

# The Effective Use of Commercial Computer Software for the Structural Design of Buildings

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*While past developments in structural software provided modest gains on the design process, new developments may require engineers to redefine their roles and responsibilities.*

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**T**o state the obvious, historical records show that there are many fine examples of structural engineering achieved prior to the use of computers in engineering. A couple of these notable structures are the Brooklyn Bridge (in 1883) and the Empire State Building (in 1931). Thousands of more humble yet equally successful examples exist. These works are a result of sound structural

design without the use of commercial computer software. Before computers, engineers used empirical design rules, approximate analysis methods, rules-of-thumb and their engineering experience and judgment. Many of these structures may be conceptually very simple compared to modern-day counterparts such as the Boston Convention & Exhibition Center or the Ray and Maria Stata Center at the Massachusetts Institute of Technology. Perhaps computer analysis of some historic structures can demonstrate a degree of over-design or a flawed understanding of stresses and strains. Yet structural design achievements before the use of computers are still very impressive and many would be impressive if engineered today with modern computer tools.

Whereas engineers in the past (before computers) needed practical means and methods to arrive at a design, today's engineers need similar practical means and methods to check designs derived from computer software and

to better understand the structure. Some of the knowledge base used in the nineteenth and early twentieth centuries is preserved in volumes like the Kidder-Parker *Architects' and Builders' Handbook*.<sup>1</sup> These resources are full of interesting engineering approaches and empirical design. Although, today, engineers are less likely to need to design an unreinforced masonry arch or other archaic systems, there is a need to know the reasonable limits and capabilities of modern structural systems.

Given enough time and money, engineers today should be able to achieve excellent structural designs without computers for the vast majority of building structures. However, today's market does not give the structural engineer that luxury. It is safe to say that computers and state-of-the-art design software is a must in the modern structural engineer's office. Not because the complexities of the structure demand it (few do), but because the market demands the productivity that such tools make possible. As code-required load and design rules get more and more complicated, engineers will need to increasingly rely on computers for productivity gains. However, many should be able to continue to perform adequate designs using approximate methods without computers. Most engineers have a sense of pride about this ability, if they have it. Whether young engineers today have it or will develop it depends on the effectiveness of training and on the effective use of commercial design software. The amazing productivity gains that current and future design software provide must become a means to free the engineer from the drudgery of code checking, numerical accounting and the anxieties of mathematical errors, and provide the engineer with a greater, not lesser, understanding of the structure and its performance.

As the engineering and construction industries continue to develop new materials and new and creative ways to use them, engineers will need to develop new rules-of-thumb, approximate methods and/or empirical designs for these materials and systems. In the past, engineers needed simple, practical methods because they did not have computers or an easily accessible wealth of information. Nowadays, however, engineers need

simple, practical methods to deal with the computers and an overwhelming amount of information.

It is also important to note that the impact of the personal computer (PC) on the design process goes far beyond that of engineering analysis and design software. Word processing, spreadsheets, office networks, data from the Internet and email have increased productivity and changed the way engineers work just as these technologies revolutionized the way almost all professional services do business.

## Historical Perspective

*The Design Process Before Computers Were Common.* Although analysis programs were available for the structural engineer to use on a mainframe computer in the 1960s, computer technology did not have a major impact on the majority of engineering offices until the advent of the PC. Before the PC, the engineer performed analysis and design "by hand," and the engineer and the architect hand-drafted the contract drawings. Information was exchanged in face-to-face meetings, telephone calls and via sketches. Proximity of the engineer to the architect was important for the speed of design production. But even with engineers working in the same office with architects (as is done in architectural-engineering firms), the pace of design production could not match that of today. Changes took at least the time to re-draft the documents and even longer for changes that required re-analysis by the engineer. The amount of work behind each change led to a more deliberative design process. These time and labor demands did not decrease (and even increased) for those projects using early applications of the mainframe computer for which the engineer had to purchase precious computer time.

For a project's schematic design, the structural engineer's deliverable was usually limited to the selection of structural materials and systems. The structural engineer sketched a typical bay of framing and worked closely with the architect to identify conditions where the typical bay of framing required adaptation to fit the architecture. The engineer used approximate techniques and/or judgment to

identify important structural parameters for the architect (such as the location of braced bays, shear walls or moment frames; depths of floor framing; and load criteria). The structural engineer would start drawing production during the design development phase of the project. By that time the architect had provided the engineer with plans, building elevations and some preliminary wall sections. The engineer would periodically get drawings from the architect throughout the design development and construction document phases as the architect added information. The engineer continued to lay out the framing modifying the "typical bay" to match the architecture and performed analysis and/or empirical design to prove out the framing. It was not uncommon to have a fair degree of "over-design" in the typical conditions that allowed the engineer to apply the same designs to other variants without re-analysis.

Young designers today may not appreciate the process and time involved in the design of structural members without the use of computer software. For a building with a structural frame, three major parts comprise the design process: gravity design of columns, gravity design of floor framing and the design of the lateral-load-resisting system. A typical "design-by-hand" process could be summarized as:

*Columns* — After locating columns in collaboration with the architect, the structural designer calculates column gravity loads for each column. Although not necessarily a precise method of computing loads, tributary areas are calculated at each floor for each column to determine gravity axial loads in the columns. The loads are tabulated for each column at each floor for each load type — dead, live and roof live. The cumulative load in each column is modified as allowed by building code live load reduction provisions. Gravity forces from the floor framing analysis, as well as forces from the lateral load analysis, are combined together in accordance with the particular design code. Member selection is generally arrived at by selecting a trial member size and then calculating all necessary design

checks. Alternate member sizes are selected until the designer is satisfied with the results of the design checks.

*Floor Framing* — For each floor member, the designer calculates tributary gravity loads. The designer then calculates shears and moments for each member. Forces from the lateral load analysis are added if the member forms part of the lateral-load-resisting system. Again, the forces are combined in accordance with the design code, and a trial member's strength and deflections are checked for code conformance.

*Lateral-Load-Resisting System* — The process includes calculating and distributing wind and seismic forces to the lateral-load-resisting frames. Of course, this process is iterative since the member sizes affect the relative stiffnesses of the frames and, thus, the distribution of forces among them. Member sizes must generate frames with sufficient lateral stiffness as well as conform to code strength checks when combined with gravity loads.

Consider the time needed for this process for each member in a large-scale building. As described above, the process requires iterations of calculations. Now, consider the additional iterations when the architecture and/or owner requirements are changing and developing during the design.

Before computers, the experience and aptitude of the structural designer had a tremendous impact on the time and quality of design. A good designer knew the design codes so well that many load combinations and design checks that would not affect the structure could be eliminated. Experience also came into play in evaluating the impact of a proposed change by the architect, and, if necessary, into defining the scope of any re-analysis and rechecking of code provisions for the areas affected by the change. For most projects, the degree of structural optimization relied on the experience and judgment of the designer.

Finally, consider the computational efforts needed for the above process to show compliance with modern codes. Earlier codes had simpler methods for developing loads, fewer

**TABLE 1.**  
**Wind Loads From the 1970 Boston Building Code**  
**(for Minimum Wind Pressures for Height & Area Locations)**

Height (ft)	P (lbs/ft <sup>2</sup> )		
	A	B	C
0 to < 25	20	20	20
25 to < 50	25	25	20
50 to < 100	30	25	20
100 to < 150	35	30	20
150 to < 200	45	30	20
200 to < 300	45	35	25
300 to < 400	45	40	30
400 to < 500	55	45	35
500 to < 600	55	50	40
600 to < 700	55	55	45
700 to < 800	65	60	50
800 to < 900	65	65	55
900 to < 1000	65	65	60
1000+	In accordance with sound engineering principles approved by the building official		

Note: From Ref. 2.

load combinations and, often, much simpler member stress checks. For example, comparisons between the 1970 Boston Building Code (BBC) and the provisions of the 2003 International Building Code (IBC), including the American Society of Civil Engineers — Minimum Design Loads for Buildings and Other Structures (ASCE 7-02), illustrate the changes in the procedures and changes in what calculations would be necessary.<sup>2,3</sup> These comparisons lend support to the argument that today's computer-aided design software is not only a means of achieving productivity, but is also a practical necessity to avoid computational errors given the context of structural design today that includes complex codes, complex designs and fast-track construction.

*Wind Loads — BBC 1970.* Minimum wind pressures for a building are prescribed in a simple table. Based on building location and height, the design pressure (distributed two-thirds windward and one-third leeward) for vertical building surfaces is explicitly listed.

The only wind load combination accounts for wind acting simultaneously on two perpendicular walls. In this case, a percentage (70 percent) of the design pressure shall be applied to each wall, with no further analysis required (see Table 1).

*Wind Loads — IBC 2003.* The IBC 2003 references ASCE 7-02 for wind load provisions. Calculations of design wind loads under these elaborate provisions include factors for basic wind speed (based on a 3-second gust), wind directionality, building importance, exposure, topography, gust effects, building enclosure, and internal and external pressure coefficients. The procedure to determine the code-prescribed wind pressure includes numerous tables, nomographs, figures and formulas. There are also multiple load cases that must be included to account for various wind load directions and load distributions. The code does provide simplified wind load provisions for regular buildings that are less than 60 feet tall, but still requires considering multiple fac-

$$p = qGC_p - q_i(GC_{pi}) \quad (\text{lb/ft}^2)(\text{N/m}^2) \quad (\text{Eq. 6-17})$$

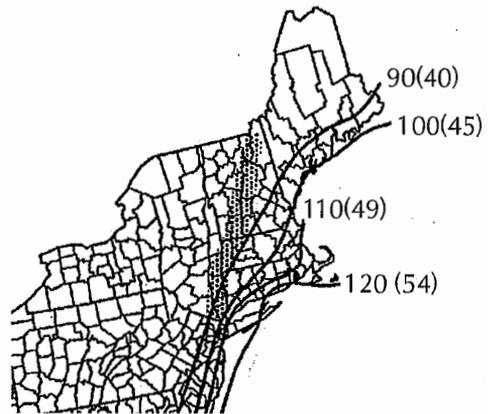
$$q_z = 0.00256 K_z K_{zt} K_d V^2 I \quad (\text{lb/ft}^2)$$

$$K_{zt} = (1 + K_1 K_2 K_3)^2 \quad K_2 = \left(1 - \frac{|x|}{\mu L_h}\right) \quad K_3 = e^{-\gamma z/L_h}$$

$$I_z = c(33/\bar{z})^{1/6}$$

$$G = 0.925 \left( \frac{(1+1.7g_o I_z Q)}{1+1.7g_v I_z} \right) \quad Q = \sqrt{\frac{1}{1+0.63 \left( \frac{B+h}{L_z} \right)^{0.63}}}$$

$$L_z = \ell(\bar{z}/33)^2$$



Wall Pressure Coefficients, $C_p$			
Surface	L/B	$C_p$	Use With
Windward Wall	All Values	0.8	$q_z$
	0-1	-0.5	
Leeward Wall	2	-0.3	$q_h$
	$\geq 4$	-0.2	
Side Wall	All Values	-0.7	$q_h$

Enclosure Classification	$GC_{pi}$
Open Buildings	0.00
Partially Enclosed Buildings	+0.55 -0.55
Enclosed Buildings	+0.18 -0.18

From Ref. 3

**FIGURE 1. ASCE 7-02 wind load formula examples.**

tors and load conditions that were not considered in previous codes (see Figure 1).

**Seismic Loads — BBC 1970.** Seismic loads reference the 1967 Uniform Building Code for earthquake loads and prescribe the use of Zone 2. The base shear is calculated using the formula,  $V = ZKCW$ . The factors ( $Z$ ,  $K$  and  $C$ ) determine the base shear as a percentage of the overall building mass ( $W$ ) by accounting for the zone location ( $Z$ ), the lateral force resisting system ( $K$ ) and the period of the building ( $C$ ). A simplified equivalent lateral force procedure distributes the base shear to each level of the building using the mass of each level. The code also includes a provision for horizontal torsional moments due to offsets between the center of mass and the center of rigidity.

**Seismic Loads — IBC 2003.** The IBC 2003 references ASCE 7-02 for seismic load provisions. The seismic loads are based on the maximum considered earthquake ground motion accelerations and response spectra. The procedure accounts for site classification, short and long periods, seismic design category, type of later-

al force resisting system and structural irregularities. The equivalent lateral force procedure is still used to determine the total base shear on the building and then distribute it vertically to each floor based on mass. The code also has numerous specifications for detailing and design requirements for building components and behavior such as drift,  $P$ -Delta effects, soil-structure interactions and accidental torsion due to offsets between the center of mass and the center of rigidity.

**Load Combinations — BBC 1970.** The code is based on working stress design and requires that the engineer consider the combined effects of lateral and vertical loads. The main gravity loads including dead, live and snow loads are considered as cumulative. There is an allowance to reduce live loads for members with large tributary areas such as columns and some girders. Lateral loads such as wind and seismic loads are not required to be considered simultaneously, but they are additive to the gravity loads. Since the lateral loads are transient, the code permits a one-third

increase in the allowable working stress of the structural materials. The load combinations are, therefore, simple enough to be done by hand. Using engineering judgment, the design engineer can determine the governing load combination in each direction and limit the load combinations to just a few cases including gravity alone, and combined gravity and maximum lateral load in each direction.

*Load Combinations — IBC 2003.* In modern codes, the design engineer can choose to design the structural members using the allowable stress design (ASD) method or the load and resistance factor design (LRFD) method. However, new codes require considering a greater number of combinations of various gravity and lateral loads. Load combinations for both ASD and LRFD methods include a number of gravity-only cases with different factors placed on each load case. When lateral loads are combined with the gravity loads, there can be hundreds of combinations due to various load factors and load directions. Generating all the load combinations required by code, or determining the controlling case for each member by inspection is nearly impossible without the use of a computer.

*Empirical Design & Approximate Analysis.* Empirical design was embedded into the first American building laws at the turn of the century and is still a part of the current American Concrete Institute and The Masonry Society (ACI-TMS) masonry code today. The New York Building Law of 1882 and the Boston Building Law of 1892 both provided a schedule for determining masonry wall thicknesses based on a system of building categories and on the building's height. These provisions, along with many other empirical building design rules, can be found in the *Pocketbook* by Kidder.<sup>4</sup> The *Pocketbook*, in its many editions, was the authority on building construction in America from 1885 to the early 1940s.<sup>5</sup>

There was a great building era in America from about 1885 to 1935.<sup>5</sup> During this period wrought iron and steel emerged as the primary building materials. Trusses, especially steel trusses in the latter half of the period, were used in every building possible. The method of analysis most designers used for trusses consisted of graphical solutions

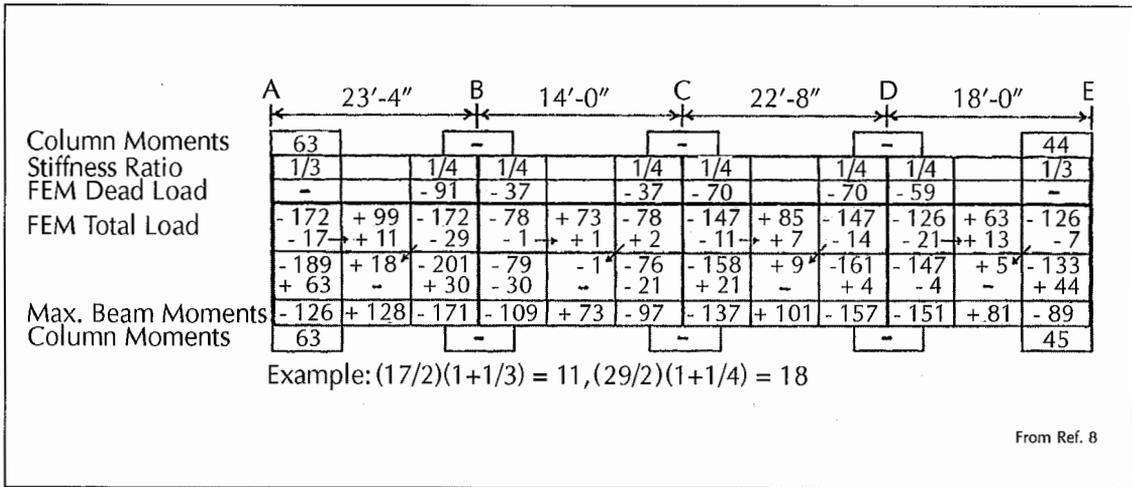
assuming pinned connections of members. The latter half of this period also saw the proliferation of high-rise buildings that spawned explicit analysis for the lateral bracing of buildings. Designers of the period developed practical analysis methods for lateral loads for braced frames, portal frames and rigid frames. Harry Schneider illustrated these methods in his 1930 publication, *Practical Wind Bracing*.<sup>6</sup> The portal method and the cantilever methods are the two most well known methods, and were used predominantly prior to the proliferation of computers. Accounting for variations on, and hybrids of, these two methods, Schneider identified four methods and summarized them as follows:<sup>6</sup>

*"The Cantilever Method —* The building acts as a cantilever, fixed at its base, and free to bend in a horizontal direction. The direct stresses in the columns are proportional to their distances from the center of gravity of the bent. The point of inflection of the beams is at mid-span. The vertical shear in the beams, which corresponds to the horizontal shear in an ordinary beam, increases from the outside of the bent to the center of gravity, but the increase is not uniform since the web of the cantilever is cut out between the columns.

*"The Portal Method —* The [axial] stress is taken by the end columns only, the direct stresses in the center columns being zero. At any horizontal plane the wind load is divided equally among all columns. The point of inflection of the beams is not always at mid-span but must be calculated from the beam moment, which is not always the same at both ends of the beam.

*"The Continuous Portal Method —* The [axial] stress in the columns is proportional to their distances from the center of gravity of the bent, the same as in cantilever method. At any horizontal plane the total wind is divided equally among all the columns, [just as] in the portal method. [As in the portal method,] the point of inflection of the beams is not always at mid-span.

*"The Smith Method —* The [axial] stress is taken by the end columns only, the same as in the portal method. At any horizontal



**FIGURE 2. Two-cycle moment distribution method.**

plane, the horizontal column shears in the center columns are equal to each other, and twice as much as either end column. The point of inflection of the beams is always at the mid-span."

Moment distribution, introduced by Hardy Cross in 1929 (and eventually refined in a 1932 ASCE Proceedings paper), provided a method for determining gravity moments in a rigid frame.<sup>7</sup> Designers found sufficient accuracy for ordinary building frames using what became known as the two-cycle method of moment distribution (see Figure 2).<sup>8</sup> (Many current designers who know of this method know of it through the PCA publication *Continuity in Concrete Building Frames*.<sup>8</sup>)

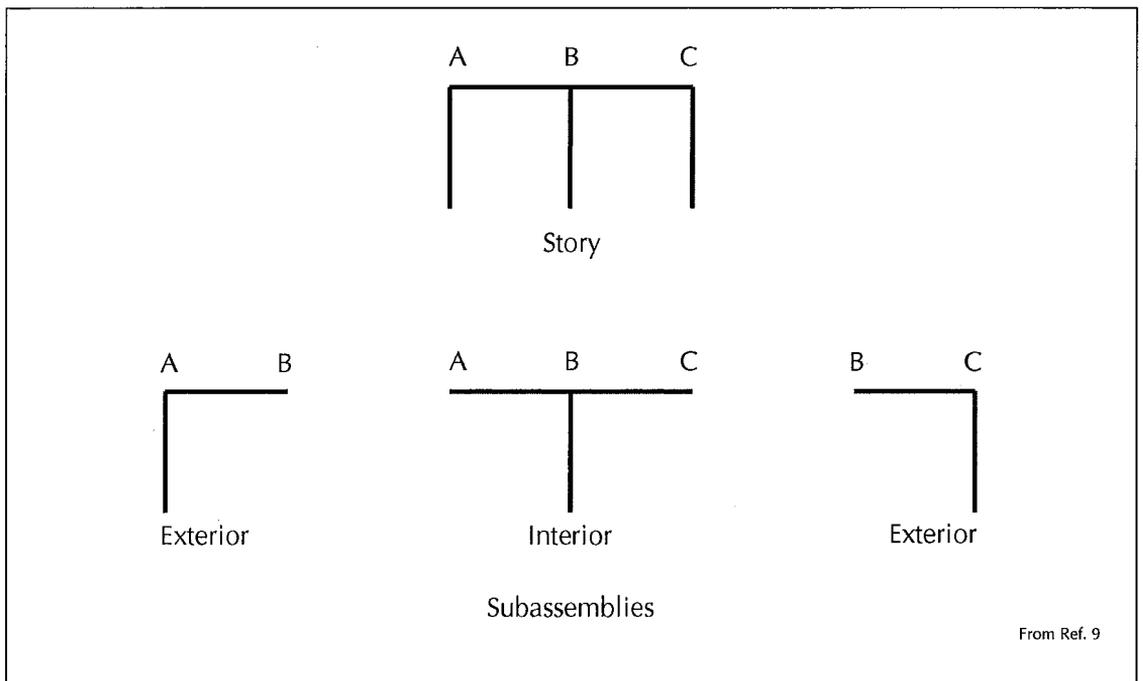
These approximate methods provide estimates of forces in the frames. In 1976, F. Cheong-Siat-Moy published a paper in the *AISC Engineering Journal* that provided a method for estimating the frame stiffness.<sup>9</sup> The paper uses the story drift index, which is the ratio of the relative sway of a story to its height, to designate the stiffness of a structure on a story-by-story basis. The paper proposes that the stiffness of a given story can be represented as the sum of the stiffnesses of its sub-assemblies, which consist of one column and the girders framing into that column (see Figure 3). The paper also provides guidelines to help increase the girders and/or the columns to meet particular stiffness require-

ments. By determining the frame stiffness based on the subassemblies the overall stiffness can be increased more efficiently than by increasing the girders only (which was traditionally the preferred method).

Other examples of approximate design methods are from the concrete industry as well and are still frequently used today. ACI 318 still includes provisions for estimating moments and shears in slabs and beams.<sup>10</sup> ACI provides coefficients for uniformly loaded beams and one-way slabs, and provides the direct design method coefficients for two-way flat slabs.

Other examples of empirical approximations include:

- Engineers traditionally estimated multi-story building periods in seconds as equal to one-tenth the number of stories. (This estimate found its way into seismic building codes and appeared as recently as the 1985 edition of the Uniform Building Code.)
- Required reinforced gravity concrete column gross cross-sectional area in square inches equals the factored axial load in kips divided by half of the concrete compressive strength in ksi.
- To determine the amount of tension reinforcement in a flexural member, ACI design guides promote the expression  $A_s = M_u/Ad$  as a simpler alternative to the rig-



From Ref. 9

**FIGURE 3. Frame stiffness subassemblies.**

orous expression derived from Whitney stress block theory.

- Required steel beam depth in inches equals a certain fraction of the span in feet (0.5 to 0.7) depending on the grade of steel and on whether the section is composite or not.
- At the time when steel predominantly had a 36 ksi yield strength and ASD was the prevailing design approach, the required section modulus in cubic inches of a continuously braced beam was the moment in kip-ft divided by two.

*Simplification & Common Simplifying Assumptions.* It was common for designers to make many assumptions for ordinary buildings that simplified analysis and design. The designer used experience and judgment to spot the situations when an assumption would be too inaccurate. Some common assumptions included:

- Column gravity axial loads determined by tributary area were sufficiently accurate even if the columns were part of a rigid frame.

- Lateral loads were distributed to lateral-load-resisting elements assuming a completely rigid or a completely flexible diaphragm.
- Three-dimensional frame buildings could be analyzed as a series of two-dimensional frames parallel to each of the two main orthogonal axes of the building.
- AISC permitted what they called a Type 2 frame connection, where the designer sized girders or beams as simple spans for gravity loads and designed web connections for the gravity shears. Angles on the top and bottom flanges connected to the column constituted moment connections designed only for wind moments.
- Lateral loads were neglected entirely for one- and two-story buildings built with concrete frames or with steel frames with masonry partitions and exterior walls.
- Thermal stresses for ordinary buildings were negligible, especially if designers followed commonly accepted rules-of-thumb for acceptable building plan dimensions without expansion joints.
- Slabs, terracotta tied arches, planks and

other floor systems were assumed to span in only one direction.

- All truss members were typically assumed to have pin-jointed member ends regardless of the degree of continuity of the chords or of the stiffness of the gusset plate connections.
- Shear deformations of flexural members were typically ignored in deflection calculations.

*The Impact of Computers.* Structural analysis computer programs were in use, at least in academia, since the late 1960s. Through the 1970s and early 1980s, computer use by practitioners was generally limited to the analysis of large and/or complex structures. Designers would develop a design using approximate analysis methods and preliminary design techniques. This preliminary structure was then analyzed in detail with the computer to obtain member end forces and deformations. The "computer" was generally a large-scale mainframe computer that the designer bought time on from an off-site source. A file of "input" described the geometry, member properties, material properties, boundary conditions and loads of the model. It was routine to check input files line by line before the computer "run" since the amount of the run time could be significant and the firm was usually buying the computer time at a premium. After receiving the "output" file, the designer would check the results for verification. Verification included checking the reactions and external forces for statics, interpreting the deformed shape and comparing results with the preliminary and approximate analysis. The designer then performed design checks on the members. If the designer deemed it necessary to change members' sizes, the designer's understanding of structural analysis determined if another computer run was necessary. Generally speaking, for the building designer, the computer programs of this era were much less a design tool than an analysis tool. Compared to today's software, they were tedious and awkward to use, and offered little in the way of graphical results. Although young, inexperienced engineers may have helped the designer with checking

input and output, it was necessary that the computer analysis be managed by an experienced designer or analyst to avoid the colossal waste of computer time and money.

During the 1980s and into the early 1990s, scaled-down versions of these mainframe analysis programs became available for use on the PC. Early PCs, by today's standards, had extreme limitations of memory and processor speed. However, engineering firms found them very cost effective, especially considering their additional use for word processing and spreadsheets. The analysis programs were still awkward to use since they still required input and output files. In addition, the early PC operating system, MS-DOS, was text-based. But computer time was now "free" (for the cost of the PC, software and training) and the input files were often text files that the designer could modify with text editors on the computer. Some software programs permitted the graphical display of information (such as displaced shapes and mode shapes).

By the late 1980s and early 1990s, the use of the computer for analysis was no longer limited to the most complex structures. PCs were getting faster, were less expensive and had more memory and computing power. There were still plenty of firms doing ordinary and small buildings without computer analysis, but firms that were using PCs for analysis were now using them for most structures as a productivity tool. Many firms were inventing ways to post-process the output files for convenient use with spreadsheets that did the design checks. With a PC on the desk of every designer, the role of a senior, experienced designer overseeing the use of computer analysis diminished in many firms since the "penalty" for computer model mistakes by inexperienced designers no longer amounted to the significant sums of money that were required by mainframe computer runs.

Through the 1990s, PCs continued to get faster with huge leaps in the amount of available memory, while also becoming less expensive. With the introduction of the graphical user interface provided by Microsoft Windows, designers now had powerful graphic tools to generate, display and check the computer models. At the same time, there

were rapid advancements in computer-aided design and drafting software. By 2000, with the Internet going mainstream, email and intra-office networks, there was a PC on close to every person's desk in every engineering firm. By then, even the most sophisticated general-purpose analysis software was configured for the PC and there was a proliferation of special-use design software for the structural engineer. Throughout the design process, the designer used various software packages in an ad hoc manner, mixing in hand calculations here and there. Perhaps one program was used for frame analysis, another for floor framing, another for checking columns and yet another for the analysis and/or design of foundations.

Development of a third generation of structural engineering software began in earnest in the late 1990s and its adoption has recently become prevalent. This generation integrates analysis and design checks into the same model. In some instances, the designer does not even need to input preliminary sizes since some of the software has design and optimization routines for member selection. Long input and output files are no longer used. The designer builds the model interactively with the software, visualizing the model in three dimensions as it is built. The designer usually has many options for viewing the output, including member-by-member reports, color-coded member stress displays, animated mode shapes and many more. Software is available that allows the designer to model all of the structural systems integrating the analysis and design of floor systems, columns, lateral load systems and foundations. Structural engineering firms see huge productivity gains with such software. It is now practical to provide complete framing plans for the entire building during schematic design and to explore alternate designs without severely impacting the design schedule. Value engineering ideas are tested and implemented late in the design phase or even during construction.

## Current Use

The current capability of commercial software to assist the engineer who is analyzing structures is impressive. There are many general-

purpose structural analysis programs from which to choose. The most common are comprehensive finite-element programs that analyze two-dimensional and three-dimensional truss, frame and plate structures under static and dynamic loads. The analysis capability goes well beyond that needed for most ordinary building structures. They include advanced non-linear capabilities and many specialty elements that allow the analyst easy creation of any structure imaginable, however complex.

Market pressures on fees for building design are compelling building designers to take full advantage of the productivity gains offered by the automation of today's building design software. The capabilities of this software include automation of framing layout, generation of loads and code-specific load combinations, member selection and optimization, embedded checking for conformance with material design specifications and generation of framing plans.

*A Review of Commercial Software for the Design of Building Structures.* The January 2005 issue of *Modern Steel Construction* listed 81 software products for the design of structural steel alone.<sup>11</sup> Many are for special purposes such as connection design, design of specialty shapes, vibration serviceability checks, etc. The focus here is on software products intended by their vendors to be comprehensive tools for the design of ordinary buildings (with an emphasis on designer productivity). To provide the reader with a reasonable sense of current capabilities, design products from four vendors whose products are in widespread use throughout the United States are summarized. Capabilities listed for each software package are not exhaustive but rather are selectively listed to convey the complexity and breadth of the current software available to the design profession.

*Computers & Structures, Inc. (CSI).* Founded in 1975, the development of CSI software spans three decades and began as a result of research at the University of California at Berkeley in the late 1960s. CSI is recognized as a leading producer of software tools for the analysis and design of civil structures. CSI produces multiple software packages tailored

to specific types of structures. SAP2000 — intended for bridges, dams, stadiums, industrial structures and buildings — was introduced over 30 years ago and features a three-dimensional object-based graphical modeling environment. SAP2000 includes a variety of analysis and design features including second order and modal analyses, damper and base isolation, and segmental construction sequencing. ETABS — developed for multi-story building structures — provides an integrated building analysis and design environment with a three-dimensional object-based graphical modeling environment. ETABS gives the engineer the ability to model and design moment-resisting frames, braced frames, staggered trusses, rigid and flexible floors, and sloped framing using steel, concrete, composite or steel joist floor systems. SAFE is a special-purpose program for the analysis and design of concrete flat plates and concrete bearing foundation systems, which can also be integrated with ETABS. CSI Detailer can be integrated with the SAFE program to generate comprehensive details of slabs, beams, mats and footings for use in drafting programs.

*RAM International (RAM).* RAM has been a leader in the development of software solutions that benefit structural engineers, detailers and fabricators since 1988. Their products are designed to aid productivity in the demanding and competitive design market. RAM produces several software packages, each customized for specific applications. RAM Structural System (RAM SS) is a fully integrated suite of building design and analysis software for gravity framing, lateral systems and foundations (including piles). RAM SS is also capable of producing computer-aided design (CAD) drawings for frame elevations, beam and column schedules, floor framing plans and foundation plans. RAM Advanse is a general-purpose, frame-based three-dimensional analysis and design software package capable of designing wood, steel, cold-formed steel and concrete members. RAM Connection is a steel connection design and optimization tool that can run independent connection design checks or run as an integrated component of both RAM SS

and RAM Advanse. RAM Concept is a special-purpose finite-element program for reinforced or post-tensioned concrete slab and mat design that is also capable of integrating with RAM SS. RAM CAD Studio works as a component of AutoCAD to help create documents that are linked with models from the RAM SS. RAM Perform is a non-linear analysis package capable of performance-based seismic design and progressive collapse modeling of buildings and other structures.

*Research Engineers International (REI).* Founded in 1981, REI produces several software packages for specialized applications, but its flagship program is STAAD-Pro 2004 (STAAD). STAAD is an object-based three-dimensional design and analysis tool capable of integrating multiple materials like steel, concrete, timber, aluminum and cold-formed steel into one structural model. STAAD can analyze buildings and bridges using a variety of building codes and it can perform linear or non-linear analyses on the structures. Advanced automatic load generators facilitate easily modeling lateral and gravity loads in complex models. REI integrated the popular steel connection design software package, DESCON, into the 2004 release of STAAD. This component of STAAD produces calculations and design shop drawings for steel connections based on loads generated in the structural model. REI also produces specialized software packages for foundation design, concrete connections and mat foundations.

*Rapid Interactive Structural Analysis (RISA) Technologies.* RISA Technologies has been an established leader in structural analysis and design software since 1987. RISA produces numerous specialized software packages. Its primary software for the building industry is the RISA Building System, which is composed of RISA-3D, RISA-Floor, RISA-Base and RISA-Foot. RISA-3D is a general analysis package with an object-based three-dimensional graphical interface capable of gravity and lateral load designs for a variety of building materials. RISA-Floor is a design tool that integrates directly with RISA-3D to design floor system gravity framing in buildings. RISABase helps the engineer design steel base plates and anchor rods for steel columns.

RISA-Foot designs and analyzes spread footings for various load conditions. Other RISA products include RISA-Tower for steel truss tower design, RISA-Masonry for masonry walls, columns and beams, and RISA-Section for calculating section properties of custom members.

*A Review of Commercial Detailing Software for Buildings.* For over 20 years, the steel detailing industry has utilized computers and detailing software programs to increase productivity. During the 1990s, the industry evolved and adopted an approach utilizing three-dimensional models of buildings to manage design information. This three-dimensional information management system helped streamline the detailing process and became indispensable to the construction community. The software programs create a level of efficiency that was not possible before the advent of computers. Project documents that used to take weeks to produce are now being created in a matter of days.

One of the leading steel detailing software packages is SDS/2 by Design Data. Design Data provides multiple products that automate detail creation, control inventory and estimate materials, as well as produce shop fabrication drawings. The connection design software SDS/2 designs connections according to AISC specifications and also produces erection drawings, piece details and complete shop drawings automatically. The software can also track fabrication and erection within the model to better manage resources on large design jobs.

*Checking Computer-Aided Designs.* Concurrent with software improvements, many experienced engineers who were designing structures in the 1970s and 1980s have developed a concern that the software tools are in the hands of engineers who lack the understanding of the behavior of structures and the methods used by the software. The civil engineering profession has been concerned about the misuse of computer software since the early application of commercial software. Those concerned by this rapidly developing technology have written papers citing case studies of improper use and highlighting the dangers to the profession. The 1991 *ASCE Structures*

*Congress Proceedings, "Approximate Methods and Verification Procedures of Structural Analysis and Design,"* and papers by Bell and Liepins, and Emkin, are examples.<sup>12-14</sup> The ASCE Technical Councils on Forensic Engineering, Task Committee on Avoiding Failures Caused by Misuse of Civil Engineering Software prepared a monograph entitled "Guidelines for Avoiding Engineering Failures Due to Computer Misuse."<sup>15</sup>

As cited by Bell and Liepins in 1997, in order to obtain meaningful and accurate results from analysis by computer, the analyst must observe, as a minimum, the following steps:<sup>13</sup>

1. Recognize the important structural actions and include them in the model.
2. Understand the performance of the elements used in the model.
3. Check the input.
4. Check the goodness of the solution obtained.
5. Interpret the computed output.
6. Validate the computed results.

Although the concerns and suggestions cited above are still appropriate today, if not more so, they are focused primarily on the analysis of structures with general-purpose analysis software. The recent, rapid advancements in the automation and integration of analysis, design and drafting in special-purpose building design software has generated a need for engineers to re-examine how to ensure the proper and responsible use of such software.

*Guidelines for Quality Assurance & Checking.* The six steps put forth by Bell and Liepins are a good place to start. However, these steps can be expanded to address the integrated design capabilities of current building structure design software. The following are suggested guidelines for quality assurance and for the checking of computer-generated designs. The six steps are expanded to include a seventh that relates to quality design. (In addition, commentary on each step highlights the issues pertinent to today's design software.)

*Step 1. Recognize the Important Structural Actions & Include Them in the Model.* Software

today still requires that the designer idealize the real structure and generate a mathematical model. Designers must understand what structural actions are important to the particular structure given its materials and geometry. Some examples include:

- Many, if not most, software packages incorporate rigid floor diaphragms in their analysis, at least as an option. The designer must decide if this approach is appropriate.
- Are the results sensitive to support flexibility? The source of flexibility might be the soil interface or portions of the foundation outside the model.
- Is the building's lateral load path, from the exterior wall down to the foundation, clearly conceived?
- Are the results sensitive to joint flexibility? In other words, are completely pinned or completely fixed joints appropriate?
- Are important building or element eccentricities appropriately accounted for?
- Is *P*-Delta important and properly accounted for?
- Are thermal, rain or other loads relevant to the design? Recent building codes require explicit design for rain ponding loads. Some jurisdictions require design for volcanic ash fallout.
- Is shrinkage and creep important to the performance of the structure?
- Are there unbalanced earth pressures on the building?
- Do building appurtenances such as stacks, jib cranes, rooftop equipment and flagpoles exert significant loads that should be considered in the model?
- Is the sense of the applied loads correct? (For example, are roof uplift loads acting upward?)
- Does the construction sequence need to be considered in the application of loads in the model?

It is easy for young designers to overlook some of these judgment calls. With the current graphic capabilities incorporating three-dimensional views with extruded, three-dimensional structural shapes, the models can

look very "real." However, the computation and design is still based on a mathematical model that approximates the real structure. Fortunately, as designers, it is usually not necessary to model the conditions precisely. Designers can decide to be conservative if the economical impact is minimal. Designers can design for upper and lower bounds for uncertain conditions or for those conditions critical to the structure.

*Step 2. Understand the Performance of the Elements Used in the Analytical Model & Know What Design Checks Are Performed & How They Are Executed.* Although most software programs have manuals, there are variations in the degree to which they document element performance and the specifics of design checks. Even if the manual states that elements are checked per a particular design specification (such as AISC LRFD, ACI 318), the manuals are silent on a lot of decisions that a designer makes in applying a design specification. Designers should thoroughly understand the design checks performed by the software and the design assumptions coded into the software as well as those that the designer has the latitude to set in the software. Some examples are:

- Understand the software's force sign convention.
- What are the assumed brace point locations?
- How is *P*-Delta accounted for? What loads are used for the *P*?
- How is the shear checked when slabs and drop beams frame into columns?
- How are concrete T-beam properties developed?
- How are short- and long-term concrete deflections calculated? Do the calculations compute cracked section properties and how are they computed?
- Are tension-only braces correctly represented in the model?
- Are deflections local to the member, or do they take into account the deflections of supporting members? (This consideration is particularly important for cantilever members.)
- Are cracked concrete member properties

considered in the characterization of element stiffnesses? (For example, a cracked shear wall will be significantly less stiff than an uncracked one.)

- How are column splices considered in the model?
- Are rigid offsets or other devices utilized to account for frame joint stiffness?
- How does the model address non-prismatic members and members with penetrations or notches?
- Are member forces computed at nodes or at member faces? Does the model allow for setting options in this regard?
- If applicable, how are base plates and anchor rods analyzed and designed?
- Are beam-column joints designed explicitly? There are extensive code provisions that apply to these, especially where seismic design is required.
- Does the model account for induced moments in singly symmetric or non-symmetric sections (for example, single angle or single tee diagonal truss members)?

*Step 3. Check the Input & the Input Generated by the Software.* Traditionally, input for analysis software could be summarized by these categories: nodal geometry, member incidences and end releases, member properties, material properties, support conditions and loads. It was common practice to print the input file containing these data and check it as part of the quality assurance process. Today's software adds design criteria and design assumptions to the categories of input. Software now has myriad menus the designer needs to open and select options from. Most have defaults that the designer can set and store, and, thus, the designer need not address each and every one of them each time they use the software. However, the designer needs to develop a way to assure that the input selections are appropriate for the particular project. Most software programs today have powerful graphic capabilities that display model information in a three-dimensional view. This capability should be used to review and check the input. Some ideas for checking input are:

- The model's physical properties: general geometry and member organization; member end releases, offsets, rigid end-zones, and member connectivity/connections (i.e., how are crossing members handled?); member sizes, material properties and orientations; and a review of auto-generated meshes of plate elements.
- Boundary conditions: supports, including support conditions — pinned, fixed, springs. Are there any special support conditions warranted by skewed members?
- Loads: Check load input tables, menus, and/or spreadsheets. Understand how the software defines and uses load types (dead loads, live loads, seismic mass, etc.) View load maps on plan views. View concentrated and nodal loads on the model. Check the results of auto-generated loads. Compare total self-weight, total wind shear and total seismic shear with approximate estimates by hand. On a floor-by-floor basis, or other rational categories, compare the total live load and/or total superimposed loads. Check scale factors for seismic design spectra. Check that the software will reverse sense of "plus-minus" loads such as wind or earthquake.
- Check that the software uses appropriate load combinations. Do so by penetrating the software to view the actual combinations and not just checking that the appropriate code or specification is selected. Review if any additional load combinations are required by the applicable material design standards (for example, for reinforced concrete, the Massachusetts building code requires the worst combination from its Chapter 16 combinations and those of the ACI 318 combinations). Review if custom load combinations are generated for unique conditions (like Massachusetts' exceptions for dead load factors, etc.).
- Global settings: units. This selection may be a global setting or it may vary from one dialogue box to another. Code checking criteria: LRFD versus ASD, U.S. versus British standards, etc. Live load reduction code and related parameters.

- Design constraints and design criteria settings. These settings are often hidden from the “screen side” of the software. Depending on the software, there can be many different settings and defaults spread over many different dialogue boxes. An incorrect or inconsistent setting can have a significant impact on the software’s output. A few illustrative examples include: composite or non-composite construction; shored or unshored construction; deflection limitations, camber limitations; shear stud lengths and diameters; concrete material strengths; maximum and minimum reinforced concrete reinforcement ratios for different elements; the extent to which slab systems brace tops of beams against lateral torsional buckling; and design-check settings (such as whether gravity loads should be considered or not in the calculation of the shear strength of a reinforced concrete shear wall).
- Check for coordination with the architect and other disciplines for: openings, stair loads, exterior wall loads, and suspended and floor-supported equipment loads.

*Step 4. Check the Goodness of the Solution.* Whether using the software for complex analysis or for the analysis and design of less complicated structures, the results and output should be inspected for software error messages and warnings. Take the time to understand any messages. It may turn out that certain warnings do not impact results, but this must not be presumed. Chase down each and every one of them and eliminate them unless there is great certainty that they do not impact the results.

*Step 5. Interpret the Computed Output & the Design Check Reports.* The design output may require interpretation and/or further calculations to arrive at meaningful results. Many times, with the new generation of building design tools, this step is simply understanding and reviewing software messages for members that do not meet design checks, or viewing color coding of members that represent demand-to-capacity ratios. However, stress output for plate elements may need more

work and interpretation to understand which stresses are being reported and which ones require a meaningful comparison to code-allowable stresses. Some considerations would be:

- Are extreme fiber stresses being reported or average stresses?
- Do orthogonal stresses need to be combined to get principal stresses?
- How do plate elements compute and report out-of plane shears?
- Review deflection reports: Are corner or center of mass drifts reported?

*Step 6. Validate the Computed Results.* The results must be assessed for validity and for any signs of unexpected response of the structure and unexpected design results. Unusual or unexpected results should be thoroughly explored until the issue is understood or the error causing the behavior is found. Some suggestions and examples for validating results are:

- Review reactions: Review locations with zero reactions and review if these represent an error or not. Review reactions for individual load cases. Do the relative magnitudes of reactions for the individual load cases make sense for the various support locations? Review individual support locations. Do the magnitudes for various load cases make sense for a given support location? Are the reactions for a given load case in equilibrium with the applied loads? Are there high shears where they are expected? Are there high overturning forces where they are expected?
- Review the deflected shapes: Do the deflected shapes make sense for the individual load cases and the intended model? Do the mode shapes make sense for the intended model? Do the periods make sense? How does the fundamental period for a building structure match code approximations? Do the deformations compare well with estimates by hand or with experience with similar structures? Look at the deflected shapes in both plan and elevation views as well as

in three-dimensional views. Review the center of mass and center of rigidity. If the software reports the center of mass and the center of rigidity, do they make sense? Do they seem rational given the deflected shapes?

- Review story shears and individual frame shears: Do the story shears relative to one another make sense? Do the story shears sum to expected base shear estimates? Review the impact of diagonal members that span more than one story. Review the frame shear (or wall, or brace) distribution at each floor.
- Spot check member forces: Look for members with zero forces and review if these are the result of an error or not. Review flexural members to verify that shears and moments act in the axes expected. For representative members, do the member forces make sense for the various load cases?
- Review member design reports: Review critical and representative member detailed design reports. Review if the design accounts for special seismic requirements such as the out-of-plane bracing of brace joints, amplified loads for member connections or for member design, etc.

#### *Step 7. Review the Quality of the Design.*

Review the design for general quality. The current generation of software does not guide users with respect to the following considerations. Assess the quality of the design with respect to these considerations:

- Is the design rational? Are the member sizes reasonable and do they fit into norms for similar buildings? If not, understand what is special about this project.
- Is the design appropriately redundant and robust?
- Did the design appropriately address serviceability (for example, ponding, vibration limits)?
- Do the deflection limits, including short- and long-term dead loads and live loads, reflect the architectural and mechanical details?
- Does the design address durability appropriately?

- Does the design address penetrations of walls, beam, etc., for openings for other trades?
- Does the design maximize regularity, repetition and simplicity?
- Are the structural costs within budget and appropriate for the building type and project requirements?
- Does the design of the foundations size the foundations using service loads and allowable bearing pressures? Does the design of concrete foundation members factor the loads for LRFD design?
- Does the design address structural checks not addressed by the software? Examples often include: diaphragm strengths and stiffness and the effects of large openings on same; local wind loads on columns; torsional effect from eccentrically placed exterior loads; load path from the diaphragm to the lateral-load-resisting members (for example, is the load path viable and are the in-plane design forces accounted for?); and combinations of wind uplift and shears on deck diaphragms.

#### *Modeling & Design Pitfalls to Look Out For.*

Despite recent advances in the capabilities of software packages, there remains the need for care to keep modeling, analysis and design from deviating from the reality of the built structure. Potentially serious problems can ensue from not properly conceiving or interpreting design models. The following are but a few examples of pitfalls that, for now, can only be avoided by the exercise of judgment by an experienced designer:

- Rigid elements introduced to model zones that are a lot stiffer than the bulk of the model can introduce numerical instabilities. For example, a designer often introduces a rigid member to model the connection between a beam element and a line element for, say, a concrete wall. The assignment of the stiffness must take into consideration the potential for numerical instability arising from some entries in a stiffness matrix being much larger than other entries. These large differences in

- magnitude will introduce numerical errors in the decomposition of the stiffness matrix. The potential for this problem will vary with the complexity of the structure, the software code and the precision of the computer hardware. Sometimes, analysis results that are orders of magnitude beyond the expected can be a sign of a numerical instability. Other times, numerical instabilities are subtly manifested and might go undetected.
- Assignment of material properties must take into account construction practices. A concrete frame analysis that assigns high-strength concrete to the column and beam elements might miss the fact that, unless otherwise specified, the concrete strengths of the beams will be the same as that of the floor system.
  - Current floor system design software does not handle slab depressions well. Large slab depressions can have the effect of invalidating otherwise valid rigid diaphragm modeling assumptions and effective width assumptions for T-beams and composite beams.
  - Software packages that model rigid diaphragms, unless otherwise directed, will usually “lock” the deformations of the members within the diaphragm. Members within the diaphragm are thus modeled as having no axial deformation or axial forces. There are certain members (such as collector members) that deliver axial forces to a braced frame and beam elements in a chevron brace where this modeling assumption is unconservative.
  - Software packages that model continuous floor systems (such as reinforced concrete slabs and beams, like ETABS), with shell or plate finite elements for the slabs and line elements for the beams require a thorough understanding of how the finite-element mesh interacts with the beam elements for the transmission of out-of-plane and in-plane forces.
  - Design of composite systems with hanging loads should account for the construction sequence: Do the hanging loads occur before or after steel-concrete composite action?

- Uplift in beams is often overlooked in programs that have settings that continuously brace the top flange of a beam. Net uplift forces will produce compression in bottom flanges that require attention by the designer perhaps with a separate “fake” loading case with the net uplift load and the deck-braces-flange setting turned off.
- Seemingly small design changes can have a dramatic impact on the behavior of a building. A rectangular building with two short sides that counts on a below-grade foundation wall to transfer lateral loads to the ground could see its behavior dramatically altered if a significant portion of one or both of the short foundation walls becomes an areaway.
- $P$ - $\Delta$  calculations should use loads that are consistent with the material code second order moment amplification provisions.
- Can load combinations be customized? Certain software packages allow customization of load combinations that allow the designer to use the 1.3 dead load factor in the current edition of the Massachusetts building code. When customized load combinations are not possible, factoring up the dead loads might be necessary. The designer must keep track of these increased dead loads for their impact on foundations, deflection checks, etc.

*Verification of Commercial Software.* An issue facing the structural design profession is the verification of commercial design software. The steps outlined above for quality assurance and checking help to verify the results for a particular design. For most common building design projects, these steps, combined with sound engineering judgment and experience, are adequate to uncover deficiencies or errors in the software that may surface due to that project’s specific parameters. However, designers must still place considerable reliance on the software doing what it claims to do without error. Designers are operating under the assumption that any errors of significance to the design will be detected during their review and validation of the results.

Thus, designers become comfortable with particular software over time as it is used, and the verification of software is limited to the validation of results on a project-by-project basis.

*Transparency Issues.* Generally speaking, unless the software is open source, its code is not available to the public. Even if it were, most practitioners do not have the programming experience and skill to interpret the code in order to verify its operation and application. What designers know about the operations and function of software is limited to what is published with the software and what they can infer from the available output reports. Designers should look for software that provides detailed explanations of operations and functions as well as output reports that provide step-by-step member capacity development and code check results and not just a final stress or demand/capacity ratio.

*Responsibilities of Vendors & Users.* There are no current standards or codified requirements for structural design software. Organizations such as the Software Engineering Institute (SEI), the Centre for Advanced Software Engineering (CASE) and the National Council of Structural Engineers Association (NCSEA) should partner with leading structural design software companies to explore ideas about guidelines and/or standards for qualifying and verifying software claims on operation and function. Perhaps the engineering industry can develop a voluntary certification program where software can receive certification after thorough review by both design experts and computer programmers. In addition, there should be a program, analogous to the American Institute of Steel Construction (AISC) certification for fabricators, where software companies are certified as maintaining good practice with respect to quality assurance and documentation.

*Documentation of Computer-Aided Design.* With increasing reliance on design software, design documentation is another issue for designers. Construction drawings and specifications document the final design. However, the calculations document the design adequacy. Policies about design documentation and the preservation of the design calculations vary among structural design firms. Some

archive the calculations with the drawings and specifications; others destroy the calculations after a specified period of time; and some destroy the calculations as soon as the building receives occupancy. Each of the various policies has its pros and cons, but many firms would agree that the design calculations, or other design adequacy documentation, must be kept at least through the firm's checking process and quality assurance program.

As engineers rely more and more on integrated analysis and design (and produce fewer and fewer hand calculations), engineers must decide how to document the design checks using input reports, graphic output and design check reports from the software. Therefore, the design documentation becomes tailored, in part, by the specific piece of software. Each firm should have a quality management program that includes guidelines on how to document the design adequacy when using design software. If a firm believes it is important to archive calculations, then decisions must be made about storing them in paper or electronic form. If storing in electronic form, the fact that software goes through version evolution and new versions are not always backward compatible must be taken into account. Perhaps it is best to keep text files documenting the input, results and design adequacy.

The following are general suggestions for computer design documentation:

- Note the name and version number of the software.
- List the software default settings for the project (including the design defaults as well as model and analysis defaults).
- Document the model (including geometry, member and material properties, and support conditions).
- Note mass, loads and load combinations.
- List the design codes and software design settings used.
- Record the analytical results (such as reactions, story shears, story deformations, etc.).
- Record member design checks, at least for the controlling load cases.
- Keep records of the result verification process.

Keeping a log of the evolution of the model used is another good idea for documentation. The model log can record the changes, and the reasons for the changes, to the model throughout the design process.

*Impact on Staff & Staff Training.* Management of today's design firms must address training issues in light of the automated nature of the software. For example, young designers do not become familiar with member design specifications by frequent use as was the case just a decade ago. The skill sets needed to design with current software are much different than the skill sets needed when design was done by hand calculations. Designs are now accomplished using automated software without the user necessarily being intimately familiar with the design standards and, perhaps more importantly, without the user being familiar with the fundamental philosophies embedded in the design standards. When the design checks were performed by hand, practitioners read the standards, codes and user commentaries before performing the calculations. In addition, industry material organizations (such as ACI, PCI and AISC) provided design guidelines and sample solutions to aid and teach the designer. With today's automated design checks, young engineers need explicit training on the design codes and standards since they may not become familiar with them through routinely performed hand calculations.

## Future Trends

The leading software vendors will continue to advance their structural design software. Most have, or are developing, a system or suite of software so that the designer can become familiar with one vendor's tools and use them for various structural materials and structural systems. The vision of the vendors is to have interoperability within their suite of software. For example, the designer will model the entire building in a modeling module, and use other software modules from the vendor to design foundations, frames, shear walls, flat plates, connections, base plates, etc., without further input of loads or structural geometry. In addition, the vendors will move to integrate the drawing production process with their

suite of software. The leading vendors already have tools, with varying degrees of sophistication, for exporting data from their software to CAD systems.

Parallel with the development of integrated analysis and design software was the development of detailing and fabrication software for the structural steel industry. Detailers can now build their own three-dimensional models from the design drawings and use specialty software to prepare detailed shop drawings and, in some instances, convey computer files directly to the fabrication equipment. AISC is promoting electronic data interchange (EDI) technology to allow the exchange of data from the design software to the fabrication software. This interchange is only one piece of a more comprehensive concept of interoperability in the construction process.

According to the National Institute of Standards and Technology (NIST), interoperability relates to both the exchange and management of electronic information.<sup>16</sup> Individuals and systems are able to identify and access information seamlessly, as well as comprehend and integrate information across multiple software systems.<sup>16</sup> The manufacturing sector, as well as financial centers and medical centers, have created interoperability standards and realized efficiencies in operations and service. The construction industry has not yet developed similar standards. Reasons for the construction industry lagging behind may include:

- relative to the manufacturing and financial sectors, the construction industry is made up of many more and smaller entities without resources to affect the industry; and,
- relationships between owners, designers and contractors inhibit communication and teamwork, resulting in fragmentation of the process.

NIST funded a study entitled "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry."<sup>17</sup> The study quantified the cost of inefficient interoperability in commercial, institutional and industrial facilities in the year 2002. Results showed that inef-

efficient interoperability cost the industry \$15.8 billion in 2002 with increased new construction costs of about \$6 per square foot.<sup>17</sup>

The use of computers for structural engineering will rapidly go beyond integrating analysis and design. Because of the potential productivity gains implied by the NIST estimate of \$15.8 billion of waste, the industry will move towards interoperability, if not by national standards, then by the dominance of commercial leaders. De facto standards have been set by the dominance of commercial leaders (such as those set by Autodesk with AutoCAD and the .dwg CAD file standard). Interoperability will come to the construction industry through highly detailed information databases for entire buildings that contain the information for all the materials and systems that comprise the building. These relational databases are called building information modeling (BIM). Autodesk and Bentley, as well as other companies, have already released such products incorporating BIM.

BIM uses the concept of object-oriented three-dimensional modeling that is already being employed by the aerospace and automobile industries. In other words, the user works with intelligent components (such as walls, doors and windows, columns, footings, ducts, etc.) to create a virtual building from which plans, elevations, sections and details are extracted in the form of drawings. The drawings look like those developed from traditional two-dimensional CAD, but they are in fact just reports from the database. Building data such as material quantities can also be extracted in the form of schedules. The object-oriented modeling allows for the rapid construction of the model.

The leading BIM software solutions also allow bidirectional editing. Changes to the extracted views or schedules affect the model as well as all other views, schedules and information throughout the model. All information is interrelated at all times in one database system. The fact that the construction documents are reports from the database ensures that they are well coordinated at least with respect to the data in the model.

All disciplines of the design team, as well as the contractor, can collaborate on the develop-

ment of the database and the model. With all the data from all the parties entered into one database, the information on the project is well coordinated. Programming embedded in the software identifies interferences or conflicts between the trades and disciplines. But BIM moves beyond just the physical representation of the building and the transformation of paper documents into electronic form. The database contains information that can assist cost estimates, scheduling, energy analysis, fabrication and maintenance.

BIM database solutions, such as Bentley Architecture and Revit (from Autodesk), are already developing relationships with structural analysis and design software to achieve interoperability with them. Similar developments are underway for mechanical engineers as well. The vision is that the model developed in BIM will include all pertinent engineering data. Data then flows from BIM to the analysis and design software with results coming back to update BIM. Proponents of the BIM concept see this new process as a means to reduce risk from the now-fragmented process that relies on the architect (or design professional leading the project) to coordinate and integrate work from several separate entities.

The value of these first-generation BIM solutions will be the coordination of data contributed from fragmented sources (architects and consultants) by providing interference checks, allowing clearer communication between participating parties and producing drawings and documents from the same database or interrelated databases. However, just as structural design software has become more intelligent and comprehensive, so too will BIM become more capable — containing or associating with analytical tools and other software, and, if not automating the design process, certainly automating the design documentation process.

No one knows the ultimate impact of BIM software on the professional services market. Outsourcing of engineering man-hours has been in the press lately. The premise for outsourcing is that overseas labor is becoming well trained and is in a position to provide engineering hours for considerably less

money. On the one hand, as design software reduces man-hours, the financial gains from outsourcing diminish. On the other hand, automated design software homogenizes the product, enabling overseas manpower to produce exactly what is done here. The ability to meet and interface with the rest of the design team to exchange and integrate design ideas becomes the major value of using a local team. What will BIM do to this equation? Will this technology make it easier for overseas engineers to contribute locally?

## Conclusion

The first and second generations of structural software led to modest productivity gains as these analysis tools had little impact on the overall design process, especially with respect to how the structural engineer interacted with the rest of the design team. The third generation of structural software in use now, by integrating the analysis and design of building-whole systems, has had a major impact on the design process. It is debatable whether structural engineers have yet fully adapted best-practice procedures for software that can almost fully automate the design and analysis of a building. And as structural software moves towards its fourth generation and is tied to BIM software that allows the automatic generation of drawings and reports, engineers will have to redefine their roles and responsibilities for what well may be a paradigm shift in the industry.

NOTE — *This article was originally presented to the 2005 Lecture Series sponsored by the Structural Group of the Boston Society of Civil Engineers Section/ASCE.*



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