Introduction

I.1 Introduction to Serviceability

Design is an effort to develop an optimal way to fulfill or satisfy a defined need. For those who work in the built environment, these answers come in the form of buildings, bridges or other structures that enclose and support the desired activities. Buildings may enclose such functions as business, residential and entertainment. One building function is to physically support people engaging in their business, relaxing in their home or enjoying a musical. The building also provides an envelope to control the environment around the occupants. Finally, a building provides a space of defined quality in which the activity is performed. Bridges may support the transportation of people or merchandise on trains or other vehicles. Air traffic control towers allow air traffic controllers to see and stay in communication with aircraft using the airfield. In summary, building and nonbuilding structures are designed and constructed to fulfill certain specific functions.

The value of a structure such as a building or bridge may be determined by the following attributes:

1. How well it performs the functions that support the desired activities,
2. The condition of the space in which the activity takes place,
3. The expected useful life of the structure that remains.

When a building or structure can no longer perform its intended functions, it has “failed.” In the industry, the term *failure* when related to a structure is usually reserved for the specific case when a structure can no longer support the loads imposed by the intended use of the structure. This type of failure is recognized as a violation of the strength limit state.

However, failure as experienced by the owner or user of a structure may be defined differently. He or she may define failure of a structure as a significant reduction in the quality of the space caused by the movement or deterioration of the structural system. For example, a laboratory technician would tell us that the structure supporting the laboratory has failed if the transient vibrations in the floor do not allow him to complete necessary experiments. An office building owner would indicate that a building structure has failed if the floor deflections result in floors that are out of level. The fact that the office floors are noticeably out of level will prevent the sale or lease of the building at a competitive price. An apartment building owner would state that the structure has failed if the number and size of cracks in the floors and walls of the apartment rooms result in lower occupancies and rent collections. A limit state violated by one of the failures listed above is a serviceability limit state.

In an effort to protect the safety and well-being of the public, governmental organizations and agencies have developed minimum guidelines for use in the design and construction of significant structures. The codes and standards focus primarily on the strength limit state. However, they also include provisions directed at protecting the public's investment in the performance and retained value of the structure. These provisions deal with the serviceability limit state.

The purpose of this design guide is to provide commentary and examples of the implementation of the provisions and requirements of the 2012 edition of the *International Building Code*® (IBC®) related to the serviceability of structures. The guide will limit the discussion of serviceability to those conditions discussed in the IBC and standards specifically referenced by the IBC. The guide focuses on building structures subjected to gravity, wind and seismic loads. Though some of the concepts discussed may apply, the guide does not specifically discuss serviceability for bridges, wind-induced accelerations or vibrations, design for expansion or contraction, or connection slip.

1. Limit States Design

The 2010 edition of *Minimum Design Loads for Buildings and Other Structures* (ASCE/SEI 7-10) defines a limit state as "a condition beyond which a structure or member becomes unfit for service and is judged either to be no longer useful for its intended function (serviceability limit state) or to be unsafe (strength limit state)." A serviceability limit state includes at least three elements—an imposed load, the behavior of the structure and some unacceptable result of the structural behavior. To evaluate the acceptability of a structural system relative to a serviceability limit state, there must be a load defined, some predicted structural behavior as a result of the load and a defined limit to that behavior.

Optimal and effective evaluation of the serviceability limit state of a structure requires a balance of imposed load, assumed structural behavior and serviceability criteria. Conservative loadings based on extreme events used to determine behavior, which are then compared to limits that result in light or minimal serviceability concerns, will yield inefficient, overconservative and expensive structures. In a similar manner, predictions of structural behavior made with an analysis assuming inelastic behavior and cracked sections for loading levels that are far below the elastic range of the structural system will yield overly conservative evaluations. Finally, the limits on behavior must be matched to the true performance of the systems involved and the expectations of the building occupants.

2. Serviceability Loadings

When determining the appropriate loads to use in serviceability design or evaluation of a structure, there are several items to consider: the expected loading levels, the code-required loadings and the timing the loads may be applied. Generally, there are three levels of loadings related to limit states—ultimate, nominal and service.

a. Ultimate Loads are loads utilized for strength design in the IBC. These loads are intended to be maximum loads that may credibly be imposed on the structural element of a system during its life. They are typically calculated by applying a load factor of greater than 1.0 to the nominal loads given in IBC Chapter 16.

Wind loads specified in IBC Chapter 16 and calculated using ASCE/SEI 7 Chapters 26–30 are ultimate level wind-load pressures. Commentary for ASCE/SEI 7 Chapter 26 discusses the change from previous editions of the code, which applied a load factor of 1.6 to wind pressures for strength design. This is apparent because of the 1.0 load factor applied to the wind force component in the strength design load combinations of IBC Section 1605.2. Seismic loads specified in Chapter 16 are calculated using ASCE/SEI 7. These loads are also treated as ultimate loads in the load combinations of IBC Section 1605.

b. Nominal Loads are defined by the IBC as the loads specified in Chapter 16. This is true for live loads and snow loads but not for wind or seismic loads. The nominal loads are intended to represent the maximum probable event expected during the structure's design life. The most frequently used time period for determination of this maximum probable event is 50 years.

Nominal live loads specified in IBC Table 1607.1 (as well as ASCE/SEI 7 Table 4.1) were determined using the informed opinions of a panel of 25 distinguished structural engineers. The loads were not derived directly from extensive and detailed field research or measurements. The loads are reviewed during each code cycle, but for the most part have remained unchanged for many years. The origin of these loads should be considered during any serviceability analysis using nominal loads or some proportion of nominal loadings. The commentary for ASCE/SEI 7 Chapter 4, Live Loads, states that floor loads measured in live load surveys are usually far below the nominal loads included in the Standard and in the IBC.

Snow loads specified in IBC Chapter 16 are calculated using ASCE/SEI 7 Chapter 7. These loads are based on a 50-year mean recurrence interval (MRI). These loads are treated as nominal loads. The code committee determines the ground snow loads using statistical analysis of weather records.

Rain loads specified in IBC Chapter 16 are determined using the amount of rain water that will be retained on a roof if the primary drainage system fails. This is considered a nominal load in load combinations of Section 1605.

c. Service Loads are not defined or utilized in the IBC. Service loads are defined in ASCE/SEI 7 in the Commentary to Appendix C, "Serviceability Considerations," as "those loads that act on the structure at an arbitrary point in time." The commentary goes further in stating that the loads appropriate for use in serviceability limit states may be only a fraction of the nominal loads. Ellingwood and Galambos (1) suggested that a return period of a defined number of years, instead of those that act at an “arbitrary point in time,” may be appropriate for evaluation of structures for unacceptable floor deflections. Based on this research, the commentary for Appendix C of ASCE/SEI 7 indicates that, for serviceable designs using the current deformation limits in the majority of published standards, serviceability load combinations involving transient loading may include the following:

Floors/Roofs - Nominal Dead Load + Nominal Live Load.

Roofs – Nominal Dead Load + 0.5 Nominal Snow Load.

For serviceability limit states involving sustained loading, creep, settlements or other long-term effects, the suggested load combination is:

Nominal Dead Load + 0.5 Nominal Live Load.

Service-level wind pressures are defined in two ways. For evaluation of components and cladding of structures, IBC Table 1604.3 allows for the wind load to be taken as 0.42 times the component and cladding loads when determining deflections to be evaluated by limits in the table. The 0.42 factor is a combination of two factors. The first is a 0.6 factor used to convert the ultimate load to a nominal load. This factor may be taken from the allowable stress design load case given by IBC Equation 16-12. The second is a 0.7 factor used to convert the nominal load to a service level load. The service level wind load is based on a 10-year MRI, instead of a 50-year MRI, which is used to determine the nominal load. The 0.7 factor is approximately equal to the square of the assumed ratio of the 10-year MRI wind speed and the 50-year MRI wind speed. The square of the ratio effectively converts the change in wind speeds to a change in wind pressures.

The second method is given in ASCE/SEI 7 commentary for Appendix C which provides wind speed maps to be used to calculate serviceability loads for MRI’s of 10, 25 and 50 years. This change in approach must be considered when applying drift limit recommendations from older references. Drift limit recommendations from several sources (2, 3) reference wind pressures using a 10-year MRI. However, the wind speed maps have been changed significantly since these recommendations were written.

d. IBC—Required Loads for use in serviceability analysis depend on the evaluation limit applied. Serviceability provisions are contained in Section 1604.3. In general, three evaluations are contained in the section. The first and second are contained in Section 1604.3.1, which states that deflections of structural members shall be limited to the more restrictive of the values given in Table 1604.3 and several referenced material standards. The third is given in Section 1604.3.6, which includes a deflection limit that may be required by a referenced standard for the nonstructural element or finish material affected by the deflection.

Table 1604.3 provides deflection limits that should be evaluated against predicted structural deflections resulting from nominal live, wind, snow and dead loads.

The standards referenced in Sections 1604.3.2 through 1064.3.5 include various deflection limitations and loading types. ACI 318 service loadings appear to reference the nominal loads specified by the IBC and ASCE/SEI 7.