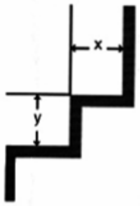
excerpt from Elementary Structures for Architects and Builders, 4th ed., R.E. Shaeffer, Prentice Hall, 2001



5

Properties of Structural Materials

5.1 INTRODUCTION

It is important for the structural designer to realize that different engineering materials have different characteristics and will exhibit different behaviors under load. A knowledge of such characteristics or properties will help to ensure proper use of these materials, both architecturally and structurally.

It is assumed that the reader will have already been exposed to the study of materials through courses in building construction or materials science. This chapter will only highlight a few selected structural materials in the interest of emphasizing the range of structural characteristics and their diversity. Tables of properties of selected structural materials are given in Appendix E.

5.2 NATURE OF WOOD

Wood is a natural material and has a broad range of physical properties because of the different characteristics of its many species. Softwoods such as fir, pine, and hemlock are most often used for structural applications, because they are more plentiful (grow fast and tall) and are easier to fabricate. These woods are generally strong in tension and compression in a direction parallel to the grain and weak when stressed perpendicularly to the grain. Wood is also weak in shear because of its tendency to split along the natural grain laminations. The allowable stresses for three selected species are given in Appendix H.

Wood is light and soft compared to most other structural materials and is easily shaped and fastened together. A minimum of materials-handling equipment is needed to erect wood structures because of their weight. Wood is also very versatile in terms of its adaptability to the making of geometric shapes and even nonlinear forms.

Most softwoods are fairly ductile and will not fail suddenly when overloaded. Because of their lack of homogeneity or uniformity, the allowable stresses are quite low compared to failure stresses. Consequently, when wood structures are properly engineered, a

statistically high margin of safety is present. Wood is often known as the "forgiving" material because of its apparent ability to sustain loads not accounted for when the structure was designed.

Wood, on the other hand, is not very stiff. It is subject to excessive deflection and creep deformation if not designed with these characteristics in mind (see Section 5.6). It is prone to damage by fire and to deterioration by moisture and insects. It expands and contracts with variations in humidity, and markedly so in the direction perpendicular to the grain. Timber structures that are to be exposed to the elements must be carefully treated or highly maintained to preserve their integrity.

The American Forest and Paper Association publishes the "National Design Specification," which is the primary reference guide for timber designers. The Association also publishes a number of useful bulletins and manuals, as do other groups, such as the Western Wood Products Association and the Southern Forest Products Association.

5.3 CONCRETE AND REINFORCED CONCRETE

Concrete is a man-made conglomerate stone composed of essentially four ingredients: portland cement, water, sand, and coarse aggregate. The cement and water combine to make a paste that binds the sand and stones together. Ideally, the aggregates are graded so that the volume of paste is at a minimum, merely surrounding every piece with a thin layer. Most structural concrete is stone concrete, but structural lightweight concrete (roughly two-thirds the density of stone concrete) is becoming increasingly popular.

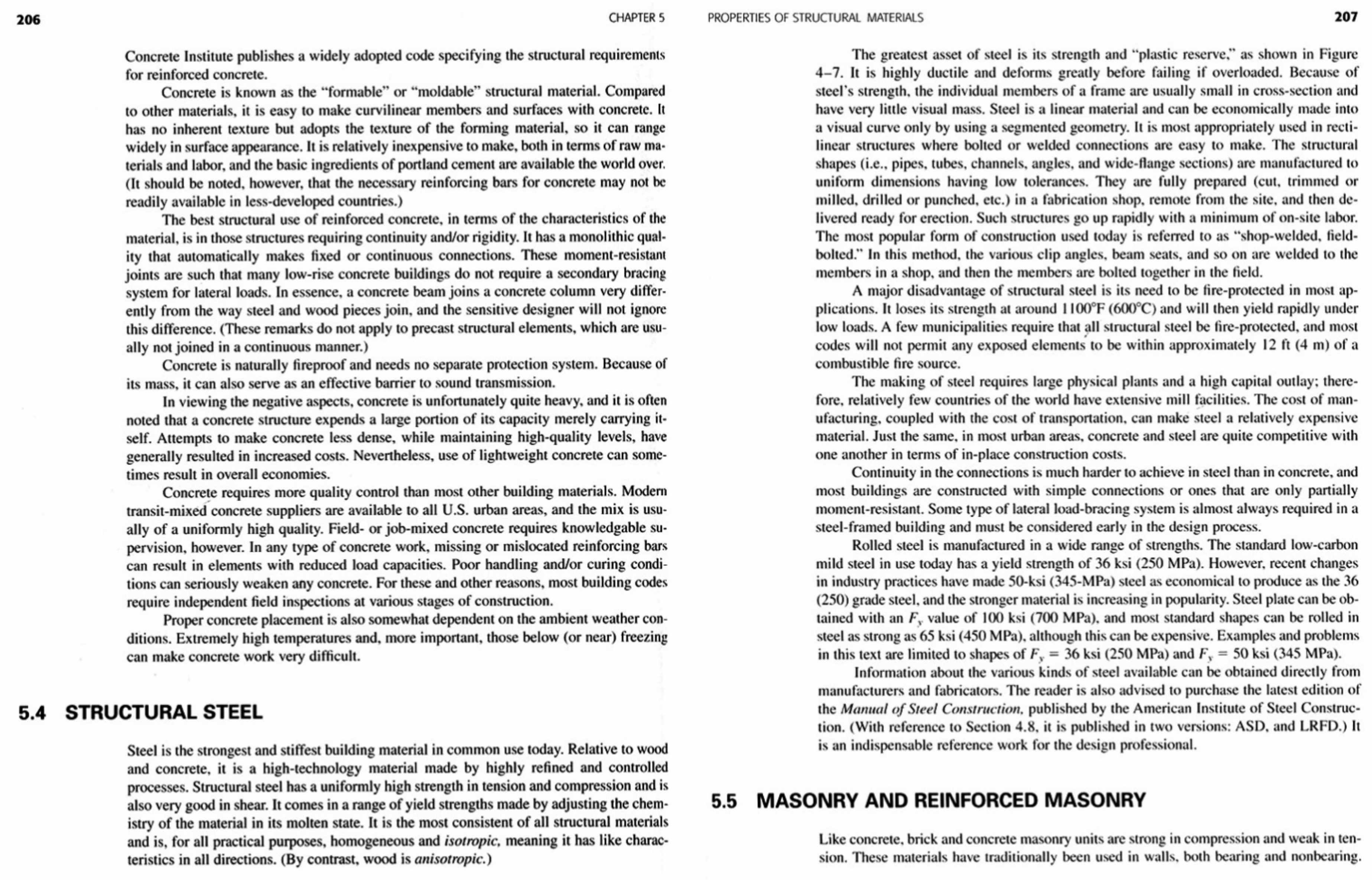
Concrete is essentially a compressive material having almost no tensile strength. As explained in Chapter 8, shearing stresses are always accompanied by tension, so concrete's weakness in tension also causes it to be weak in shear. These deficiencies are overcome by using steel bars for reinforcement at the places where tensile and shearing stresses are generated. Under load, reinforced concrete beams actually have numerous minute cracks, which run at right angles to the direction of major tensile stresses. The tensile forces at such locations are being taken completely by the steel "re-bars."

The compressive strength of a given concrete is a function of the quality and proportions of its constituents and the manner in which the fresh concrete is cured. [*Curing* is the provision of an appropriate environment surrounding freshly placed concrete while it gains its initial strength. During this time (7 to 14 days in duration), the concrete should be kept at a reasonable temperature and must be prevented from "drying out," because the presence of water is necessary for the chemical action to progress.]

Coarse aggregate that is hard and well graded is particularly essential for quality concrete.

The most important factor governing the strength, however, is the percentage of water used in the mix. A minimum amount of water is needed for proper hydration of the cement. Additional water is needed for handling and placing the concrete, but excess amounts cause the strength to drop markedly.

These and other topics are fully covered in the booklet "Design and Control of Concrete Mixtures," published by the Portland Cement Association. This is an excellent reference, treating both concrete mix design and proper construction practices. The American



Concrete Institute publishes a widely adopted code specifying the structural requirements for reinforced concrete.

Concrete is known as the "formable" or "moldable" structural material. Compared to other materials, it is easy to make curvilinear members and surfaces with concrete. It has no inherent texture but adopts the texture of the forming material, so it can range widely in surface appearance. It is relatively inexpensive to make, both in terms of raw materials and labor, and the basic ingredients of portland cement are available the world over. (It should be noted, however, that the necessary reinforcing bars for concrete may not be readily available in less-developed countries.)

The best structural use of reinforced concrete, in terms of the characteristics of the material, is in those structures requiring continuity and/or rigidity. It has a monolithic quality that automatically makes fixed or continuous connections. These moment-resistant joints are such that many low-rise concrete buildings do not require a secondary bracing system for lateral loads. In essence, a concrete beam joins a concrete column very differently from the way steel and wood pieces join, and the sensitive designer will not ignore this difference. (These remarks do not apply to precast structural elements, which are usually not joined in a continuous manner.)

Concrete is naturally fireproof and needs no separate protection system. Because of its mass, it can also serve as an effective barrier to sound transmission.

In viewing the negative aspects, concrete is unfortunately quite heavy, and it is often noted that a concrete structure expends a large portion of its capacity merely carrying itself. Attempts to make concrete less dense, while maintaining high-quality levels, have generally resulted in increased costs. Nevertheless, use of lightweight concrete can sometimes result in overall economies.

Concrete requires more quality control than most other building materials. Modern transit-mixed concrete suppliers are available to all U.S. urban areas, and the mix is usually of a uniformly high quality. Field- or job-mixed concrete requires knowledgable supervision, however. In any type of concrete work, missing or mislocated reinforcing bars can result in elements with reduced load capacities. Poor handling and/or curing conditions can seriously weaken any concrete. For these and other reasons, most building codes require independent field inspections at various stages of construction.

Proper concrete placement is also somewhat dependent on the ambient weather conditions. Extremely high temperatures and, more important, those below (or near) freezing can make concrete work very difficult.

5.4 STRUCTURAL STEEL

Steel is the strongest and stiffest building material in common use today. Relative to wood and concrete, it is a high-technology material made by highly refined and controlled processes. Structural steel has a uniformly high strength in tension and compression and is also very good in shear. It comes in a range of yield strengths made by adjusting the chemistry of the material in its molten state. It is the most consistent of all structural materials and is, for all practical purposes, homogeneous and *isotropic,* meaning it has like characteristics in all directions. (By contrast, wood is *anisotropic.*)

The greatest asset of steel is its strength and "plastic reserve," as shown in Figure 4–7. It is highly ductile and deforms greatly before failing if overloaded. Because of steel's strength, the individual members of a frame are usually small in cross-section and have very little visual mass. Steel is a linear material and can be economically made into a visual curve only by using a segmented geometry. It is most appropriately used in rectilinear structures where bolted or welded connections are easy to make. The structural shapes (i.e., pipes, tubes, channels, angles, and wide-flange sections) are manufactured to uniform dimensions having low tolerances. They are fully prepared (cut, trimmed or milled, drilled or punched, etc.) in a fabrication shop, remote from the site, and then delivered ready for erection. Such structures go up rapidly with a minimum of on-site labor. The most popular form of construction used today is referred to as "shop-welded, field-bolted." In this method, the various clip angles, beam seats, and so on are welded to the members in a shop, and then the members are bolted together in the field.

A major disadvantage of structural steel is its need to be fire-protected in most applications. It loses its strength at around 1100°F (600°C) and will then yield rapidly under low loads. A few municipalities require that all structural steel be fire-protected, and most codes will not permit any exposed elements to be within approximately 12 ft (4 m) of a combustible fire source.

The making of steel requires large physical plants and a high capital outlay; therefore, relatively few countries of the world have extensive mill facilities. The cost of manufacturing, coupled with the cost of transportation, can make steel a relatively expensive material. Just the same, in most urban areas, concrete and steel are quite competitive with one another in terms of in-place construction costs.

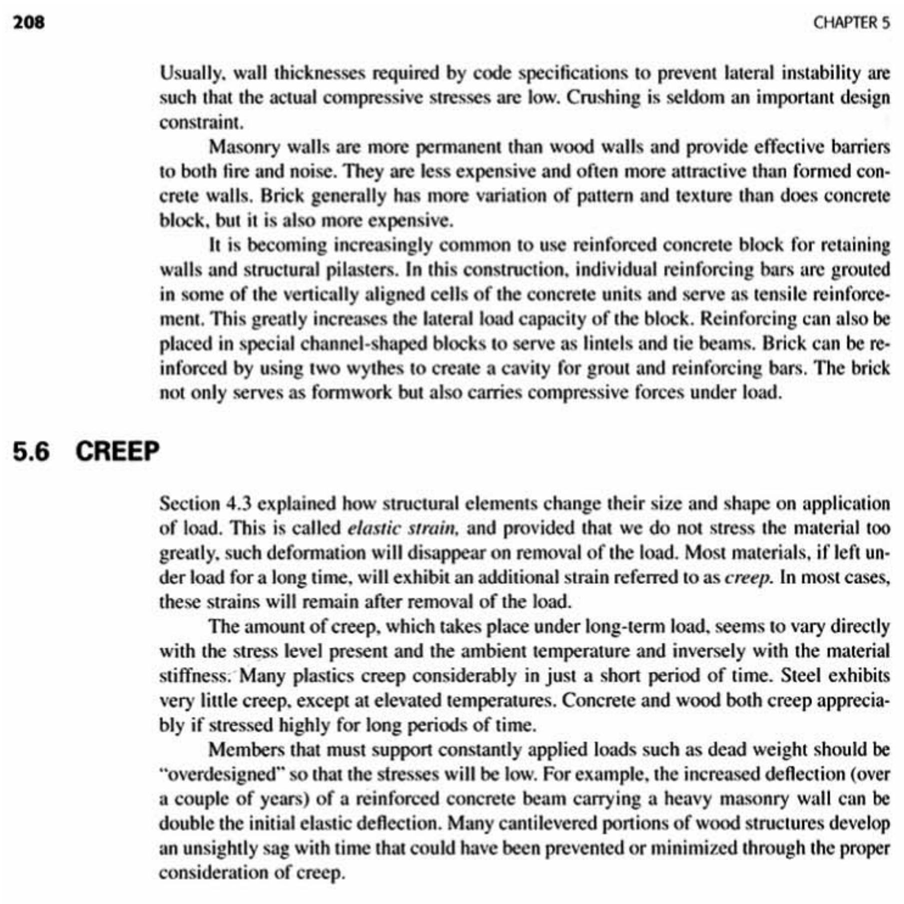
Continuity in the connections is much harder to achieve in steel than in concrete, and most buildings are constructed with simple connections or ones that are only partially moment-resistant. Some type of lateral load-bracing system is almost always required in a steel-framed building and must be considered early in the design process.

Rolled steel is manufactured in a wide range of strengths. The standard low-carbon mild steel in use today has a yield strength of 36 ksi (250 MPa). However, recent changes in industry practices have made 50-ksi (345-MPa) steel as economical to produce as the 36 (250) grade steel, and the stronger material is increasing in popularity. Steel plate can be obtained with an F_y value of 100 ksi (700 MPa), and most standard shapes can be rolled in steel as strong as 65 ksi (450 MPa), although this can be expensive. Examples and problems in this text are limited to shapes of $F_y = 36$ ksi (250 MPa) and $F_y = 50$ ksi (345 MPa).

Information about the various kinds of steel available can be obtained directly from manufacturers and fabricators. The reader is also advised to purchase the latest edition of the *Manual of Steel Construction,* published by the American Institute of Steel Construction. (With reference to Section 4.8, it is published in two versions: ASD, and LRFD.) It is an indispensable reference work for the design professional.

5.5 MASONRY AND REINFORCED MASONRY

Like concrete, brick and concrete masonry units are strong in compression and weak in tension. These materials have traditionally been used in walls, both bearing and nonbearing.



Usually, wall thicknesses required by code specifications to prevent lateral instability are such that the actual compressive stresses are low. Crushing is seldom an important design constraint.

Masonry walls are more permanent than wood walls and provide effective barriers to both fire and noise. They are less expensive and often more attractive than formed concrete walls. Brick generally has more variation of pattern and texture than does concrete block, but it is also more expensive.

It is becoming increasingly common to use reinforced concrete block for retaining walls and structural pilasters. In this construction, individual reinforcing bars are grouted in some of the vertically aligned cells of the concrete units and serve as tensile reinforcement. This greatly increases the lateral load capacity of the block. Reinforcing can also be placed in special channel-shaped blocks to serve as lintels and tie beams. Brick can be reinforced by using two wythes to create a cavity for grout and reinforcing bars. The brick not only serves as formwork but also carries compressive forces under load.

5.6 CREEP

Section 4.3 explained how structural elements change their size and shape on application of load. This is called *elastic strain,* and provided that we do not stress the material too greatly, such deformation will disappear on removal of the load. Most materials, if left under load for a long time, will exhibit an additional strain referred to as *creep.* In most cases, these strains will remain after removal of the load.

The amount of creep, which takes place under long-term load, seems to vary directly with the stress level present and the ambient temperature and inversely with the material stiffness. Many plastics creep considerably in just a short period of time. Steel exhibits very little creep, except at elevated temperatures. Concrete and wood both creep appreciably if stressed highly for long periods of time.

Members that must support constantly applied loads such as dead weight should be "overdesigned" so that the stresses will be low. For example, the increased deflection (over a couple of years) of a reinforced concrete beam carrying a heavy masonry wall can be double the initial elastic deflection. Many cantilevered portions of wood structures develop an unsightly sag with time that could have been prevented or minimized through the proper consideration of creep.