I tried inserting one or more layers of steel bars 0.25 to 0.4 in. in diameter between the middle layers of mesh, thus attaining thicknesses of 2.5 to 4 in.

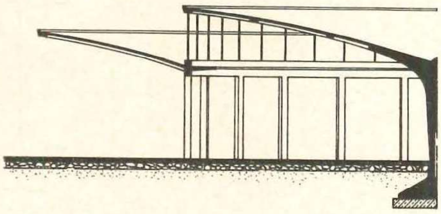
The material thus obtained did not behave like regular concrete, but presented all the mechanical characteristics of a homogenous material.

Experiments with the new material demonstrated immediately its most important and fruitful properties: absence of cracks in the cement mortar even with a large amount of strain because of the subdivision of the reinforcement; and elimination of forms since the mesh acted as a lath to retain mortar.

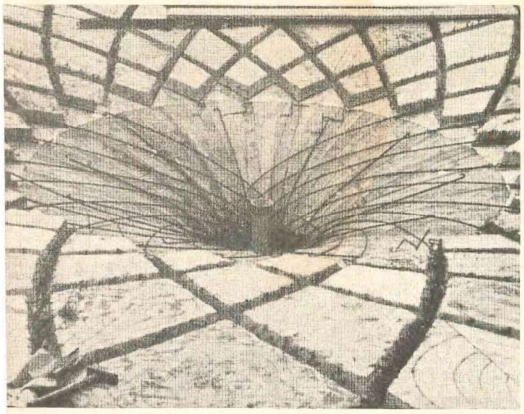
During the last few years I have constructed buildings in which Ferro-cemento was not only conveniently and interestingly applied, but also was a decisive design factor both technically and architecturally.

The most important of these applications is the large undulated shell of the central hall of the Turin Exposition Building, which spans 300 ft. The shell is built with prefabricated elements of Ferro-cemento, connected by reinforced concrete arches at the top and the bottom of the undulations.





A highly expressive geometric pattern was formed in the ceiling of this restaurant designed by A. La Padula through a refinement in Nervi's prefabrication techniques. Precast, coffered sections, about 1-in. thick were assembled on a platform with spaces left between for reinforcing of the stiffening ribs



Reinforced concrete is the most revolutionary material of our entire building history. The essence of the revolution consists in the possibility of realizing structures in perfect conformance to statical needs and visually expressive of the play of forces within them.

The most elementary structural elements acquire new and expressive interest. Beams lose the prismatic rigidity of wooden struts and of standard metal sections, and may plastically follow the variations of stress. Columns free themselves from the constant cross-section of stone and masonry pillars. Three-dimensional structures, like domes and barrels, acquire a freedom of form unknown to masonry.

The full development of reinforced concrete depends partly on the mental development of the designer, who must consider the concrete structure as the materialization of the most efficient structural system, but also on the refinement of construction procedures. Through study of these construction methods the rigidity of wooden forms can be eliminated, allowing the economic realization of curved surfaces and elements of variable cross-section, as required by the flow of stress.

Architecturally and structurally, concrete is promising in the field of skin-resistant structures, that is, those structures whose strength is a direct consequence of the curvatures and corrugations of their surfaces.

We cannot deny that the practical realization of large form-resistant structures presents great design difficulties. These theoretical difficulties are, in my opinion, neither unsurmountable nor great. Not only is the theory of structures being continuously developed, but even today we can solve satisfactorily the most complicated structural problem by experimental stress analysis. The real difficulty to be overcome is the general lack of intuitive understanding about the structural behavior of these resistant systems, and the difficulty of communicating such intuitive knowledge to others.

The many examples of form-resistant structures such as flowers, leaves, sea shells, etc., are either too small in scale to involve the weight of our body or the strength of our muscles, or, being decorative, do not suggest a direct structural experience. Other examples of form-resistant structures, like automobile bodies, airplane wings, and ship hulls, polarize our attention exclusively towards mechanical systems and, hence cannot be translated easily into civil engineering structures. Thus resistance due to form, although the most efficient and the most common type of resistance to be found in nature, has not built yet in our minds those subconscious structural intuitions which are the basis of our structural schemes and realizations. In other words, we are not yet used to thinking structurally in terms of form.

How can we define and limit the technical potentialities of a material which in fifty short years has conquered the most varied fields of construction? Its structural limitations are hard to foresee. Although our knowledge of concrete is anything but complete, we are already capable of building concrete bridges spanning over 1000 ft (a few years ago Freyssinet designed a bridge spanning over 3000 ft), thin shell barrels and domes spanning over 1000 ft, framed structures for very tall buildings and dams capable of withstanding the pressure of many hundreds of feet of water.

When the actual behavior of concrete under load and in time is better known, when laboratory practices capable of producing 14,000-psi concrete are commonly applied in the field, and when plastic redistribution of stress in complicated structures is foreseeable, the amazing results achieved so far will be easily surpassed.

The shape of things to come is clearly illustrated by the construction of airplane wings of prestressed concrete designed by Freyssinet and built by the Brequet Co. (*See Technique et Science, Aeronautique*, October, 1953). An actual *flying stone* has been realized. What else are we to expect from such a wonderful structural material?