Structural Modeling and Analysis

The Natchez Trace Parkway Bridge, here under construction. As noted (cf. Frontispiece), it was the first arch bridge built in the United States from precast concrete segments. Thus, it philosophically is akin to the masonry structures that we show later in the book because it is built up of discrete, blocklike segments. Of course, the designers had the dual advantage of better materials (e.g., the precast, steel-reinforced segments) and of better analysis techniques, the subject which with this book is concerned. (Photo by J. Wayman Williams.)

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Structural Mechanics: The Big Picture

This book is about structural mechanics, that is, about the modeling and analysis of how structures behave in the real world. As a discipline, the material we cover is in part an extension of coursework titled "Statics" and "Strength of Materials," and it can also be viewed as a subset of the "Theory of Elasticity," a subject typically taken as a graduate course. This very brief epistemological lesson is meant to remind the reader that what we are about to cover derives from larger principles, some versions of which will be familiar.

1.1 Structures and One-Dimensional Structural Elements

We begin by looking at some structures, the real, physical objects that are our focus. We show pictures of several interesting structures in Figs. 1.1–1.4 (and elsewhere in the book, including some abstract structural elements on the book's cover). We also start by connecting with an ancient building material, stone. There is some appeal in the simple-minded idea that masonry structures – such as Egypt's pyramids, China's Great Wall, and the Mayan temples of Central America – represent some version of a pile of bricks, one on top another. Each of these structures seems rooted to its foundations by its own weight. In fact, as we see in the two Roman structures shown in Fig. 1.1, masonry arches have been used to construct relatively light and airy structures. Other masonry structures – such as the Salisbury Cathedral of Figs. 1.3(a) and 1.4(b) – show great artistry in their flying buttresses and their majestically open clerestory spaces. However, as can be seen in Fig. 1.4(b), there are no interior floors in these graceful cathedrals because it is impossible to build a flat span over a space with a material that cannot support tensile forces. As with the Coliseum and other stone structures, the design of such graceful structures is an accomplishment based on recognizing the arch as a structural form that most effectively uses stone, a material that functions well only in compression.

In Fig. 1.2 we show pictures of three beautiful bridges (and several others are shown in the frontispiece and the title pictures of Chapters 1–3, 5, 6, and 8–10). Our imagination is fueled by bridges that span both broad reaches and very deep gorges. Think of the archetypal pedestrian bridge, hung from rope or cables, that has been a focus of stories ranging from Thornton Wilder's classic novel, The *Bridge of San Luis Rey*, to the epic adventures of Indiana Jones.

But bridges have evolved, and interestingly enough, they moved away from cable suspension through arches of various materials, including stone (Fig. 1.2(a)), iron, steel (Fig. 1.2(b)), and concrete (Fig. 1.2(c)). Only since the end of the last century have we returned to the notion of suspending a structure from cables, resulting in well-known suspension bridges such as New York's George Washington bridge (pictured immediately

Figure 1.1a.
Figure 1.1. These two Roman structures – a water-carrying aqueduct and a famous stadium – were built of stone almost two thousand years ago. They use the properties of stone as expressed in the form of an arch to lasting and beautiful advantage. They are (a) the Pont du Gard in Remoulins, France (photo by Colin O'Connor from *Roman Bridges*, Cambridge University Press, 1993; courtesy of the author); and (b) the Coliseum in Rome (photo by Clive L. Dym).

preceding Chapter 8) – which now carries a second deck for which the bridge was designed, although it wasn't added until almost thirty years later – and cable-stayed bridges such as the Chesapeake and Delaware Canal Bridge (pictured immediately preceding Chapter 2).

Another facet of structural development is shown in Fig. 1.3, wherein we see some snapshots of the evolution of the "skyscraper" – a term whose very meaning has also evolved with our ability to build taller and higher. While the cathedrals of the middle ages were tall structures, they were essentially one-story structures. Designers had learned to support tall and slender walls with flying buttresses, but they were unable to build floors to span the spaces between their tall walls. The development of the skyscraper had to wait in part for the development of a material (rolled steel) and of configurations (beams and trusses) that would enable floors for buildings. One of the intermediate steps was Gustave Eiffel's tower of iron in Paris (Fig. 1.3(b)), the shape of which conforms to an optimal expectation of design for wind. The Hancock Center (Fig. 1.3(c)) is emblematic of the modern skyscraper not only because of its great height and volume, but also because of its presentation of its structural form as a clear expression of that structure's function.

The structures we have shown so far can be summarized almost as one dimensional, or at least planar structures with loads anticipated to act in the plane of the drawings (which

Figure 1.1b.

are all elevations). There are clearly three-dimensional aspects to these structures and their loads, but their behavior can be viewed or modeled in one- or two-dimensional ways. On the other hand, there are structural types wherein large surface areas (other than vertical walls) are evident and for which special models and design and analysis techniques are required. In the civil engineering domain, these *surface structures* are typically roofs, and we show a few in Fig. 1.4.

Figure 1.2a.
Figure 1.2. Three beautiful bridges, each of which expresses the beauty of the arch with a different material. They are (a) the Puente del Diablo, built by the Romans in Martorell, Spain (photo by Colin O'Connor from *Roman Bridges*, Cambridge University Press, 1993; courtesy of the author); (b) Robert Maillart's Salginatobel Bridge, built near Schiers, Switzerland, in 1930 (photo courtesy of M.-C. Blumer-Maillart); and (c) Othmar Amman's Bayonne Bridge between Bayonne, New Jersey, and Staten Island, New York, completed in 1931 (photo by J. Wayman Williams). The bridges represent a similar aesthetic, although their technological details are quite different. For example, the Salginatobel is a three-hinged concrete arch, whereas the Bayonne is a two-hinged steel arch.

These structures are special because they are meant to be relatively thin, curved surfaces so that their weight can be supported. Note, however, that we mean thin in comparison with the dimensions they span, not necessarily in an absolute sense. Clearly the masonry and concrete roofs shown in Fig. 1.4 are not going to be all that thin. By way of contrast, the walls of aircraft, spacecraft, or submarines are really pretty thin because, in these cases, weight is much more at a premium than it is for a typical civil engineering structure.

One of the things we can learn from this very brief history is that there are models of structural behavior that can be expressed in terms of some simple structural elements. As a starting point, we can note that structures can be seen as being of one of two basic types. One type has the principal direction or shape of the structure aligned or virtually coincident with the direction of the load it is supporting, the most familiar example being a cable or rope supporting a weight or structure at its end. Such structures are often called *funicular structures*, and they include structural devices that work in compression as well as in pure tension, for example, the compression bars in a truss. Arches are also considered to be funicular structures because the compressive thrusts that they exhibit in supporting

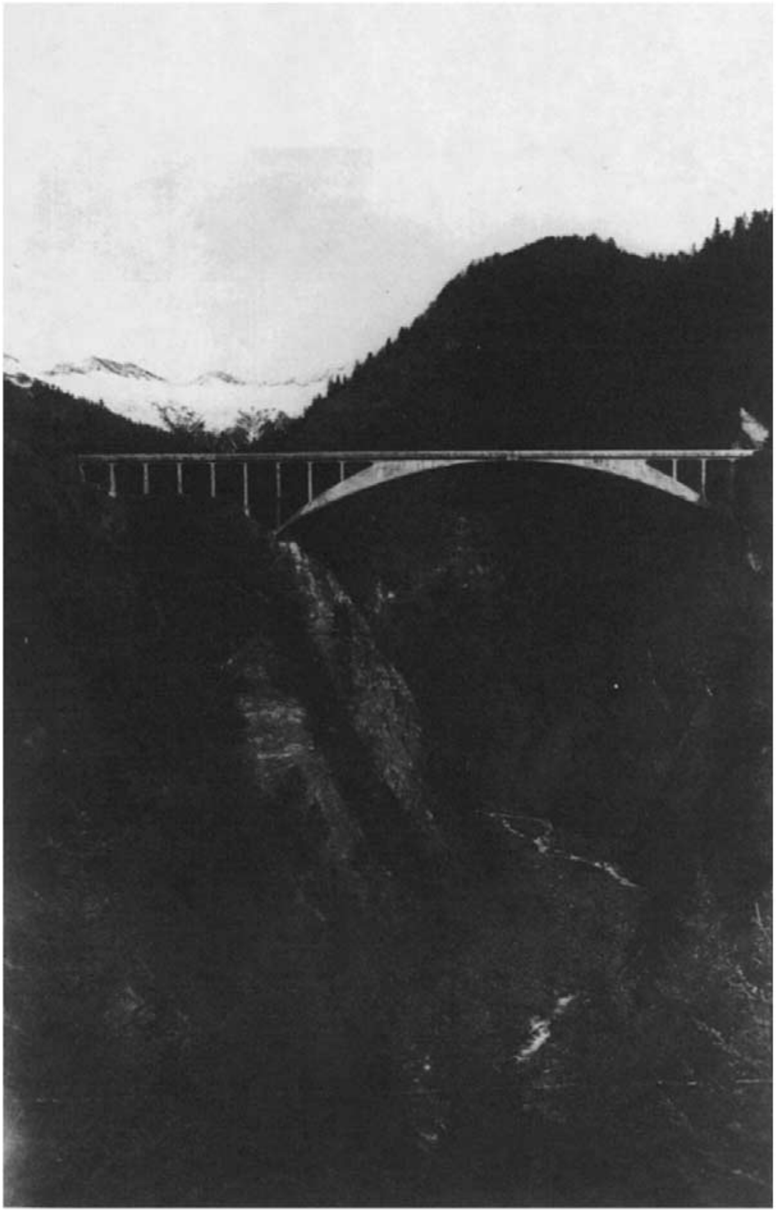

Figure 1.2b.

loads lines up with the (curved) shape of the arch. The point is that for these structural elements – and they can be one- or two-dimensional – the sense of the principal structural action is coincident with both the shape of the structure and the direction of the applied loads.

In the second type of structure, the load is applied perpendicular or normal to the line or plane of the structure. The structural action that supports the load occurs in the line or plane of the structure, although we will see that deflections due to the loads occur normal to the plane of the structure (i.e., in the same direction as the loading). Beams and bridges clearly work this way, as do the surface structures that we have shown in Fig. 1.4.

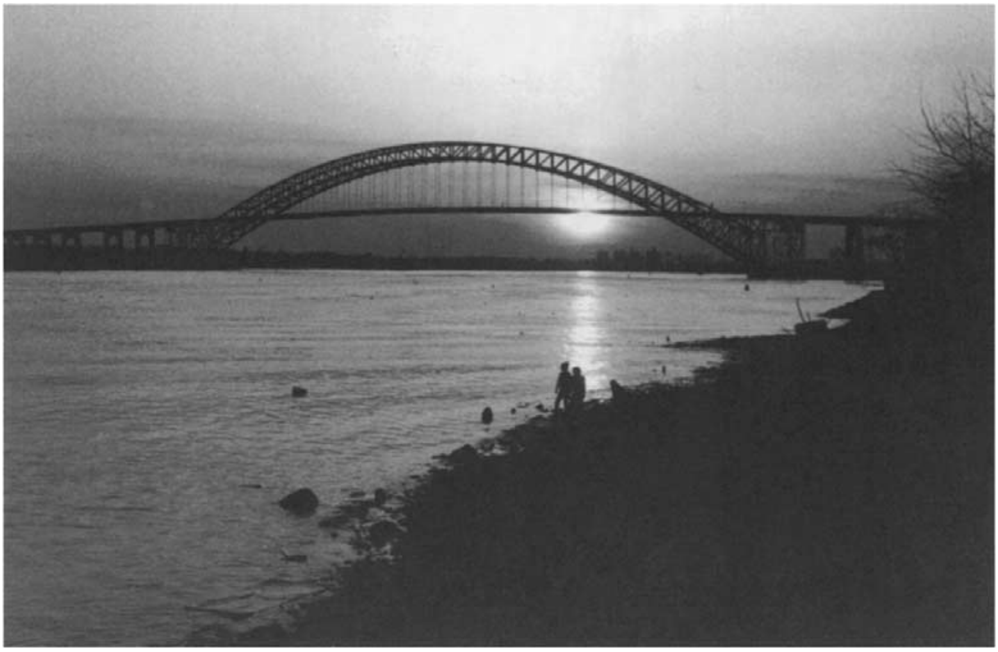

Figure 1.2c.

The net effect of this dichotomy is that we need different kinds of models for analyzing different kinds of structural behavior. We have shown some one-dimensional versions of the models in Fig. 1.5, and we will discuss them in greater detail in Section 2.1.

Something else we can learn from our brief history – and remember that we did not intend to provide a comprehensive history of structures – is that structural engineering comprises both art and science. We should recognize that structural engineering has evolved over time, as we have mastered new technologies, including those of materials, fabrication and assembly, tools for analysis and design, and better insight into the behavior of structures and the ways we can model that behavior. Thus, a first course in structures such as this one is just the first step into a field with a long and interesting history, as well as a future filled with serious and equally interesting challenges.

1.2 The Conceptual "Elements" of Structural Mechanics

Let us imagine that we want to design a structure, say, a suspension bridge, a high-rise building, or a football stadium. What does it mean to "design" such structures? What ideas, models, techniques, or calculations do they have in common? Is there a theory that binds them together?

There is such a theory, and we can outline it in general terms as a set of six physical quantities, unified by three fundamental sets of basic principles (expressed in well-known equations) and to which are applied some common design criteria or behavioral goals, which we want the structure to meet. This book is about the elements of this theory, and the six *basic physical quantities* that we use to describe various aspects of structural behavior are as follows.

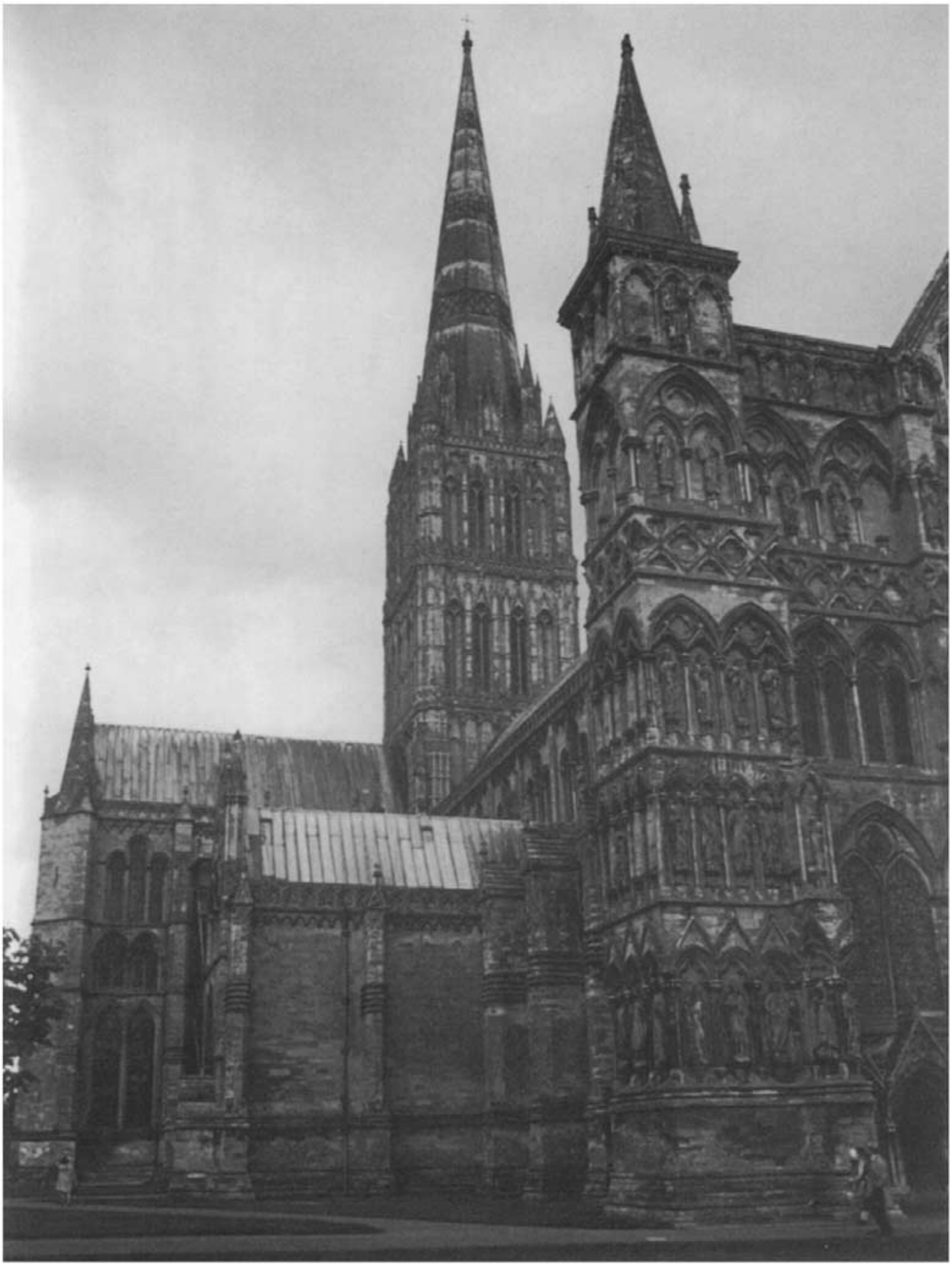

Figure 1.3a.

Figure 1.3. Three different expressions of the human urges to reach (and "scrape") the sky, each representing a different technological time. These tall buildings are (a) Salisbury Cathedral, Salisbury, England, built around the twelfth century (photo by Clive L. Dym); (b) Gustave Eiffel's Tower, Paris, France, finished in 1889 (photo by David P. Billington); and (c) the Hancock Center, Chicago, Illinois, completed in 1970 (photo by J. Wayman Williams). Fazlur Kahn of Skidmore, Owings, and Merrill was the structural designer of the Hancock Center, and he designed a very tall, framed tube that clearly shows in its X-bracing the structural form that carries all of the wind and most of the gravity loads acting on the building.

Figure 1.3b.

1.2.1 Loads

These are the forces that the structure is expected to carry or support. They may include the dynamic forces that result from a train traversing a bridge, the forces produced by the winds whistling by a tall building, and the forces produced as stadium fans respond in near unison to a play on the field. These *external loads* are regarded as *givens*, that is, as conditions of use that the structure is expected to accomodate. We can often specify these external loads pretty well, in which case we can say we are dealing with *deterministic*