Structural Safety and Its Quality Assurance

Edited by

Bruce R. Ellingwood

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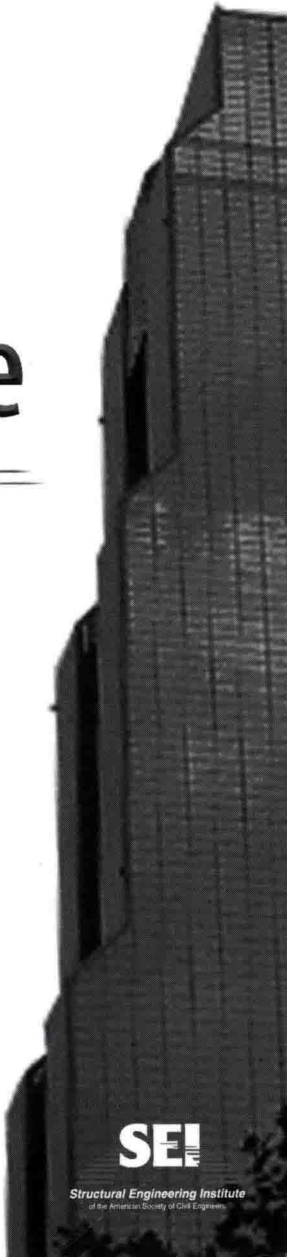

STRUCTURAL SAFETY AND ITS QUALITY ASSURANCE

SPONSORED BY
Committee 9A/10 of the Council on Tall Buildings and Urban Habitat (CTBUH)

The Structural Engineering Institute of the American Society of Civil Engineers

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Foreword

The structural engineering profession plays a key role in the assurance of safe and serviceable building performance. While structural design codes and standards provide the foundation of good engineering practice, the responsibility for proper interpretation and implementation rests with the structural engineer. The safety level that is inherent in any code or standard represents a value judgment on the part of the code-writers (and, by inference the engineering profession and the citizenry) on the question, "How safe is safe enough?" In the field of building construction, this value judgment is based on historical experience. In a time where technology evolved relatively slowly, this approach to structural safety assurance generally was adequate.

However, codes are not a complete guarantee of safety. It came as a surprise to many that numerous buildings and other structures that had been designed to code performed poorly in the views of their owners and occupants in the Northridge Earthquake. One might argue that competent design should take care of the safety issues addressed explicitly in prescriptive codes. On the other hand, structural engineers must pay particular attention to matters that are not covered explicitly in the code or where current prescriptive code provisions may be insufficient. This is especially important for large or monumental structures, including tall buildings. Recent concerns regarding structural behavior under severe fires and building integrity against abnormal loads leading to the possibility of progressive collapse are only two of the many cases in point where structural engineers must apply additional quantitative tools. Buildings meet a fundamental human need for shelter, as well as support the economic infrastructure of a community. The performance of a building can impact a large number of people at once, not only building occupants which may number in the hundreds or thousands but entire communities. Accordingly, the consequences of less than adequate performance in human and economic terms range from severe to catastrophic. Structural engineers practice their art in the public arena. Failures in the built environment invariably are widely publicized, may lead to costly and non-effective remedies, and invariably spark extensive (and expensive) litigation. Expectations of the profession are higher than ever, and penalties for inadequate professional performance are increasingly severe.

Significant advances in the science of structural engineering have revolutionized its practice during the late 20th century. Despite these advances, numerous sources of uncertainty remain in the building process – structural loads and construction material properties are unpredictable; supporting databases are limited; structural systems often cannot be modeled accurately enough to identify performance limits of concern; and the construction process and quality assurance are not perfect. The consequence of uncertainty is risk. Risk is inherent to all human endeavors, and cannot be eliminated entirely. It must be managed through professional practice and informed decision-making in the face of uncertainty. The structural engineering profession is at the forefront in managing risk to the built environment in the public interest. The Council on Tall Buildings and Urban Habitat provides essential technical support to structural engineers in this endeavor.

The Council on Tall Buildings and Urban Habitat (CTBUH) is concerned with the safety, serviceability and economy of tall buildings and their role in modern society. Monographs of the Council facilitate professional exchanges among those involved in all aspects of planning, design, construction, operation and maintenance of tall buildings and serve as a mechanism for international exchange, cooperation and progress. Some recent publications of interest address fire safety, design, codes and special building projects, and tall buildings in the 21st century. The Topical Group on Design Criteria and Loads has responsibility for coordinating council activities in the areas of structural loadings, structural safety and quality control.

An ASCE/IABSE International Conference on Planning and Design of Tall Buildings in 1972 led subsequently to the Monograph (in five volumes) on Planning and Design of Tall Buildings (published in 1978 – 1981), which dealt with safety issues in load modeling, structural analysis and design, and has become a classic reference in the field. In the intervening two decades, the advances in the science and practice of structural engineering noted above have been paralleled by advances in structural reliability theory and applications that provide essential tools to support the structural engineer in assessing uncertainty and managing risk in tall building design and construction. Accordingly, CTBUH Committee 9/10, *Structural Safety and Quality Assurance*, was formed in 1996 to develop a Monograph that would summarize these recent advances in the context of modern international building practices and provide an appraisal of their advantages and limitations as risk management tools.

The Monograph addresses major issues pertinent to meeting the performance goals of tall buildings related to safety, serviceability, durability and economy. Chapters 1 – 3 introduce safety issues in the context of tall building design and summarize the role of building codes and regulations in safety assurance. The current trends toward internationalization of building practices and their significance in terms of ensuring building performance are discussed. Chapters 4 through 9 summarize available quantitative methods for modeling common structural loads, treating the effects of uncertainty in risk-informed building analysis and design of buildings and the structure/foundation system, and assessment of existing structures. Chapters 10 through 12 address the important areas of quality assurance and control, highlighting management techniques that are essential to ensuring that the constructed building is consistent with the building as designed and minimizing the likelihood that human error might derail the design/construction process. Each committee member had responsibility for preparation of a chapter. However, the Monograph has been reviewed by the Committee as a whole and by the Editor, and represents a consensus of the membership.

The field of structural reliability provides a quantitative link between the practice of structural engineering and its social consequences by providing quantitative tools for the management of uncertainty and risk in design and construction. In recent years, the field has grown beyond an academic discipline, and many of these tools have become accessible to professional engineers and decision-makers. The new evolving paradigm of performance-based engineering, with its focus on relating building performance to the needs of the building stakeholders above and beyond the fundamental safety objective of traditional prescriptive codes (which often has been poorly articulated), will cause this trend to accelerate. This Monograph provides a key source of information for the structural engineering profession as it takes the next steps toward implementing these tools in tall building design and construction.

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Chapter 1

Introduction

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Buildings are designed and constructed to provide protected space for people to live or work comfortably. The structural safety and the aesthetics are equally important to the functionality of the structure and the comfort of the users. Economical requirements are often the major concerns to achieve this comfort. Environmental aspects are also design issues of buildings particularly those of large scale. Although the height of buildings has been limited by structural safety criteria, engineering technology has been continuously advanced such that buildings have been designed and constructed to greater heights in the last few decades.

Codes and regulations are authorizing documents which provide a required level of safety to buildings through specifications. Usually these are only the minimum requirements. Although these codes and regulations are revised according to the state-of-the-art information at the time of the revision, in many countries these codes and regulations have been used for a long time without revision. Due to some unique issues specific to tall buildings, technical developments specific to tall buildings may not always be reflected in these codes and regulations. The unique features of tall buildings pose additional challenges during the design process. Furthermore, any structural failures would have a higher potential to cause severe consequences since the number of occupancies in tall buildings is significantly higher than in ordinary buildings. Hence, it becomes necessary for the structural professionals involved with tall buildings to keep abreast of the state-of-the-arts development and to utilize the information appropriately.

For tall buildings, issues other than safety must also be considered which may not be the case for ordinary buildings. As buildings get taller, they become more slender. There is higher potential for the slender building to induce motion sickness to its occupants under the wind with loads. A slender building also has a higher potential for mechanical malfunction such as the use of elevator when insufficient damping is available. These are just a couple examples of serviceability failure that tall building designers have to consider. While catastrophes from serviceability failures are rare, economic loss can be tremendous.

Tall buildings such as Kula-Lumpur and Sears Towers were not designed to just meet the clients' need. They also become an icon in society. They may represent an engineering break through, or may reflect societal, cultural, and historical values. Hence, once these buildings are completed, they are expected to be around forever. This poses additional challenges to engineers – durability and maintainability of the structure.

As mentioned earlier, tall buildings impact many users directly and indirectly in society. These buildings usually are located at the business centers of major cities. Any adverse effect on the building would not just affect its occupants it also affects other business establishments. For example, when unexpected maintenance or serviceability failure force half of the occupants of a full building to stay home, the food service businesses near the building will be affected. The impact on these people would be greater as they are usually small business owners. Marginal loss to them financially is high compared to big corporations. Furthermore, with today's global market and business transactions, one can easily imagine the economic loss due to a single incidence of design or serviceability failure. Fatal accidents are no longer the only concern that engineers have to address when designing tall buildings.

For a very tall building, structural safety is still an essential attribute. People expect buildings to be safe against gravity loads, winds, earthquakes, and other possible actions which can cause significant impact on the buildings. However, engineers know that absolute safety is impossible. Nature can produce extraordinary wind speeds or dangerous ground motions. Terrorist acts such as the one that caused the collapse of World Trade Center on September 11, 2001 are design criteria that engineers would not even imagine during the design process.

Professional engineers have an important role of providing an appropriately safe building by utilizing the state-of-the-arts technical tools and information. This monograph attempts to support the professionals in this respect. Students, aiming to be professional engineers, can expect to confront a wide variety of issues on the structural safety of tall buildings.

Structural reliability studies of the last four decades have made big strides in modeling the uncertainties of materials and loads and accounting for engineering modeling imperfection. Results of these studies have been successfully implemented into many design specifications and used widely in many parts of the world. Since these specifications may not always be applicable to tall building design, this monograph presents fundamental concepts of reliability analysis which can be implemented to the engineer's design process or provide starting point for further investigation by engineers into reliability-based design.

Also addressed are other issues associated with tall buildings such as durability in structural safety, quality assurance, quality management, quality controls in construction, and human factors influencing the safety of structures. There are other such issues, as serviceability which is not presented in detail in this monograph for several reasons. One reason is that it is desired that the monograph does not become too voluminous. The second reason is that those topics may interfere with other committee's activities within the Council. Issues regarding designs for un-natural causes such as the collapse of World Trade Center are still in the discussion stage and are not included in this monograph.

This monograph is composed of 11 chapters in addition to the introduction and concluding chapters. The 11 chapters cover the following topics: safety concept, role of codes and regulations, load modeling, reliability analysis, reliability-based design, durability in structural safety and quality assurance, assessment of soils and foundations, assessment of existing structures, quality management of structural design, quality control in construction, and human error. Each chapter is essentially self-contained with an extensive list of references for readers to explore the topic more thoroughly.

Chapter 2

Safety Concepts and Risk Management

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2.1 Introduction

There are many facets to safety. Curiously, safety is best achieved by looking at its converse, at the many ways in which failure can happen (Stevens 1998). This is partly a technical matter: where failure probabilities are low, they are better handled directly rather than as probabilities of survival, which are nearly equal to unity. But it is also a psychological matter. It is better by far to be wary of failure rather than to expect success. Where failures are rare, prudence and wariness are the ultimate guards of safety.

This monograph considers many of the factors ensuring that failures seldom if ever occur in tall buildings. It cannot be comprehensive in detail – that would require far more than a single volume. It does attempt, though, to be comprehensive in its overview, and to bring to the reader's attention matters which might sometimes be forgotten during design, construction and the subsequent monitoring and maintenance of tall buildings.

The discussion is limited to structural safety, and therefore does not deal with serviceability and the business and financial side of creating a building. Neither does it deal with fire safety, even though the maintenance of structural safety in case of fire is a significant issue in building design. Nevertheless some of the tools and approaches dealt with in subsequent chapters can also be adapted for use in fire engineering.

Structural safety is dealt with here as a matter of avoiding structural failure. Historically the primary emphasis has been on avoiding injury and loss of life. This view has changed following the Northridge earthquake, an event causing relatively few casualties but resulting in serious economic loss. Since then there has been a growing realization by structural engineers that design for structural safety must aim at minimization of economic loss as well as protection of people. It is a reflection of what society wants. The primary focus must still be on prevention of harm to people, but now the social consequences of a major disaster must be taken into account. Of course, this relates more to large-scale disasters such as the World Trade Center attacks, or earthquakes and wind storms where many structures fail, rather than to more localized failures such as that of the Hyatt Regency walkways (Marshall et al, 1982).

In addition to being good business practice and a moral issue, structural safety is clearly a social matter. The community demands it. Ever since Hammurabi set out the first crude building codes (Edwards, 1904), society has wanted to require suitably safe structures. Building codes are the means by which society seeks to ensure safety. However, codes in themselves are not a complete guarantee of safety. They are necessary but not sufficient. In a sense, their role is to reduce the need for designers to think of some aspects of structural safety. The correct view of the relationship between codes and design is not that design is essentially a matter of following codes, but rather, that design should principally focus on those matters not covered by codes. This might not be so important with minor structures, but tall buildings are complex, and it becomes imperative that designers should think beyond the code. What is needed is a systemic way of thinking about safety. In part this requirement is covered by quality assurance, but quality assurance, too, has its limitations.

Safety and risk are closely related concepts. Yet they are very different in nature. Risk is quantifiable, but safety, particularly personal safety, generally is not. It is something to be achieved or assured. Matousek (1992) says "Safety is a quality characteristic and should therefore not be restricted to being a mathematical factor." The nature of safety has been discussed elsewhere at some length (Elms, 1999). Suffice to say that in understanding the nature of safety and how it could be approached; the engineer should also be aware of the related concepts of risk, hazard and vulnerability. For tall buildings, safety is achieved within a broader context of risk management by considering the hazards to which the building and its parts might be subjected, and relating this to the vulnerability of the structure. Hazards can be both natural hazards and those deriving from some human cause.

2.2 Overview

Figure 1 gives an overview of the different issues associated with safety. The diagram essentially gives a map which is followed by the rest of this chapter. It also picks up the major themes of the book and shows some of the relationships between them.

Starting with structural safety at the centre and working outwards, the diagram has three main segments: design, construction, and the monitoring and maintenance required during the lifetime of a building. Next comes a band containing some issues common to all three segments: information management, quality assurance, risk management, human error management and quality control. Quality assurance and human error are dealt with in later chapters, while risk management is discussed below.

Outside the common-issue band, each segment contains some of the issues contributing to safety. This chapter is primarily concerned with design, so the two non-design segments contain fewer issues.

Foundations are important to the safety of the structure, but will not be treated further as an independent topic.

Underlying any design exercise is a philosophy, or a broad and strategic way of attaining design goals. To some extent this was touched on above when it was stated that the aim should now be to deal with not only protection of people from harm but also with protection of property and minimization of loss. The attitude of the engineer to code requirements, that design should really start after the code requirements have been met, can also be thought of as philosophical issue in the design process. In a practical situation it is important to understand the underlying methodological framework. An example is the capacity design approach, where undesired failure modes are dominated by more desirable and benign modes. The latter will occur first and ensure that the undesired modes never occur. A fuse is designed into the structure. Another example of a design philosophy is displacement based design for earthquakes.

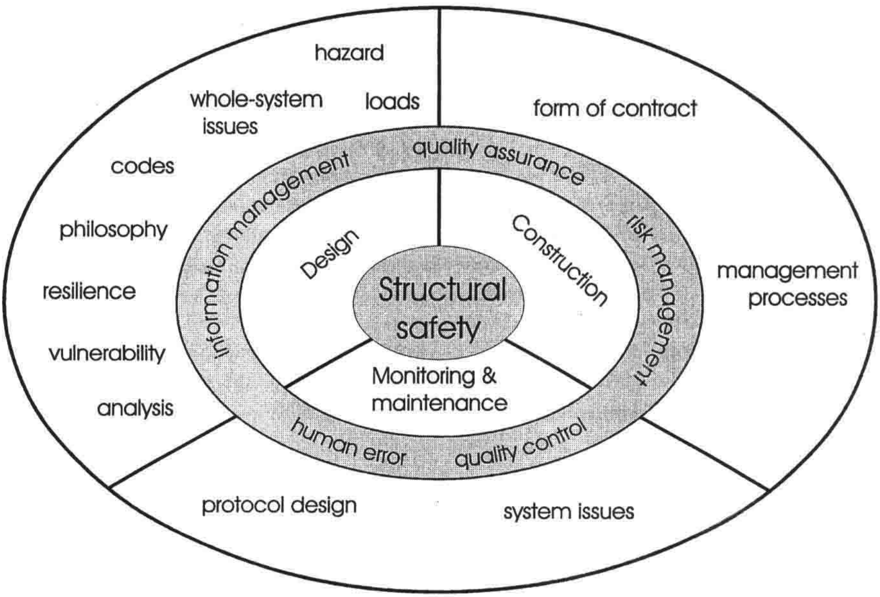

Figure 1 Safety issues

2.3 Design

Generally speaking, society ensures that its structures are safe through the use of building codes. A code, whether prescriptive or performance-based, is essentially a set of rules designed and calibrated to ensure that structures will not fail due to certain causes; that is, due to known and specified demands. An important implication is that there are other failure causes which are not covered by codes, or which are covered inappropriately. For example, most structural codes do not deal well with human factors. They are sometimes assumed to be covered by modifying load and resistance factors, but this assumes that failure will be prevented by simply increasing strength, say. Yet most failures caused by human error have little to do with design strength. A different approach is needed. The underlying question is, to what extent structural design should specifically allow for totally unexpected demands and events.

Most structural codes are prescriptive and state precisely what must be done, what loads must be catered for and so on. However, there is a move towards introducing performance-based alternatives, some of which are now in place. Such codes require a more sophisticated understanding and analysis.

A code for building structures is essentially a means by which a minimum level of safety is achieved no matter to what structure the code is applied. There is a tension between a simpler code which results in a larger variation in safety levels between structures and a more complex and detailed code which achieves a smaller variation in safety by a more precise targeting of specific structural types. By "simpler" and "complex" is meant the degree to which the code disaggregates structures into different types, shapes, materials and usage. Suppose two codes use different ranges of variation to achieve the same minimum level of safety. It follows that the code with the greater variation must produce a higher average safety level over all structures to achieve the same minimum. The simpler code, with its higher variance, therefore leads to a higher overall cost to society (Figure 2). No satisfactory principle has yet been proposed for deciding on the appropriate level of code complexity.

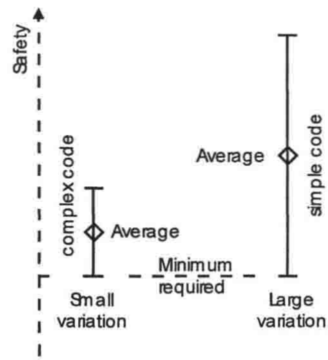

Figure 2 Simpler codes lead to higher average costs

The issue of codes is dealt with more extensively in Chapter 3 and elsewhere (Elms 1999).

Design must take uncertainty into account. It is not just a matter of uncertainty in loads and materials. Structural safety could be threatened by unpredictable events such as sabotage or human errors. For this reason structures must be designed to be robust, to have resilience. That is, they should not fail in a brittle manner, and neither should progressive collapse be possible triggered by a limited failure at one point. The need for this is well understood in shipbuilding and also in the aerospace industry, where the fail safe design philosophy and the introduction of crack stoppers were introduced in the 1950s following major failures such as that of the De Havilland Comet. The requirement to design against progressive collapse has been well-documented in the building industry (Ellingwood and Leyendecker, 1978), but is not always remembered.

One source of unpredictability is error in the design and analysis process. This can be managed in two ways: by ensuring a quality control process is in place, and by managing risk through monitoring secondary indicators of potential trouble.

Quality control requires independent checking procedures to be in place. Beyond this, there are the good quality assurance practices of ensuring that documentation is trackable and so on. Chapters 10 and 11 deals with quality control in design, construction and maintenance. Quality assurance has a significant limitation: it assures the quality of management systems, but not of their content. It will ensure that all procedures have been followed correctly, but it will not normally pick up whether the result of the procedure is correct or appropriate. That is why independent checks are necessary.

The second approach is to look for indicators of proneness to error. An initial set was proposed by Pugsley at an early stage (Pugsley 1973). He suggested that the following factors indicated an increased proneness to structural failure

1. new or unusual materials
2. new or unusual methods of construction
3. new or unusual types of structure
4. experience and organisation of design and construction team
5. research and development background
6. industrial climate
7. financial climate
8. political climate

Pugsley did not intend the list to be definitive. He was discussing the approach, not the detail, and said "Clearly this list could be extended, or each item expanded, or restated under a smaller number of broader heads." The aim was simply to give a framework by which an engineer or a group of engineers could look at a structure or project "and have a good chance of assessing in broad terms its accident proneness."

With a little modification the list of indicators can be made more general. In item 3, for instance, "structure" could be replaced by "product". Item 4 could be expanded to include ongoing management. The phrasing could also be changed to make the items consistent with one another: as the list stands, the presence of some items ("new or unusual materials", for instance) is intended as a bad sign, while others (such as "industrial climate") are neutral. There is also a question of the completeness of the list. An appropriate addition could be "system complexity".

Blockley (1980) has taken the idea further in developing a list of 25 questions to deal with matters "not normally taken into account in structural safety calculations".

In the context of the design process, use of such indicators is related to risk management of the process. The idea is to monitor the indicators and use them as a warning of increased risk within the process. If, for instance, there are novel methods of construction or unusually tight budgetary constraints, then it would be necessary for management to be more than usually wary of error.

Other indicator methods are discussed elsewhere (Elms 1999).

A different approach to dealing with uncertainty is to view the structure as a system and to think of design, analysis, and construction as systemic processes. Safety can then be thought of as a matter of ensuring the soundness or "health" of the relevant systems. System health requires the fulfillment of five criteria (Elms 1998A, B). A system will become unhealthy, or in the limit fail, if there is a failure of one or more of the criteria, namely a failure in

- *Balance*, where some of the elements of the system are too large and others are too small with regard to the system's purpose;
- *Completeness*, where the system has elements missing which are essential to its fulfilment;
- *Cohesion*, where something is wrong with the system's structure, and with the way its elements relate to one another;
- *Consistency*, where elements or connections in the system are inconsistent either with each other or with the system's purpose;
- *Discrimination*, where the various parts of a system and the way they interrelate are unclear, ambiguous or confused.

The five criteria are applicable both to the design itself and to the process of design and its effective management. For example, the balance criterion could be applied to the relative effort spent on analysis, design and project management.

Despite the apparent simplicity of the healthy-system criteria, their application in practice requires care and experience. This is to be expected partly because the approach is subjective and partly because the systems dealt with are complex.

Turning now to the analysis phase of design, there is much to be said for analysis that finds probabilities of failure directly. Though a number of quantitative techniques are available, they are generally suited to specific types of problem and cannot easily be transferred to others. Thus the event- and fault-tree methods widely used for the analysis of failure in chemical plants, nuclear power stations and generally in complex system situations are unsuitable for use in structures. There are a number of ways of categorizing risk and safety problems (Elms 1998C). The key issue here is that, unlike chemical plants, structures are not readily "differentiable". That is, they cannot easily be separated into individual parts whose failure probabilities can be estimated separately. There are, however, techniques especially suited to the tightly coupled systems that are structures. They are the first-order second-moment (FOSM) or first order reliability methods (FORM) discussed in Chapter 5.