# STRUCTURAL DESIGN CODES: THE BRIDGE BETWEEN RESEARCH AND PRACTICE

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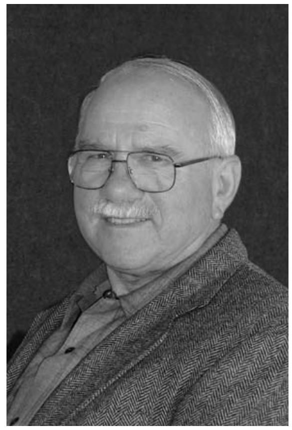

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## Summary

Research on the behavior of structural components and systems has always played an important role on the development of the design standards that regulate and unify the work of structural engineers. After a review of the history of design code experience in North America, this paper discusses the tasks ahead for promulgating future standards for looming future design tasks. It is concluded that a new paradigm for these regulations must replace the current system with its many prescriptive rules. A case is made for Performance-Based Design as the future format to be implemented.

**Key Words:** Design standards; performance-based design; building codes;

## 1. Introduction

Structural design is a major activity of the profession of structural engineering. Structural design is an art wherein the design engineer participates in the creation of a structure, such as a building, a bridge, a tunnel, an antenna, etc. The contribution of the structural engineer is recognized and appreciated by the general public to various degrees, depending on the visibility of the skeleton or the shell of the edifice.

The structural design engineers/artists have many paints and brushes in their palettes: mathematics, solid and fluid mechanics, physics, chemistry etc., i. e. the hard sciences taught in their engineering education; experience; judgment; concern for the common good of society; consideration for the environment; and many more attributes acquired in professional practice. The artist-designers can call on their creative spirit to design an infinite kaleidoscope of outcomes. But wait, there is really no such utopia! There are some severe restrictions on this freedom, namely, economics, the needs of all the other members of the design team, and, last but not least, the demands posed by the requirements of the *structural design standards*, sometimes also called *codes* or *design specifications*. The subject of this presentation is the past, present and future role of these standards, and the relationship between the structural design engineers, the codes, and structural engineering research.

## 2. Structural Design Codes

Structural design codes in the United States have their origins in the early decades of the 20$^{th}$ Century, when structures were designed by individual organizations according to proprietary criteria, and it became evident that building authorities had no consistent methods for comparing designs [1], [2]. Such governmental agencies had to evolve new methods to ensure safe designs. It thus became necessary to promulgate rules that were uniform for all providers of structural design in their jurisdiction. These rules, or codes, were developed to define minimum criteria of safe design. The experience of this author is principally with developments in the design of metal structures in North America, and so the following observations are drawn from that background. With minor variations the situation is likely to be the same in other parts of the world and for other materials. As an example of illustrating the relationship between structural engineering research and an official design standard, the evolution of the *Standard Specification* of the American Institute of Steel Construction (AISC) for the Design, Fabrication and Erection of Structural Steel for Buildings will be used [3 through 6]. The author has also been member of code-committees of the American Iron and Steel Institute (AISI) [7], the Steel Joist Institute (SJI) [8], the Aluminum Association (AA) [9], the American Society of Civil Engineers (ASCE) [10], and the Canadian Standards Association (CSA) [11]. The abbreviated history of the AISC Specification, as shown in Table 1, illustrates the increasing role of scientific structural engineering research in the evolution of this design standard. First, however, one must define *research* as it is understood here. It means experimental, theoretical, analytical, and/or numerical study performed for the purpose of providing input to the specification, frequently, but not exclusively, by members of the code committee, doing research often sponsored by the authority originating the standard.

Table 1 *History of AISC Specification*

| **Year of adoption** | **Design Criteria** | **Code pages** | **Commentary pages** | **Committee Members** | **Researcher Members** |
|---|---|---|---|---|---|
| 1923 | ASD | 11 | 0 | 5 | 0 |
| 1936 | “ | 19 | 0 | * | * |
| 1949 | “ | 30 | 0 | * | * |
| 1963 | LSD-ASD | 44 | 46 | 26 | 5 |
| 1969 | “ | 103 | 44 | 36 | 6 |
| 1978 | “ | 93 | 68 | 43 | 9 |
| 1989 | “ | 83 | 68 | 43 | 14 |
| 1986 | LSD | 91 | 66 | 42 | 14 |
| 1993 | “ | 110 | 92 | 46 | 13 |
| 1999 | “ | 124 | 113 | 46 | 14 |
| 2005 | “ | 196 | 231 | 40 | 12 |

ASD: Allowable Stress Design.
LSD: Limit States Design (in the USA, LRFD, Load and Resistance Factor Design).
LSD-ASD: LSD in pseudo ASD format.
* No external committee is recognized in the documents.

Table 1 lists the dates on the adopted editions of the AISC code, the number of pages of mandatory rules, the number of pages of the commentary explaining the rules, the number of code committee members, and the number of research professors.

The first edition of the AISC Specification was adopted by the American Institute of Steel Construction in 1923. It had, as such, no legal standing of its own until it was officially adopted by governmental authorities such as city, municipal, state, national and other building departments. As time progressed, another layer was added to the process, namely, the incorporation of the industry design code, either by direct inclusion or by reference, into a *model building code* that was, in turn, approved as a legal document controlling structural design by a government agency. Figure 1 depicts a very simplistic schematic pyramid of the code hierarchy as it exists today in the US. At the bottom of the pyramid are standards that control the material (American Society for Testing Materials, ASTM), the assembly of the structure, and the loads on the structure (for example, the load code of the American Society of Civil Engineers, ASCE7 [10]). The next layer consists of the design codes developed by industrial professional or trade associations such as AISC, American Concrete Institute, ACI, Aluminum Association, AA, American Iron and Steel Institute, AISI, and many others). These industry codes the become parts of the next layer of *model building codes*, such as for example the International Building Code, IBC [12]. These model building codes are essentially an assembly of everything that is below in the pyramid, and they are in a format that can be adopted totally or in part by legal building authorities. The structural design engineer then sits atop and must justify his or her work to the legal guardians of public good.

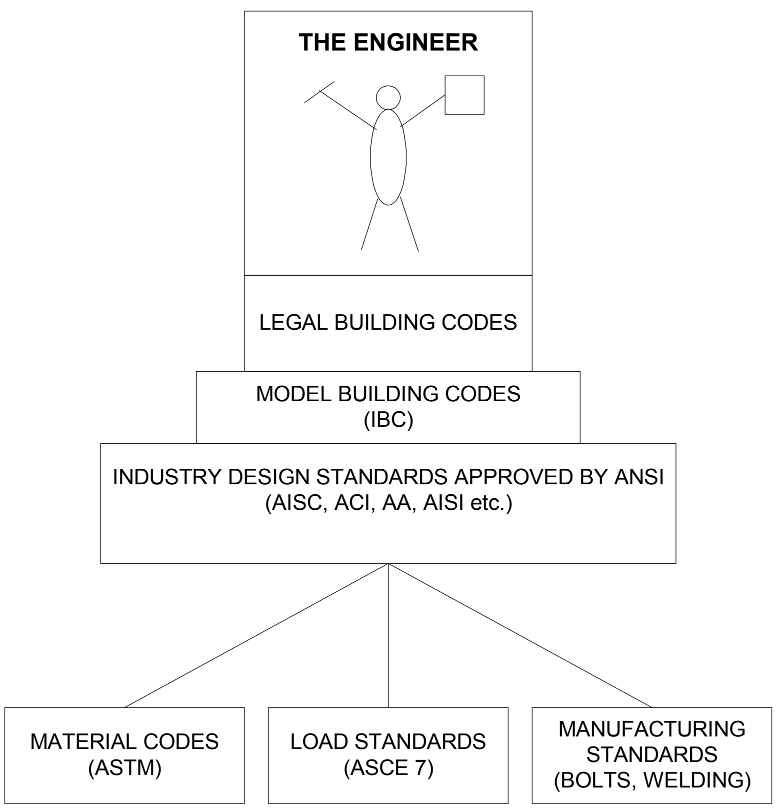


Fig. 1 *Schematic of the code hierarchy*

An important development occurred gradually over the last two decades of the 20$^{th}$ Century: The standards were developed and maintained by advisory committees that acted as advisors to a particular industry's professional or trade association, say, AISC of the steel fabrication industry. The official representatives of this association then approved the standard that was recommended to them by the advisory committee. Many of these advisors were members of companies associated with the industry, and some of the academic contributors performed research sponsored by the industry. Even though, in the experience of the author, the process of producing a code has been of the highest professional level, increasingly the outside users of the code, and society in general, has viewed it as a rather cozy arrangement for the benefit of the particular industry. Laws and regulations have intervened, so that by the year 2000 all the industry codes in the US have to go through another rigorous review cycle by the American National Standards Institute (ANSI). For the industries involved this was a painful pill to swallow, but by now there is agreement that this additional requirement is a good and useful step.

It is within the context of the scheme presented in Fig. 1 that the AISC Specification's history is viewed in this presentation. The first edition was a scant 11 pocketbook pages long. After the first edition in 1923, there were three major changes in the standard: in 1963, 1986 and 2005. For the first 40 years the method of design was according to the classical precepts of *allowable stress design*. The determination of forces was based on linear elastic theory, and the strength of members was determined to be about 2/3 of an elastic limiting stress. After the first edition, the changes and expansions were handled essentially internally by the AISC, as the need arose for adding new types of construction. The framers of the first edition were constituted as follows: two consulting engineers working for architecture firms, one engineer with a fabricator company, and two structural engineering professors. The code was essentially a set of rules based on prevailing good practice, ensuring that designers would use the same allowable stresses everywhere in the US for the proportioning of fabricated steel structures.

In the 1950s it became evident that developments in industrial practice, such as welding, high-strength bolts, composite beams, and thin-web plate girders, needed to be incorporated into a modern design code in order to again avoid the chaos of every company using their own in-house rules. There were also numerous ideas that emerged from military research during the Second World War, especially from the aircraft industry. Among these were, for example, the resolution of the column paradox by F. R. Shanley [13], and the utilization of post-buckling strength in stiffened thin-walled panels. Ideas of inelastic reserve capacity and energy absorption were utilized by Baker in the design of bomb-shelters, and methods of plastic design were being developed by his team at Cambridge University in England. The concept of an arbitrary Factor of Safety was challenged by Pugsley [14] and Freudenthal [15], and the possibility of rational probability-based design began slowly to emerge. The theories of elastic stability and elasticity became widely known from publications in Europe and by the English language books of Timoshenko [16] in the United States. The Theory Plasticity, developed by William Prager and his colleagues at Brown University [17], provided the theoretical basis for the development of Plastic Design. At the same time the development of efficient methods of linear structural analysis, coupled with the availability of computers to solve the equations, promised a new dawn of structural engineering. It was, indeed, a very exciting time to be a graduate student in the 1950s, when the author commenced his studies at Lehigh University in Bethlehem, Pennsylvania. His first assignment was to assist Jonathan Jones of the Bethlehem Steel Company in the translation of the German stability design standard, DIN 4114.

From the late 1940s to the 1970s AISC, AISI, The Welding Research Council, the Federal Highway Administration and others sponsored research at Lehigh University's Fritz Engineering Laboratory under the leadership of Lynn Beedle to develop the research background for rules to be incorporated into design criteria for steel building and bridge structures. The results of this research were incorporated into the 1963 edition of the AISC Specification. As can be seen in Table 1, the size of the document increased, a commentary was added, and the number of committee members increased. Among these committee members there were also academic researchers who were actively involved in the research that was the basis of the design rules. The new code was a *Limit States Design* code (LSD), rather than a traditional *Allowable Stress Design* code (ASD), although a part of the specification was dressed up in the disguise of ASD to preserve accustomed tradition. The 1963 edition introduced extensive new criteria for frame stability, local buckling, lateral-torsional buckling; it permitted the utilization of post-buckling strength for plate girder webs, and it had extensive provisions for plastic design. Subsequent editions expanded the coverage as industry demand and research response generated new material that was judged to be necessary for incorporation. The size of the code and its commentary increased greatly from 1963 to 2005 (from 44 to 196 pages for the code, and from 46 to 231 for the commentary, respectively). The number of committee members has been kept to about 40 members roughly distributed into one-thirds steel industry engineers, design engineers, and academic engineers. Most of the latter are, or have been, active research contributors to the AISC code.

The point of the discussion above is to summarize the history of one representative structural design standard up to the present time (2006). Similar histories could be told from all countries and organizations represented in IABSE. The conclusions reached by the author of this paper about the current status of structural design standards are the following:

1. The present code documents are many times the size of the first codes from which they evolved. There are many reasons for this, and following is a list of some of them:
    a. There are many more types of structures, connections, materials and industrial applications today than 80 to 100 years ago.
    b. Industry and government have made money available for research that benefited the sponsors, and all of society, by promulgating codes for designing safer and more economical structures.
    c. The demands of the culture of litigation have resulted in very precise language requirements and detailed elaborations of design criteria, thus requiring many more sentences and paragraphs than would otherwise be necessary.

2. Developments in the technology of testing materials, structural components, members and whole structures have resulted in the evolution of many structural research laboratories in Universities. New products from industry and novel types of structures can be tested, and the results made promptly available to the standards developers. The seamless integration of theoretical study, physical testing and numerical experimentation has resulted in a mature understanding of the behavior of structures. Structural engineering has been in the first wave of

many developments that are now finding use in many other areas of technology and science.

3. In the USA the predominant driver for advancement in structural engineering in recent years has been the research on the behavior and design of structures to resist earthquakes. The primary sponsor for this development has been the US National Science Foundation (NSF). Several generations of structural research engineers and scientists, and many excellent research facilities, have resulted from this sponsorship. Enormous amounts of basic and applied research have produced data and design methods that have been adopted into design codes.
4. The role of structural engineering academics has had an enormous influence on all modern structural design codes. To this author it sometimes seems that this is overwhelming and maybe intimidating for the practitioner members of the code committees. Sometimes deference is made by the generalist to the specialist. Thus some of the design criteria become overly complicated, and the designer may have trouble seeing the forest from the trees.
5. All current design codes in the US have a basis in more-or-less sophisticated applications of reliability analysis. The underlying aim is to produce structures that have approximately uniform reliability against exceeding a limit state. This purpose has been largely achieved between designs within any given code, say fabricated steel structures, but it is not uniform across codes, say between steel bridges and steel buildings that are designed by different codes.

To sum up the present status of structural design specifications in the USA: They are principally based on scientific academic research, they are large and complicated, they are prescriptive, they are formulated in awkward language in order to be legalistically unambiguous, and new revisions are issued too frequently. To this perhaps too critical an assessment it must be added that the current US structural design codes are finely crafted documents that produce safe and economical structures. In the opinion of this author, they are at the pinnacle of their evolutionary development. Further changes in format and content are likely to be incremental refinements. New developments in the future will necessarily have to be along a new path. The theme of this IABSE Symposium is to define the future of structural engineering. In this future there must be also a new view of the role of design codes.

## 3. The Future of Structural design Codes

Structural design codes exist to insure uniformity of design criteria across structure types and across a region, and to permit control of structural designs by authorities whose duty it is to ensure public safety. In contemporary standards this means the achievement of uniform reliability. In the previous parts of this paper it was shown that the current codes in the USA, and probably also in the world at large, are approaching the dinosaur stage, and it is time to think about what can be done for the future. One thing is clear: there will be a continued need for standards for the sake of public safety. In the case of large projects, such as major bridges and large special structures, it is permissible to override the standards by promulgating project specific criteria that are developed by the most knowledgeable and experienced professionals and where all phases of the project are subject to peer review [18]. Such an approach is hardly justifiable economically for the majority of structural designs [19].

So if the present documents are becoming too cumbersome, then what shall be done? The answer that is often proposed in discussions and read in the structural engineering literature: *Performance-Based Design (PBD).* The word is not new, nor is the concept untried. In the USA there was a large effort in the National Bureau of Standards (NBS, now the National Institute of Standards in Technology, NIST) during the early 1970s to develop PBD standards for prefabricated innovative housing systems [19]. Industrial specifications, such as for example, the Standard Specifications, Load Tables and Weight Tables for Steel Joists and Joist Girders of the Steel Joist Institute [8], are actually primitive forms PBD standards, if not explicitly named so, but certainly so in intent.

Modern efforts of PBD have been championed by many engineers and a large literature exists on the subject. One representative paper by Ellingwood [19] proves a snapshot of the history and future prospect of PBD. In the USA the principal impetus for PBD has come from the fire engineering and the earthquake engineering community. A result of the extensive research sponsored by the US Federal Emergency Management Agency (FEMA) [20] in the aftermath of the Northridge Earthquake is a document that gives recommendations for the PBD of new steel moment-frame buildings. Performance objectives are stated in terms of performance levels for immediate occupancy for frequent earthquakes (50% chance of being exceeded in 50 years), and for collapse prevention for a maximum considered earthquake (2% in 50 years). Performance goals are stated in the form of recommended minimum confidence levels, such as, for example, 90% confidence level for collapse prevention for inter-story drift. Tools of various degrees of complexity are provided or recommended in the document for performing the PBD operation. The FEMA report, of course, is not a design standard, and it is not it has not been implemented in a building code.

In spite of the great deal of discussion and research, the introduction of PBD into national structural design codes in the USA has been slow. However, a big step has been taken by the new 2005 AISC Specification [6]. This latest edition has included for the first time in its history a chapter on "Structural Design For Fire Conditions", and this chapter is explicitly in the format of PBD. The text defines PBD as:

> "*An engineering approach to structural design that is based upon agreed-upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against those design goals and objectives using accepted engineering tools, methodologies and performance criteria.*"

The performance objectives are given in three short paragraphs, the first of which will be quoted here to emphasize the spirit of the method:

> "*Structural Components, members and building frame systems shall be designed so as to maintain their load-bearing function during the design-basis fire and to satisfy other performance requirements specified for the building occupancy.*"

The significance of the inclusion of this PBD-based portion of a document that has been approved by ANSI and adopted by the national model building codes is that engineers will need to pay attention and begin to modify their way of performing their daily job. It remains to be seen how the design professionals will react to this new approach in the

AISC Specification. However, a first step has been taken, and this will lead to further enhancements of PBD as further experience is accumulated by the structural design community.

It is evident to this author that the future of structural design codes lies in the implementation of Performance-Based Design methodologies. For this to happen there will have to be a much broader discussion and participation than has thus far taken place. So far the driving forces have originated mainly from intellectual and research sources. Far more participation must now come from the structural designers, building code officials, lawyers, contractors, the building trades and owners. So far this is not evident in the USA, and it is difficult to foresee the events that will initiate a broader effort toward making PBD universally accepted and codified. However, it is sure that the structural engineering research community will have to play a significant role in making PBD practically possible.

## 4. Research Tasks

While the discussion continues about the best way to make new structural design codes in the mold of Performance-Based Design, there is immediate work to be done by the research and the code-writing community to make structures safer. The theme of this IABSE Symposium, “Responding to Tomorrow’s Challenges in Structural Engineering”, provides a guide to some future needs for research. Following are some of these challenges:

1. Structural design codes are mainly directed toward the design of safe new structures in their final occupied state. There is still a lack of comprehensive design standards for a number of other design assignments that structural engineers face with in increasing frequency. Such challenges as are posed by the following activities have requirements that are different from those that govern the new structures. Conventional practice is to apply the standards for new structures for these altered design conditions. The statistics and the reliability requirements for these situations are different when much is known about the past history of the site, the load history, the structure, etc. Such challenges requiring codification based on available experience and research are, for example,

    a. Refurbishment of structures for new uses or occupancies.

    b. Repair and strengthening of structures after damage due to catastrophic events.

    c. Redesign or re-evaluation due to changed circumstances in occupancy, use or loading. This could be, for example, increases of demand from higher traffic loads, new insights gained about the nature of a type of demand, or different wind loading on a structure after newer adjacent buildings change the wind climate, etc.

    d. Use of recycled structural elements in new constructions. Examples are the re-use of mass-fabricated steel trusses (steel joists), or the utilization of prefabricated prestressed concrete girders from bridges that were dismantled in bridges that are to be replaced because of functional obsolescence, etc.

e. Preservation of heritage buildings [21].

2. Very much is known from research and experience about the effects of earthquakes and wind storms on structures, and this knowledge has found its way into design codes, often dominating the volume of requirements. There are other natural and man-made catastrophes that are considered in codes, but the basis for the required actions on the structure have not the same quality of the statistical data and the reliability assessment as the wind and earthquake designs. Such other events are flood loads, earth pressures, ponding from fluids, ice loads, scour, impact from vehicles, blast, fire, etc. Much research work to develop reliable data on these events will need to be performed over the future so that eventually there will be a uniformity of reliability across all load types and structures.
3. New construction practices will require more research to define loads and resistances. One such practice is the "rapid construction" of bridges so that traffic will not be disrupted for long on a busy highway. The effect of moving whole bridges, or large subassemblies, will necessitate the development of new design standards. Structures that are built with monitoring devices, or with motion damping systems (*smart structures*), are not the same as those without such furniture. Designers should have standards available at their disposal that would take advantage of the increased reliability these devices provide.
4. Many new materials have become available to the structural designers. Some examples are: high-performance steel, high-performance concrete, fiber-reinforced composites, glass etc. There are a variety of ways these new materials are combined with traditional materials so that many possible combinations for composite action are possible. The quality of the data on the basic material properties of some of the new materials is sometimes not very good, and designers have to rely on proprietary data from manufacturers for information. This makes it difficult to arrive at material statistics to develop the probabilistic factors in the design codes. Standardization of materials testing and data evaluation is needed for progress in using some of the new materials.
5. In the opinion of this author the most promising avenue to achieve uniform reliability of structural behavior under serviceability conditions is to produce reliable data on serviceability limit states. Strength limit states are based on a century of solid research, but serviceability limit states in structural design codes, if they are included at all, are based on past practice that has been hallowed by long tradition but little science. Considering that many structural designs are governed by serviceability criteria, it surely should be a big priority to determine the statistics for the loads and structural systems so as to be able to have a rational way of making designs with consistent reliability across all structures.
6. In order to eventually implement PBD into design standards, it is necessary to provide the tools that can be used by the engineers in their work. Such tools have been discussed above for the seismic design. Programs for direct analysis of steel and composite frames have been developed [22]. So far, however, these are research tools, and there are far too few of them. Standards should be promulgated so the software developers can generate robust computational tools.

This list could surely go on for many more pages. One thing is for sure, there is much research yet to be done in order to keep the world's design standards abreast with new ideas and new design challenges.

## 5. Discussion and Conclusion

Structural engineers at the beginning of the 21st Century stand on a very tall mountain that is covered with many trees. The accumulated knowledge about structural behavior, analysis, loads and methods of design is immense. A lot of this knowledge is hidden inside the mountain in the form of previous insight and former experience. One question that has always occurred to this author is whether it is cost-effective to "mine" this "ore", or whether is less expensive to perform new research on the new problems, even though earlier work could be helpful. The analogy of the many trees on this mountain refers to the diversity of contemporary information and the multitude of codes and regulations that a structural engineer must consider.

The discussion above focused on the contribution of research on the content of design codes, and what future research can contribute to current and future standards for traditional design of new structures as well as for unconventional and novel design tasks that the new Century poses to the structural engineer. There is, indeed much that needs to be done, and there are workers and laboratories capable of performing whatever work is needed. In the opinion of this author, the most important job, however, is to find ways by which the engineer in the office and out on the construction site can have the wisdom, the time and the ability to absorb and efficiently use what research has introduced into the laws and standards.

The major challenges facing the structural engineering research community is not the means for solving the problems posed by the demands of the building industry. The scientific tools and the experience to use them are highly developed, and there are many experts available. The big challenges are to select the proper problems to be considered, and to transmit the resulting body of knowledge to the code-writing bodies, and finally to the practicing engineers. The implementation of Performance-Based Design methodology into every-day application in the design office will need the involvement and cooperation of not only the research - code committee - design engineer community, but also the owners, fabricators, contractors and the skilled labor trades. For this all to happen we need to define clear goals and to make plans so that these goals can be achieved. What better platform for this work than the International Association of Bridge and Structural Engineers?

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