Jerome Connor · Simon Laflamme

Structural Motion Engineering

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Preface

Conventional structural design procedures are generally based on two requirements, namely safety and serviceability. Safety relates to extreme loadings, which have a very low probability of occurring, on the order of 2 %, during a structure's life, and is concerned with the collapse of the structure, major damage to the structure and its contents, and loss of life. Serviceability pertains to medium to large loadings, which may occur during the structure's lifetime. For service loadings, the structure should remain operational (i.e., the structure should suffer minimal damage and, furthermore, the motion experienced by the structure should not exceed specified comfort limits for humans and motion-sensitive equipment mounted on the structure). Typical occurrence probabilities for service loads range from 10 to 50 %.

Safety concerns are satisfied by requiring the resistance (i.e., strength) of the individual structural elements to be greater than the demand associated with the extreme loading. Once the structure is proportioned, the stiffness properties are derived and used to check the various serviceability constraints such as elastic behavior. Iteration is usually necessary for convergence to an acceptable structural design. This approach is referred to as strength-based design since the elements are proportioned initially according to strength requirements.

Applying a strength-based approach for preliminary design is appropriate when strength is the dominant design requirement. In the past, most structural design problems have fallen in this category. However, the following developments have occurred recently that have limited the effectiveness of the strength-based approach. First, the trend toward more flexible structures such as tall buildings and longer-span horizontal structures has resulted in more structural motion under service loading, thus shifting the emphasis from safety toward serviceability. Second, some of the new types of facilities such as space platforms and semiconductor manufacturing centers have more severe design constraints on motion than the typical civil structure. For example, in the case of micro-device manufacturing, the environment has to be essentially motion free. Third, recent advances in material science and engineering have resulted in significant increases in the strength of traditional civil engineering materials. However, the material stiffness has not increased at the same rate. The lag in material stiffness versus material strength has led to a problem with satisfying the requirements on the various motion parameters. Indeed, for very high-strength materials, the motion requirements control the design. Fourth, experience with recent earthquakes has shown that the cost of repairing the structural and nonstructural damage due to the motion occurring during a seismic event is considerably greater than anticipated. This finding has resulted in more emphasis placed on limiting the structural response with various types of energy dissipation and absorption mechanisms.

Structural motion engineering is an alternate paradigm that addresses these issues. The approach takes as its primary objective the satisfaction of motion-related design requirements such as restrictions on displacement and acceleration and seeks the optimal deployment of material stiffness and motion control devices to achieve these design targets as well as satisfy the constraints on strength. Structural motion control is the enabling technology for motion engineering. This book presents a systematic treatment of the basic concepts and computational procedures for structural motion control. Numerous examples illustrating the application of motion control to a wide spectrum of buildings are included. Topics covered include optimal stiffness distributions for building-type structures, the role of damping in controlling motion, tuned mass dampers, base isolation systems, linear control, and nonlinear control. The targeted audience is practicing engineers and graduate students.

This work was motivated by the authors' interest in the design of structures for dynamic excitation and by members of the Structural Engineering Community who have been enthusiastic supporters of this design paradigm.

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Introduction 1

1.1 Source of Motion Problems

In general, a "designed" structure has to satisfy a set of requirements pertaining to *safety* and *serviceability*. Safety relates to extreme loadings that have a low probability of occurring during a structure's life. The concerns here are the collapse of the structure, major damage to the structure and its contents, and loss of life. Serviceability pertains to moderate loadings that may occur several times during a structure's lifetime. For service loadings, the structure should remain fully operational (i.e., the structure should suffer negligible damage and, furthermore, the motion experienced by the structure should not exceed specified *comfort limits* for humans and motion-sensitive equipment mounted on the structure). An example of a human comfort limit is the restriction on the acceleration; humans begin to feel uncomfortable when the acceleration reaches about 0.02 g. A comprehensive discussion of human comfort criteria is given by Bachmann and Ammann [9].

Safety concerns are satisfied by requiring the resistance (i.e., strength) of the individual structural elements to be greater than the demand associated with the extreme loading. The conventional structural design process proportions the structure based on strength requirements, establishes the corresponding stiffness properties, and then checks the various serviceability constraints such as elastic behavior. Iteration is usually necessary for convergence to an acceptable structural design. This approach is referred to as *strength-based design* since the elements are proportioned according to strength requirements.

Applying a strength-based approach for preliminary design is appropriate when strength is the dominant design requirement. In the past, most structural design problems have fallen in this category. However, a number of developments have occurred recently that have limited the effectiveness of the strength-based approach.

First, the trend toward more flexible structures such as tall buildings and longer span horizontal structures has resulted in more structural motion under service loading, thus shifting the emphasis from safety toward serviceability. For instance,

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the wind-induced lateral deflection of the Empire State Building in New York City, one of the earliest tall buildings in the USA, is several inches, whereas the wind-induced lateral deflection of the former World Trade Center towers was several feet, an order of magnitude increase. This difference is due mainly to the increased height and slenderness of the former World Trade Center towers in comparison with the Empire State tower. Furthermore, satisfying the limitation on acceleration is a difficult design problem for tall, slender buildings.

Second, some of the new types of facilities such as space platforms and microstructure manufacturing centers have more severe design constraints on motion than the typical civil structure. In the case of micro-device manufacturing, the environment has to be essentially motion free. Space platforms used to support mirrors have to maintain a certain shape within a small tolerance in order for the mirror to properly function. The design strategy for *motion-sensitive structures* is to proportion the members based on the stiffness needed to satisfy the motion constraints, and then check if the strength requirements are satisfied.

Third, recent advances in material science and engineering have resulted in significant increases in the strength of traditional civil engineering materials such as steel and concrete, as well as a new generation of composite materials. Although the strength of structural steel has essentially doubled, its elastic modulus has remained constant. Also, there has been some percentage increase in the elastic modulus for concrete, but this improvement is still small in comparison to the increase in strength. The lag in material stiffness versus material strength has resulted in additional structural motion, shifting design constraints from strength to serviceability. Indeed, for very high strength materials, the serviceability requirements may dominate.

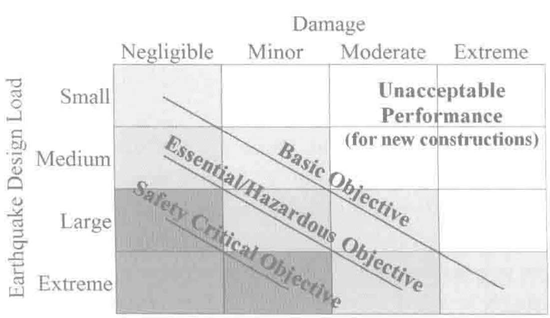

Fig. 1.1 Performance-based design objective matrix for seismic excitation

Fourth, experience with recent earthquakes has shown that repairing the damages resulting from two motion-related effects, high floor acceleration and inelastic deformation, can be very expensive, often exceeding the initial cost of the structure. Therefore, the focus in Seismic Design is shifting toward dual objectives: preventing the loss of life; and minimizing the total cost of damage over the life of the structure.

The latter goal is associated with *performance-based design*. Figure 1.1 shows the objectives of this approach, which is rapidly gaining acceptance within the seismic design community.

1.2 Structural Motion Engineering Methodology

Structural motion engineering is an approach that is more effective for the motion-related design problems just described. This approach takes as its primary objective the satisfaction of motion requirements and views strength as a constraint, not as a primary requirement. Motion engineering employs structural motion control methods to deal with the broad range of issues associated with the motion of structural systems, such as the specification of motion requirements governed by human and equipment comfort and the use of energy storage, dissipation, and absorption devices to control the motion generated by design loadings. Structural motion control provides the conceptional framework for the design of structural systems where motion is the dominant design constraints. Generally, one seeks the optimal deployment of material and motion control mechanisms to achieve the design targets on motion as well as satisfy the constraints on strength.

In what follows, examples are presented that reinforce the need for an alternate paradigm having motion rather than strength as its primary focus. These examples deal with the issue of strength versus serviceability from a static perspective for building-type structures. The dynamic case is treated later in Chap. 2.

1.3 Motion Versus Strength Issues: Static Loading

1.3.1 Building Type Structures

Building configurations must simultaneously satisfy the requirements of site (location and geometry), building functionality (occupancy needs), appearance, and economics. These requirements significantly influence the choice of the structural system and the corresponding design loads. Buildings are subjected to two types of loadings: *gravity loads*, consisting of the actual weight of the structural system and the material, equipment, and people contained in the building; and *lateral loads*, consisting mainly of wind and earthquake loads. Both wind and earthquake loadings are dynamic in nature and produce significant amplification over their static counterpart. The relative importance of wind versus earthquake depends on the site location, building height, and structural makeup. For steel buildings, the transition from *earthquake dominant* to *wind dominant* loading for a seismically active region occurs when the building height reaches approximately 150 m. Concrete buildings, because of their larger mass, are controlled by earthquake loading up to at least a height of 250 m, since the additional gravity load increases the seismic forces.

In regions where the earthquake action is low (e.g., Chicago, Illinois), the transition occurs at a much lower height, and the design is governed primarily by wind loading.

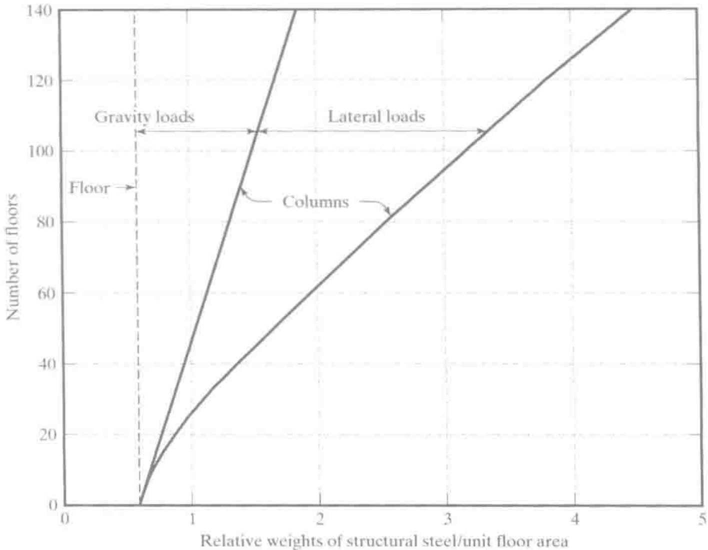

Fig. 1.2 Structural steel quantities for gravity and wind systems

When a low-rise building is designed for gravity loads, it is very likely that the underlying structure can carry most of the lateral loads. As the building height increases, the overturning moment and lateral deflection resulting from the lateral loads increase rapidly, requiring additional material over and above that needed for the gravity loads alone. Figure 1.2 illustrates how the unit weight of the structural steel required for the different loadings varies with the number of floors. There is a substantial structural weight cost associated with lateral loading for tall buildings [101].

To illustrate the dominance of motion over strength as the slenderness of the structure increases, the uniform cantilever beam shown in Fig. 1.3 is considered. A cantilever beam is a reasonable model for a rectangular building. The lateral load is taken as a concentrated force p applied to the tip of the beam and is assumed to be static. The limiting cases of a pure shear ($d/H \approx 1$) beam and a pure bending beam ($d/H \approx 0.1$) are examined.

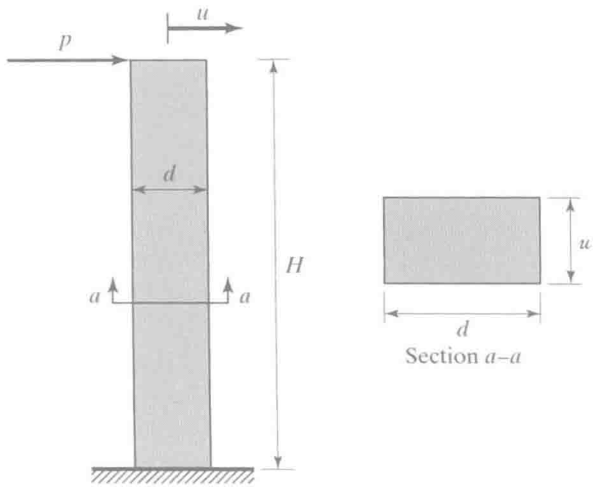

Fig. 1.3 Building modeled as a uniform cantilever beam

Example 1.1 (Cantilever Shear Beam). The shear stress τ is given by

$$\tau = \frac{p}{A_s} \tag{E1.1.1}$$

where A_s is the cross-sectional area over which the shear stress can be considered to be constant. When the bending rigidity is very large, the displacement, u, at the tip of the beam is due mainly to shear deformation and can be estimated as

$$u = \frac{pH}{GA_s} \tag{E1.1.2}$$

where G is the shear modulus and H is the height of the beam. This model is called a *shear beam*. The shear area needed to satisfy the strength requirement follows from Eq. (E1.1.1):

$$A_s|_{\text{strength}} \geq \frac{p}{\tau^*} \tag{E1.1.3}$$

where τ^* is the allowable stress. Noting Eq. (E1.1.2), the shear area needed to satisfy the serviceability requirement on displacement is

$$A_s|_{\text{serviceability}} \geq \frac{p}{G} \cdot \frac{H}{u^*} \tag{E1.1.4}$$

(continued)

(continued)
where u^* denotes the allowable displacement. The ratio of the area required to satisfy serviceability to the area required to satisfy strength provides an estimate of the relative importance of the motion design constraints versus the strength design constraints

$$r = \frac{A_s|_{\text{serviceability}}}{A_s|_{\text{strength}}} = \frac{\tau^*}{G} \cdot \frac{H}{u^*} \tag{E1.1.5}$$

Figure E1.1a shows the variation of r with H/u^*. Increasing H/u^* places more emphasis on the motion constraint since it corresponds to a decrease in the allowable displacement, u^*. Furthermore, an increase in the allowable shear stress, τ^*, also increases the dominance of the displacement constraint.

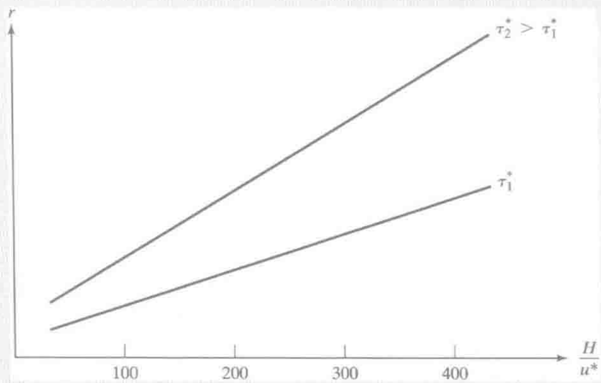

Fig. E1.1a Plot of r versus H/u^* for a pure shear beam

Example 1.2 (Cantilever Bending Beam). When the shear rigidity is very large, shear deformation is negligible, and the beam is called a "bending" beam. The maximum bending moment M in the structure occurs at the base and equals

$$M = pH \tag{E1.2.1}$$

(continued)