Computers and Steel Design

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INTRODUCTION

Computer aided structural engineering is no longer an idea that has to be sold. In steel structures it is widely used from start to finish—from planning to erection. Nevertheless, it's still at a critical stage. Further development is essential and the present incidence of misuse is disturbing.

Inevitably, use of the medium will continue to grow and its scope expand. Promotion of the process is one of the two themes of this paper. The other is the need to minimize its misuse.

AISC SPECIFICATIONS

For reasons that will become clear, it is appropriate to take two milestone editions of the AISC Specification as points of reference. The first is the 1963 Edition for which Ted Higgins deserves great credit.[1] The second is the 1986 LRFD Specification developed under the leadership of Bill Milek and Gerry Haaijer.[2]

The 1963 Specification introduced to general American practice findings from many years of research: the effective length concept, amplification factors, semi-tension field behavior, plastic design, etc. But although it was published when computers were coming into use, philosophically it was rooted in pre-computer practice. This is evident in a 1954 note of George Winter's proposing adoption of the effective length concept. He said: "It is the purpose of the present effort to suggest such relatively simple improvements to present design practice which would result in minimum changes to customary procedures and yet would lead to sizeable economy where present procedures are over-conservative, and to assured safety where present methods are unsafe."[3]

The 1986 LRFD Specification was the next major advance. Among other things, it forces recognition of the variability of loads and resistances. And in requiring consideration of both response under service loads, when normal structures are elastic, and resistance to factored loads, when inelastic behavior would be probable, it emphasizes the importance of both modes of behavior. It should lay to rest any remaining notions that "elastic design" and "plastic design" are independent, competing philosophies. It also recognizes that today's designers have computers. Its basic provisions are simpler than earlier ones, but it is useful to have a computer on hand to make the multiple numerical checks sometimes required. Nevertheless, it was not conceived as a computer dependent code nor is it necessarily one. For example, it is written so that both elastic and inelastic action can be accounted for without the use of advanced computerized analysis.

The genius of Higgins, Winter, and other innovators of their time is captured in the quoted statement of Winter's. They were able to introduce basic concepts into practice in simple ways. They did their work thoroughly and it still serves us well. But times change. In the 1950s the computer was not the powerful, potentially dominating force it is now. Now there are different problems and different opportunities. The development of a medium that will enable the user to take full advantage of its enormous computational power without becoming subservient to it involves some of each.

CORNELL RESEARCH

It was with this in mind that we started our Cornell research on the use of interactive graphics in the mid 1970s. Graphics had become a reality and computers powerful enough to enable designers to use advanced methods of analysis were on the horizon. It seemed obvious that here at last was the computerized medium that would enable engineers to retain intimate control of their work. In all of this research we've emphasized problems involving nonlinearity and three dimensionality. We've also viewed analysis as an integral part of design, which means that the engineer should have the ability to call immediately upon either analysis routines or design sequences. He should be able to restart, redo, or enter any place in the process in almost any order.

A few pictures sketch the course of this research. Figure 1 is a black and white reproduction of one of our initial efforts: a 1977 color coded image of force distribution and plastic hinges in a small plane frame. Figure 2 is a load-displacement response curve from the second order inelastic analysis on which the first figure was based. Progressive plastic hinge formation, the strength limit point, and post-limit behavior are evident. Figure 3 takes us to 1985. It contains results of a linear, time-history dynamic analysis of a three dimensional frame.

Figure 4 is of the control menu of CU-STAND, an integrated analysis and design program for research and education we developed in the mid '80s. The "Analysis" section has provisions for first and second order elastic and inelastic analysis. The "Strength Design" and "Stiffness Design" sec-

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tions have routines for obtaining adequate strength and stiffness.

Figure 5 is the menu in the Strength Design section of CU-STAND that enables the user to apply selected LRFD design equations. For example, by pointing to "Compression" and "Moment Z," the interaction equation for axial compression and strong axis bending is selected as a design check and displayed on the computer screen for information. If details of this equation are desired they can be obtained on the bottom of the screen. The column equation is shown as an example. This menu illustrates the type of feature included to enable the user to keep in direct, visual control of his work. The computer makes the calculation, but the designer tells it exactly what to do.

Figure 6 illustrates the use of CU-STAND in a 1990 research study of the elastic and inelastic behavior of a 22-story rigid frame building.

Details of CU-STAND and other programs developed by Cornell graduate students in the course of their research have been reported in numerous technical papers.[4]

COMMERCIAL PROGRAMS

Much of the type of technology just illustrated can now be found in commercial programs. For example:

1. As graphical displays, Figs. 1 and 2, which were novel 15 years ago, are primitive compared to the graphics of today's commercial programs.
2. Commercially, three dimensional linear elastic analysis of frames and continua is now handled thoroughly. Two dimensional second order elastic frame analysis programs are also widely available.
3. Commercial programs that integrate analysis and design in a coordinated interactive graphics package also exist. Figure 7 contains illustrations from one such package, the Intergraph workstation-based MicasPlus system which contains three units: MPA (Analysis), MPD (Design), and MPMD (ModelDraft).[5] MPA has frame modeling, analysis, and analysis postprocessing capabilities. Line, plane, and solid elements are available, as are linear elastic static and dynamic analysis and nonlinear elastic static analysis. MPD evaluates results generated by MPA. It contains provisions of several American and foreign steel and concrete specifications. They can be used either in selecting member sizes or to check the adequacy of preassigned members. MPMD is an associated drawing production package. To my knowledge, the analysis and design capabilities of commercial programs of this type are still limited to those for which there is a clear demand.
4. Commercial inelastic analysis programs are available, but in civil engineering practice they are presently used mainly for special studies. Figure 8 contains results of one application, the use of a second order inelastic analysis program to verify the intended post yield behavior of an earthquake resistant frame consisting of outer braced "super columns" connected by moment resistant link beams, a system that does not fit conveniently into code defined categories. This study, which demonstrates some of the potential of advanced analysis, was made by engineers of the firm of Skidmore, Owings, and Merrill. The program ANSR-III, with graphical postprocessing developed by the SOM staff, was used.[6] In Fig. 8b, the dots that represent plastic hinges in successive stages of an equivalent static analysis verified that, as intended, there would be extensive yielding in the link beams prior to any yielding in the braced bays. This desirable mode of response, which has better energy dissipation proper-

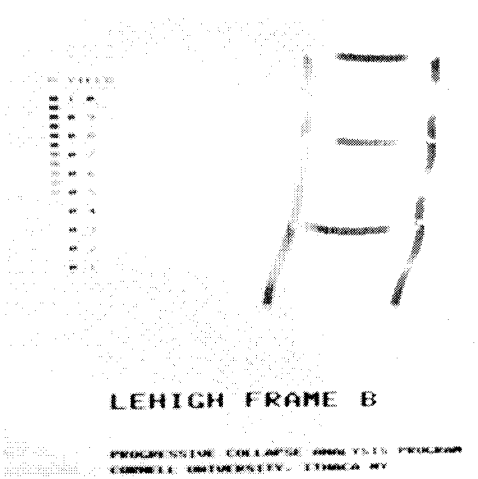


Fig. 1. Plane frame force distribution, 1977.

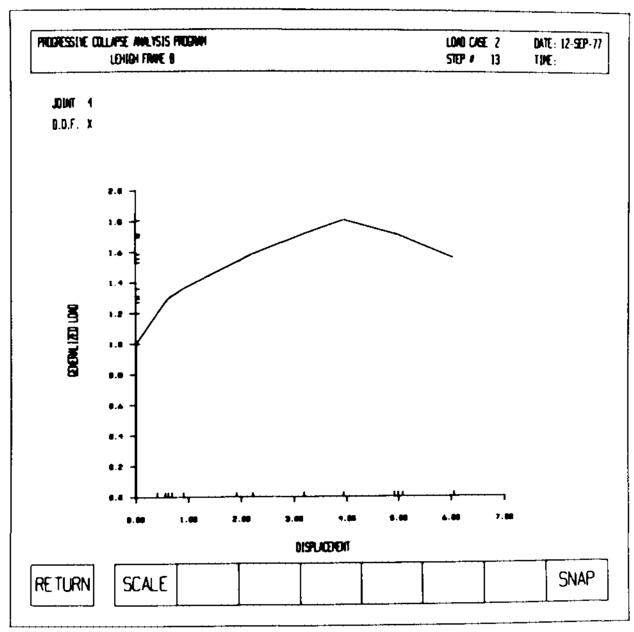


Fig. 2. Plane frame response curve, 1977.

ties than one in which buckling in the braced frames comes first, was further confirmed by a separate inelastic dynamic analysis.

Thus we see that some subjects of earlier research, such as the use of interactive graphics and three dimensional analysis, have passed into the realm of commercial product development. Others, notably the development of practical, comprehensive, second order inelastic analysis, still require further research and a demand from practice that will justify the cost of software development.

One of the undesirable side effects of the continuing revolutions in hardware and underlying software that have made the advances of the last fifteen years possible has been a complication of the task of developing and assimilating applications software. The needed fusion of workstation and personal computer technologies is coming, but too slowly. And the variety of operating and graphics systems remains an obstacle to program dissemination.

TECHNOLOGY AND THE INDIVIDUAL

Even though today's computer aided engineering systems are not the ultimate in all respects, the better ones are indeed very powerful. They enable an engineer to consider framing concepts deemed impractical in earlier times and to carry them to fruition as safe, economical structures through studies and analyses that would have been impossible before the computer. But, contrary to what is often said, computerized technology places more—not less—of a burden on the individual. Use of the best programs requires a thorough knowledge of structures and an understanding of their capabilities and limitations.

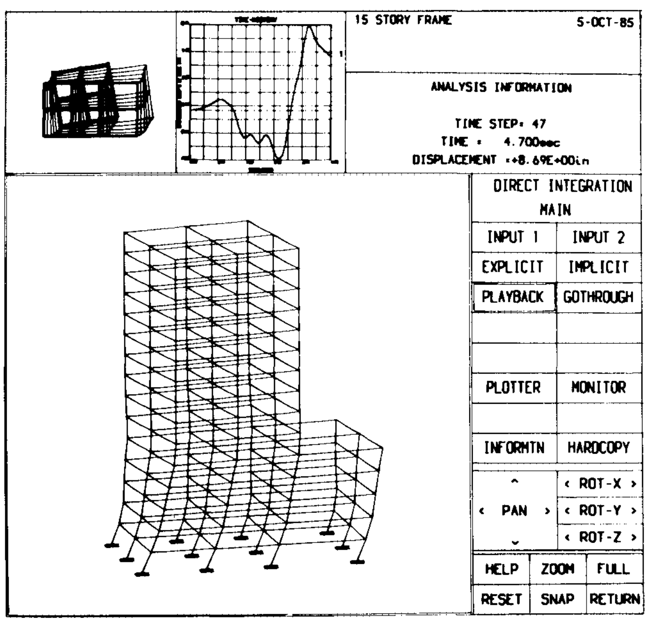


Fig. 3. Earthquake analysis, 1985.

Unfortunately, these criteria are not always met. In a recent *Engineering News Record* article,[7] leaders in the development and application of computer aided engineering expressed alarm over the incidence of its misuse. They gave numerous examples and some of them predicted that a catastrophic failure attributable to computer misuse is only a matter of time.

I share their concern, but abuse of the computer is not the only problem in structures. In my own experience the most alarming examples are violations of the principles of good weld design and practice that have contributed to serious failures. I am reminded of Omer Blodgett's Higgins Award papers on the do's and don'ts of welding.[8] For years I've used these and examples of my own in lecturing students on awareness of the problems, as well as the virtues, of welding.

My point is not to condemn welding, but rather to point out that although computer misuse has its special characteristics and dangers, it is but one example of the eternal problem of coping with side effects of advancing technology. There are no complete solutions to this, but one thing is clear: trying to halt the advance is not the answer.

Directions in research and development, education, and standardization that should further the use of computers and reduce their abuse will be discussed below. But ultimately, regardless of anything that might be done, safe computer use depends on the individual. The user has the responsibility to apply sound technology intelligently and conscientiously, and to stand behind the results.

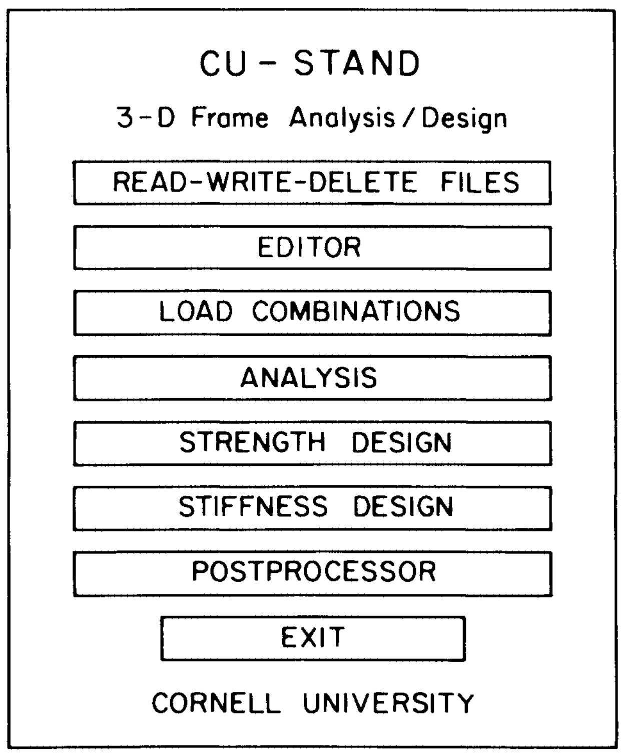


Fig. 4. CU-STAND control page, 1988.

The important point is to be mindful of this. By that I mean to ask oneself at the start of a job: do I know how to do it, will I take the time to do it decently and, if in the end I fail, will I be ready to accept the consequences? If answered honestly, this exercise can make the difference between using sophisticated technology without proper preparation, taking the time to understand it and learn how to use it, or falling back on less advanced but sound methods that one knows well.

RESEARCH AND DEVELOPMENT

The line between research and development isn't a sharp one. Commercial organizations and universities have a role in each, but some distinctions can be made:

Commercial Research and Development

Commercial software organizations are active in the further development of three dimensional elastic analysis. But I don't see comparable coverage of steel design provisions, to the extent available in AISC's ELRFD for example.[9] As a minimum, practice should be ready for a commercial interactive graphics analysis and design package in which ELRFD is the integrated component used for code checking the results of a linear or nonlinear elastic analysis. One feature should be graphical interactive control of the reanalysis-redesign cycle.

There are other things that can best be done commercially. They include the development of: 1) robust, efficient, and thoroughly debugged software; 2) efficient graphics; 3) easily transportable software for both workstations and advanced personal computers; 4) clear instructions, written in the language of structural engineering; and 5) easily mastered interactive controls that enable the user to obtain precisely the information he wants when he needs it, and that don't flood him with unwanted, undigestible information—in short, a system that is responsive but unobtrusive.

Beyond the obvious there will be countless opportunities for commercial software development that can't be foreseen but that are certain to arise. They will only be recognized where there is close contact and dialogue between structural engineers and imaginative software experts.

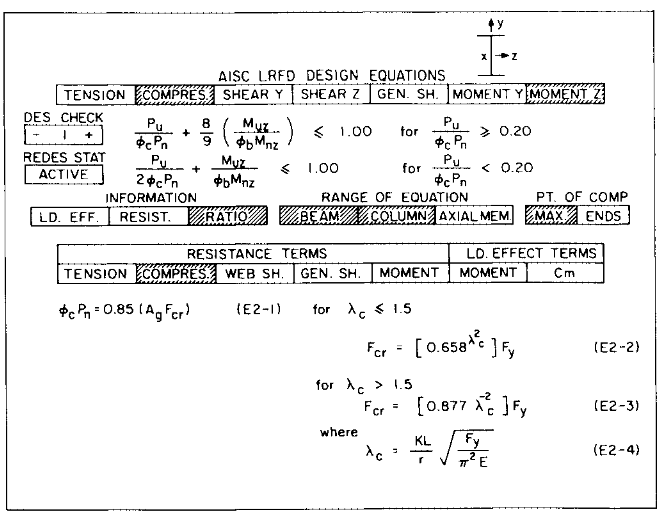


Fig. 5. CU-STAND LRFD equation page, 1988.

University Research

My comments on research can be separated into a brief statement of what we are now doing at Cornell and my impressions of the general climate in university research:

Cornell Research. For the near future our research in computer aided engineering will focus on the development of practicable numerical methods for handling some of the outstanding nonlinear problems in analysis and design.[10] One effort is directed toward the inclusion of inelastic torsional-flexural effects in existing programs. Another, under the direction of my colleague, Greg Deierlein, deals with the simulation of the geometric and material behavior of semi-rigid connections.

These projects are in the natural progression of the line of research we have been pursuing for 15 years. And they are examples of the university research I referred to as still needed for the development of practical, reasonably comprehensive second order inelastic analysis.

The General Climate. Measures of the vitality of university research can be conflicting and misleading. Judged only on the volume of output it looks healthier than ever before. Thirty years ago I could keep up on the technical literature; I could study many of the papers related to steel behavior, analysis, or design. Twenty years ago I was reduced to reading journal abstracts, ten years ago to skimming their tables of contents, and now I can't get through all of the table-of-contents services that cross my desk.

Much of this material is beyond the limits of helpfulness however; at one end it is too close to theoretical mechanics to have any near-time application to design and at the other end too trivial a modification of things done before to be of value. And much that is relevant is narrowly focused and heavily explored. For example, a good second order inelastic analysis

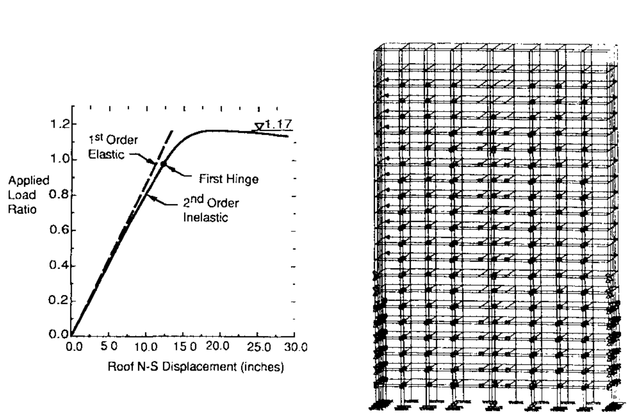


Fig. 6. Building frame study, 1990.

program should be able to detect limit points and trace post limit behavior. But this is a tricky, mind challenging problem that has spawned a minor industry in the field of numerical analysis: the search for "the best" solution. Unfortunately, so many schemes are being suggested that it is difficult for potential users to sort out the useful from the merely clever.

By another measure, research spending, recent signals are not ambiguous, they're clear and they're disturbing. In its latest report on the nation's research, the National Science Board said overall spending on research by the Federal Government, industry, universities, and private sponsors slowed during the second half of the 1980s and began to fall in 1989. This is happening at a time when similar investments in Japan and Germany are rising rapidly. The chairman of the NSB, who is also President of the University of Michigan, has said that when coupled with educational woes it, "should give us

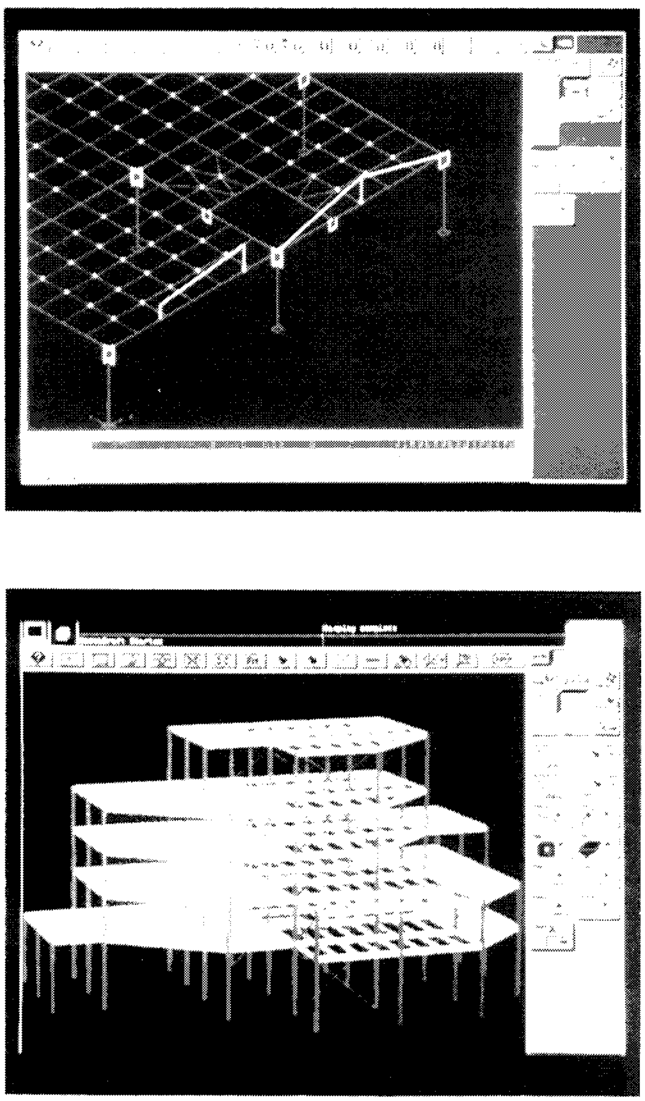
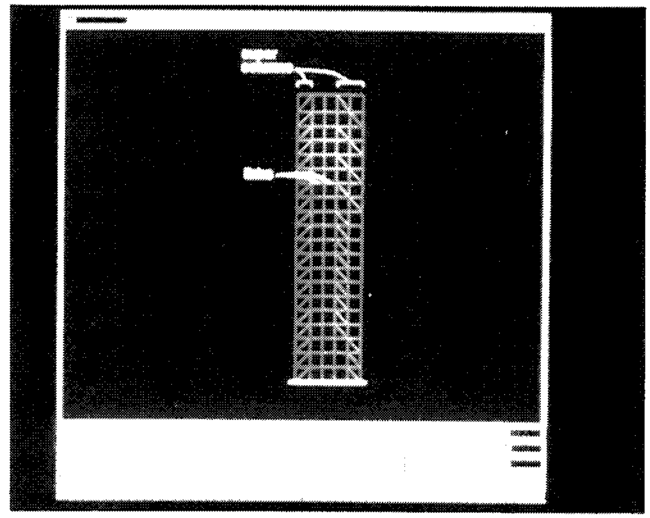


Fig. 7. Integrated analysis and design program. Courtesy of the Intergraph Corporation.



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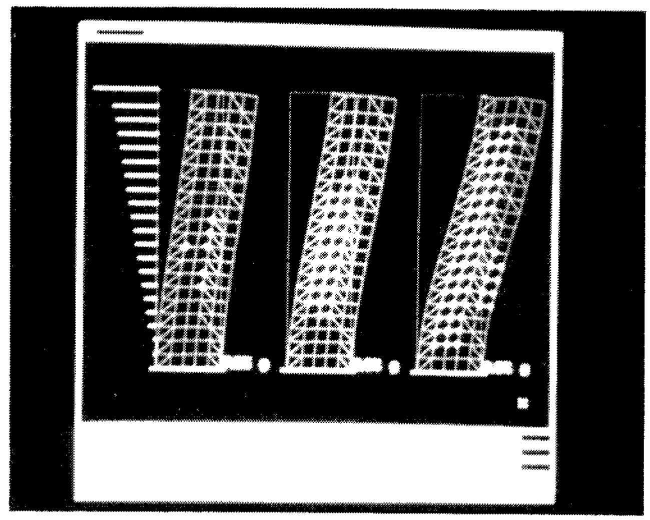

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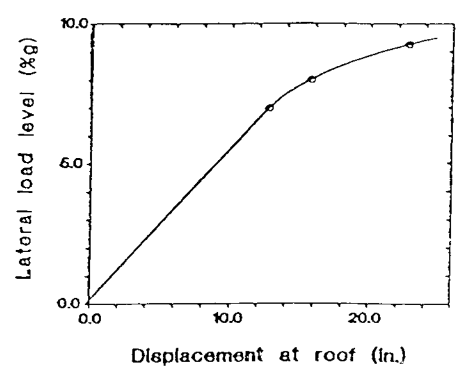

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Fig. 8. Earthquake resistance, inelastic behavior study. Courtesy of Skidmore, Owings & Merrill.

real concern for the vitality of our research enterprise." Erich Bloch, former director of the National Science Foundation was more blunt. He said, "It's bad news and it will probably get worse."[11]

With respect to research in steel structures, the picture is every bit as gloomy. In the National Science Foundation, the major supporter of this type of university research, funding for all individual project research related to structural steel has recently been less than one and one half million dollars per year. This is poor support for potential contributors to one of the country's basic industries. And I don't see the NSF funded centers making a major difference. Steel research in The National Center for Earthquake Engineering Research in Buffalo, for example, is minimal. The ATLSS Center at Lehigh is doing significant steel research, but it has a broad mission that requires it to spread its resources over a number of activities. It can't concentrate on fundamental problems in steel, as Lehigh did in the heyday of its research on plastic design.

Specifically, and perhaps selfishly, I feel there is not enough activity and competition in the area between structural mechanics and design practice. By this I mean the transformation of established knowledge of behavior and analysis into workable design procedures. If the computer aided engineering of steel structures is to develop as it has the potential to do, more research of this type is needed. Many of the outstanding problems have been around for more than a hundred years. But they remain challenging, and we now have the computational environment essential to dealing with them.

EDUCATION

The need for a good education in structures as a prerequisite for the use of a computerized analysis or design system can't be overemphasized. No designer without one should be permitted to sit down unattended to the computer.

Eight years ago, in commenting on AISC's Partner in Education Workshop recommendations on engineering education, I said, "The suggestions are good, but I feel they do not go far enough since they are limited almost entirely to the four-year undergraduate curriculum. I see little chance, for example, that the typical good student can attain anything close to a true understanding of modern structural analysis in an undergraduate program structured as most American curricula are today, and as they will be if the present scheme of things continues."[12]

Since then there has been renewed emphasis on undergraduate education in many universities as escalating costs have made them increasingly aware of their dependence on student tuition. More professors are spending more time with undergraduates inside and outside the classroom, and effective pedagogy is receiving more attention. All of this is to be applauded. But it relates mainly to how things are being taught and not to the subject matter covered.

The changes in teaching methods are intended to increase the student's understanding and retention of the subject matter. The interactive computer graphics programs now used at a number of institutions to supplement undergraduate instruction in structural analysis are examples of recent developments that do this. But the problem of adequate coverage of the basic subject matter of contemporary structural engineering in the undergraduate years of the broad gage programs now in vogue remains a formidable one and, to me, an impossible one. There are a number of topics that I feel require graduate or professional study.

There is much that is good in American engineering education and in criticizing it I'm entering an arena in which the debate has been limitless, tiresome, and largely unproductive. But I do so because I believe that, particularly in the education of young people for the engineering of steel structures, it has shortcomings that leave too many of them unprepared to use present technology properly and without the background to keep abreast of future developments.

The mechanics of computer programming and computer use is not a concern. Today's young engineers are well prepared in this respect. But the following are examples of the topics I believe cannot receive adequate coverage in the undergraduate years:

Connections. Universities should not be expected to cover all aspects of connection design and detailing. But explanation of the properties and characteristics of connecting devices and the modes of behavior of major types of connections should be treated. Also, the computer is making it possible to treat connections as the structural elements they truly are by including their properties in the analysis of a system. To take advantage of this one needs an understanding of partially restrained connections and how they influence the behavior of the whole frame.

Stability. It is the nature of steel structures that all of their strength limit states—except fatigue, fracture, and tension member yielding—are in fact stability limits. An engineer should have an understanding of the various manifestations of this complex phenomenon as well as of the scope and limitations of the classical and contemporary schemes used for dealing with them. I question whether many young engineers going into practice today have the elements of this understanding.

Structural Analysis. Knowledge of the principles of contemporary methods of numerical analysis—matrix and finite element methods in particular—is essential to the understanding of computerized analysis. And so is an appreciation of the physical significance of analytical results. For example, whereas in making calculations manually the choices of support (boundary) conditions are limited, in computer programs any combination of all degrees of freedom may be selected with little thought. If, as is often the case, the solution is sensitive to the choice, numerically consistent but completely unrealistic results may be obtained.

Nonlinearity. All design requires accounting for the possible effects of geometric and material nonlinear behavior in some way. But a good understanding of their physical causes and the mathematical methods for handling both requires going beyond elementary mechanics of materials and structural analysis.

Torsion. Understanding the ways in which steel sections can resist twisting (the significance of the "J" and the "C_w" quantities in the steel manuals) is another subject that requires going beyond elementary mechanics of materials.

Just as ominous for the future, if I am correct, is my impression that many of the graduate students now studying for the doctorate in structural engineering are not obtaining the depth of understanding of these subjects that they should have as tomorrow's teachers and leaders of research.

STANDARDIZATION

Years ago, Hardy Cross commented on design practice in an article on "Standardization and Its Abuse," subtitled "Intelligent Standards Versus Standardized Intelligence."[13] He distinguished between the creative and the routine aspects of engineering, and what he said can't be improved upon. To quote: "As the size and complexity of projects increased, the time came when there was more work to do than men to do it or time in which to think out problems. It became desirable and even necessary to set up a series of routine procedures for analysis and design. This meant the development of a series of formulas and rules and standards which could be followed within limits by men trained in that vocation." He observed that there appeared then an intellectual "assembly line" without which it would be impossible to turn out the volume of work that comes from engineering offices. And, after noting tragic results of standardization used without discrimination or control, he balanced the picture by saying, "The important point is that some types of planning, designing, and experimenting can be put on an assembly line and some types can be put on an assembly line of skilled brains only, but much of the most important work cannot be done by using fixed rules, standardized formulas, or rigid methods."

Standards, therefore, are essential but they are not everything. Over the years the AISC specifications have been more discriminating than any of the other standards I know of in providing for the everyday problems that can be reduced to simple routines and those that may benefit from special attention, and in stopping short of the line between the routine and the creative sides of engineering. I think credit should go to the mix of steel men, consulting engineers, and academicians on its Specification Committee, and the checks and balances they exert on each other. George Winter was too level-headed to do so, but I can imagine another academic of his time proposing adoption of the effective length concept in a way that would bring Ted Higgins down on him to make certain it didn't require every designer to calculate eigenvalues, an impractical task in the 1960s.

But Cross also had the right thing to say about changing times: "Old techniques must be changed and often abandoned, new techniques developed.... Development and advancement are largely dependent upon research which, by necessity, deals with controlled study of small isolated details. There is usually a long period before such details can be assembled into generalizations. Many try to seize upon these details before they have been digested and apply them at once. What are supposed to be results of investigations are often incorporated in specifications and codes before the investigation itself has been completed, much less digested."

Again the effective length concept is a useful example. Some years ago I wrote a book that contains many pages on effective lengths and I stand by what I said then, so I don't think I can be labeled an enemy of the "K factor." But at bottom it is faulty; it's based on the impossible notion of an ideal structure. As an essential for general design it has to go eventually.

Right now, second order elastic analyses programs that eliminate the need to calculate B_1 and B_2 factors and their associated effective length coefficients are available. I wish more engineers would use them. One of my reasons for getting into computer aided engineering research 15 years ago was my belief that practical nonlinear analysis methods can be developed that will make obsolete the need to rely on "K's" for estimating effects of member interaction. I expected them to be in common use by this time. But now I feel like the man who conceived of the humanoid thinking machine HAL in his movie "2001." He said recently the only error he made was that he didn't call the movie "2101."

But it must also be acknowledged that there are places where effective lengths are still the best, or only, practical expedient for routine design. This is the motivation for much of the present research in inelastic analysis: the hope of further reducing dependence on factors such as these which, if not calculated in some sensible way, can be grossly misleading.

Thus in this respect I have conflicting emotions:

On the one hand I am bothered by the slow pace of change. One of the legacies of the exceptional work of earlier times is that old notions have become so embedded in our thinking and our activities—in evaluation of structural alternatives, teaching of steel design, research directions, design office software, etc.—that change has become difficult. We see this in the slowness of the adoption of LRFD. I see it also in the research directed toward applying to design the advances in analysis made possible by the computer. In their lingering utility we tend to overlook the fact that the introduction of effective lengths and other contributions of the 1950s and '60s were not intended to put an end to progress. Witness

Winter's emphasis on "simple improvements" and "minimum changes to customary procedures."

On the other hand I see the present as a period of assimilation of uncustomary ideas and breathing time during which investigations that will advance computer use can be completed, assembled into generalizations, and incorporated in the standards that are essential to their use in practice.

THE AISC LRFD SPECIFICATION

The AISC LRFD Specification is a key link in relating this research to practice, and it should remain so after limit states design becomes the norm and as long as research related to the use of computers in design reaches some new, useful stage. In preparation for impending developments, I would urge special attention to four areas:

Connections. Expansion of present provisions for partially restrained connections to facilitate inclusion of their properties in system analysis.

System Reliability. The future will take engineers closer to the point at which they can analyze and proportion structures as true systems. Present resistance factors are based largely on studies of isolated elements or very small assemblages. One wonders what relevance they have to the resistance of systems of any size. Resistance factors based on the reliability of sizeable systems are needed.

Analysis. "Analysis" has always been a coequal partner with "design" in determining the proportions of a structure. But before 1963 the word "analysis" didn't even appear in the AISC Specification. This may have been appropriate in pre-computer days, when any analysis other than a clearly approximate scheme was generally impossible. But the computer has changed that. Analysis is still much of an art, but there is now a hierarchy of analytical methods and some established features of analysis that deserve a chapter in specifications.

Serviceability Requirements. The requirements for serviceability are only loosely defined in the present LRFD specification and not tied to a particular method of analysis. These, too, deserve more attention than they now receive.

Each of these items is the subject of active research. Indeed, the last four Higgins Lectures—Murray's, Bertero's, Gerstle and Ackroyd's, and Ellingwood's—dealt directly or indirectly with one or more of them. But each requires further study and, in the end, the consensus of the Specification Committee. Most also involve judgment as to how far the Specification should go. When is it in danger of leaving the "routine" and invading or even preempting the "creative" side of engineering?

CONDITIONS OF PRACTICE

The extent to which an engineering organization should embrace computerized technology is a decision that can only be made after weighing all the business and technical factors that affect its operation. An outsider, particularly a non-practitioner, is in no position to offer general advice. But my subject of the use and misuse of new technology makes a few comments on the technological factors unavoidable.

To make a point I'll use a simplified picture: that there are just two types of practice: 1) the large A & E or multidisciplinary engineering organization; and 2) the small structural engineering office. My experience has been that the same levels of creativity, intelligence, and expertise can be found in each and both can produce structures of high quality. But I'll assume that the large organization has resources of capital and manpower the small one doesn't have.

In this imaginary world, I would have little sympathy for the large organization that didn't keep abreast of, and take advantage of, the latest advances in technology. This would mean, for example, adopting the AISC LRFD Specification wholeheartedly, and having the latest in computer hardware and computer aided engineering software. It would also mean the continuing education and training of its engineers in the use of the new technology and having a staff to advise and assist in its use and to maintain it. The possibility of producing a more finally engineered, more reliable product should be all the motivation the large, adequately endowed organization would need to adopt such policies.

I would, however, have understanding for the small practitioner who tries to keep abreast of change but finds the present pace too fast for the constraints on his time and money. Such a person should have no difficulty in making the transition from the concepts of ASD to those of LRFD. But continually upgrading computer hardware and software as new models and versions are announced could be impossible. It seems to me the only response to such constraints would be to accept them and to continue a practice based on the conscientious application of the principles and methods mastered by the talent at hand. I'm an obvious believer in the possibilities of computer aided engineering, but a position that the newest program or machine is essential to the production of a fine structure would be fatuous, as any glance at history will show.

CHANGING TIMES

Strange things have happened to the image and maybe even the substance of engineering over the years. In looking to the future it is worth considering the change.

The Nineteenth Century

One hundred years ago Robert Louis Stevenson gave a view of nineteenth century civil engineering in an account of the work of his grandfather, Robert Stevenson, a pioneering civil engineer:[14]

"He was above all things a projector of works in the face of nature, and a modifier of nature itself. A road to be made, a tower to be built, a harbour to be constructed—these were problems with which his mind was continually occupied, and for these and similar ends he traveled the world for more than half a century, like an artist, notebook in hand.

"I find him writing; and in truth what an engineer most properly deals with is that which can be measured, weighed, and numbered. These are his conquests, with which he must continuously furnish his mind, and which, after he has acquired them, he must continually apply and exercise.

"These are the certainties of the engineer; so far he finds a solid footing and clear views. But the province of formulas and constants is restricted.... With the civil engineer, the obligation starts with the beginning. He is always the practical man.... He has to deal with the unpredictable, with those forces that are subject to no calculation; and still he must predict, still calculate them, at his peril. His work is not yet in being, and he must foresee its influence.

"It is plain there is here but a restricted use of formulas. In this sort of practice, the engineer has need of some transcendental sense.... The rules must be everywhere indeed; but they must be modified by this transcendental coefficient, everywhere bent to the impression of the trained eye and the feelings of the engineer."

The Twentieth Century

In a current book, the social critic Neil Postman argues that cultures can be classified into three types: tool-using (like Europe in the Middle Ages); technocracies (like nineteenth century England) which regard science as a means of achieving progress and improving the human condition; and "Technopolies" or totalitarian technocracies which subordinate "all forms of human life to the sovereignty of technique and technology" and create a culture without a moral foundation.[15] He views late twentieth century America as a Technopoly.

In outlining the premises of a Technopoly, Postman cites notions of "scientific management" which include the beliefs that "the primary, if not the only, goal of human labor and thought is efficiency; that technical calculation is in all respects superior to human judgment; that in fact human judgment cannot be trusted because it is plagued by laxity, ambiguity, and unnecessary complexity; that subjectivity is an obstacle to clear thinking; that what cannot be measured either does not exist or is of no value; and that the affairs of citizens are best guided and conducted by experts." In fairness it should be noted that Postman is not speaking only, or even primarily, to engineers. But if there is any truth in his analysis of a condition and its causes, engineers are among the guilty.

The Future

I believe that most of today's engineers would agree that, even after a hundred years, Stevenson's picture of engineering as an enterprise that requires human understanding and judgment is still closer to the mark than Postman's opinion of it as a mechanical, culture destroying process. I, for one, would like to see it remain so. One of the main objectives of the Cornell research I mentioned has been to demonstrate ways in which the engineer can retain control over the application of advanced methods of analysis and design. My hope, therefore, is that my comments may stimulate some thought, and maybe even some action, on directions in research, education, and practice that can help keep it this way while assimilating tomorrow's technology.

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