CHAPTER

1

Structural Design Process

1.1 Nature of the Process

This book is primarily intended as a textbook for students enrolled in professionally accredited architecture programs. A secondary audience includes interns preparing for the architectural registration exams. There may also be limited markets for professional architects, structural engineers desiring to better understand the architect's approach to structures in the context of the larger design problem, and persons interested in pursuing a career in either architecture or structural engineering.

Architects have a huge array of issues to address in architectural practice. Among these are the following: keeping rain out of a building, getting water off a site, thermal comfort, visual comfort, space planning, fire egress, fire resistance, corrosion and rot resistance, vermin resistance, marketing, client relations, the law, contracts, construction administration, the functional purposes of architecture, the role of the building in the larger cultural context, security, economy, resource management, codes and standards, and how to make a building withstand all the forces to which it will likely be subjected during its lifetime. This last subject area is referred to as *architectural structures.*

Because of the extraordinary range of demands on an architect's time and skills and the extraordinary number of subjects that architecture students must master, architectural structures are typically addressed in only two or three lecture courses in an accredited architectural curriculum in the United States. These two or three lecture courses must be contrasted with the ten or twelve courses that will normally be taken by a graduate of an accredited structural engineering curriculum. This contrast in level of focus makes it clear why a good structural engineering consultant is a very valuable asset to an architect. However, having a good structural consultant does not relieve the architect of serious responsibility in the structural domain. All architects must be well versed in matters related to structures. The architect has the primary responsibility for establishing the structural concept for a building, as part of the overall design concept, and must be able to speak the language of the structural consultant with sufficient skill and understanding to take full advantage of the consultant's capabilities.

Most books on structures are written by structural engineers for an audience of structural engineers. This focus is not appropriate in nature to the needs of the architect, who must understand how structure fits into the larger design context. Furthermore, it is not appropriate in scale, inasmuch as the texts required by an engineering student over the course of that student's education will fill an entire cabinet. Given the wide range of other learning responsibilities of an architecture student, there is not enough money to acquire, or time to use, an entire cabinet full of books on structures. To support the learning needs of architecture students, a text is needed that is different in both scope and approach from the reference material provided for engineers.

It is the goal of this text to supply the architecture student with a comprehensive set of learning and reference materials to help prepare that student to enter the workforce as a serious professional, competent to deal with structural issues at the level, and in the manner, appropriate to architects. This book can also serve as a valuable reference for architectural interns preparing for the architectural registration examinations.

1.2 General Comments Regarding Architectural Education

Structural design is one of the more rigorous aspects of architectural design. Much knowledge has been generated and codified over the centuries that human beings have been practicing in and developing this field. This book gives primary attention to those things that are known, quantified, and codified.

However, very few things in the realm of architecture yield a single solution. To any given design problem, there are many possible solutions, and picking the best solution is often the subject of intense debate. Therefore, no one should come to this subject matter assuming that this text, or any text, is going to serve up a single, optimized solution to any design problem, unless that design problem has been so narrowly defined as to be artificial.

In design, there is always a great deal of latitude for personal expression. Design is purposeful action. The designer must have an attitude to act. Architecture students develop an attitude through a chaotic learning process involving a lot of trial and error. In going through this process, an architecture student must remain aware of a fundamental premise: the process is more important than the product; that is, the student's learning and development are more important than the output. The student has a license to make mistakes. It is actually more efficient to plow forward and make mistakes than to spend too much time trying to figure out how to do it perfectly the first time. To paraphrase the immortal words of Thomas Edison: To have good ideas, you should have many ideas and then throw out the bad ones. Of course, throwing out the bad ones requires a lot of rigorous and critical thinking. No one should ever fall in love with any idea that has not been subjected to intense and prolonged critical evaluation and withstood the test with flying colors. Furthermore, important ideas should be subjected to periodic reevaluation. Times and conditions change. Ideas that once seemed unassailable may outlive their usefulness or, at the very least, need updating in the light of new knowledge and insights.

This text focuses primarily on exploring the known, quantified, and codified, but it also honors the chaotic learning process described here. On some projects, students will be given fairly wide latitude to generate concepts and to explore. Optimally, the educational experience will be stronger if the student explores this subject matter in the context of a design process, such as would occur in a studio environment, where feedback is provided by enlightened people with a wide range of experience and philosophical points of view.

In pursuing this subject matter, it is valuable to have a frame of reference regarding the roles of the architect, as the leader of the design team, and the structural engineer, as a crucial contributor of expertise and hard work needed to execute the project safely and effectively. The diagram in Figure 1.1 will help provide that frame of reference.

In contemplating the diagram in Figure 1.1, keep in mind that design and analysis are two sides of the same coin and that the skills and points of view of architects and engineers, although distinctive, also overlap and sometimes blur together. The most effective design teams consist of individuals with strong foci who can play their respective roles while having enough overlap in understanding and purpose that they can see each other's point of view and cooperate in working toward mutually understood and shared goals. The most harmful poison to a design team is to have such a separation in points of view and understanding that a rift develops between the members of the team. Cooperation is the watchword in this process, as in all other team efforts.

1.3 Background of the Reader

The prerequisites of a student for optimum utilization of this text include the following:

- A working knowledge of plane and solid geometry (This is absolutely fundamental to the design of architecture and should be a part of any architect's basic repertoire.)
- A working knowledge of arithmetic (This is part of the basic repertoire of any educated, thinking person. No architect can make good judgments without the arithmetic that reinforces a sense of scale, proportions, and economy.)
- An introduction to trigonometry and vectors
- Basic skills in sketching
- Basic skills in fashioning scale models out of cardboard, wood, plastic, and/or metals
- A basic knowledge of computers, including word processing, spreadsheet analysis, and computer-aided design (CAD)

An understanding of calculus is helpful, but this book is crafted in such a manner that calculus is not crucial to grasping the concepts.

A computer with appropriate software is such a powerful tool for learning and exploration that any course of study that does not take advantage of that tool is far from ideal in preparing an architecture student for the future workplace. Therefore, students intending to use this text to maximum advantage in a full assault on the subject

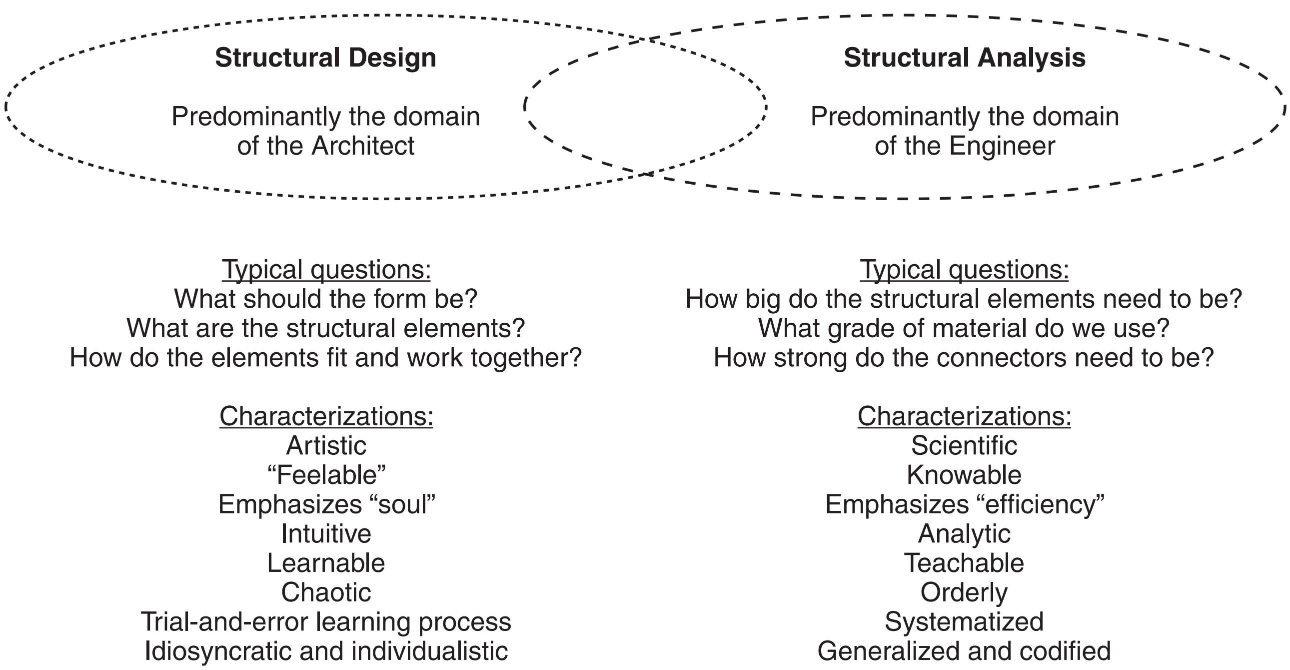


Figure 1.1 Nature of the design process and roles of the design participants.

should have access to a computer with word processing, a spreadsheet program, and a structural analysis program. Examples of the latter are Multiframe, Strudl, SAP, RISA, STAAD.Pro, Tekla Xsteel, S-Frame, ETABS, MIDAS, ProSteel 3D, and RamSteel. This book will provide examples of the principles of analysis on which these programs are based. It will also take the student through many of these examples in the form of assignments designed to reinforce the concepts.

The computer analysis programs are important for several reasons:

1. They eliminate much of the tedious math, allowing the student to focus on concepts and to explore the behavior and attributes of many more structural forms than would be possible if the student were straddled with the responsibility of carrying out all of the math longhand.
2. The computer facilitates the analysis of very complex three-dimensional structures that simply could not be done reliably by longhand analysis.
3. The programs provide visualization tools that are invaluable for exploring both geometry and structural behavior.

1.4 Vehicles for Delivering the Concepts

1. Freebody diagrams. These are at the absolute heart of structural design. Understanding how freebodies are constructed and interpreted is vital to the most basic concepts in structures.
2. Math (primarily geometry and arithmetic). These give scale and rigor to everything the architect does in structural design.
3. Spreadsheet programs for computers. These programs are powerful aids in organizing and carrying out computations. They provide:
   - Sophisticated and rapid computational tools
   - Ease of use
   - A record of the inputs that can be used in checking and troubleshooting
   - A record of the equations that can be used in checking and troubleshooting
   - Graphic output for visualization and presentations

   These programs are already commonplace tools for architects to use in generating budgets and doing value analysis. Applying them in a structures course to generate computational templates is an obvious match.
4. Computer simulations showing axial forces, axial stresses, moments, bending stresses, shear forces, shear stresses, and deformation under various loading conditions. These programs are a requirement in any serious course in structures. The ease they provide in visualizing and exploring structural behavior is simply unprecedented. The use of these programs is featured heavily in the examples and assignments in this book.
5. Physical testing and physical models demonstrating the structural behavior of elements and/or systems of elements. The tactile feedback provided by physical experiments and models is a powerful aid to a student's comprehension. They are not easy to make in a manner that truly simulates the behavior of a full-sized structure, but they are worth the effort. Some phenomena, such as buckling, are better understood in physical models than in any other learning media. Moreover, models teach students about statistical variations in performance that are not apparent in purely computational processes. There is nothing like testing a series of models that were intended to be identical to help students understand why safety factors are important.
6. Design solutions embodied in actual building structures. There are vast insights to be gathered from the successful designs born of great minds that have grappled with this subject over the centuries. These should be revisited often, each time with a fresh eye to see things that may have been overlooked before. They should include examples where the integration of structure with the other building systems has been addressed in at least a competent, if not inspired, manner.
7. Practical examples in value engineering—that is, demonstrating efficient ways to determine the structural costs of providing greater architectural amenities—such as the following:
   - The structural cost of increasing span to reduce the number of columns interfering with efficient space planning
   - The structural cost of using rigid frames, as opposed to shear walls or triangulating struts, as a way to promote freer movement of people and equipment through a structure
   - The structural cost of introducing openings for admitting natural light to illuminate the interior of a building
8. Data on properties of materials.
9. Data on dimensions and section properties for common structural elements, such as standard rolled and formed steel sections.
10. Load tables for columns, beams, and trusses. These are particularly helpful for quick sizing and for doing cost-benefit analysis for common building types. Introducing students to the great compendia that are the source of this information is also an important goal of this text.
11. The written word. Words alone are a poor means of understanding and communicating structural

behavior. However, words provide a indispensable tool in organizing our ideas about the subject.

12. Assignments and projects. Exercise is the primary road to learning.

1.5 Expectations Regarding the Outcome of the Learning Process

Learning goals for a student working with this book are expressed in terms of three levels of achievement in design activity.

The first level of structural design activity is primarily qualitative, including the following:

- Concept generation—that is, understanding what kinds of elements need to be included in the structural system to deal with the entire array of vertical and lateral loads on a structure; understanding how to make the structural system mesh with the spatial and functional requirements of the architectural design.
- Applying simple rules of thumb to establish the proportions of structural elements—for example, the depth of a parallel-chord truss will typically be in the range of 0.042 to 0.062 times the span of the parallel-chord truss; the final depth will depend on a variety of structural, economic, and architectural factors to be worked out in later stages of the design process.

Architects should be able to perform these design activities competently and should do them routinely in practice.

The second level of structural design activity is semi-quantitative, including the following:

- Geometric definition of a structure (This can be fairly straightforward, such as in the case of a system of beams and columns laid out on a regular grid, to quite challenging, such as in the case of a hyperbolic paraboloid network, a geodesic dome, or a free-form structure like architect Frank Gehry's art museum in Bilbão.)
- Quick, approximate sizing of elements, such as beams and open-web joists, using tables of standard elements
- Cost estimating

Architects should be able to perform these activities competently enough to have a sense of what an engineer might be doing in support of the architect on a given project. A significant goal of this text is to provide students with a sufficient understanding of the structural issues and engineering design processes to confidently engage an engineer in the overall design process. Some architects will choose to perform these functions in practice; others may choose to have their engineering consultants perform such functions.

The third level of structural design activity is highly quantitative, including the following:

- Final sizing of elements using precise computational processes
- Calculations involving complex interactions between structural members constituting structural systems

Architecture students completing a rigorous course of study using this text will:

- Be able to apply a standard software analysis program to simple structural systems
- Understand the principles and issues involved
- Understand the complexity of the process
- Understand the power and limitations of analytic methods
- Understand the issues, state of the art, and vocabulary necessary for interacting effectively with a structural engineer

Most architects will choose to have their engineering consultants perform these highly quantitative design functions. However, the computer analysis tools used in this course are examples of what will be prevalent in practice within the next decade. The architect and engineer can use these tools in a collaborative process of generating architectural form.

The education that an architecture student can receive in completing a rigorous course of study using this text will provide a very good commonsense understanding of architectural structures. As indicated earlier, this educational experience is not the equivalent of a full education in structural engineering. Structural engineers take many more courses in this focus area and are responsible for a great many kinds of information that the architect will typically be unprepared to address. Sometimes, the commonsense understanding that architects acquire from this text, and as a byproduct of experience as an architect, will provide the architect with some insights that some engineers do not have. However, the architect should not allow that fact to delude him or her into believing that he or she has all the skills to produce a major architectural work without the assistance of a competent and motivated structural engineer. One of the architect's major tasks as a designer is to acquire and properly utilize good engineering consulting services to assist in generating economical and safe designs.

1.6 Types of Structural Action

There are three primary kinds of structural action that architects and engineers use in creating structures for human habitation and use:

1. Axial tension, involving a tension force along the axis of a member.

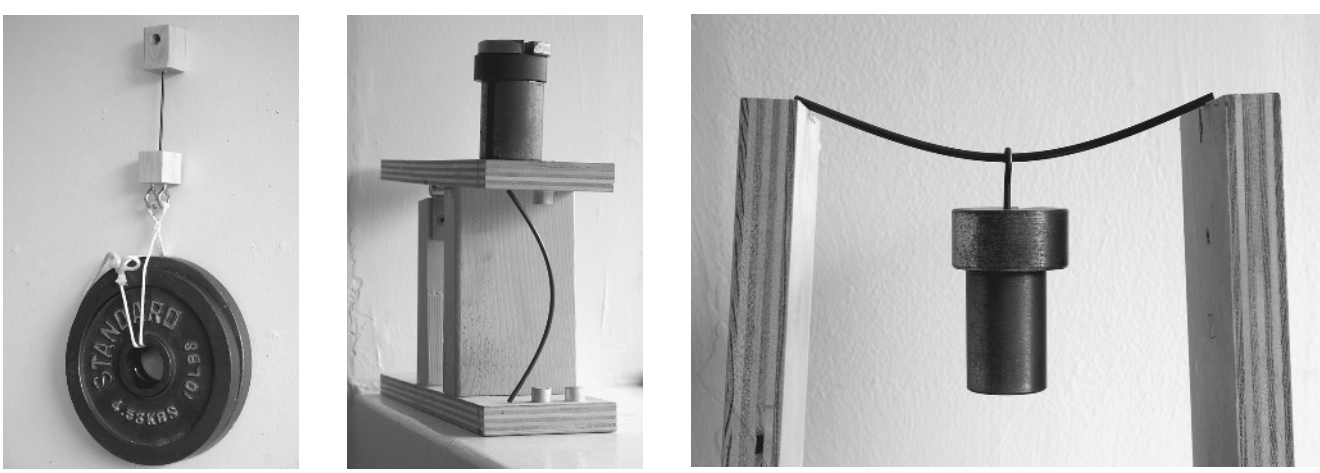
2. Axial compression, involving a compression force along the axis of a member. Such members are usually referred to as *columns* or *compression struts.*
3. *Bending*, also referred to as *flexure*, involving forces lateral to the axis of a member. Such members are usually referred to as *beams.*

In Figure 1.2(a), a $1/8$ in.-diameter × 6 in.-long PVC rod is subjected to axial tension. More than 9 kg of weight has been hung off the rod. It would have supported substantially more weight, but the testing was limited by concern about dents in the floor. In Figure 1.2(b), the same rod is subjected to axial compression in a small testing device. Buckling failure occurred at 0.8 kg of axial compression force, which is less than a tenth of what it easily held in tension. In Figure 1.2(c), the same element is being used in bending, where massive deformations are observed at a lateral force of 0.4 kg. This demonstration illustrates the hierarchy of structural efficiency: tension members tend to be more efficient than compression members, which tend to be more efficient than bending members.

Tensile members are limited by the yield stress of the material. They can also be severely limited by means of making connections at the ends of the members. In Figure 1.2, the PVC rod was glued deep into the two sturdy wooden blocks, which ensured that the end connections would develop most or all of the potential tension capacity of the rod.

Compression members are limited by the yield stress of the material and by buckling, wherein the element begins to radically change shape, moving laterally out from under the load, before the yield stress of the material is reached. (*Laterally* means to the side, i.e., perpendicular to the axis of the element.) The tendency to buckle can be diminished by redistributing the material in the member cross section. For example, a $1/16$ in.-thick × 3 in.-wide × 36 in.-long piece of styrene plastic will not support its own weight without buckling laterally. If that same sheet of material is cut lengthwise into seven equal-width strips and those strips are glued together, they form a solid bar that is almost exactly square. This solid, square bar not only supports its own weight, it can support about 15 lbs of compression force, as shown in Figure 1.3(a). If that same sheet is cut into four $3/4$ in.-wide strips and reassembled into a square, hollow section 36 in. long—see Figure 1.3(b)—that section can hold over 100 lbs in compressive force. The process of reconfiguring the material has given the column extra breadth, which has stiffened it against buckling. This idea of configuring material to achieve structural efficiency is at the heart of the design process.

In regard to spanning methods, suspension structures rely primarily on elements working in pure tension, arches rely primarily on elements acting in pure compression, and trusses are composed of an assembly of elements that are each working in either pure tension or pure compression. As such, these methods of spanning tend to be more structurally efficient than the use of beams. However, beams are simple to design and fabricate and in many situations are the most economical means of spanning. It would be difficult to imagine replacing a standard 2 × 6 wood rafter in the roof of a house with a tiny truss. The minor material savings achieved by the truss would never offset the cost of detailing the truss. At the other extreme, we would have difficulty imagining replacing the lacy cable structure of the Golden Gate Bridge with a huge, solid beam. Structural efficiency tends to be more important for long spans or heavy loads. For short spans and light loads, the simplest



(a) (b) (c)

Figure 1.2 (a) Axial tension, (b) axial compression, and (c) bending.

(a) (b)

Figure 1.3 (a) A solid rod and (b) a hollow tube.

and most expedient structure is generally the most economical and appropriate. How to achieve structural efficiency is a major theme of this book.

Bending elements are limited by leverage effects. Beams, particularly shallow beams, have a major mechanical disadvantage relative to the applied forces. This point is addressed in more detailed and more precise terms in later chapters. In the meantime, simple experience and intuition can be used to develop the idea of leverage. It can be clear from experience that the shape of a structural element is important and that "structural depth" is crucial to structural performance. For example, if we want a strong beam, we will set a wood 2 × 10 on edge to resist gravity forces. Yet if we wanted to break the same board, we would lay it on its side. Laying the board on its side reduces both the strength and the stiffness of the element in responding to gravity forces. A wide, flat beam is not only weaker, that is, easier to break, but also less stiff. Typically in our culture, we associate stiffness with strength. When we pound on a wall or jump up and down on a floor and perceive very little movement, we assume that these elements are very strong. Although there is a correlation between stiffness and strength, the correlation between those properties is far from perfect. For example, we can create a broad, flat cantilever beam that is both flexible enough and strong enough to be used as a diving board. This apparently contradictory set of traits is also useful in the leaf springs of a motor vehicle. However, in structural applications, stiffness and strength will be highly correlated, and we will be seeking to create structures that are both strong and very stiff. Most of the time the primary motive for seeking stiffness is either to reduce distracting vibrations or to improve the perception of quality on the part of the building occupants. Sometimes, however, the desirability of stiffness goes beyond perception and becomes a life safety issue. For example, an overflexible flat roof may begin to deflect under the weight of a deluge of rain. The deflection creates a bowl shape that causes more water to accumulate. The added water causes a deeper bowl to form, resulting in an even greater accumulation. This process is referred to as *ponding*. Ponding has more to do with the stiffness of the roof than with the initial strength of the roof. Two roofs may both be rated to carry the prescribed snow or live load, but one may be flexible enough to accumulate water and the other stiff enough to resist that accumulation. Ponding takes the importance of stiffness beyond perception and comfort into the realm of life safety.

In Figure 1.4(a), the 1⁄16 in.-thick × 3 in.-wide styrene sheet is being used as a beam oriented with the broad faces horizontal. Just as it failed to hold its own weight as a column, it fails to hold its own weight as a beam. In Figure 1.4(b), the beam is oriented with the broad faces vertical; that is, it is set up on edge. In this case, it supports its own weight plus a small additional weight. The top edge of the beam is in compression and is starting to buckle to the side, accounting for the curved top edge of the beam.

Adding more weight causes the beam to buckle quickly to the side, as shown in Figure 1.5(a). Although this beam has the attribute of being quite deep, which is the direction we want to take it, it has the disadvantage of not being laterally very stiff. To help address this deficiency, we can cut the sheet of styrene into three strips of about equal width and glue them back together to form an I-section, as shown in Figure 1.5(b). The I-beam tends to exhibit slightly greater vertical deflection than the simple sheet set on edge, which means that the I-beam is slightly less stiff relative to vertical deformation. However, the I-beam is much stronger, by virtue of the fact that it is laterally much more stable than the simple sheet in Figure 1.4(b). The greater strength is apparent in the fact that it carries more than ten times as much weight.

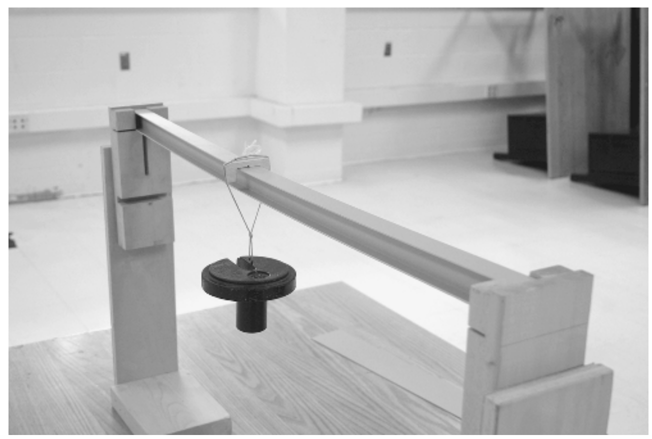
There is a consistent theme in both columns and beams. The columns need breadth in both directions to avoid buckling in either direction. Beams need depth to provide leverage in resisting the load and lateral breadth to avoid lateral buckling. In the preceding examples, breadth and depth have been achieved by connecting

(a)

(b)

Figure 1.4 (a) A very shallow beam and (b) a deep beam.

(a)



(b)

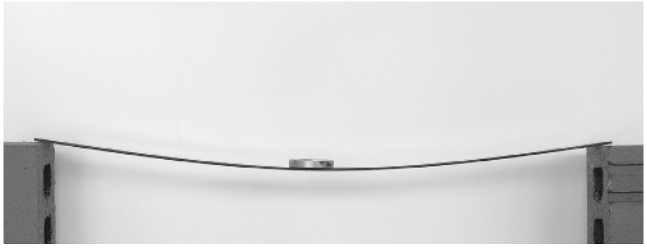
Figure 1.5 A sheet of material (a) set on edge and (b) configured as an I-beam.

perpendicular sheets of material to form a shape that is substantially more stable than either sheet would be on its own. Each sheet has a weak direction, which is shored up by the perpendicular sheet material connected edge-on to it. This notion of mutually stabilizing sheets of material is one to which we will return many times in conceptualizing structures.

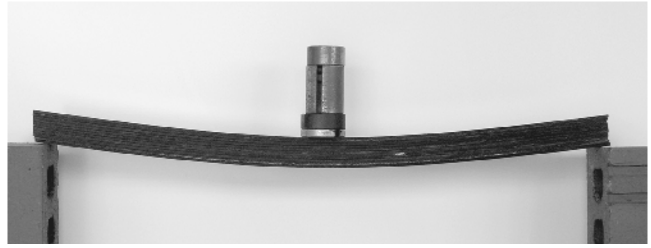
I-beams are a classic example of combining perpendicular sheets of material to form a stronger composite shape. In the United States, most I-beams are not fashioned by joining sheets of material, but are made by a rolling process in which a big lump of steel, called a *billet,* is gradually squeezed and deformed until it takes on the final I-shaped section. In this manner, the perpendicular sheets of material are made as integral parts of the whole and there is no process required to connect the parts. For very large I-beams, the rolling process is not economical and the beams are made by welding steel plates together. The quality of the welds is crucial to ensuring the composite action of the plates.

The importance of ensuring composite action is illustrated by the following experiment. A shallow beam is made of acrylic plastic ⅛ in. deep and 1.5 in. wide. Under a 0.1 kg force, it deflects noticeably, as shown in Figure 1.6(a). Stacking ten of these beams and imposing ten times as much load produces almost exactly the same deflection, as shown in Figure 1.6(b).

Effectively, each beam in the stack of ten beams is acting to resist one tenth of the load. In other words, the stacked beams look like a very deep beam, but the stack is actually acting like ten independent beams. In essence, stacking the ten beams with 1.0 kg on top is equivalent to placing the ten beams side by side and putting 0.1 kg on each beam. In contrast, when the ten beams are not



(a)



(b)

Figure 1.6 (a) A shallow beam and (b) ten shallow beams stacked.

simply stacked, but are properly glued together, they deflect much less and can carry much more load, as shown in Figure 1.7.

The message of this demonstration is that achieving structural depth by combining elements requires that the elements are sufficiently well connected that they can resist the shear forces occurring between them during bending. The classic example of this effect is making a concrete deck work in composite action with the steel beam supporting the deck. Achieving this composite action can significantly increase the effective overall depth of the spanning system. For example, a 6 in.-deep concrete slab working in composite action with a 12 in.-deep steel I-beam increases the structural depth from 12 in. to 18 in. To achieve this composite action, steel shear studs are welded to the top of the beam. These shear studs are embedded in the concrete, which is poured around them.

The concept of perpendicular sheets of material, which accounts for the outstanding structural performance of building components, such as I-beams and square tubes, can also be applied at the scale of the building itself. For example, a thin wall is the structural equivalent of a thin sheet of material. The base of that wall can be broadened by attaching it to a footing, as shown in the model in Figure 1.8(a). This base is typically very narrow because the gravity force transmitted down through the wall is distributed along a long footing, which distributes the force very evenly into the soil. In a house, the wall footing is usually a 1 ft.-wide strip of concrete. In some situations, where the soil quality is particularly poor, the footing might be slightly wider than 1 ft. This footing does little to help stabilize the wall, which can be blown over in a slight breeze; see Figure 1.8(b).

This is true even of walls that we think of as heavy and stable, such as walls made of concrete masonry units. One of the most common causes of death on construction

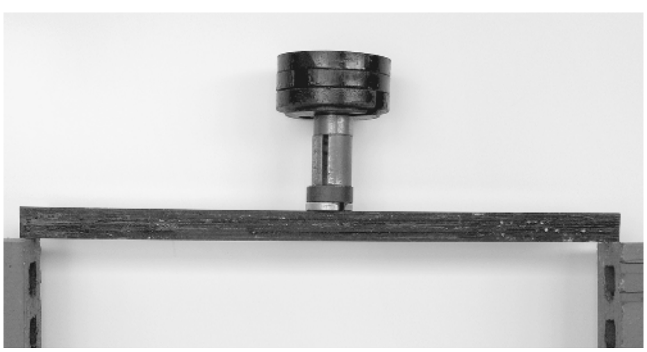
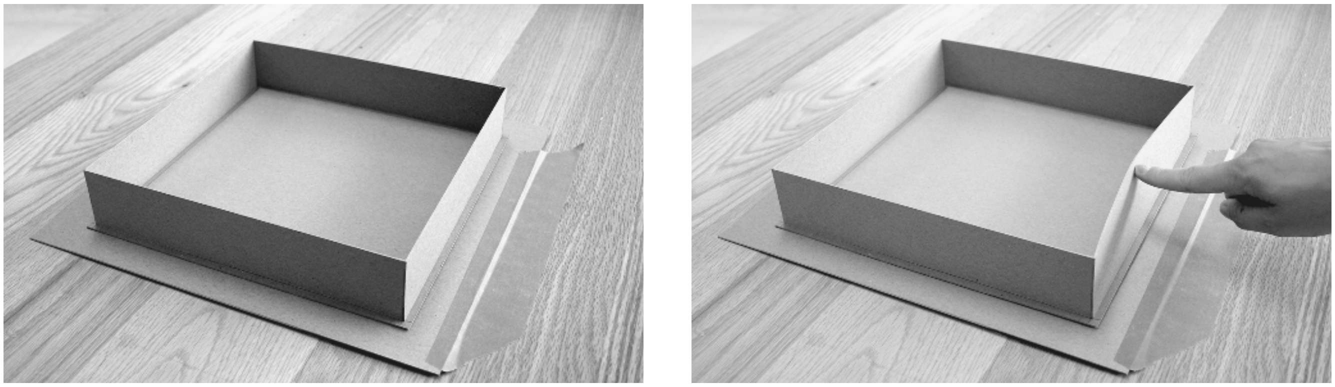


Figure 1.7 Ten shallow beams glued to form one deep beam.

(a)

(b)

Figure 1.8 (a) A thin wall (b) subjected to lateral force.



(a) (b)

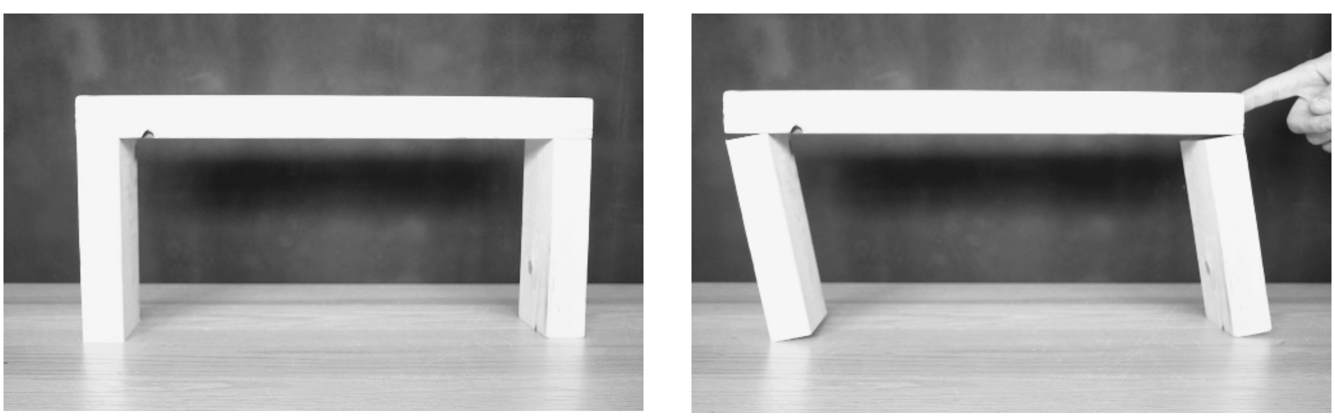
Figure 1.9 (a, b) Walls stabilizing each other at the ends.

sites is the overturning of masonry walls that have not been properly shored up during the construction process. Clearly, an individual wall of this sort is of no structural value by itself. This wall makes sense only as part of a larger system, with other parts that compensate for the weaknesses of this wall. One way to help this wall is to connect it to other walls perpendicular to it. This is what is normally done anyway, inasmuch as achieving an enclosed space requires more than one wall. Figure 1.9 illustrates the idea. Each of the four walls is stabilized at its ends by other walls set perpendicular to it. Now the weakness of each wall is near the center of the wall, where it is far removed from the stabilizing benefits of any perpendicular sheets of material.

The walls perpendicular to the wall being exposed to wind overpressure are put in a state of shear as the wall being loaded leans against them. These perpendicular walls are sometimes referred to as *shear walls*. They must be properly constituted to resist a shearing force. Many of the walls used in standard construction are capable of resisting substantial shear force. However, this is not always true. For example, classic post-and-beam construction is very poor in resisting lateral forces, as illustrated in Figure 1.10.

Standard wood stud construction eliminates this deformation of the wood frame by adding sheets of material in the plane of the wall, such as plywood or oriented strand board (OSB), which provide the diagonal forces to keep the wall from racking. See Figures 1.11, 1.12, and 1.13.

The composite construction of sheet material, such as plywood or OSB, with studs is another example of mutually bracing, perpendicular sheets of material, in that the studs are set with their long cross-sectional dimension perpendicular to the OSB sheet. The OSB sheet is very thin and very vulnerable to lateral buckling, similar to that observed in the thin sheet of plastic that we tried to use as a beam in Figure 1.5. By itself, the OSB is not a very effective structural element, but when braced frequently by studs, its structural effectiveness is greatly enhanced. OSB and plywood are typically considered as providing the shear resistance for walls in one- or two-story buildings, using only nails to connect the OSB or plywood to

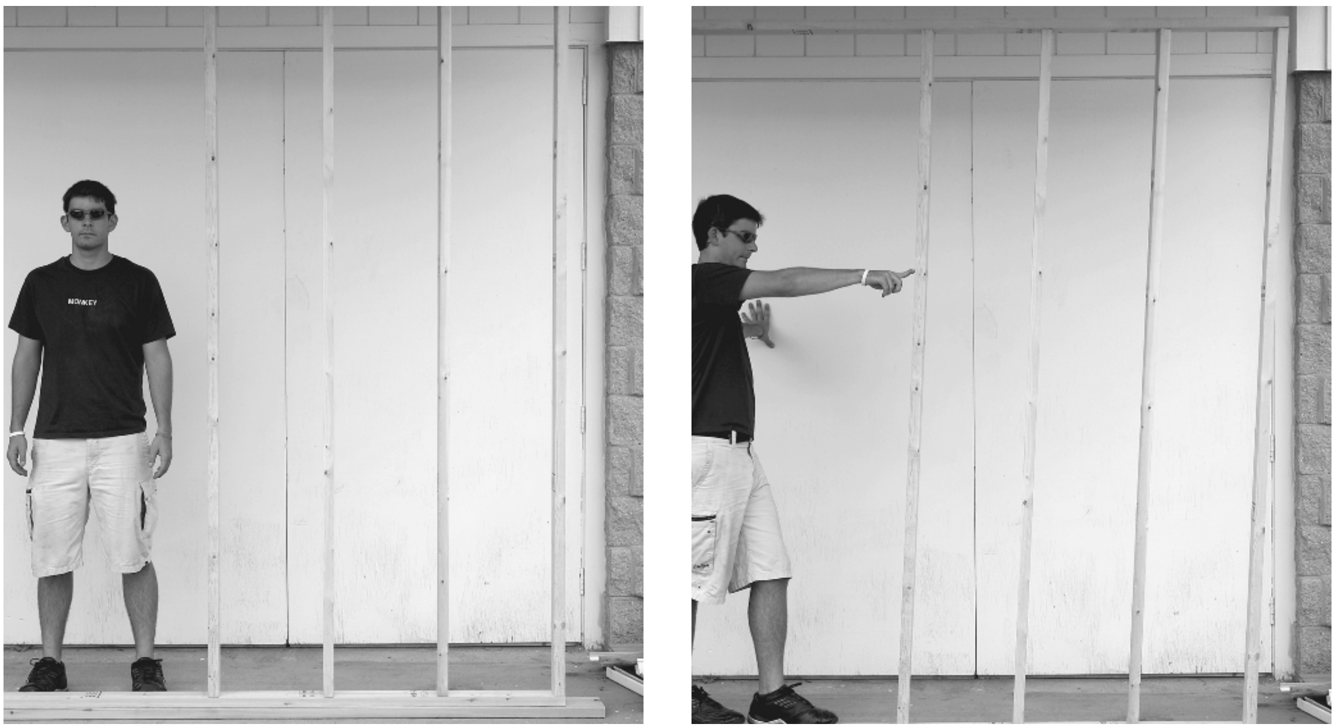


(a) (b)

Figure 1.10 (a, b) Post-and-beam construction deforming (racking) under shearing load.

(a) (b)

Figure 1.11 (a, b) Sstandard method of nailing shoe and top plate to the studs.

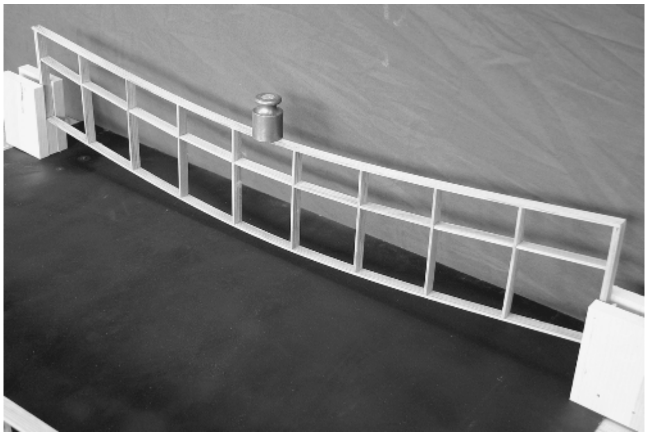


(a) (b)

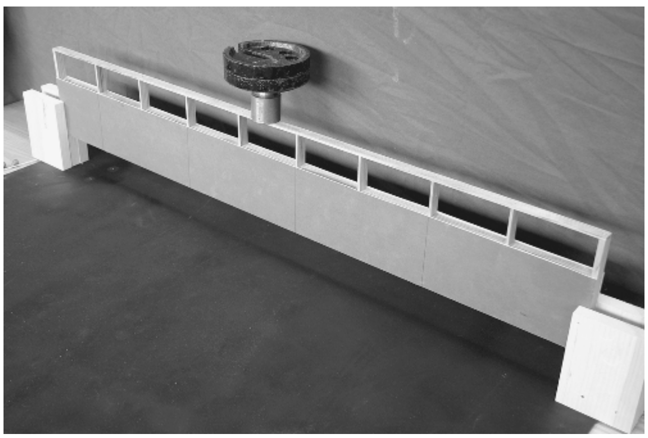
Figure 1.12 (a, b) Racking of studs under shearing force of a single finger.

(a) (b)

Figure 1.13 (a, b) Nailing sheets of OSB to studs, a top a plate, and shoe to enhance lateral resistance.



(a)



(b)

Figure 1.14 (a) 2×6 wood beams nailed together and (b) creating a box beam using plywood and 2×6 wood beams.

the studs. However, with the use of screws and glue, plywood box beams can be used for roofs spanning up to a hundred feet. Figure 1.14 illustrates the point. The model in (a) shows an assembly of wood sticks scaled to be the equivalent of a 2×6 wood beam, which is deflecting dramatically under a 0.5 kg weight. The model in (b) has chipboard glued to each side to create a box beam, similar to what could be done using plywood in a real structure. The model in Figure 1.14(b) barely deflects under five times as much load.

These kinds of box beams can be put together to form a folded-plate roof like the one in the model in the Figure 1.15.

Openings, such as doors and windows, undermine the shear capacity of a stud-and-plywood wall. Windows and doors are architecturally essential elements. Therefore, understanding the amount of opening that can be made in a shear wall without undermining its structural effectiveness is crucial. The building codes give pre-

Figure 1.15 Model of folded-plate roof.

scriptive rules for the percentages of walls in various situations that can be given over to openings. When the designer wants to exceed those limits, a more detailed analysis has to be done and special measures beyond the standard stud construction methods may be required.

Good shear walls perpendicular to the ends of the wall being loaded still do not solve the problem of the weakness of the wall being loaded near the center of that wall (Figure 1.9(b)). This weakness near the center of the wall can be addressed by using another perpendicular sheet of material, which may be either a floor or roof diaphragm, as shown in Figure 1.16.

A floor or roof acting in this mode is called a *diaphragm floor* or *diaphragm roof*. A diaphragm is a planar element that:

- Serves a primary purpose, such as roof decking spanning from roof joist to roof joist, to support forces perpendicular to the planar element, such as snow or maintenance workers on the roof

Figure 1.16 Floor or roof diaphragm stabilizing the top edge of a loaded wall.

- Serves a secondary role as a deep beam resisting forces parallel to the plane of the element

In Figure 1.16, the force parallel to the plane of the roof decking is created by the wall pressing against the edge of the roof. The diagram in Figure 1.17 suggests the nature of the interaction, wherein:

- The upper edge of the loaded wall presses against the edge of the roof.
- The diaphragm roof acts as a very deep, horizontal beam carrying the horizontal force on its edge to the tops of the side walls (i.e., the walls parallel to the direction of the force).
- The side walls serve as shear walls, carrying the force down to the footings.
- The horizontal force of the roof diaphragm along the top edge of one of the side shear walls, combined with the horizontal force in the other direction of the footing

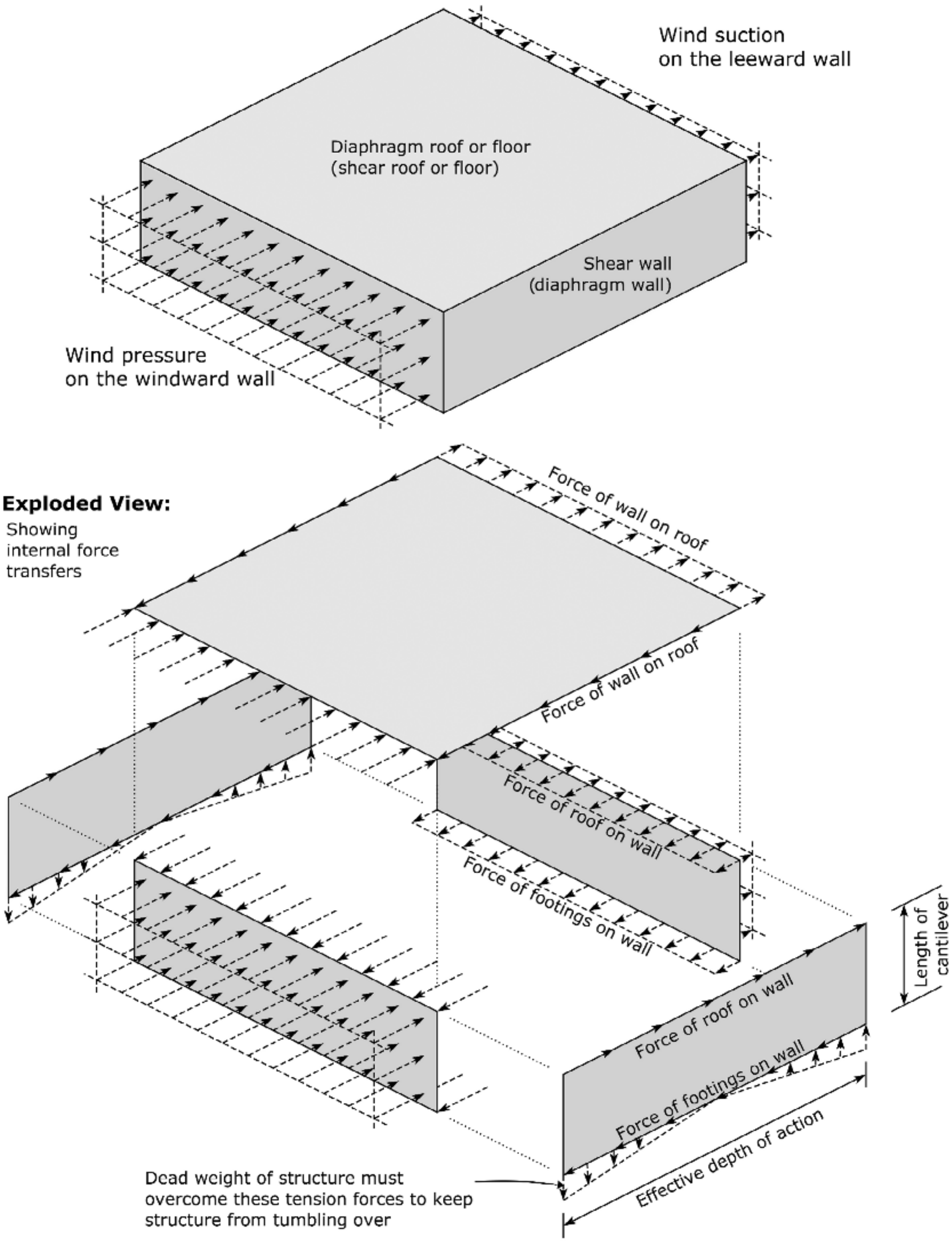
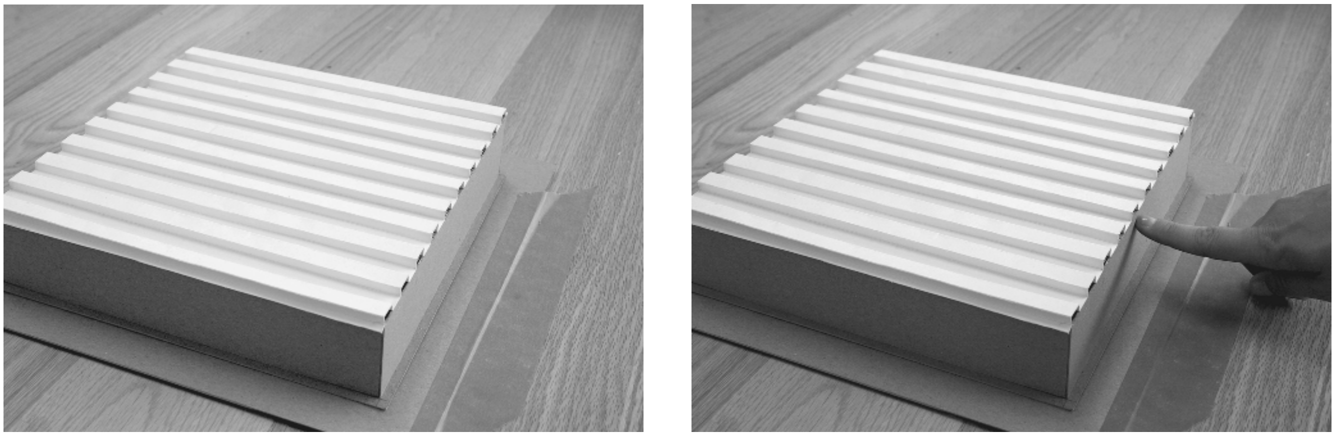


Figure 1.17 Forces on loaded wall, diaphragm roof, shear walls, and footings.



(a) (b)

Figure 1.18 (a, b) Diaphragm action of corrugated roof for force parallel to corrugations.

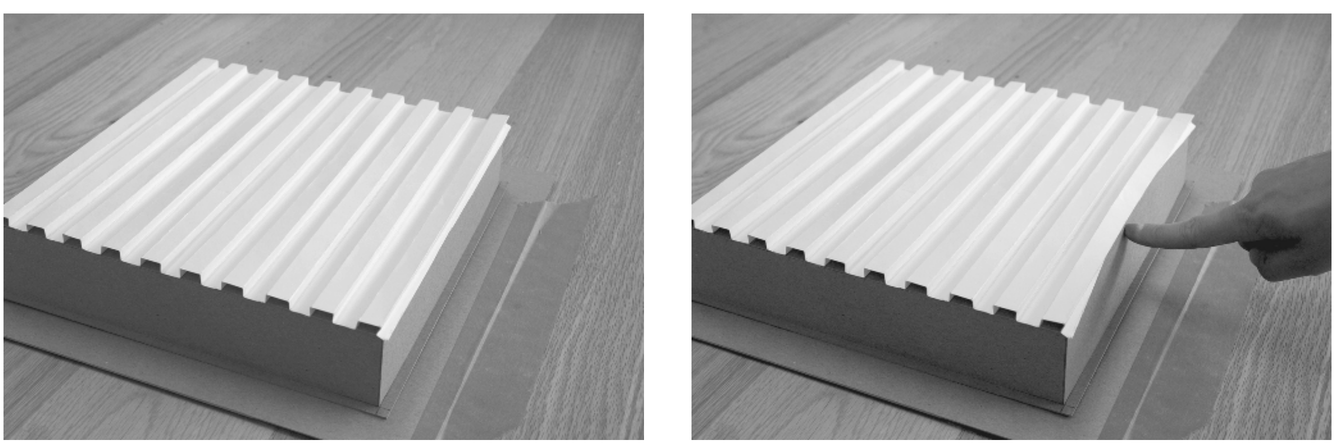
on the bottom of the side shear wall, tends to make the shear wall rotate. To avoid this, the footing must also create hold-down forces on the shear wall on the windward end of the shear wall and upward forces on the leeward end of the shear wall. These forces have to do with the overturning effect, which can be equilibrated only by the self-weight of the wall and of the footing.

The properties that allow a roof to work as a horizontal beam, that is, as a diaphragm, are the same properties that allow a wall to work as a cantilevered beam relative to forces parallel to the wall; that is, to work as a shear wall. Shear walls could be referred to as *diaphragm walls,* or diaphragm roofs as *shear roofs*. This text, however, sticks to the custom of associating the word *shear* with walls and the word *diaphragm* with roofs and floors.

In steel construction, the roof diaphragm is normally made of corrugated steel decking. A very thin steel sheet is run through a rolling system to form it into corrugated deck. It resists buckling really well for forces parallel to the corrugations, as shown in Figure 1.18.

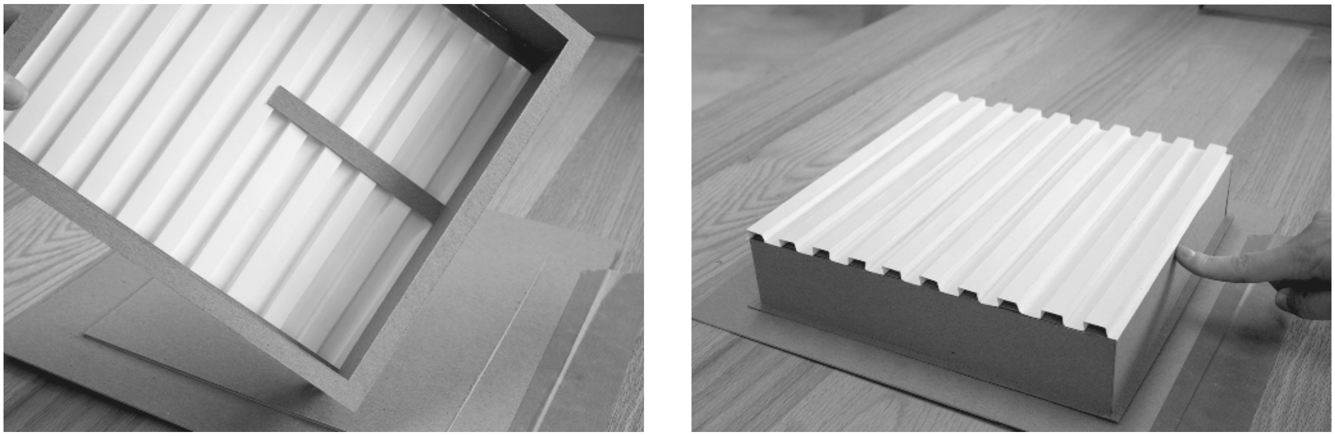
In this model, the corrugations are represented as very coarse; that is, they are out of scale with the rest of the model. This was done to make the effects more apparent and to simplify the model building process. The decking is vulnerable to forces perpendicular to the corrugations, where the decking acts somewhat like an accordion. In a sense, the corrugations represent a kind of "prebuckling" of the steel sheet. The effect is demonstrated in Figure 1.19.

Corrugated decking, like the OSB in the shear wall example shown in Figure 1.13, is greatly benefited by the other structural elements in the system. For example, the



(a) (b)

Figure 1.19 (a, b) Corrugations crumpling at the point of application of the force.



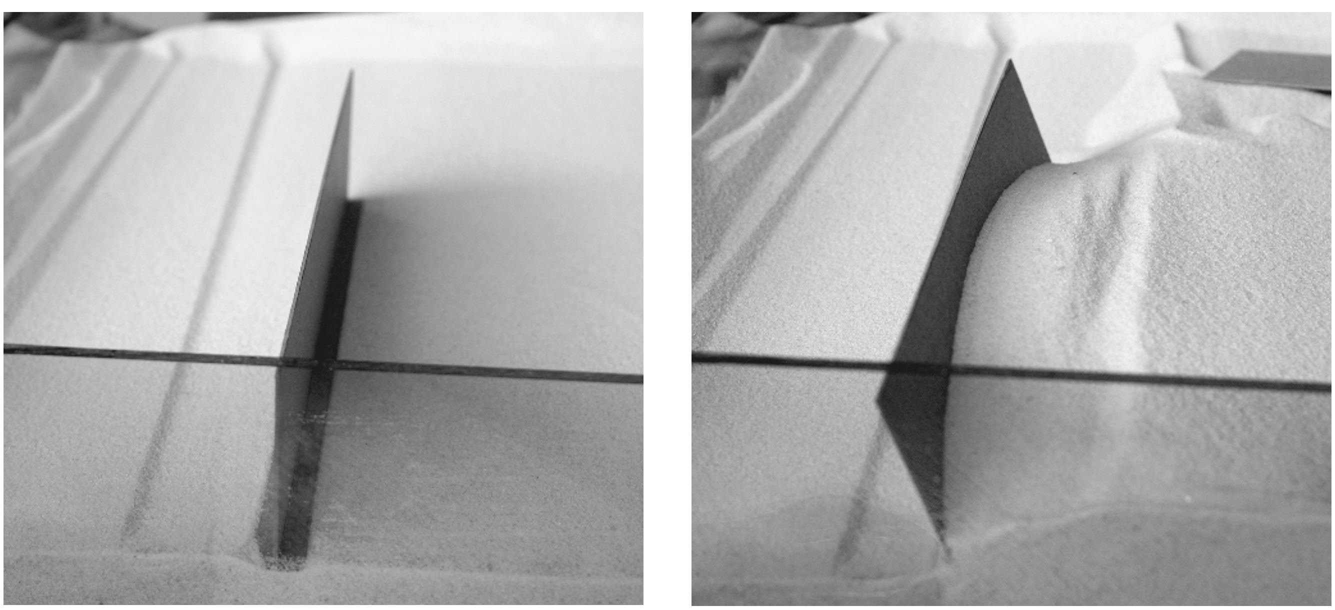
(a) (b)

Figure 1.20 Drag strut (a) improves decks' resistance to crumpling (b).

corrugated decking will be supported every few feet by spanning members, such as trusses or beams. These spanning members connect all the flutes of the corrugated decking by a continuous strut. Any force delivered to that spanning member is then delivered to every flute of the deck, which helps to distribute the forces over the decking and allow the decking to function more effectively as a diaphragm. This suggests that the connection at the top of the wall should be detailed in such a way that the forces of the wall go directly to the spanning members, rather than directly to the decking. This normally happens if the wall is working in bearing to support the spanning members. Sometimes a stiff wall engages the roof decking at a location where there is not a spanning member. To get a force transfer between the wall and the diaphragm, a special element called a *drag strut* can be welded to the bottom of the decking, similar to what is shown on the left in Figure 1.20.

In addition to wind forces, we sometimes want walls to resist the pressure of soil, which is normally much higher than wind pressure. Thin walls on narrow footings are totally inappropriate for resisting such large lateral forces, as shown in Figure 1.21.

With relatively minor additional thickness and reinforcing, such walls can be made to work well in situations where the soil pressure is exerted from all sides of the



(a) (b)

Figure 1.21 Thin wall on narrow footing, (a) standing alone and (b) under soil pressure.

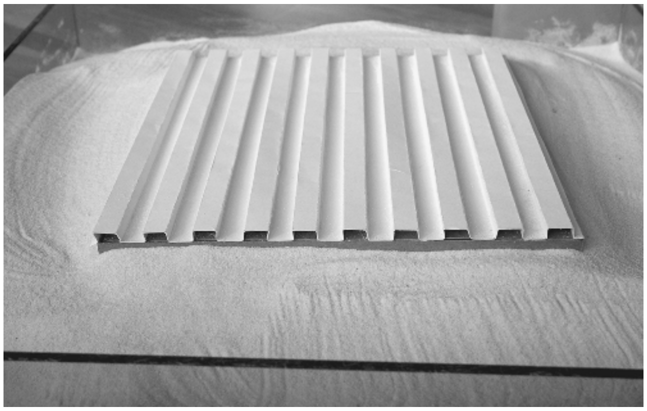


Figure 1.22 Soil on all sides of a basement wall.

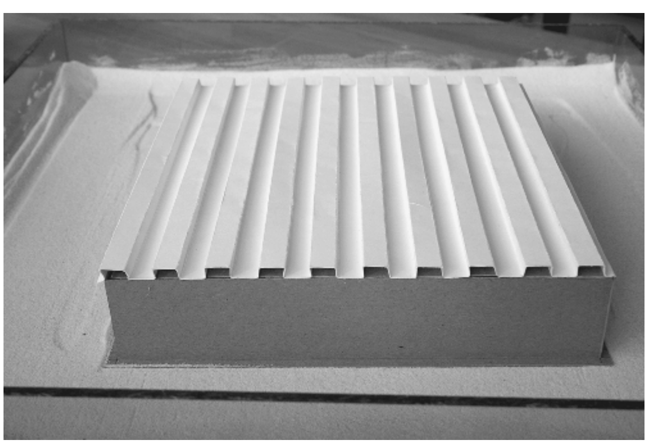
building and the floor or roofing system at the top of the loaded wall is capable of taking the inward force of the soil in compression. This is the geometric and structural situation normally encountered in full basements in buildings. In this situation, the wall is spanning from the footing up to the roof or floor diaphragm, which works in compression to keep the tops of the walls from falling inward (see Figure 1.22).

Sometimes the terrain makes it desirable to have a walkout basement, which means that there is soil pressure on one side of the building, but not the other. This situation is depicted in Figure 1.23, in which (a) shows the model with no soil pressure and (b) shows the model with soil pressure on the right side. The image in (b) shows that the model has skidded to the left under the influence of the soil pressure. This behavior can be observed in a lightweight building with shallow footings. Usually, the side walls start to skid, but the walls perpendicular to the force cannot skid because the soil resistance at the footing is too great. This causes the building to break up as it moves laterally.

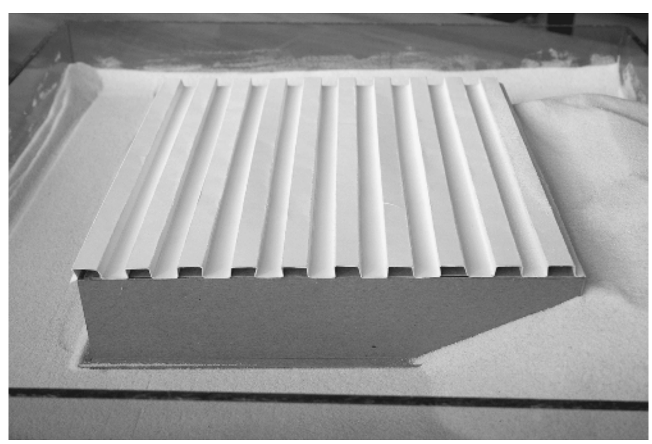
This loading condition creates forces in the structure that are difficult to analyze and design for. It also transmits a substantial amount of force through many building components that do not need to be loaded. Therefore, it is customary to account for unbalanced soil loads by designing the loaded wall as a cantilevered retaining wall. In this mode of operation, the wall has no restraint at the top and it must be connected to the foundation with a strong enough joint that the wall functions as a vertical cantilever beam. To make this work, the footing must be very strong and must be designed to avoid turning over under the influence of the wall. The standard design for a cantilevered retaining wall works similarly to a classic sheet metal bookend, where the weight of the books rests on the foot of the bookend, thereby stabilizing the bookend against overturning. In the case of the cantilevered retaining wall, soil rests on the top of the broad foundation, stabilizing it against overturning. This arrangement is shown in Figure 1.24, in which (a) shows the wide footing and (b) shows the soil against the right face of the wall, which is called the *stem*.

The footers for cantilevered retaining walls require much more excavation than wall footings that are designed to carry only gravity forces. This can be a serious issue where site limitations make it difficult to perform the excavations without encroaching on adjacent property or structures. Cantilevered walls are self-sustaining, or without the benefit of other, perpendicular walls to brace them, which requires that they be very thick walls. The benefit of cantilevered retaining walls is that they take the burden of the load at the point of application of the load, protecting the rest of the structure from that burden.

In the case of a wide building, such as the one shown in Figure 1.23, lateral forces tend to make the building skid across the land. For narrow buildings, the major concern becomes overturning of the entire structure, as shown in Figure 1.25. Such structures need to be held

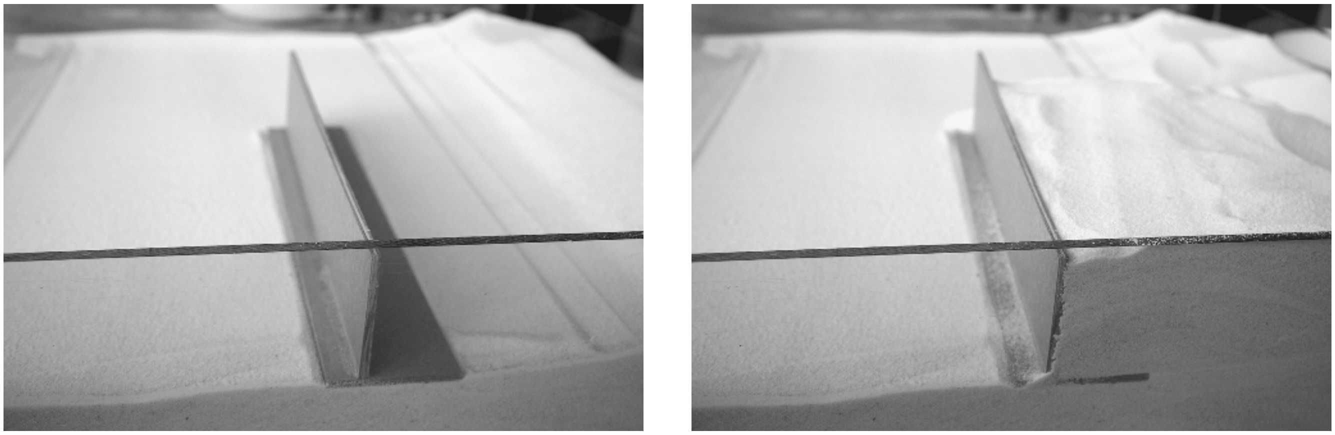


(a)



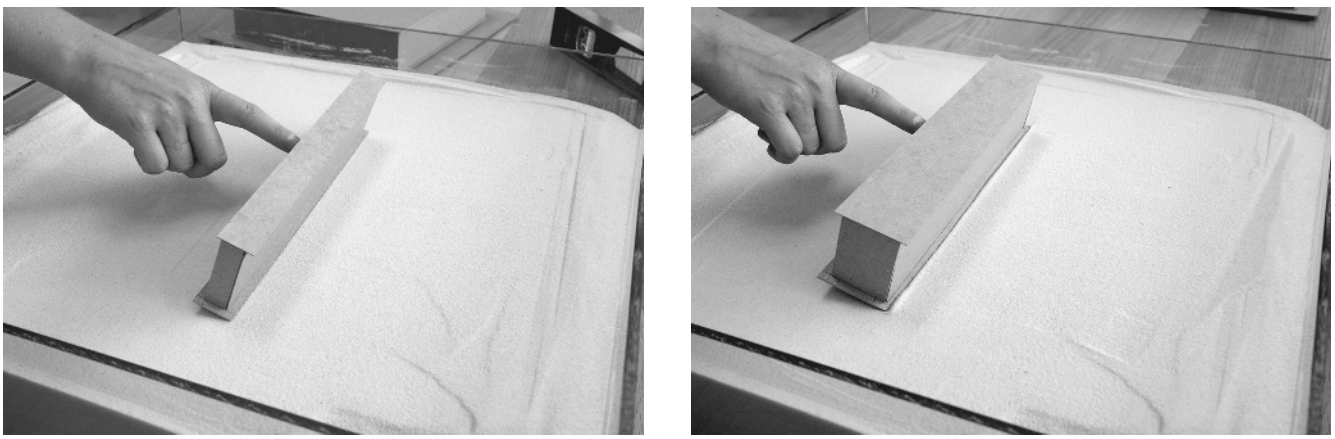
(b)

Figure 1.23 (a, b) Building skidding under influence of soil on one side.



(a) (b)

Figure 1.24 Cantilevered retaining wall (a) before and (b) after loading.



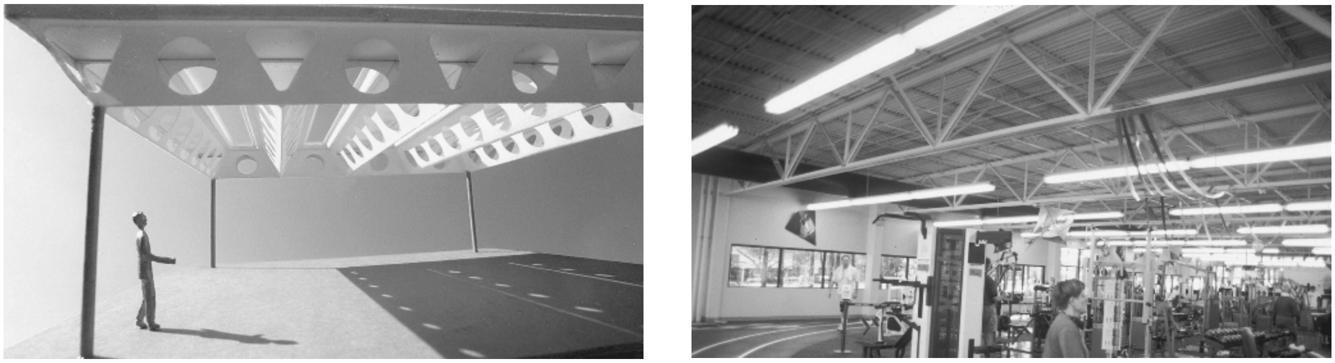
(a) (b)

Figure 1.25 Buildings with tall, narrow proportions tending to turn over under lateral forces.

down by large, heavy footings or by piles or ground augers reaching deep into the soil.

Thus far, the focus has been on the structural benefits of mutually bracing, perpendicular sheets of material. These sheets can have openings in them to serve a variety of purposes. For example, in walls, door and window openings are normally desired. Typically, doors are rectangular because that shape is simple to frame and fits the human body. Windows are usually rectangular simply because of the simplicity of framing. From a structural point of view, other shapes may be preferable to rectangles. For example, circular or triangular holes can be cut in the solid web of a beam, as shown in Figure 1.26(a), or, for maximum lightness and transparency, slender struts can be used in a triangular pattern, like the truss in Figure 1.26(b). In (a), the beams are triangular in cross-section, consisting of three sheets of mutually bracing material. No additional bracing material is required. In (b), the truss supports the roof diaphragm, which in turn provides lateral stabilization for the top edge, or top chord, of the truss. The bottom edge, or bottom chord, of the truss needs lateral bracing struts because there is no sheet of material available at the bottom of the truss to stabilize the bottom of the truss.

These spanning elements can have large rectangular openings, although this configuration is far from optimal from a structural point of view. In this case, the portions of the structure that remain must be very strong beamlike elements that are joined with rigid connections to produce something called a *rigid frame*. A *rigid joint* is defined as a joint that maintains the angle between the elements being joined, even under full loading on the structure. A rigid frame that is used to span is sometimes called a *Vierendeel truss*. Rigid frames tend to be much heavier and more difficult to fabricate than triangulated trusses. As a consequence, they are rarely used for resisting gravity forces.



(a) (b)

Figure 1.26 Beams with (a) holes and (b) a truss.

The term *truss* has come to be associated with fully triangulated spanning elements, and the terminology *Verendeel truss* is at odds with the common usage of the term. For example, it would be rare that the mention of the word *truss* would bring the image of a rigid frame to mind. Verendeel trusses can be quite elegant, as illustrated in Figure 1.27, showing a pedestrian bridge in the Oakbrook shopping mall in Oakbrook, Illinois.

The bridge in Figure 1.28 represents the ultimate in lightness and transparency in structural sheets. Uniform

Figure 1.27 Rigid-frame spanning elements (Verendeel trusses) supporting a pedestrian bridge.

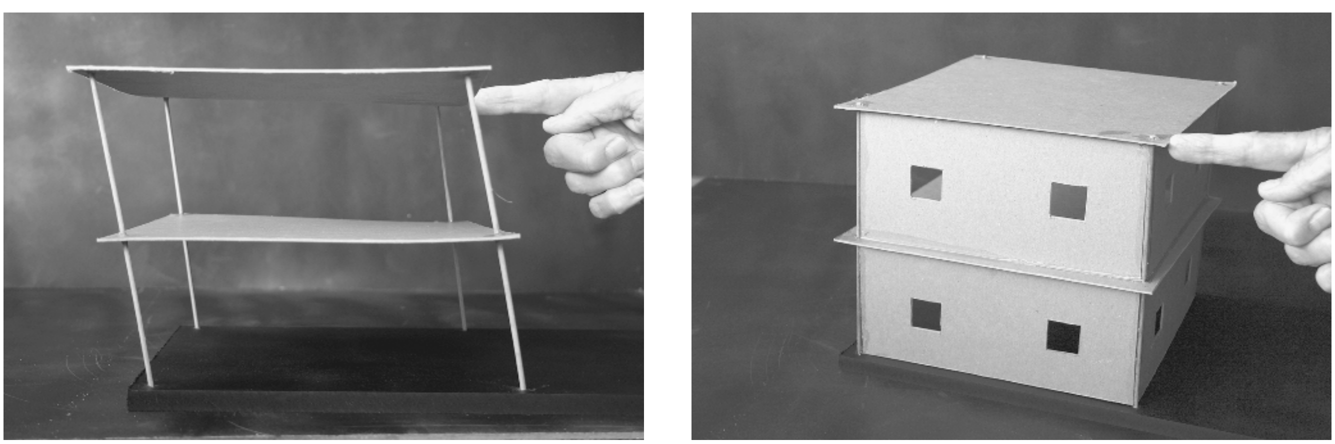
Figure 1.28 The Golden Gate Bridge.

gravity loads are being carried by two suspension cables. These cables would change shape drastically under a concentrated gravity force, such as the weight of a very heavily loaded vehicle or a closely spaced convoy of trucks. To "smooth out" the nonuniformity of the gravity loads, trusses are provided in the same vertical plane with the suspension cables. The trusses are supported by suspenders hanging from the suspension cables. Each cable, with its associated truss, forms a very strong and rigid "sheet" of material that is minimal and very transparent. Material has been put only where it needs to be. It may initially be difficult for the student to think of these slender cables as part of a sheet of material, but getting that concept established in his or her mind is crucial to understanding this subject matter.

In the same bridge, lateral forces of wind are resisted by horizontal trusses, one at the bottom of the side trusses and one at the top of the side trusses (just below the roadbed). These horizontal trusses are the perpendicular "sheets" of material that reinforce the vertical "sheets" consisting of the cables and the side trusses.

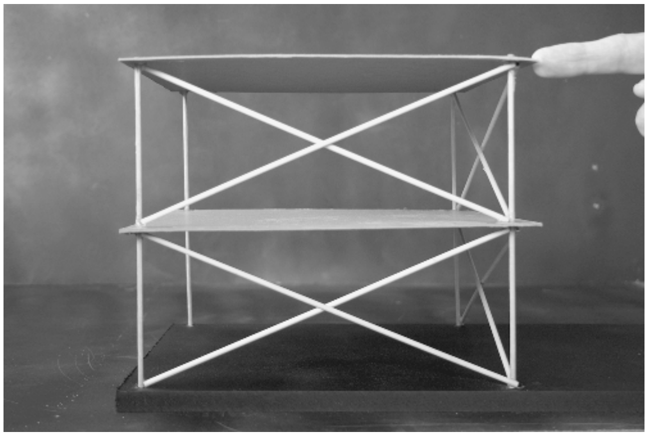
The principles and structural systems applied to resisting gravity loads can also be applied to resisting lateral forces on buildings. Figure 1.29 shows a building with no appreciable resistance being racked by a lateral force (a). That same structure can be stabilized by shear walls (b). These shear walls are the structural analog of the solid-web beam in gravity systems.

The same structure can also be stabilized by triangulation, such as cross-bracing, which would be the analog

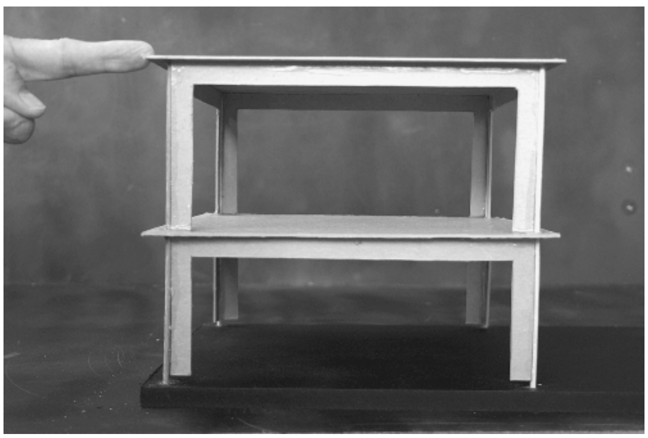


(a) (b)

Figure 1.29 (a, b) Structural frame stabilized by adding shear panels.



(a)



(b)

Figure 1.30 Bracing with (a) triangulation and (b) a rigid frame.

of a truss used to span against the forces of gravity; see Figure 1.30(a). It can also be braced using beamlike elements forming a rigid frame; see Figure 1.30(b).

The use of rigid frames is much more common in dealing with lateral bracing than in gravity spanning for buildings because they provide the kind of openings that allow human traffic to easily pass through at a variety of locations. Moreover, for some very tall buildings, the inherently large dimensions of the columns make rigid-frame action very effective and practical. One of the most beautiful and practical examples of this mode of construction is the Sears Tower, designed by Skidmore, Owings & Merrill of Chicago (see Chapters 7 and 10). In the Sears Tower, as is the case in most rigid-frame steel structures, the rigid joints were achieved through welding, which makes the material essentially continuous in all directions. Achieving rigid joints with wood is much more problematical than with steel. The unidirectional nature of wood fibers creates a challenge in making the material continuous in more than one direction through a joint. The only effective way to achieve this result is to split the material in one direction and let material running in another direction pass between the two split pieces. To get a rigid connection between the intersecting members, the material that has been split apart must effectively encase the material passing through. This arrangement is illustrated in Figure 1.31, wherein 2 × 6 wood beams, with blocking elements in between, have been sandwiched around a 2 × 4 wood beam running perpendicular to the two 2 × 6 wood beams. In a really good rigid joint, the blocking members should be pressed down against the 2 × 4 and glue should be used to fill any fine voids and to ensure that the blocking elements do not slip where they are connected to the 2 × 6s. In this demonstration model, there was no glue. In spite of that fact, this single joint is now more than capable of taking the maximum force from the person who was able to rack the standard stud wall frame with a single finger (as was shown in Figure 1.12(b)). The use of moment joints is clearly a more complicated method of achieving lateral stability in a wood structure than by the use of plywood or OSB sheathing to create a shear wall.

(a)

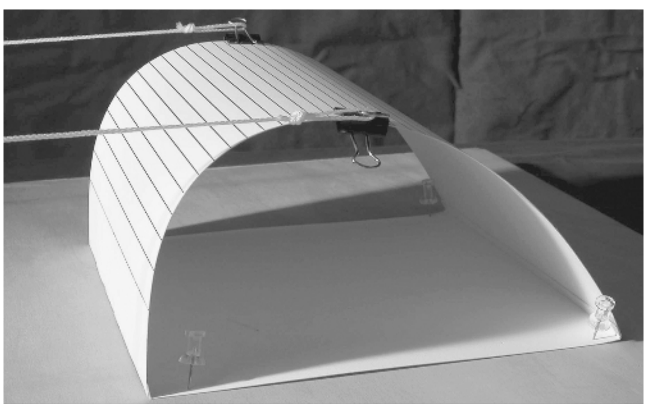
(b)

Figure 1.31 (a, b) Rigid joint in wood.

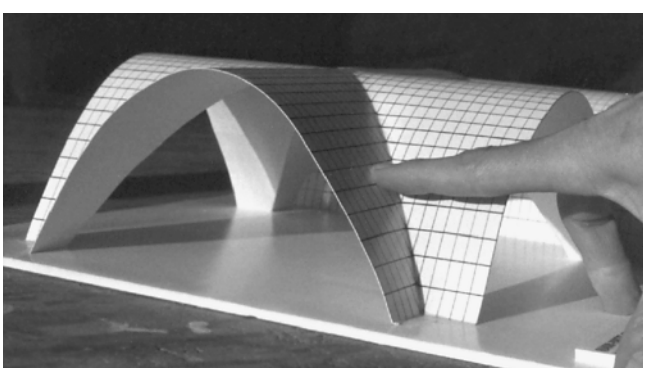
The mutually bracing sheets of material do not have to be perpendicular to each other. They simply have to meet at an angle that puts each sheet substantially out of the plane of the other sheet. For example, a tube with a triangular cross section can function extremely well structurally, even though the sheets of each face are meeting each other at 60°, instead of 90°. In fact, such a tube can even work well with a cross section that is a 45°-45°-90° right triangle.

Sometimes, the sheets of material may not even be planar elements. In Figure 1.32(a), a thin-shelled barrel vault is extremely vulnerable to lateral forces, which cause roll-through deformation. The curved sheets of material in the thin-shelled cross vault in Figure 1.32(b) are very effective at bracing each other everywhere except at the top, where the sheets merge into a locally flat area where the sheets become essentially coplanar.

Domes, which have no flat parts, are even subtler examples of this phenomenon. No matter in which direction you push on a dome, there is part of the dome that is essentially "edge on" to the force. That material is crucial in keeping the dome surface from deforming; see Figure 1.33.



(a)



(b)

Figure 1.32 (a) A thin-shelled barrel vault and (b) a thin-shelled cross vault.

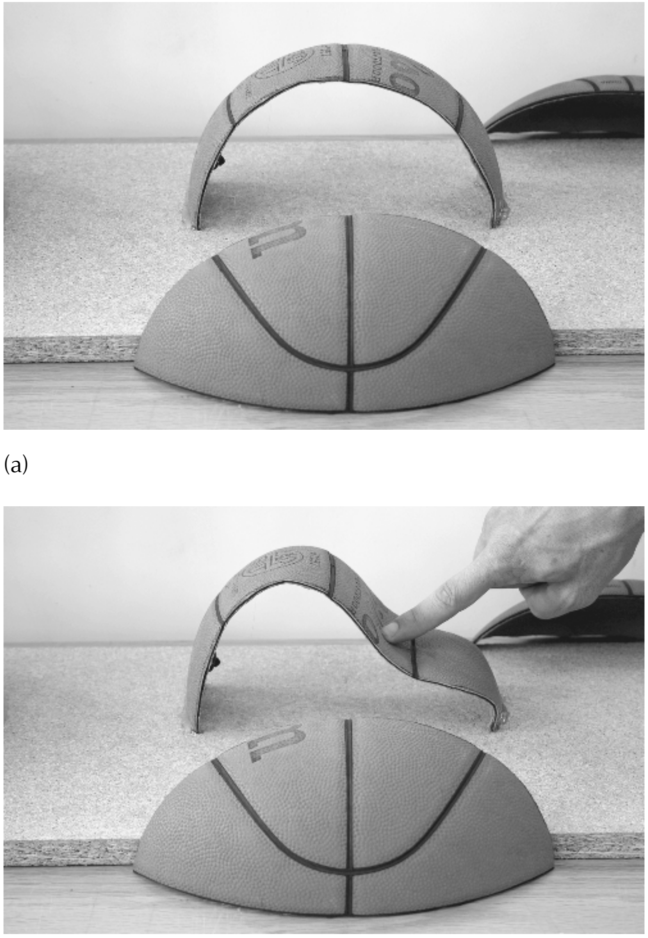
(a)

(b)

Figure 1.33 (a, b) A dome subjected to lateral load.

In Figure 1.34(a), the sides of the dome are cut away. The remaining portion of the dome is extremely vulnerable to lateral force on its surface (b).

There is a fourth, somewhat less common form of structural action called *torsion*. Torsion involves an element's being subjected to a torque that causes it to twist about its axis. The most common form of torsion is seen in the drive shaft of a motor vehicle. Elements that work well in other kinds of structural action, such as bending, do not necessarily work well in torsion. For example, I-beams work very well in bending and are about the worst structural form for addressing torsion. Closed tubes are the best structural form for working in torsion. Figure 1.35 illustrates this point. There are three plastic elements, each constructed from the same amount and type of styrene plastic. The elements are a square tube (top), a thick, solid bar (middle), and an I-section (bottom). The I-section has the smallest torque and largest amount of twist. The hollow tube has the largest torque and the least amount of twist.



(a)

(b)

Figure 1.34 (a, b) Dome with sides sliced away, showing roll-through deformation.

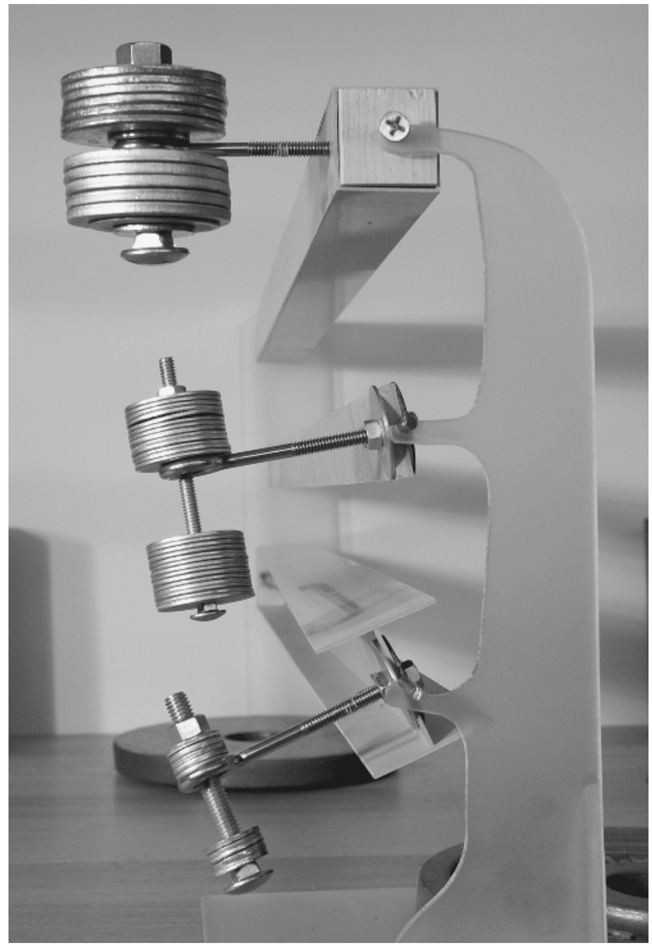
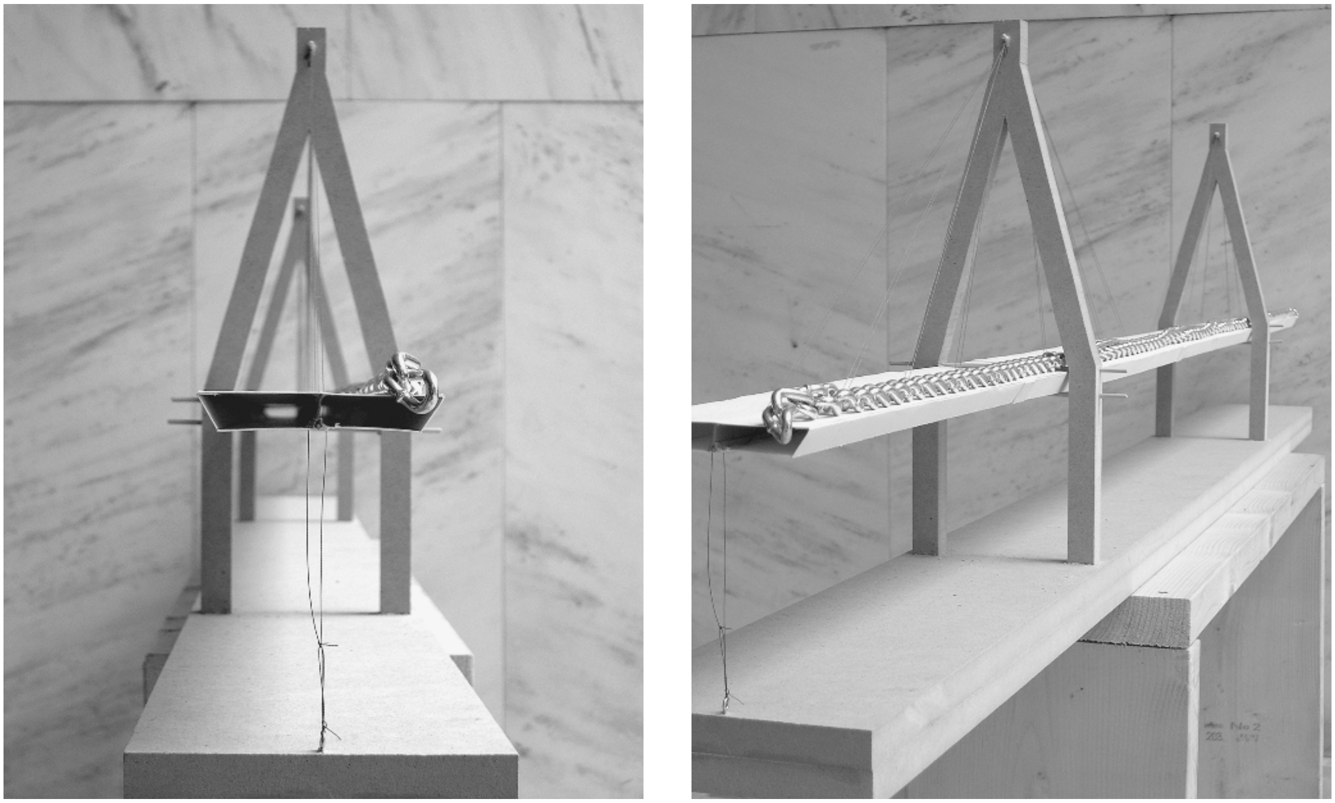


Figure 1.35 Torsion in a tube, a slab, and an I-section.

The Sunshine Skyway Bridge in Tampa, Florida, is an example of a structure that relies on torsion for stability. The roadway is supported along its centerline by a plane of tension stays that are in turn supported by the towers. If these stays were the only means of support for the roadway, any asymmetric loading, such as might occur with heavy traffic on one side of the bridge, would cause the bridge to twist over, dumping the traffic into the bay. The cross section of the roadway is a closed tube that is connected at the towers so that it will not rotate. Asymmetric loading on the roadway is carried through this torsional action. It is crucial that this tube closes on itself. The following figures illustrate this point. In Figure 1.36, stays support the centerline of the roadway, which is tubular in cross section and is restrained against rotation at the towers by wooden pins above and below the roadway. Asymmetric loading is simulated by a heavy chain resting on the right side of the roadway. Removing the pins at the towers causes the roadway to tilt dramatically, dumping the load. The tubular roadway is working very well in torsion to resist this asymmetric loading.

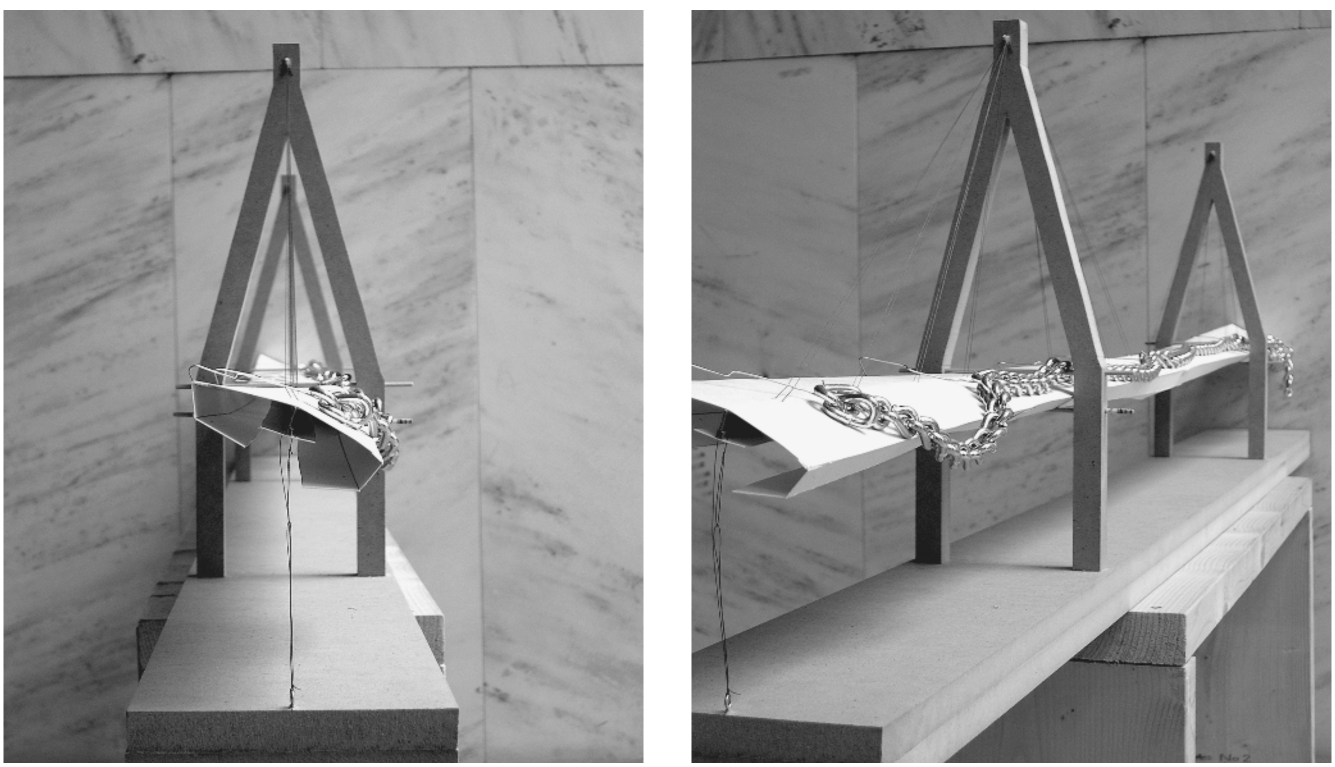
Figure 1.37 shows what happens when the tube is split along two lines on the bottom of the roadway. Neither the total amount of material in the cross section nor the depth of the cross section has been changed by making these slices. However, the torsional capacity of the roadway has been drastically diminished, as indicated by the amount of twist. The twist has induced such a severe tilt in the roadway that the chain has to be tied to the bridge to keep it from slipping off.

The most common situation in which torsion is encountered in buildings is in curved beams, which tend to twist under loading. For such structures, the ideal beam cross section is a closed tube. However, thin-walled tubes have serious problems with wall buckling when an attempt is made to roll them into a curved form. Wide-flange elements are usually much easier to roll into a curved shape. Sometimes it is more economical to simply use a heavy wide-flange beam, even though that may not be the most structurally efficient shape.



(a) (b)

Figure 1.36 (a, b) Two views of a model bridge with stays down the centerline.



(a) (b)

Figure 1.37 (a, b) Effect of slicing a roadway so that it is no longer a closed tube.

1.7 Design Guidelines for Spans and Proportions of Common Members and Systems

As demonstrated with the plastic beams (Figure 1.4 and Figure 1.5), depth is crucial to their being able to span effectively. The required depth of a beam is not an absolute matter, but a relative matter. It has to do with proportions: the longer the beam, the deeper the beam needs to be. The same general argument applies to all kinds of spanning elements. The tables in Figures 1.38 through 1.44 show typical spans and proportions for some of the common spanning systems that are discussed in more detail in other parts of this book. The spanning members are drawn to scale, with the scale being indicated at the top

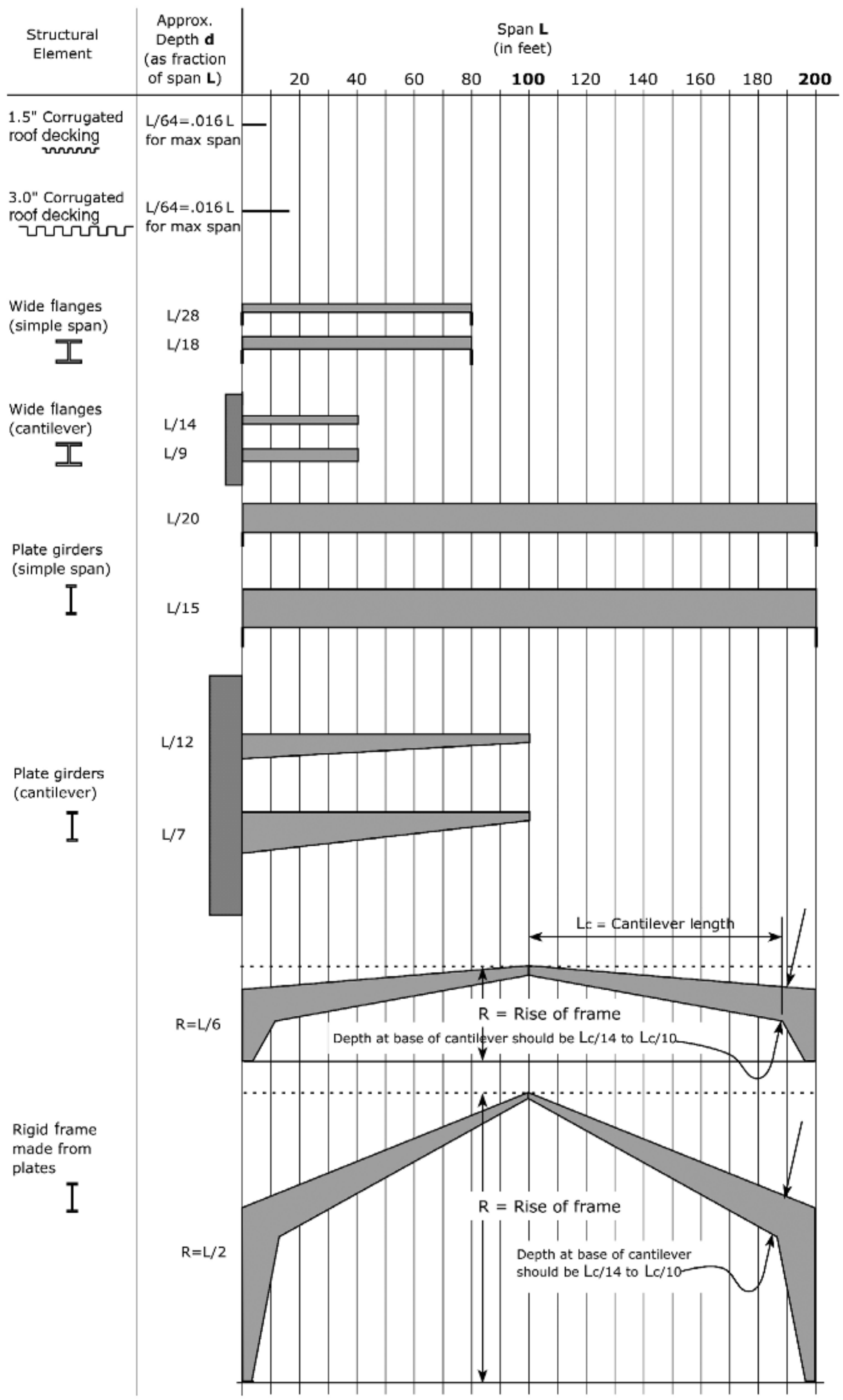


Figure 1.38 Spans and proportions of steel spanning systems—page 1.

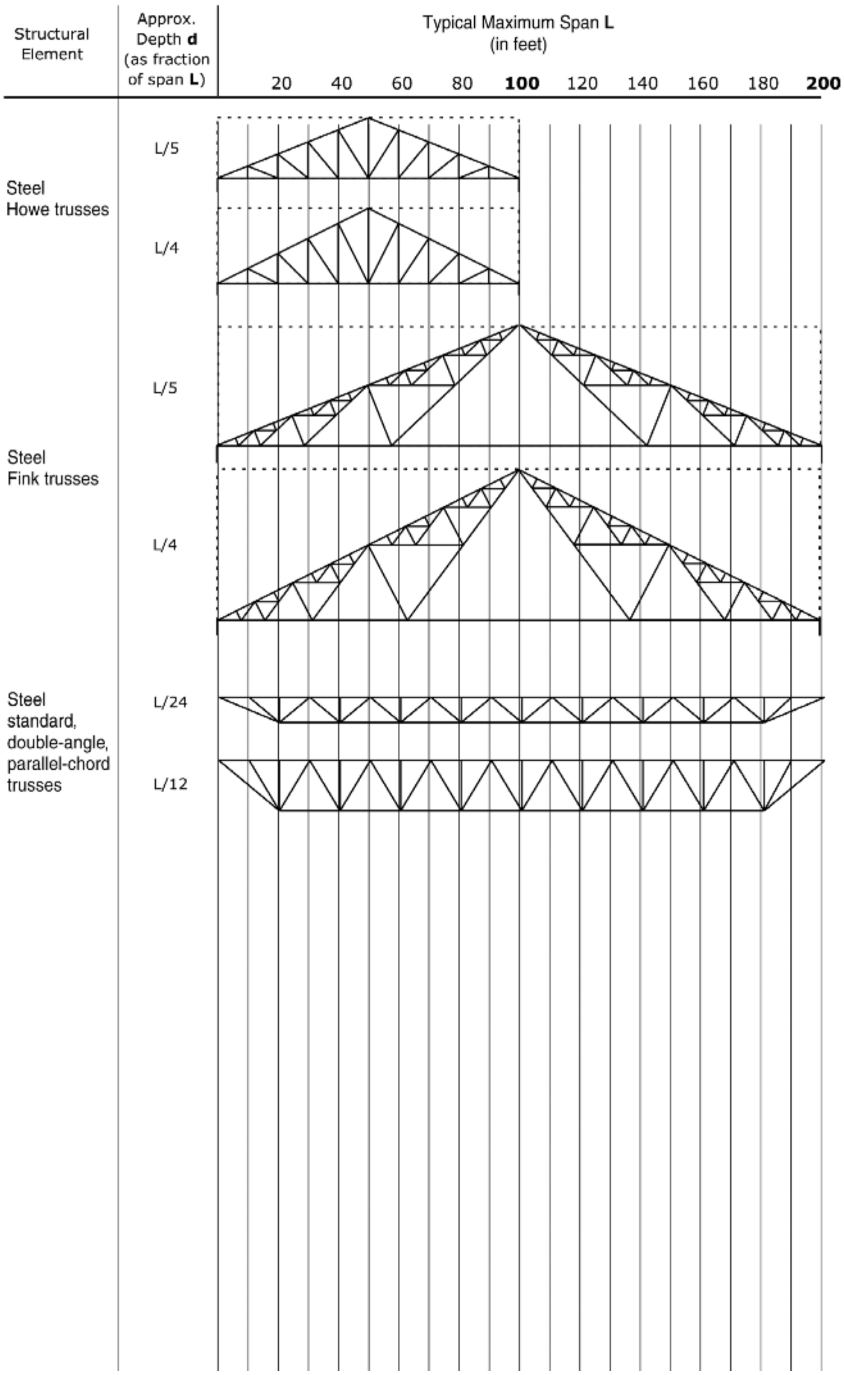


Figure 1.39 Spans and proportions of steel spanning systems—page 2.

of each page. Most of the pages put the top of the scale at a span of 200 ft and one page goes to 1,000 ft. In interpreting the data, the first thing the reader should look at is the scale at the top of the page.

For each spanning system, there are two diagrams drawn, one indicating the shallowest proportions that would be commonly used and the other indicating the deepest proportions that would commonly be used. Both the diagrams shown for a particular spanning element are drawn at a length indicative of the maximum length that is commonly expected to be seen for that element. All these spans and proportions are indicative of common practice at the time of the writing of this book. Every one of these spanning systems could be driven to greater spans by a highly motivated designer. Therefore, these upper limits should not be interpreted as absolute, but

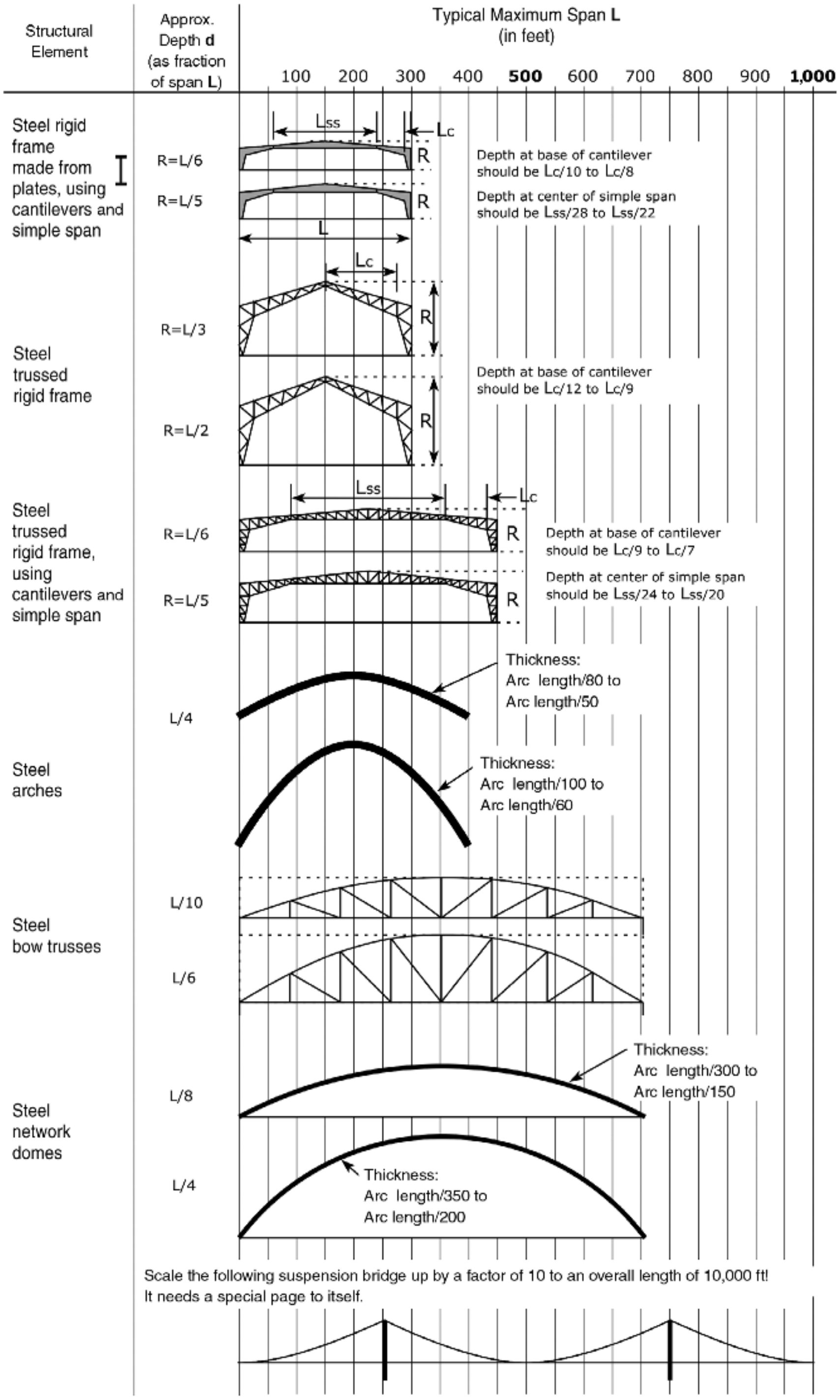


Figure 1.40 Spans and proportions of steel spanning systems—page 3.

simply as indicators of the practical limits to the span of the system. Similarly, the limits of the proportions, as indicated by the two diagrams, should also be understood as indicators of common practice, and not as any kind of absolute limits. These pages can be consulted in the early stages of design to get an idea of what is economically practical with these systems.

Assignment 1.1: Problem on Spans and Proportions of Steel Spanning Elements

1. A steel parallel-chord truss is to span 80 ft. With proportions near the shallower end of the range indicated in the guidelines, its depth would be what? ___________

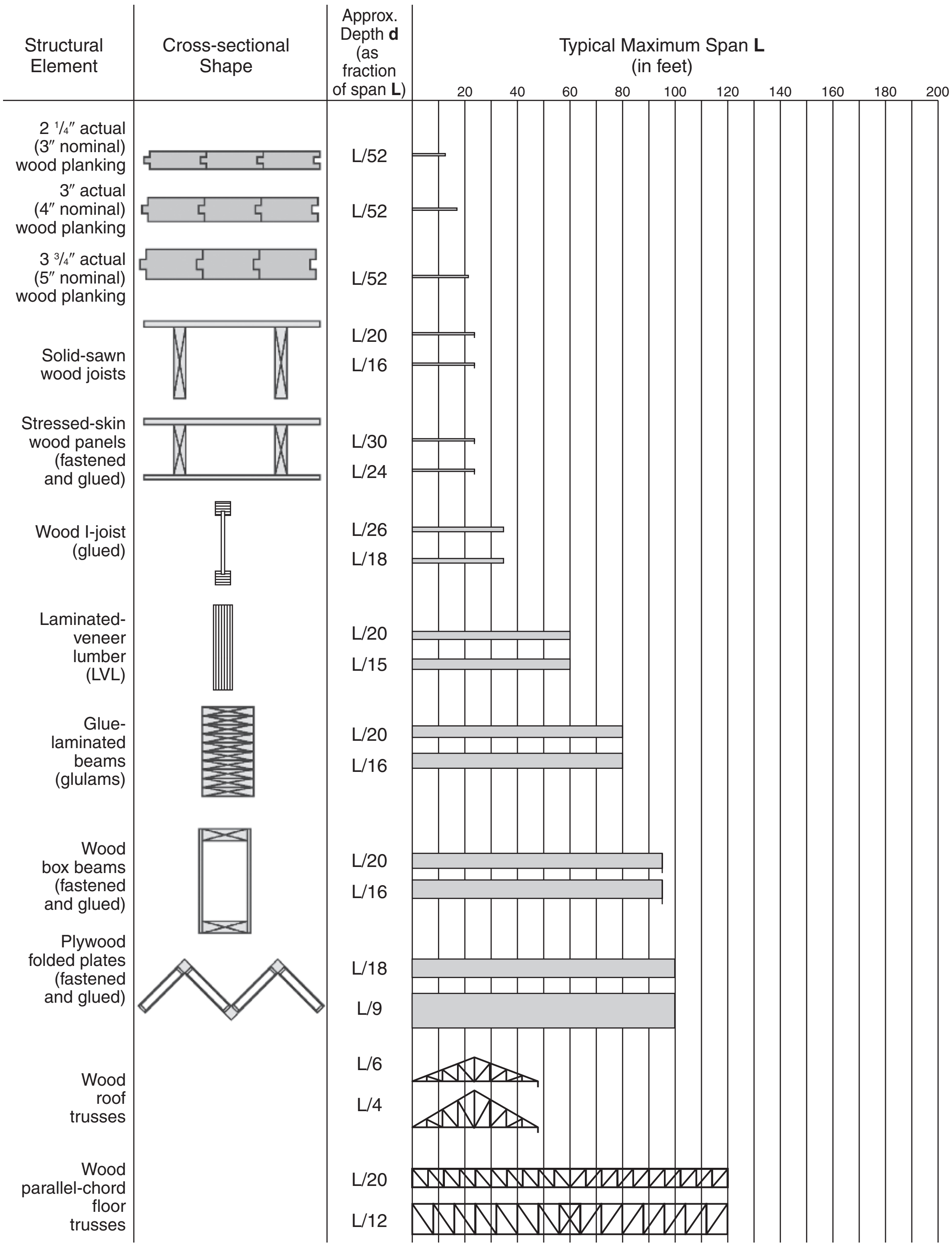


Figure 1.41 Spans and proportions of wood spanning systems—page 1.

With proportions near the deeper end of the range indicated in the guidelines, its depth would be what? __________

2. For a steel bow truss of relatively deep proportions spanning 60 ft, what would the depth at the center of the truss be? __________

3. A wide-flange cantilevered beam projecting out 20 ft, having fairly shallow proportions, would be how deep? _________

4. A solid-sawn wood joist is spanning 16 ft. With proportions near the shallower end of the range indicated in the guidelines, its depth would be what? __________

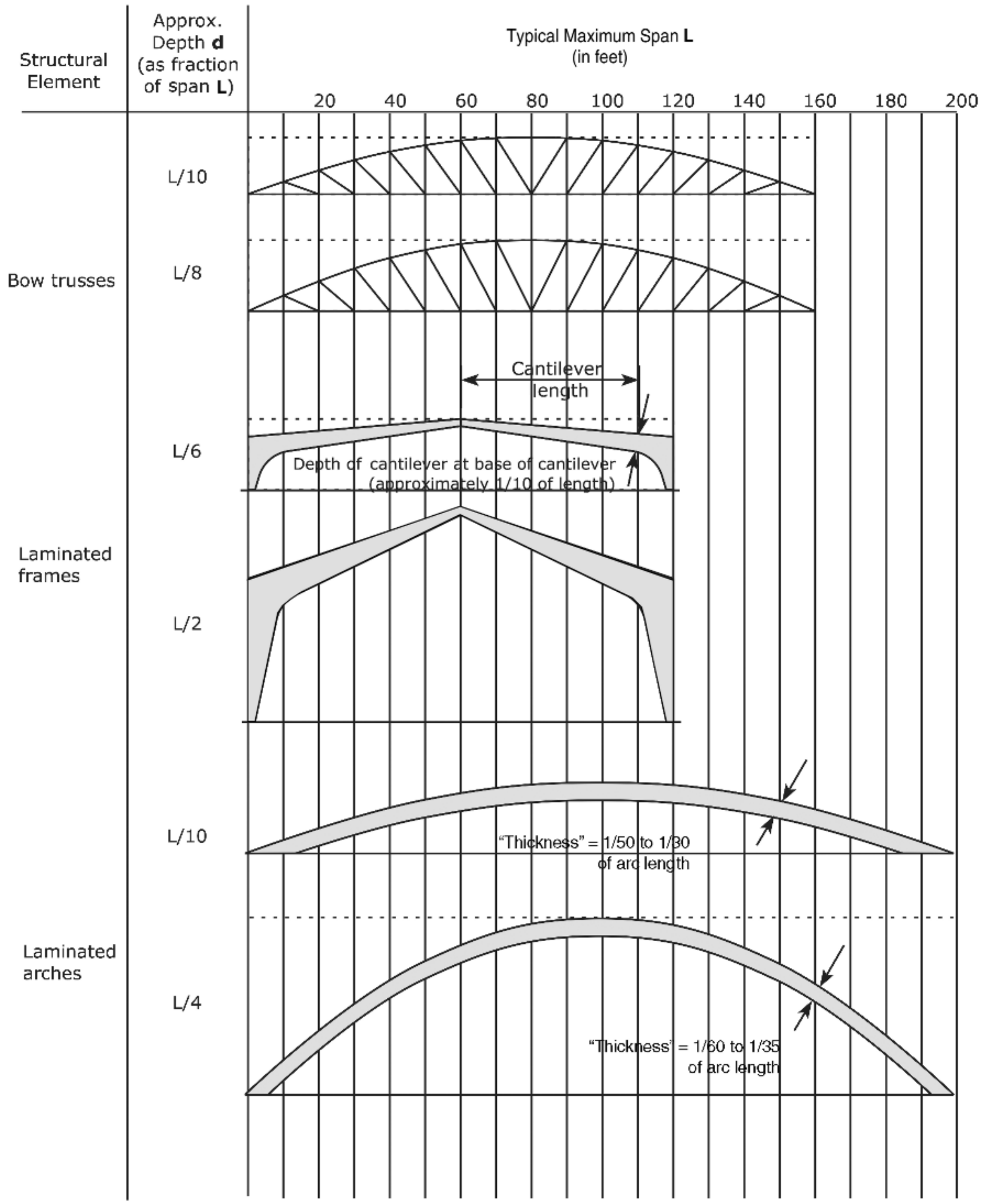


Figure 1.42 Spans and proportions of wood spanning systems—page 2.

With proportions near the deeper end of the range indicated in the guidelines, its depth would be what? __________

5. A steel rigid frame is spanning 140 ft. What would be the shallowest rise within the range indicated in the guidelines? __________ What would be the highest rise within the range indicated in the guidelines? __________

6. For a simple concrete slab spanning 25 ft in two directions and supported continuously around the boundary by beams or bearing walls, what is the shallowest depth within the guidelines? __________

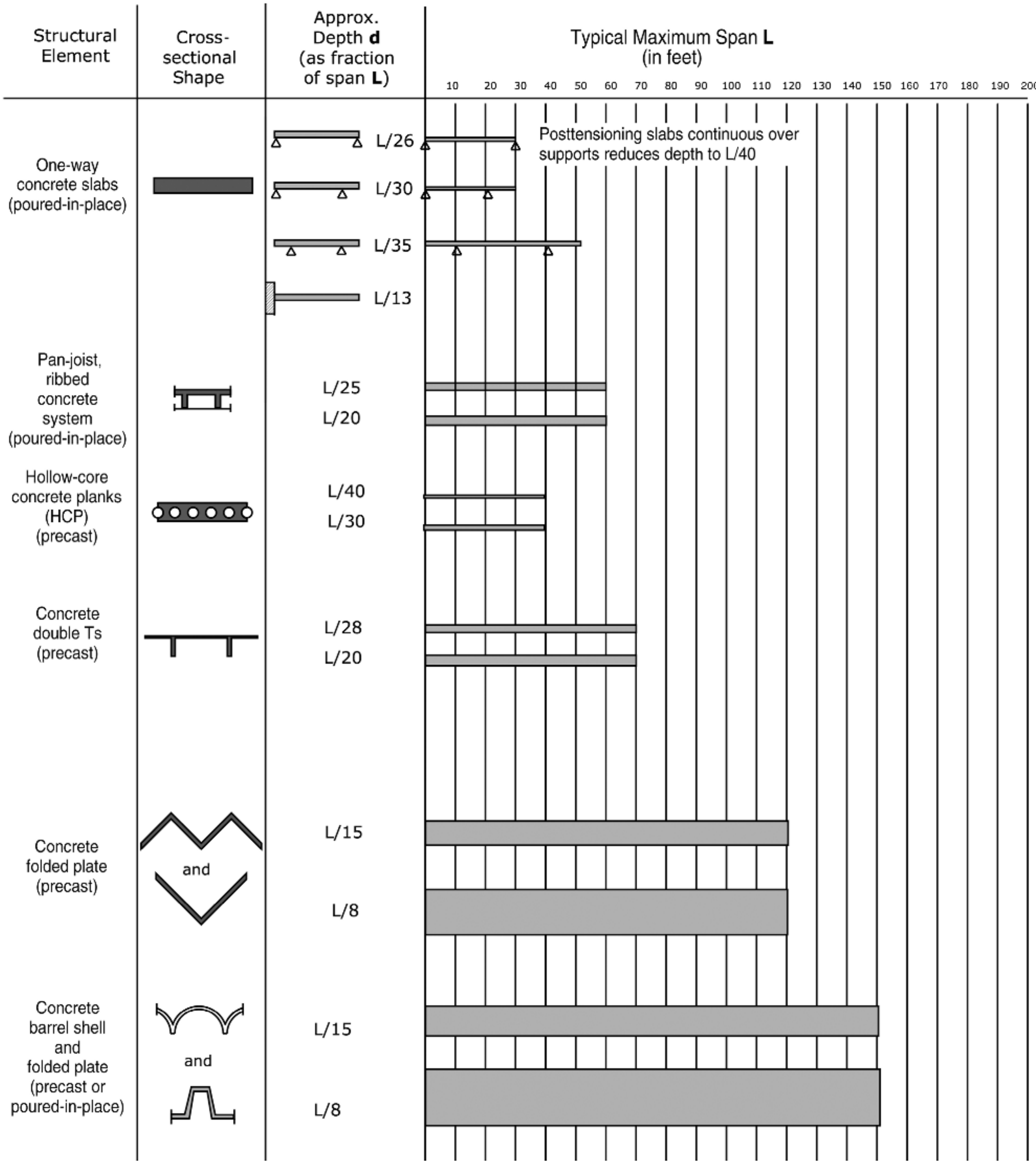


Figure 1.43 Spans and proportions of concrete, linear spanning systems—page 1.

What is the maximum depth within the guidelines? ____________

Assignment 1.2: Structural Design/Model Project

Providing interior illumination using natural light is commonly referred to as *daylighting.* Daylighting involves an interesting challenge in structural design, inasmuch as it requires extensive openings, or apertures, to admit the light. In this project, students will design a steel structure that admits daylight for illumination. The building will have an identified purpose and will address the following requirements:

1. Most of the roof surface will be opaque and well insulated.

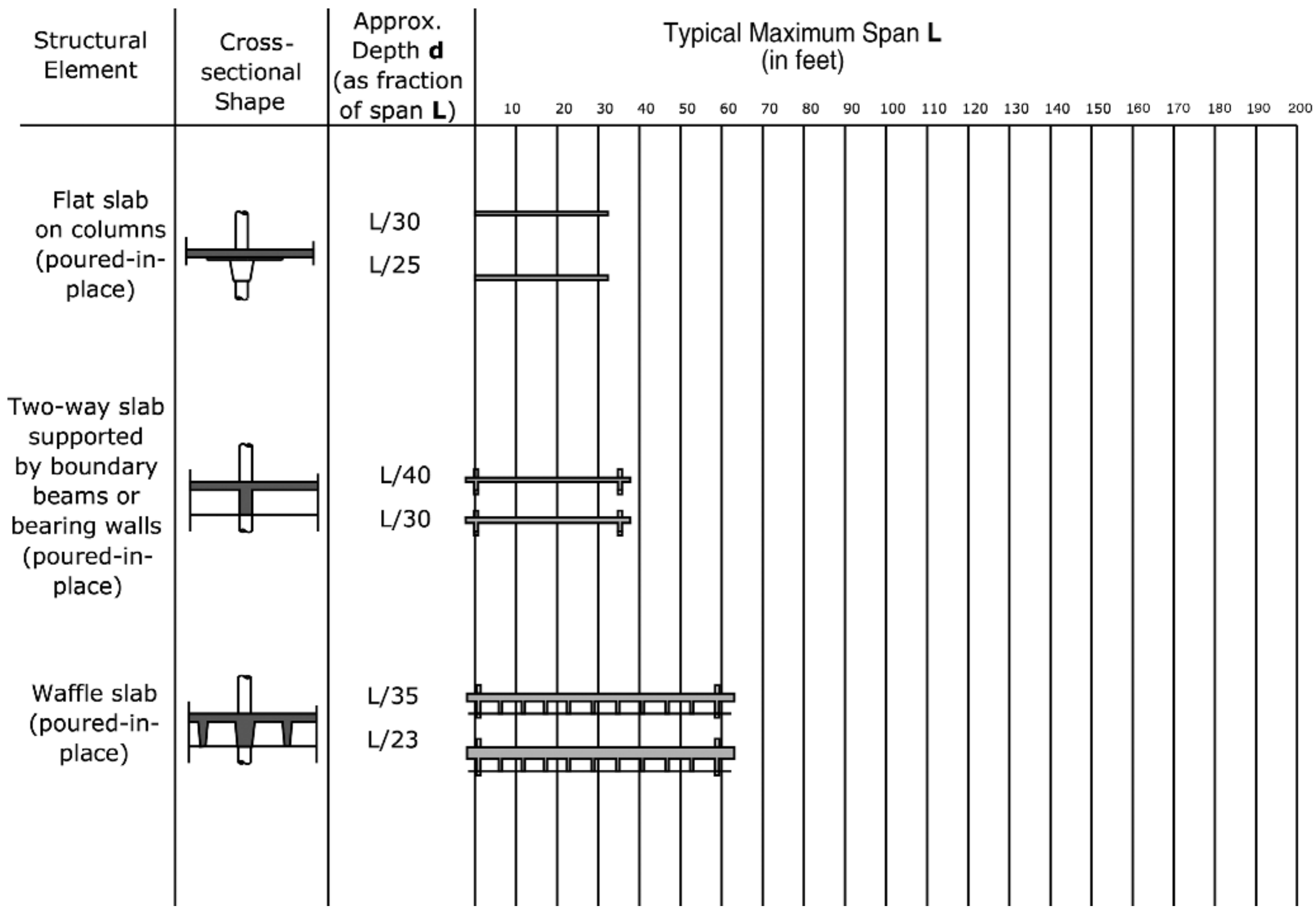


Figure 1.44 Spans and proportions of concrete, two-way spanning systems—page 1.

2. Within the roof will be openings to admit daylight.
3. These openings will represent approximately 20 percent of the floor area being illuminated.
4. The openings will be vertical and facing north and south.
5. The openings will be distributed/located in such a manner as to produce fairly uniform light throughout the interior of the structure.
6. A means will be identified by which glare from beam sunlight can be avoided at all times of year. This may involve the use of baffles, banners, or some other elements that intercept the beam sunlight admitted through the south-facing glazing.
7. The spans involved should be large enough to be challenging—at least 50 ft.
8. The design must provide adequate rigidity so that the glass in the openings will not shatter.
9. The spanning members will have appropriate proportions.

For the physical model:

- Materials and connections used in the model should behave in a manner that is reasonably representative of the materials from which the actual structure would be created. In your model, as in the real structure, connections that work are more important than pretty connections. Realistic simulation of structural behavior suggests that you do *not* build your model on a thick, rigid slab of material. One of the most tenuous parts of a structure is the connection to the ground. The ground generally has significant compressive capacity, minimal shear capacity, and no tensile or bending capacity. The model should attempt to reflect these facts. This is a tough part of the assignment. Start collecting

Model Creator(s):	If there are multiple creators, evaluators should keep in mind the level of effort and quality of work appropriate to the number of creators.
Model Evaluators:	

1. Evaluate the elements for resisting each of the following forces:

Vertical forces:

Dead load:

Snow/live load on roof:

Live load on floors:

Wind suction on roof:

Horizontal forces:

Wind, earthquake, live, or impact forces in N–S direction:

Wind, earthquake, live, or impact forces in E–W direction:

Total value: 50 pts | Points deducted

With regard to each of these forces:

A. Are the proportions of the bending elements **(d/L)** consistent with the guidelines?

B. Do the compressive elements have adequate **breadth** and/or **bracing** to resist buckling?

C. Are there elements that looke like some common structural element, but are really acting like something else?

---

2. Is the model-building technique effective in simulating the structural behavior that would be expected from the structure?

Total value: 10 pts | Points deducted

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3. Are the daylighting apertures appropriately
- oriented?
- sized?
- located?
- protected with overhangs?
- provided with beam sunlight blockers/diffusers?

Total value: 20 pts | Points deducted

---

4. Does the design show innovation, creativity, or a willingness to take risks?

Total value: 5 pts | Points deducted

---

5. Artistic/aesthetic evaluation:
Is the structure inspiring?
Is it dramatic?
Does it stimulate curiosity?
Does it have pleasing proportions?

Total value: 5 pts | Points deducted

---

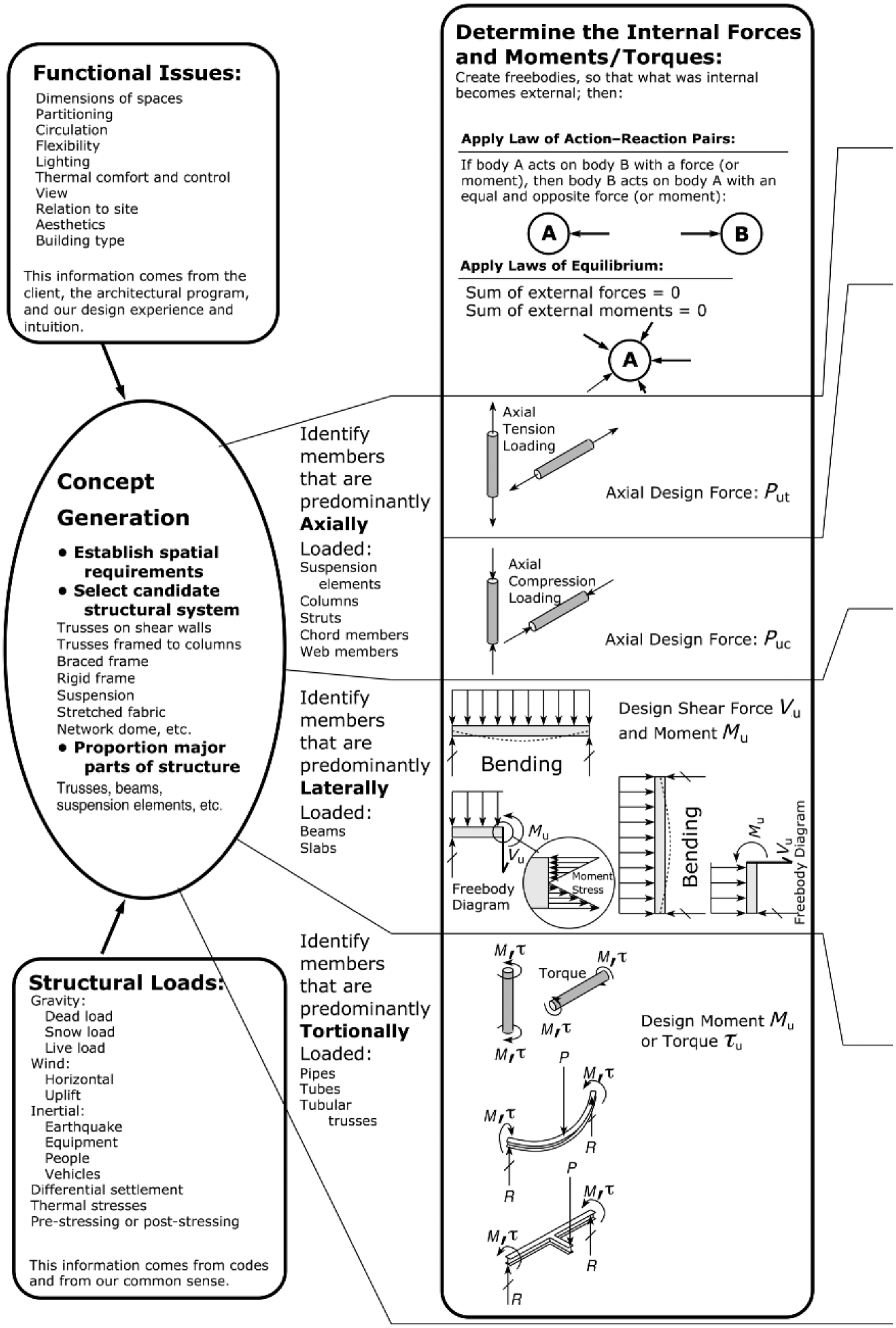
6. Would the structure serve the intended function well?
Does it shed rain well?
Are there heat trains?
Does the space have sufficient size and the right proportions for the function?
Are entry and egress properly provided?
Are there safety issues?

Total value: 10 pts | Points deducted

Total points deducted

Final evaluation of DL model: /100

Figure 1.45 Evaluation of Structural Design/Model Project.



(a)

Figure 1.46 Flowchart for structural design process—page 1.

Design Members

Choose material: note yield stress and material stiffness E
Choose shape of X-section
Choose connector concept
Size X-section
Work out details of connections

Tension element

(Fails by material tearing (yielding))

$$A_t \geqq \frac{P_{ut}}{\Phi_t F_y}$$

P_{ut} from factored loads

"Slender" Compression Element

(Fails by crushing of material or buckling of the element)
Chose radius of gyration large enough that slenderness ratio (L/r) allows a reasonably high allowed compressive stress F_{CR}.

$$A_C \geqq \frac{P_{uc}}{\Phi_C F_{CR}}$$

P_{uc} from factored loads

Other issues:
Buckling of parts of X-section (e.g., wall buckling)

Shear (use reasonable area in vertical rectangle)
A = area of rectangle
= cross-sectional strength for shear

$$A \geqq \frac{3}{2}\frac{V_u}{\Phi_v F_{yv}}$$

V from factored loads

3/2 factor accounts for nonuniform stress distribution

Moment (use I-section with wide flange for stability)
S = section modulus
= cross-sectional strength in resisting moment.

$$S \geqq \frac{M_u}{\Phi_b F_y}$$

M_u from factored loads

(**b** is for bending. It should be **m**, for moment stresses, but history has made it otherwise.)

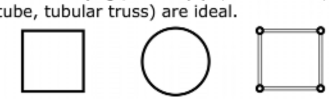
Deflection (use deep I-section)
I = moment of inertia - cross-sectional stiffness

$$I \geqq \frac{f(w,L)}{E} \times \frac{L}{\Delta}$$

where f(w,L) is a function of the unfactored load and span

Other Issues:
Lateral stability, flange buckling
bearing surface, bolt sizing, etc.

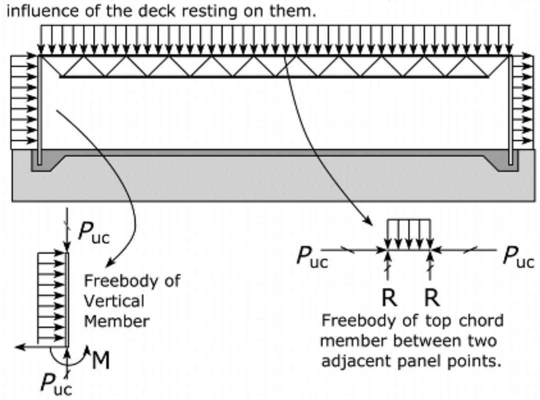
To achieve tortional strength and stiffness:
Use a section with a large
Angular Moment of Inertia J.
Tubular elements (e.g., round pipe, round tube, square tube, tubular truss) are ideal.



Some of the above are hard to produce in curved forms (e.g., the walls of square tube buckles during rolling). In such applications, the I section may prove to be satisfactory if a version is used with thick flanges and web:

Design Members with Combined Stresses

Some members are in multiple states of stress. For example, the vertical members in the following structure have axial forces from the weight of the roof and lateral forces from the wind. The top chord members are in compression under the influence of the overall truss action and they are bending under the influence of the deck resting on them.



For a member to be satisfactory under the combined axial load and bending load, it must satisfy the following condition:

The fraction of the member's capacity consumed for axial compression + the fraction of the member's capacity consumed for bending must be less than or equal to 1.

$$\left(\frac{f_c}{\Phi_c F_{CR}}\right) =$$ the fraction of the element's compressive capacity that is consumed under axial load

f_c = actual compressive stress under the axial load

$\Phi_c F_{CR}$ = allowed compressive stress under the axial load

$$\left(\frac{f_b}{\Phi_b F_y}\right) =$$ the fraction of the element's moment capacity that is consumed in the lateral loading, where

f_b = actual moment stress under the lateral load

$\Phi_b F_y$ = allowed moment stress under the lateral load

Procedure: Add together the two fractions from above.

$$\left(\frac{f_c}{\Phi_c F_{CR}}\right) + \left(\frac{f_b}{\Phi_b F_y}\right) \leqq 1$$

This equation states that the fraction of the element's capacity that is consumed for all the loads on it, i.e., for the combination of axial and lateral loads, must not exceed ONE, i.e., it will not exceed the safe capacity of the member.

This design process is highly itertive, involving trial and error. In such a situation, we:
1. Make an educated guess regarding which loading condition is the most demanding on the member
2. Oversize the member for that loading condition
3. Test the member to see if it is adequate to resist the combined stresses from the two loading conditions
This is called a UNITY check.

The details of the equation above vary from material to material and over time, as refinements are made in the methodology, but for purposes of this text the equation above captures the gist of the sizing process for combined stresses. The more detailed calculations for combined stress should be performed by a qualified structural engineer.

(b)

Figure 1.46 Flowchart for structural design process—page 2 *(Continued).*

materials early and do experiments to see how best to connect those materials. Explore how best to express the structural behavior of your design.

- A sequence of models in partially completed states would be useful if you are exploring a new structural concept. In this manner, the structural function of each part can be demonstrated as it is added to the structure. If you want to build several good models, group projects will be considered. Discuss your team plan with the instructor before proceeding. The additional level of effort needed to justify additional team members should be apparent in the project.
- Write a succinct one-page description of the rationales underlying your design. This should include a description of which elements bear primary responsibility for each of the common loads that would have to be addressed, especially gravity and wind in all directions, including wind suction on the roof. See the loads checklist at the beginning of Chapter 2. Discuss materials, methods of connection, and fabrication and construction issues.
- Put a scale figure in the model to indicate its size.

Make your design something that excites you. It should represent structural beauty, as you define it at this stage in your development as a designer.

Assignment 1.3: Structural Model Analysis/Evaluation

To stimulate active student participation in the discussion and analysis of the structural models, the class will be divided into groups. (Three students per group seems to be a manageable size that offers diversity of ideas without being so large that voices get lost. The instructor will make the final decision on the size of the groups.) Each group will prepare a detailed (but concise) written analysis of four models other than their own.

The student groups will be formed by students signing up together. The sign-up sheet will indicate the method by which three models will be assigned to each group. In addition to the three assigned models, each group will select one other model for review. Each group is encouraged to select a model that is as different as possible from the models that are assigned. If a group has been assigned a model that is substantially incomplete, the group is encouraged to choose another model to replace it.

Each group is to choose a location in which to work and to mark that location with a sheet of paper with the letter representing the group (A, B, C, etc.). Then, each person in the class is responsible for taking his or her model to the location of the group that will be reviewing it.

To bring some structure and discipline to this process, an evaluation sheet has been provided (see Figure 1.45). On the evaluation sheet, various design issues are listed and point values are assigned. This evaluation sheet will be the point of departure for all discussions of the models. As you proceed in your discussions, you may want to make suggestions regarding additional issues that should be included on the sheet or for changes in the assignment of points. It is recommended that you use a pencil so that you can edit your work.

When the instructors do the final grading of the models, they will simultaneously grade these reviews. Serious, thoughtful reviews will get high marks.

In each group, all three individuals will participate in all four reviews. A review should reflect the sentiments of all the members of the group. Moreover, the grade for all group members will be the same, so it is truly a collective effort. To ensure that the work is fairly distributed, each group member should assume responsibility for the actual write-up of at least one of the model projects.

Each group member should review all write-ups and provide editorial comments to the person primarily responsible for the write-up.

One week later, lab time will be allocated for students to present their evaluations to the class and to lead class discussion of the projects. As you write up the evaluations, think about what you consider important to present to the class. Prioritize the issues for each model. These presentations should not ramble. They must get to key issues and should focus on a few key points, such as: "This aspect of the design/model is particularly deficient" or "one of the really strong points of this design/model was . . ." Think of your task as being to enlighten your fellow students—not to fill time.

1.8 Flowchart of the Structural Design Process

The flowchart in Figure 1.46 describes the structural design process that is followed in practice. Some of the concepts outlined here will be fully understood only as the reader goes through each of the chapters of this book. However, the gist of the process should be apparent in what is shown. This flowchart will be a kind of road map for the process. As you learn new things, you will periodically return to this road map to help you know where you stand in learning about the process. At this first encounter with the road map, you are encouraged to study it and try to understand its salient features. Even though its details will in some ways exceed your understanding at first encounter, it is still worth beginning the process of getting the map in your head. Otherwise, there will be a tendency to see each chapter of this book as isolated and episodic, rather than as part of a coherent process.