Chapter Four

Structural Requirements
4.1 Basic Requirements

Modern developments in materials production, construction techniques, and methods of structural analysis have introduced new freedoms in architectural design, considerably widening its scope. Subsequent chapters will illustrate the results achieved in this field, describing and analyzing the most commonly used structural systems of contemporary architecture.

These new freedoms do not exempt modern structures from satisfying certain basic requirements which have always been the foundations of good architecture, and which may be listed under the following headings: equilibrium, stability, strength, functionality, economy, and aesthetics.

4.2 Equilibrium

The fundamental requirement of equilibrium is concerned with the guarantee that a building, or any of its parts, will not move. Obviously, this requirement cannot be interpreted strictly since some motion is both unavoidable and necessary; but the displacements allowable in a building are usually so small compared to its dimensions that the building appears immovable and undeformed to the naked eye.

The laws governing the motion of bodies, published by Isaac Newton in 1687, are called Newton's laws. The particular cases of these laws governing equilibrium, i.e., the lack of motion, are of basic importance in structural theory because they apply to all structures and are sufficient for the design of some of them. Such structures, called statically determinate, support loads by developing forces whose values do not depend on the material used. Structures that cannot be designed on the basis of Newton's laws only and require a knowledge of material properties are called statically indeterminate. Most modern structures are statically indeterminate.
Certain elementary conditions that will ensure the equilibrium of particularly simple structures can be easily visualized. An elevator hanging from a cable is supported by the pull of the cable; the cable, in turn, hangs from the pulley at the top of the building. If the elevator weighs one thousand pounds and is at rest, the cable exerts on the elevator a pull of one thousand pounds. The weight of the elevator and the upward pull of the cable are equal and "balance out"; the elevator is "in equilibrium" (Fig. 4.1). Two men pulling on a rope with equal forces do not move: the rope is in equilibrium (Fig. 4.2). But if one of the men exerts a greater pull than the other, he will yank his opponent from his stand, and both the men and the cable will move: equilibrium is lost. Similarly, if a sculpture weighing one thousand pounds is set on a column, the column exerts an upward push of one thousand pounds on the sculpture (Fig. 4.3). If the column exerted a smaller upward push, the sculpture would move down, and there would be lack of equilibrium.
4.3 Stability

The requirement of “rigid-body” stability is concerned with the danger of unacceptable motions of the building as a whole. When a tall building is acted upon by a hurricane wind and is not properly rooted in the ground or balanced by its own weight, it may topple over without disintegrating (Fig. 4.6). The building is unstable in rotation. This is particularly true of tall narrow buildings, as one may prove by blowing on a slim cardboard box, resting on a rough surface (lest it should slide).

The danger of rotational instability is also present when a building is not “well balanced” or is supported on a soil of uneven resistance. If the soil under the building settles unevenly, the building may rotate, as the Leaning Tower of Pisa still does, and may eventually topple over (Fig. 4.7).

A building erected on the side of a steep hill may, by its own weight, have a tendency to slide down the slope of the hill. This may happen either because the building slides on the soil, or because a layer of soil adhering to the foundations slides on an adjoining layer (Fig. 4.8). The second occurrence is not uncommon in clay soils when water seeps through the ground, transforming the clay into a scaly material.
All these cases of instability are related to the soil, and to the building foundations. From the viewpoint of economy and usage, foundations are a "necessary evil"; moreover, they are out of sight so that the layman is seldom aware of their importance and cost. For example, the foundations of a heavy structure erected on loose sand permeated by water must allow the building to "float" on such a soil: they are built by means of "rafts" which, in structure, are similar to the hull of a ship (Fig. 4.9). A raft or a mat foundation allow the weight of the building to be spread over a larger soil surface, thus reducing the pressure on soils of low bearing capacity. With soils of average bearing capacity the weight of the building is usually supported on isolated rectangular spread footings of reinforced concrete.

Elaborate precautions against failures must often be taken to guarantee the stability of structures. Wood, concrete, or steel piles can be driven into the soil to depths which permit the building to be supported either by the friction between the surface of the piles and the soil [Fig. 4.10(a)] or by a deeper layer of solid rock [Fig. 4.10(b)]. The piles may be rammed into the soil or may be made to slide into it by rapid vibrations. Soils may also be consolidated by chemical means. The design of proper foundations is based on thorough soil investigations, but soil mechanics is a complex science and, to this day, most of the damage to buildings comes from faulty foundations, even though their cost may reach 10 per cent or more of the total cost of the building.
4.4 Strength

The requirement of strength is concerned with the integrity of the structure and of each of its parts under any and all expected loads. To check strength, the structural system is first chosen, and the expected loads on it are established; the state of stress is then determined at significant points of the structure and compared with the kind and amount of stress the material can safely stand. Factors of safety of varying magnitude are used to take into account uncertainties in loading conditions and material properties (see Section 3.2).

Rigidity should not be confused with strength: two structures may be equally safe, even though one deflects more than the other under the same loads (see Fig. 3.8). Although it is often a measure of strength against loads, rigidity may be a sign of weakness in a structure subjected to temperature changes, uneven settlements, and dynamic loads (see Sections 2.5 and 2.6).

Certain structural weaknesses may lead to modest damage, while others may produce the collapse of the structure. Hence, the engineer must check strength under a variety of loading conditions to obtain the worst stress situation at significant points of the structure. The structural engineer is inclined to believe that a structure collapses only if faulty design is compounded with faulty construction, and helped by an act of God. The cautious pessimist fears, instead, that a structure may collapse at the slightest provocation. In practice, completed structures do collapse, although in relatively small numbers; moreover, owing to the plastic behavior of structural materials (see Section 3.1), most collapses do not occur suddenly and seldom take human lives (see Chapter 13).

The strength of a structure is often evaluated according to the rules and regulations of codes. These procedures are usually safe, although uneconomical when they ignore newly developed systems and materials, but should not be applied blindly, that is, without careful consideration of their original purpose. "Code commentaries" are used to clarify these purposes.

The responsibility for strength rests squarely on the shoulders of the structural engineer. Every day his job is made more complex, and safer, by the increased theoretical knowledge and the improved tools at his disposal. Among the new tools, the electronic computer deserves special mention. These "electronic brains" allow the performance of otherwise impossibly lengthy calculations in a matter of a few seconds or minutes, and are particularly useful in the kind of basic calculation to be performed daily by the structural engineer. In fact, the electronic computer has already supplanted the engineer in lengthy routine calculations, but at the same time has done much more than that.

The possibility of repeating a long calculation in a matter of minutes allows the consideration of a variety of combinations of shapes, sizes, and materials, and the choice of "the best" among a number of designs. Computers have thus brought about the "partial optimization" of structural solutions, which until a short time ago was no more than theoretically possible.

Moreover, the computer permits a more accurate analysis of problems of exceptional complexity—for example, those connected with earthquake design—by "mathematical modeling" of the structure. Before the advent of the computer the rigorous analysis of such problems cost so much in both time and money that approximate solutions were mandatory, involving wasteful use of materials. Today large savings and greater safety are obtained by the more detailed and realistic studies computers make possible.

When the mathematical analysis of an exceptionally difficult problem cannot be carried through realistically by mathematical modeling, the designer may save the problem by means of a test on a structural model of the building. The construction of a reduced-scale model requires a thorough knowledge of material properties, of appropriate scale ratios for lengths and thicknesses (which usually differ), and of correct scale ratios for static and dynamic loads. A number of laboratories, properly staffed and equipped for structural model testing, exist in the world today: dams, bridges, high-rise buildings, and other exceptional structures are sometimes designed on the basis of these tests.
In the rare cases in which doubts may exist even about the reliability of a model test, the engineer may decide to test a full-scale structural member. This procedure is usually adopted when an important component, appearing repeatedly in a structure, does not lend itself to a clear analysis. It is a costly and time-consuming method, and though it yields incontrovertible information on the behavior of a structural element, it is seldom resorted to.

4.5 Functionality

Structural functionality is concerned with the influence of the adopted structure on the purposes for which the building is erected. For example, long-span floors could be built by giving them upward curvature, as in the dome of a church; their thickness and their cost might thus be greatly reduced. But, since the pull of gravity is vertical, floors must be horizontal.

Suspension bridges are rather flexible structures. The Golden Gate Bridge in San Francisco sways laterally as much as 11 feet each side of vertical under strong winds. Such motions obviously must be limited, not only so that fast-traveling cars not be swayed from their paths, but also because the pressure of a steady wind produces aerodynamic oscillations capable of destroying a bridge if it is too flexible (see Section 2.6).

The excessive flexibility of a structure may impair its functionality even under static loads. Thus, most codes limit beam deflections to one 360th of their spans in order to avoid plaster cracks in ceilings. Aluminum, which is three times as flexible as steel, in many cases requires design for deflection rather than for strength. Worsened conditions may arise under dynamic loads: a stream of traffic may produce a continuous and uncomfortable vibration throughout a flexible adjoining structure, seriously impairing its usefulness. Buildings over subway or railroad tracks are often supported on lead insulation pads to avoid such vibrations.

4.6 Economy

Sometimes economy is not a requirement of architecture. Some buildings are erected for monumental or symbolic purposes: to aggrandize the owners in the eye of the public or to enhance spiritual values. Monuments to the state or to "corporate images" fall in the first category; churches belong in the second. Their cost has little relation to their financial value.

But the utilitarian character of structure is so fundamental that even the structural systems of nonutilitarian buildings are influenced by economy. In other words, a strict structural budget must always be contended with unless the structure itself is an advertising display: an aluminum structure may be required, regardless of cost, in order to emphasize the ownership of the building by an aluminum manufacturer.

In the great majority of cases the structural engineer is expected to make competitive cost studies and, other things being equal, to choose "the most economical structure." In a modern building other engineering costs, particularly those concerning mechanical systems (heating, air conditioning, electrical, and plumbing) and architectural details far outweigh structural costs. The cost of the structure is usually not more than 20 to 30 per cent of the entire cost of a building. Hence, even a substantial reduction in structural costs seldom represents a saving of more than a small fraction of total building costs. It must be always remembered that the adopted structure must produce the
greatest economy in the total cost of the building and not in the cost of the structure alone. Deeper beams may reduce somewhat the cost of the structure while increasing substantially the cost of the curtain-wall, the partitions, and the mechanical systems, thus increasing the cost of the building.

The cost of the structural design itself represents usually less than 1 per cent of total building costs. The money allotted to structural design is sub-divided into a budget for the preliminary design, in which the system is established, and one for the final design, which includes preparation of the working drawings and specifications, a check of the shop drawings prepared by the contractor, and, sometimes, inspection or complete supervision during construction. Final drawings are elaborate pieces of workmanship, and may cost many thousands of dollars apiece.

The two largest cost components of a structure are materials and labor. In this connection, two basic types of economy are encountered in the world today. In the first, usually found in the more advanced industrial countries, the cost of materials is relatively low and the cost of labor relatively high. In the second, usually encountered in less developed countries, this ratio is reversed.

The solution of the structural problem is influenced in a fundamental way by the ratio of materials to labor costs. In the first type of economy, all kinds of machinery (cranes, conveyors, excavators, compressors, electrical tools) are used to reduce labor costs and to speed construction; easily assembled, prefabricated elements are the rule; steel is often the typical material. In the second, labor is used in large amounts for both transportation and construction; small elements are employed to minimize the use of heavy equipment; masonry, bricks, and concrete are typical materials. But different ratios of materials to labor costs may influence the choice of structural system even in different areas of the same country.

Continuous changes in productivity and economic balance introduce a variety of intermediate conditions, depending on location and time. Concrete is be-

coming more favored and more competitive in countries where steel reigned until a few years ago. Metallic structures are becoming popular in countries where, up until now, concrete had been the most economical material.

The availability of heavy equipment is one of the main limits upon the use of large prefabricated elements in construction. Some of the most interesting work done in Europe in the recent past was conceived with basic elements not exceeding the capacity of the most readily available cranes, which was of a few tons. On the other hand, elements weighing tens of tons are commonly used in the United States even in construction jobs handled by small contractors.

Availability of skilled manpower limits methods of construction in a variety of ways. Ferrocement as used by Nervi is not economical in the United States at the present time, because of the pouring by hand of cement mortar between the superimposed wire meshes (see Section 3.3). Cement guns commonly used to spray concrete cannot be adapted in this case, because the velocity with which the mortar is ejected makes it bounce off the meshes. The use of specially designed guns may solve the problem. Most of the delicate stone work typical of medieval buildings is ruled out today by the lack of stone masons, whose tradition of apprenticeship has vanished. Similarly, a shortage of certified welders may make it impossible to consider an otherwise economical welded steel structure and require bolted or riveted steel construction instead. Even a lack of equipment to test the execution of the welded joints may rule out such a solution.

Other more subtle factors may also decisively influence cost. At times, the regulations of local codes tip the economic balance in favor of a specific material by imposing restrictions on another. For example, certain codes limit the thickness of flat concrete slabs to no less than a given value. The application of this regulation to curved slabs, which structurally could be much thinner, may make uneconomical the construction of a small reinforced-concrete dome. The inadmissibility of aluminum as a structural material was typical, in the recent past, of the limitations imposed by certain codes.
Fire regulations may favor concrete because of its fire-resistant properties, and comparative fire insurance costs may just as decisively recommend this material.

The initial cost of a structure is but one factor in its economy; maintenance is another. The low maintenance costs of concrete and aluminum structures may swing the balance in their favor, when compared with that of steel structures. Similarly, energy considerations influence the economy of a structure through its life cycle cost.

Speed of construction influences the amount of loan interests to be paid during the financially unproductive building period, and is another factor to be considered in the choice of a structural system. Prefabricated elements, whatever their material, allow simultaneous work on foundations and superstructure, and shorten construction time; hence, they are becoming increasingly popular. Governing bodies and labor unions have at times retarded or accelerated the adoption of modern structural systems. Political considerations have had the same effects.

Economy in structure is obtained through the interplay of numerous and varied factors to be weighed carefully in order to develop the most appropriate structural system and method of construction for each set of conditions. This analysis is so complex that, in the case of large buildings, it is entrusted to specialists called construction managers who advise the architect and his engineers during the design phase and the contractor during the construction phase.

4.7 Aesthetics

The influence of aesthetics on structure cannot be denied; by imposing his aesthetic tenets on the engineer, the architect often puts essential limitations on the structural system. In actuality, the architect himself suggests the system he believes best adapted to express his conception of the building, and the engineer is seldom in a position to change radically the architect's proposal.

In some cases the architect consults with the engineer from the very beginning of his design, and the engineer participates in the conception of the work, making structure an integral part of architectural expression. The balance of goals and means thus achieved is bound to produce a better structure and a more satisfying architecture.

The influence of structure on architecture and, in particular, on aesthetics is more debatable. It was remarked in Section 1.1 that a totally sincere and honest structure is conducive to aesthetic results, but that some architects are inclined to ignore structure altogether as a factor in architectural aesthetics. Both schools of thought may be correct in their conclusions, provided their tenets be limited to certain fields of architectural practice. No one can doubt that in the design of a relatively small building the importance of structure is limited, and that aesthetic results may be achieved by forcing the structure in uneconomical and even irrational ways. At one extreme, the architect will feel free to "sculpt" and thus to create architectural forms which may be inherently weak from a structural viewpoint, although realizable. Large environmental sculpture involves an even more extreme case of structural design almost entirely influenced by aesthetics.

At the other end of the scale, exceptionally large buildings are so dependent on structure that the structural system itself is the expression of their architecture. Here, an incorrect approach to structure, a lack of complete sincerity, or a misuse of materials or construction methods may definitely impair the beauty of the finished building. The beginnings of an aesthetics of structure itself are being established by semiotics, the science of nonverbal communication (see Chapter 14).

The influence of structure on modern architecture is so prevalent that some architects have wondered whether the engineer may not eventually take over
the field of architectural design. The growing importance of technical services and of structure suggests such a danger. And a grave danger it would be, since the engineer, as a technician, is not trained to solve the all-encompassing problems of architectural design. But these fears may, after all, be unjustified: the engineer, while participating creatively in the design process, knows that in a group society his role is limited to a collaboration with a design team and its leader. This leader is and, hopefully, will always be the architect, whose role is both that of creator and, more and more, that of coordinator.

4.8 Optimal Structures

A discussion of the basic requirements of structure leads naturally to the question of whether or can satisfy all these requirements and obtain “the best structure” for a given building.

To answer the question we should first clarify “for whom” the structure is to be best. For the user, it should be the most practical or satisfying. For the owner it should, probably, be the least expensive. For labor it should employ the most man-hours. For the supplier of a specific material the best structure should use that material in large quantities. For the structural engineer it might be the easiest to analyze, the most interesting to study, or the most daring, depending on whether he is more interested in profit, theoretical skill, or personal satisfaction and fame.

From the viewpoint of the basic requirements considered in the previous sections, the best structure may be the most stable, the strongest, the most functional, the most economical, or the most beautiful.

Thus it is obvious that the question of establishing the “best” structure does not have a simple, single answer. On the other hand, one may strive for the best structure under a number of specific limitations. For example, optimal solutions have been established in aeronautical engineering under the assumption that minimum weight is the only criterion by which structural elements ought to be judged. Similarly, the standard rolled wide flange or W-sections, and the beam I-sections, which are basic elements in all steel structures, have been studied geometrically to approach maximum strength per unit weight when used as beams or as columns (the two shapes are geometrically different).

One may establish more general criteria for “the best” column by considering a variety of shapes and materials and by comparing costs. But it soon becomes apparent that the large number of factors in even a simple problem of this kind makes it practically impossible to establish the values of these factors leading to an “optimal” solution. The column, one of the simplest structural elements, may have a variety of shapes (square, round, I-shaped, boxed); each shape may have a variety of sides- or radii-ratios; the thickness of each side may be different; the length of the column may be large or small compared to its lateral dimensions; the column may be supported on a foundation, or be one of a series of super-imposed vertical columns; the materials to choose from may be many; the load to be supported by the column may be centered, or off center. It is understandable that the group of structural specialists of the Column Research Council has been at work for decades in the United States in order to establish simple criteria of strength and design for columns of steel and aluminum.

A question of common concern is the determination of the “lightest structural system,” which supposedly spans the “longest distance” with the “minimum weight” of materials. Even considering a single material, simple studies show that different structural systems do not vary in weight as much as one may believe. The weight saved by the use of certain structural elements is often found to be required in their connections. Sometimes a system appears lighter than others, until a check of its flexibility shows that additional material is needed to stiffen it and make it functional.

The evolution of structural systems is a slow and delicate process. This should not discourage the serious student from investigating new possibilities or the practicing engineer from adopting new techniques. Let them simply be aware that a field as old and tried as Structures does not bear new fruits without the lavishment of incomparably more effort than that required by a routine application of established principles.