Structural Engineering for the 80's and Beyond

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Shortly after its founding in 1921, the American Institute of Steel Construction took the step that established its future. It is described in the preface to the Institute's first specification: "In 1923, AISC undertook the work of promoting uniform practice in the industry, and in order that its efforts would not be interpreted as being unduly influenced by commercial interests it selected a committee from among the leading talent in the academic, engineering and architectural professions to prepare a Standard Specification on the Design, Fabrication, and Erection of Structural Steel."[1] The committee, consisting of two practicing engineers, an architect, and two academicians, was indeed an eminent one,[2] and did its job well. The specification produced the same year was less than nine pages long, but met its objectives and gained the respect of the engineering profession.

The consistency and integrity with which the principles of that statement have been applied over 61 years are remarkable. I know of no other standard sponsored by a private industry that has achieved and maintained the worldwide recognition the AISC Specification has.

The statement is also relevant as evidence of the AISC's long dedication to structural engineering. This conference is in that tradition. Although many of us here are not in the steel industry, all of us have some stake in steel as a construction material. In recent years, the impression we outsiders have been getting is that America's steel producers are losing interest in structural steel. Nothing could be more timely, therefore, than this demonstration of the fabrication industry's belief in the future of the engineering of steel structures.

The agenda is an ambitious one. Structural engineering is an applied science, an art, a craft, a profession and a business. The talks to follow, and the seminars of the next two days, describe new technology that will affect all parts of it. They, and not these remarks, will provide the panorama of things to come. The best a keynote speaker can do is to set the stage by offering a few views of the way things were, the way they are now, and the way they may be in the not too distant future. To evaluate such remarks, listeners first need an idea of the speaker's biases. Therefore, there are some preliminaries to settle:

For the past eight years I have been involved in research at Cornell on the application of interactive computer graphics to problems in structural engineering. Our aim is to find ways to use this medium to advance the analysis and design of steel-framed structures. Our work covers the full scope of design, but our research emphasis has been on non-linear and three-dimensional problems of both a static and a dynamic nature. My role has been to conceive and guide the research. I am not an expert on computer hardware or software. The problems I help define are addressed by graduate students in structural engineering, supported by a staff of computer systems specialists.

Naturally, I will emphasize the things I know best: the analysis and proportioning of structures, and the influence of the computer on our affairs. But this is not a report on Cornell research. Rather, its theme can be found in the writings of Hardy Cross: "Various sources aid the engineer in determining strength. No one of them is more important than another. Analyses, tests, experience and such intuitive common sense as may be personally developed about structural stability; these are all helpful, but they can also be dangerously misleading. Evidence from the four sources rarely agrees completely. Great engineers are those who can weigh this evidence and

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[1] *Standard Specification for Structural Steel for Buildings*, American Institute of Steel Construction, New York, 1923.

[2] W. J. Thomas of Geo. B. Post and Sons, W. J. Watson of Watson Engineering, E. R. Graham of Graham, Anderson, Probst and White, Architects, G. F. Swain of Harvard University, and M. S. Ketchum of the University of Illinois. All were prominent, and two were honorary members of the American Society of Civil Engineers. Among the many buildings designed by Graham's firm was the Wrigley Building, the present AISC headquarters.

arrive at a reasonable answer through judgment as to its dependability."[3]

I would prefer that Cross had said "good engineers" rather than "great engineers." Few can attain greatness, but most of us can try for a level of wisdom sufficient to appreciate what he meant and to apply that knowledge with at least fair success. I didn't quote this statement just to quibble with it, however. To me it is a constant reminder of the realities of design.

THE PAST AND THE PRESENT

Cross was writing about pre-computer and pre-World War II engineering. Those of us who were students then will remember they were rather dogmatic times: "slope deflection is a method of *exact* analysis," "the yield point of structural steel *is* 33,000 psi," and so forth. To understand what Cross was getting at in citing the inadequacy of analyses and tests, it is necessary to look beyond the dogma to how things really were at the time. Also, before looking into the future, it is necessary to take stock of where we are now. Several examples that compare the state of the art in Cross's time with present conditions may help.

In presenting these examples, the words "analysis" and "test" will be interpreted broadly, as I think Cross meant them to be. So, too, will be the duration of the pre-computer era. We are now over 30 years into the computer age, but it was not until the late 1960's that the computer started to have a major influence on civil engineering practice. Much that was done into the 1970's did not depend on the computer.

First, consider the simple column. Figure 1 contains two column design curves in use in the early 1960's. One is the curve introduced into the AISC Specification in 1963. The other is the curve of British Standard 449 at the time. Practically, it did not make much difference which curve one used, the result required about the same amount of steel for a given loading condition. But they were rationalized in completely different ways. The British curve was explained on the basis of the Perry-Robertson formula, a formula resulting from the analysis of a strut that is initially bowed, but free of residual stress. The American curve was explained on the basis of the tangent modulus formula, a formula resulting from the analysis of a perfectly straight strut, but one encumbered by residual stress. Fortunately, on both sides of the Atlantic the theories had been tempered by reasonable judgment of test data, and the agreement shown was achieved. This is as it should be, but it can hardly be said to be perfect analysis—on either side of the ocean.

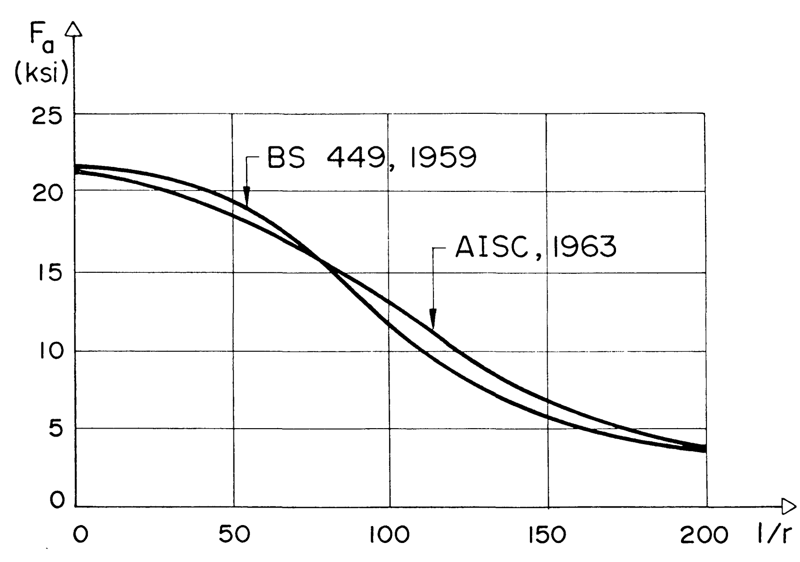

Fig. 1. Column design curves

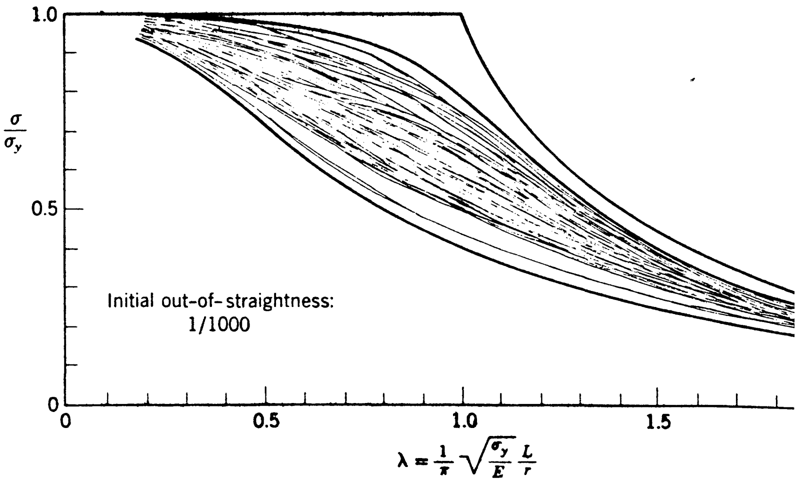

Fig. 2. Column behavior curves

The computer has made it easy to include the effects of both initial imperfections and residual stresses in simple columns. Figure 2 contains the results of computer calculations of the strength of 112 column shapes and types, each having an initial bow of 1/1000 of the length and a prescribed residual stress distribution.[4] The calculations are in good agreement with tests. This is gratifying, but what should be done with this power? Figure 2 represents only a small sample of an almost unlimited variety of shape, imperfection, and initial stress parameters. No analysis of isolated columns can furnish a clue to the interaction among members of a frame, a factor of fundamental importance. The figure shattered any illusions that may have remained regarding the sanctity

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[3] Cross, H., *Engineers and Ivory Towers*, edited by R. G. Goodpasture, McGraw-Hill, New York, 1952.

[4] Bjorhovde, R., "*Deterministic and Probabilistic Approaches to the Strength of Steel Columns.*" Ph.D. dissertation, Lehigh University, May, 1972.

of the simple curves in Fig. 1. But the older curves are still serviceable. Should they be abandoned? There are, at present, no clearly correct answers to these questions. **Second, consider the rigid frame in Fig. 3.** It has been known for a long time that, if loaded to failure, the frame's response will be as described by the non-linear load-displacement curve in the figure. However, before World War II, the best that could be done in practice was to analyze this frame by a linear elastic method. As the figure indicates, a linear elastic analysis may represent service load behavior very well, but it reveals nothing regarding ultimate resistance. To make elastic analysis generally useful, engineers employed it in conjunction with design rules that reflected in numerous, often hidden, ways the actual nonlinear behavior that all real structures exhibit.

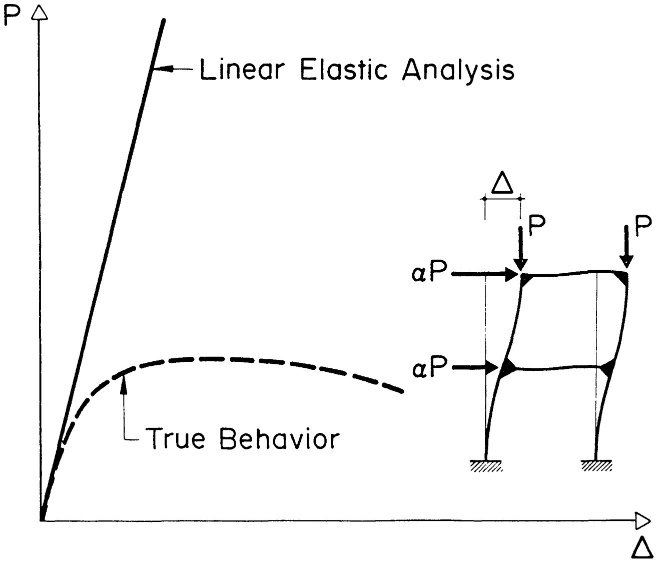

Fig. 3. Frame analysis

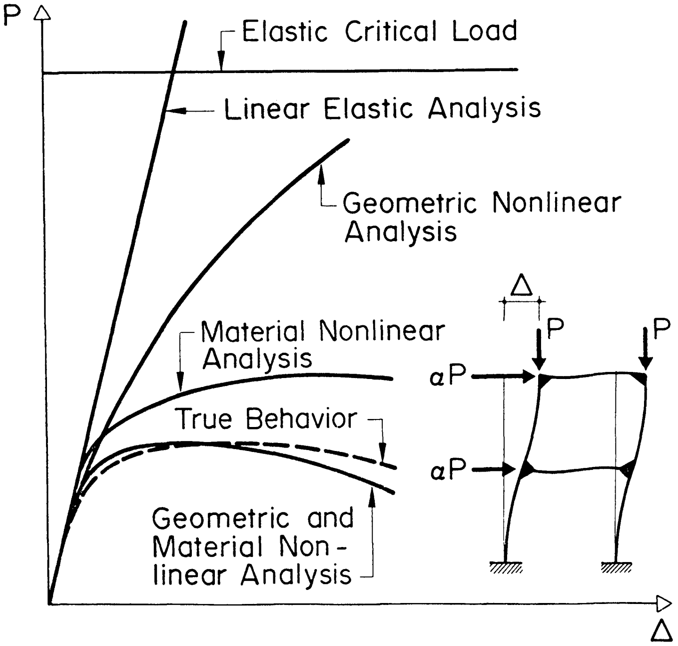

Fig. 4. Frame analysis

With the computer, a number of different types of frame analysis become practicable. The results of five are shown in Fig. 4: (1) a linear elastic analysis; (2) an elastic critical load analysis; (3) an elastic analysis that includes the effects of displacements (geometric non-linearity); (4) an elastic-plastic analysis that includes the effects of yielding (material non-linearity); and (5) an analysis that includes both geometric and material non-linearity. The higher order methods may predict the total structural response of a frame quite faithfully. But the frame shown is a simple one. Is it economically feasible to apply the more exact methods to realistically large three-dimensional frames of complex geometry? Is enough known about the real ultimate resistance of three-dimensional frames to use these methods with confidence and, if not, what experiments are needed to provide the required evidence? What sort of member proportioning procedures should be used in conjunction with non-linear analysis? The non-linear results of the figure are far in advance of the single straight line of Fig. 3, but they still represent the analysis of a frame alone, and not of a building with all of the components that may provide effective load resistance. Again, there are questions to answer and work to be done before the full potential of higher order methods can be realized.

Third, consider the treatment of joints in pre-computer times. A practice that had come down from the 19th Century was to analyze a building frame as simply connected under gravity load and moment-resistant under wind load. It is only a mild exaggeration to say that in designing this way the engineer deals with three buildings: the first is the building he analyzes for vertical loads (Fig. 5a), the second is the building he analyzes for horizontal loads (Fig. 5b), and the third is the building he builds (Fig. 5c). I never knew Cross, but I suspect that as a scholar he was amused by this procedure, as a teacher he was confounded by it, but as an engineer he found it useful and often the responsible course to follow.[5]

For several reasons, this design procedure is still used—and defensible. One reason is the difficulty of reproduc-

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[5] Support for this conjecture can be found in another of Cross's observations: "In reinforced concrete it has been necessary to set up elaborate standards. Out of this work came a narrowly circumscribed standardization of procedures, which is called the 'theory of reinforced concrete' and to which unfortunate students are exposed. Few will question that the standardized theory of reinforced concrete is perhaps as complicated a bit of nonsense as has been conceived by the human mind. It does, however, work pretty well as a check on undiscriminating, unintelligence." (*ibid*)

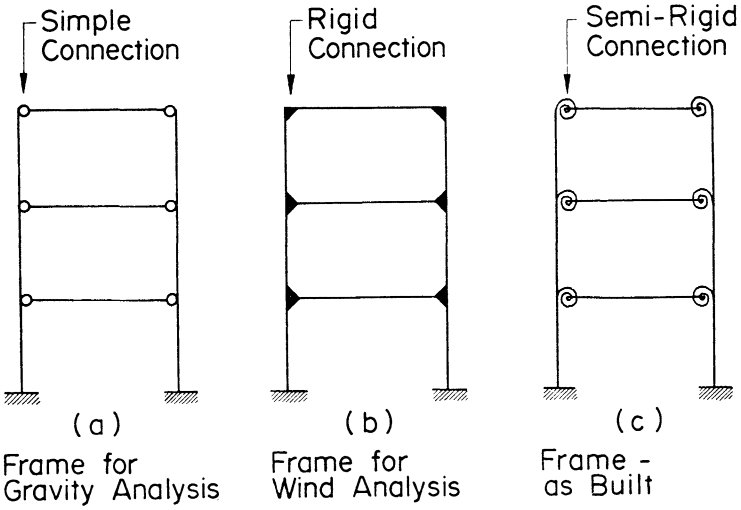
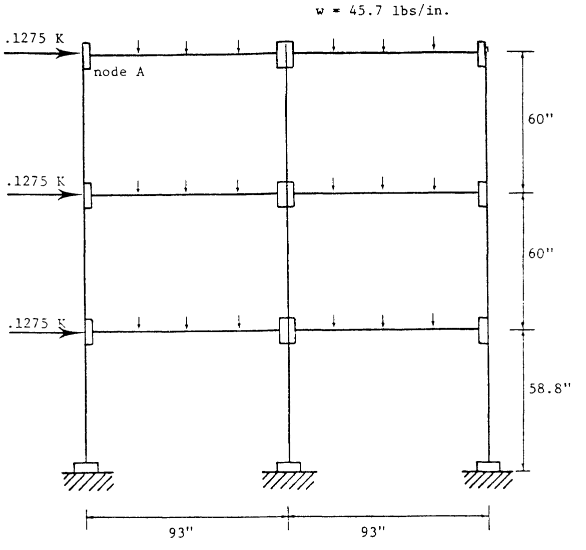


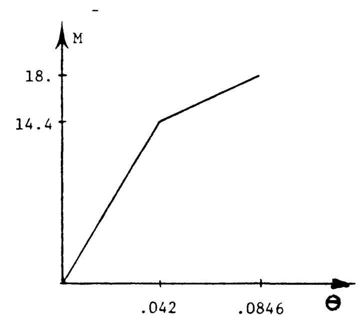
Fig. 5. Frame design



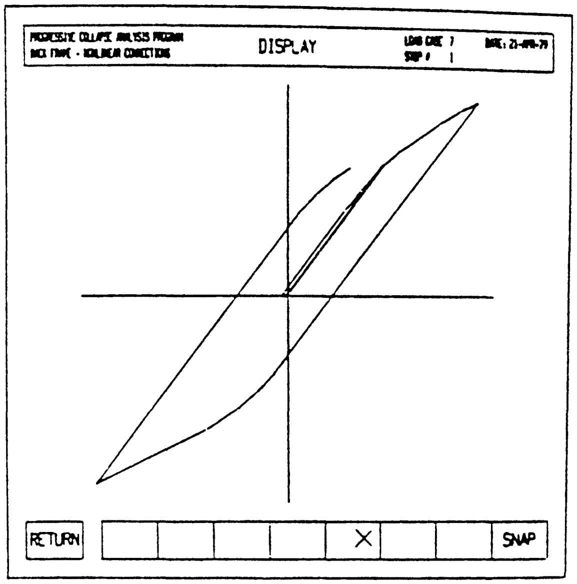
Properties: Beams $I = 2.0453\ in^4$ $A = 1.062\ in^2$ $E = 30000\ ksi$

(a) Frame

Columns $I = 1.0030\ in^4$ $A = 0.6746\ in^2$ $E = 30000\ ksi$



(b) Connection M-θ Diagram



(c) Displacement of Joint A

Fig. 6. Semi-rigid frame analysis

ing in analysis the real semirigid behavior of most connections. Methods for including connection deformation in the slope deflection method were developed in the 1930's, but did not find favor. They complicated an already laborious analysis, and were still only a linear approximation of a decidedly non-linear phenomenon. The computer overcomes these shortcomings. Analysis of the type illustrated in Fig. 6 can now be performed routinely. Figure 6c is a load-displacement diagram for a joint of a frame with semi-rigid connections of specified moment-rotation characteristics subjected to a fluctuating loading. When such analyses can be performed realistically on structures of practical size, another gap between analysis and behavior will be closed. But there is the rub. Connections are so diverse and so complex that large amounts of experimental and analytical data on connection deformation must be collected and systematized before reliable semi-rigid frame analysis can become common practice.

Fourth, consider one of the ingredients of analysis, the loading: for illustration, take snow load. Figure 7 is a ground snow map that appeared in the 1972 edition of ANSI Standard A58.1.[6] Although of relatively recent issue, it is an interpretation of data collected largely in the pre-computer era and it is representative of the type

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[6] *Building Code Requirements for Minimum Design Loads in Buildings and Other Structures, ANSI A58.1 - 1972,* American National Standards Institute, New York.

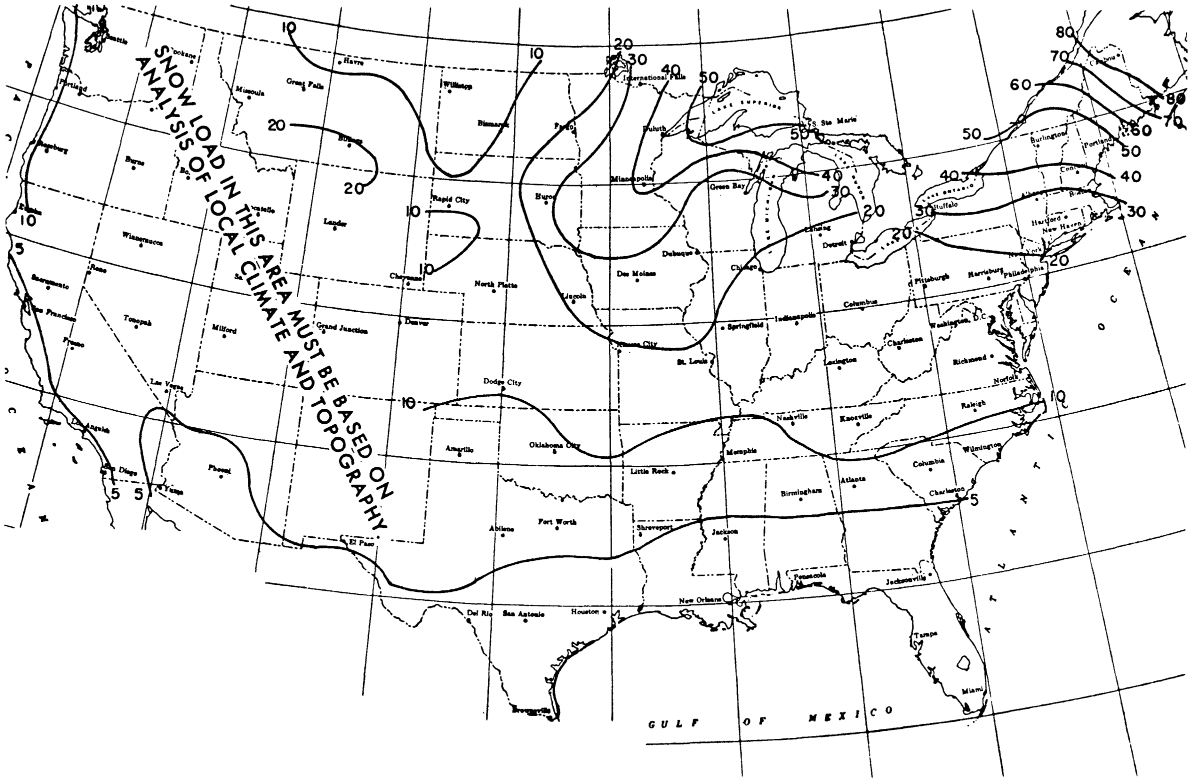


Fig. 7. Ground snow map—1972 ANSI A58.1

of guidance available then. It was a comforting map. It gave the engineer a number to use in design—in most of the country, that is. However, the fact that the mountainous regions of the West were not charted made it clear that selection of the proper design value is not always a simple matter.

Figure 8 is the ground snow map in the 1982 edition of ANSI A58.1. It was compiled with the aid of computerized collection and interpretation of data from a large number of reporting stations. Scientifically, it is vastly superior to its predecessor and gives much more reliable information for most of the country. But just as refined analysis of columns showed how complicated they are, the black and gray areas of high variability are dramatic illustrations of the difficulty of prescribing environmental loads on a regional basis. It destroyed the illusions many of us in the East had regarding the loads we had used with confidence for many years. Now, however, there is the question of how great collections of data can be made available to the practicing engineer in forms that are reliable for design yet closer to his finger tips than in Fig. 8. The same question holds, of course, for many other types of phenomenological information.

These have been simple illustrations. Any engineer who remembers the pre-computer era could extend the list indefinitely. One conclusion is that before the computer, the profession made do with procedures and data which were obviously inadequate in some major respect. Great structures were built. But they were built by good engineers using very imperfect tools.

Of course, engineers were not scientifically ignorant at that time. The ideas and most of the knowledge were there. What was needed was known, but progress was hindered in many ways: the eternal problems of insufficient time and money, the often overwhelming obstacle of the staggering calculations required for the application of accurate structural theory, and the need for the collection and interpretation of large amounts of information and experimental data. When it was introduced, the computer promised to be the means to overcome many of these obstacles.

The examples demonstrate the computer has, indeed, made it possible to do things which were too formidable to undertake in former times. But that is not news. It is more to the point to consider a couple of questions. First: has the result been progress—that is, are today's structures better because of the use of the computer and computer-related technology? I think they are. It is still true that all the analyst puts on paper—or in the computer—and all that is tested in the laboratory is only evidence for the judgment of the engineer, just as it was when Cross wrote. But the gap between analysis and test has

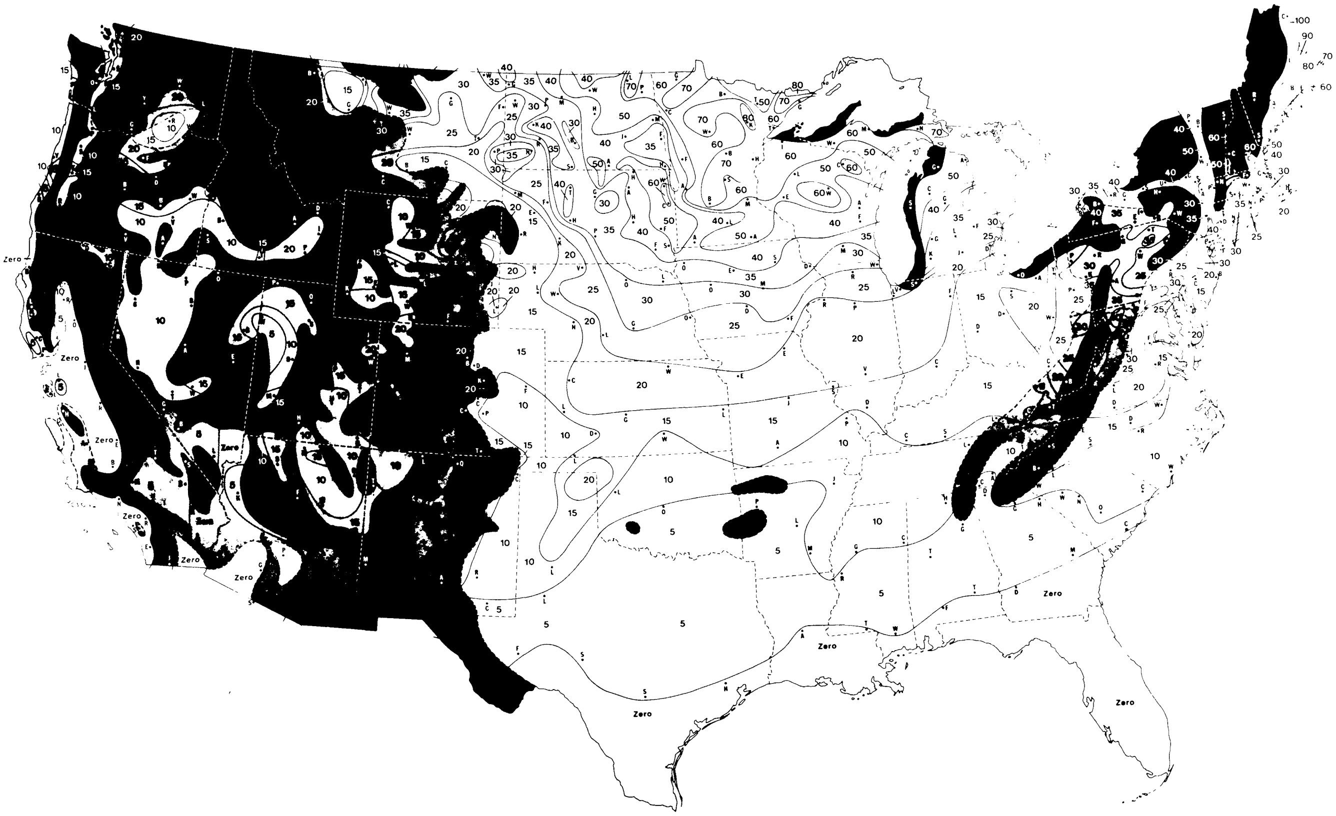


Fig. 8. Ground snow map—1982 ANSI A58.1

narrowed in many ways. And I believe the overall record shows the new technology enables engineers to come closer to meeting design objectives—functionality, economy, or aesthetics—than they formerly could.

Second question: has there been a computer revolution in structures? The evidence requires a different answer. The computer has caused an amazing acceleration in the continuous development of the profession. However, these examples show structural engineering is not revolution-prone, and that much of what has been accomplished in 30 years is only the beginning. Masses of data have been collected, but many of them are still only incompletely digested or only a fraction of the number required for generality or reliability. Light has been shed on scientifically murky regions of design, but more clarity is needed before they will have been placed on a true scientific base.

FUTURE DIRECTIONS

Where does structural engineering go from here? Two things seem certain: it will not go backwards, and what we now call high technology will become more and more commonplace in practice. Perhaps I can forecast the tone of some developments by sketching a few of the things we are trying to accomplish in our research at Cornell.

One is the development of humanly controlled computerized technology. We believe the computer's power for numerical analysis and design should be exploited, but that it should be done in ways to make the computer a natural, unobtrusive contributor to the design process and not something held in awe, fear or disdain. Perhaps a realistic goal is to develop instincts to trust the computer where it merits trust, and question it where it does not—just as one does with human associates.

A second objective is indicated by our previously mentioned emphasis on non-linear and three-dimensional problems of both a static and dynamic nature. Again Cross said it well. "Men must learn to think more clearly in space and be less restricted to two-dimensional design. They must pay more attention to movements and vibrations" (*ibid*).

We believe interactive computer graphics is the most promising medium to date for advancing such aims. To illustrate, a typical work station used in our research is shown in Fig. 9. The devices in the picture are an alphanumeric terminal, a large picture scope capable of displaying dynamic images, and a digitizing tablet and stylus. After logging onto the system, almost all subsequent communication is through the digitizing tablet. Movement of the stylus on the tablet is duplicated by a small cross, or cursor, displayed on the screen. Thus, a particular area of the screen can be identified by simply "pointing" to it. Through the manual operation of the stylus, commands may be issued and the flow of the

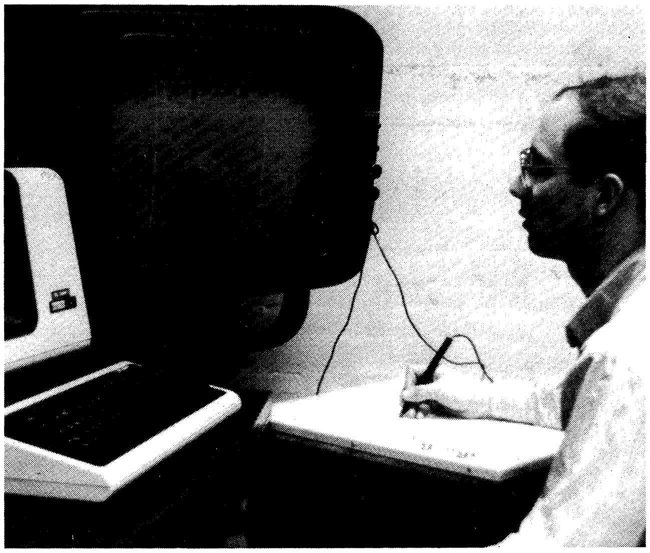


Fig. 9. *Interactive graphics research work station*

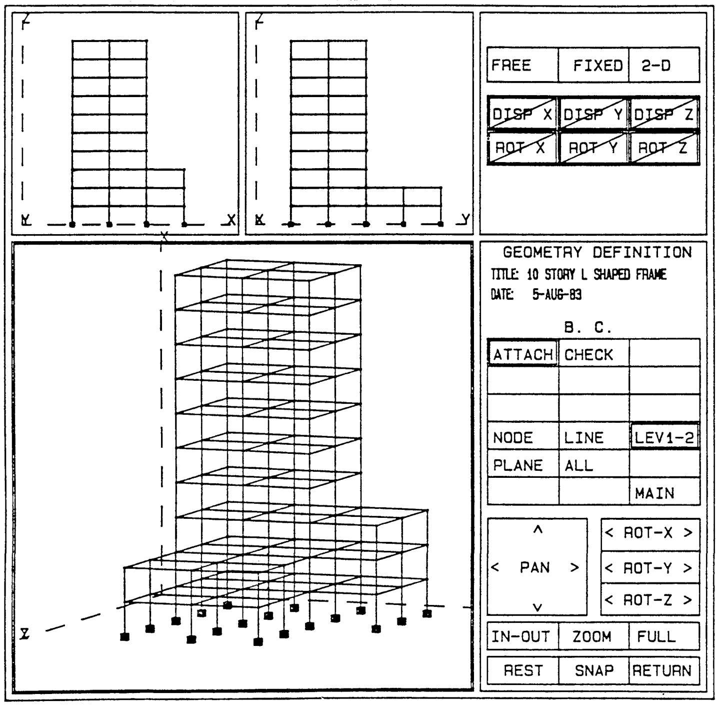
computer program controlled. Numerical data can be entered by displaying a small numerical keypad on the screen and designating digits, much as one uses the keys of a pocket calculator. The work station is served by an advanced virtual memory mini-computer and conventional hard-copy facilities.

We have been fortunate to have stations of this sort for over five years. They have been at least equal in performance to anything commercially available. But they are ad hoc in arrangement and just about outdated. Integrated stations having more functional layouts and equivalent or superior graphics are coming on the market. Dr. George Keyworth, President Reagan's science advisor, has predicted, "With multi-megabit RAMs around the corner, we can envision today's engineering students, sometime soon in their careers, having the computing capacity of, say, a CRAY-2 sitting on their desks."[7] A convenient working environment such as a refined station with even a fraction of this power is one of the essentials for control of the computer by the engineer. But this is only a prerequisite. What is done with the hardware counts.

What we are doing has been reported in numerous papers, which I will not try to summarize here.[8] I will just mention a few features, all drawn from the research of Dr. Carlos Pesquera.[9]

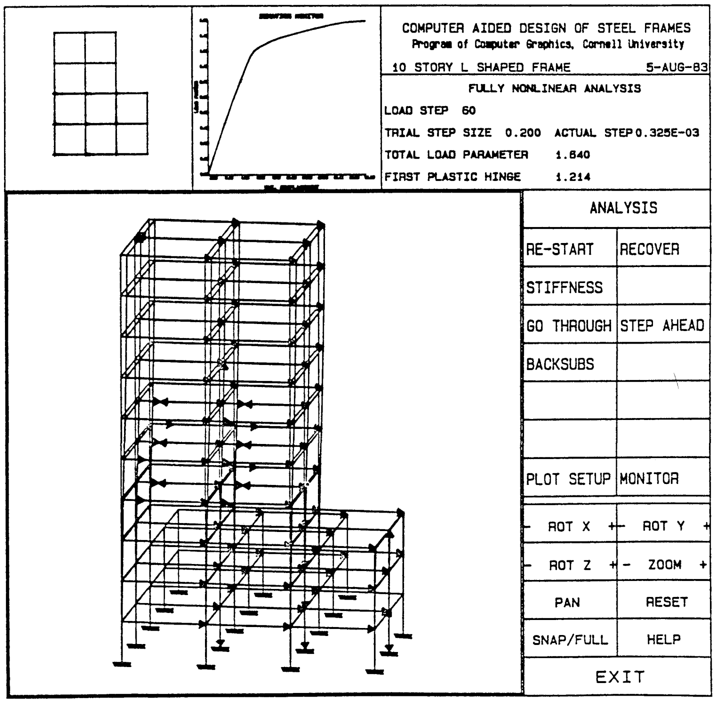
One has been the development of a graphics preprocessor to enable the complete definition of a problem to be accomplished interactively: structure, geometry, member sizes, support conditions and loads (Fig. 10).

If one wishes, he can then analyze the structure to collapse using full three-dimensional analysis which includes consideration of both geometrical and material non-linearities. Selected response parameters can be monitored during the course of analysis (Fig. 11).



GEOMETRY DEFINITION
TITLE: 10 STORY L SHAPED FRAME
DATE: 5-AUG-83

Fig. 10. *Building frame definition*



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COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
10 STORY L SHAPED FRAME                    5-AUG-83
FULLY NONLINEAR ANALYSIS
LOAD STEP  60
TRIAL STEP SIZE  0.200  ACTUAL STEP 0.325E-03
TOTAL LOAD PARAMETER    1.640
FIRST PLASTIC HINGE     1.214
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Fig. 11. *Non-linear analysis of building frame*

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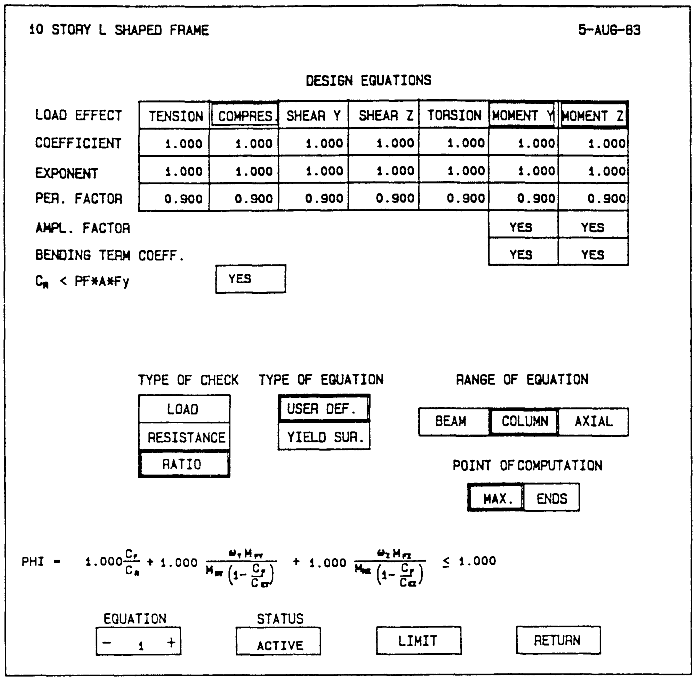
[7] Keyworth, G. A., *Technology and National Policy in the United States, The Bridge*, Vol. 13, No. 3, Fall, 1983, The National Academy of Engineering, Washington.

[8] See, for example, McGuire and Pesquera, "Interactive Computer Graphics in Steel Analysis/Design—A Progress Report," *Engineering Journal*, AISC, 3rd Qtr. 1983.

[9] Pesquera, C. I., "Integrated Analysis and Design of Steel Frames with Interactive Computer Graphics," Ph.D. thesis, Department of Structural Engineering, Cornell University, Ithaca, January, 1984.



10 STORY L SHAPED FRAME 5-AUG-83

DESIGN EQUATIONS

LOAD EFFECT	TENSION	COMPRES.	SHEAR Y	SHEAR Z	TORSION	MOMENT Y	MOMENT Z
COEFFICIENT	1.000	1.000	1.000	1.000	1.000	1.000	1.000
EXPONENT	1.000	1.000	1.000	1.000	1.000	1.000	1.000
PER. FACTOR	0.900	0.900	0.900	0.900	0.900	0.900	0.900
AMPL. FACTOR						YES	YES
BENDING TERM COEFF.						YES	YES

C_R < PF*A*Fy: YES

TYPE OF CHECK: RATIO

TYPE OF EQUATION: USER DEF.

RANGE OF EQUATION: COLUMN

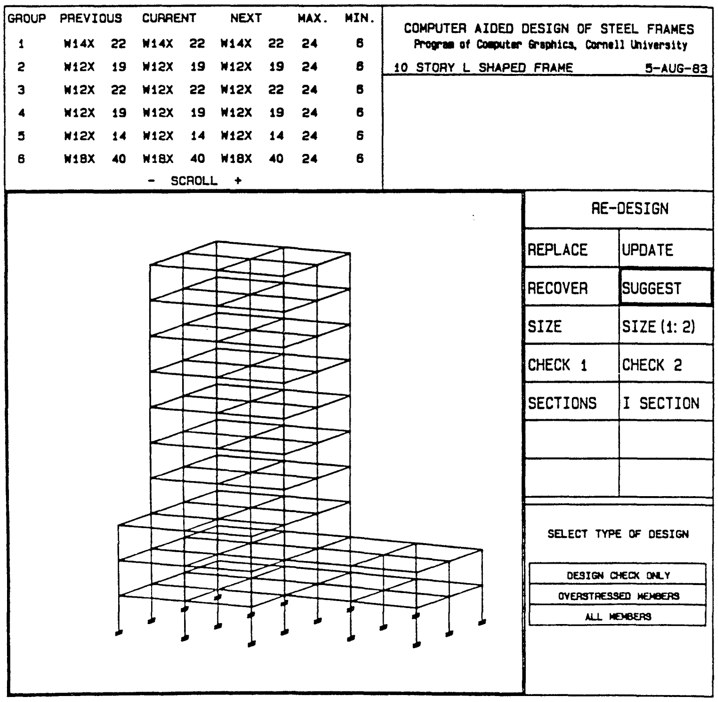
POINT OF COMPUTATION: MAX.

$$\text{PHI} = 1.000\frac{C_f}{C_R} + 1.000\frac{\omega_Y M_{fY}}{M_{RY}\left(1-\frac{C_f}{C_{eY}}\right)} + 1.000\frac{\omega_Z M_{fZ}}{M_{RZ}\left(1-\frac{C_f}{C_{eZ}}\right)} \le 1.000$$

EQUATION: 1

STATUS: ACTIVE

Fig. 12. Design equation definition



GROUP	PREVIOUS		CURRENT		NEXT		MAX.	MIN.
1	W14X	22	W14X	22	W14X	22	24	6
2	W12X	19	W12X	19	W12X	19	24	6
3	W12X	22	W12X	22	W12X	22	24	6
4	W12X	19	W12X	19	W12X	19	24	6
5	W12X	14	W12X	14	W12X	14	24	6
6	W18X	40	W18X	40	W18X	40	24	6

COMPUTER AIDED DESIGN OF STEEL FRAMES
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10 STORY L SHAPED FRAME 5-AUG-83

Fig. 13. Re-design control display

If, on the other hand, he decides to proceed in a way more conventional up to now, he can have the computer analyze the structure by an elastic method, then check the trial design for compliance with a specification. For example, the user can write specification formulas for tension, compression, shear or combined effects by selecting appropriate terms from a menu (Fig. 12). After inspecting the assembled equation for correctness, he can have the computer apply it to all the members of his trial design. The results of the review can be seen in various ways: numerical answers displayed on the scope, blinking of members that lie within a user-specified range of the design goal, etc. Redesign can then be performed either automatically or under the interactive control of the designer (Fig. 13).

In summary, our idea is to have the computer perform the exacting numerical tasks of analysis and member review, while the engineer stays in control by following the progress of the analysis, define as he would by hand the design equations, and picture the results, without being servant to a machine. The man makes the decisions, the computer performs the calculations. To use such a system intelligently, one has to understand the principles of the analysis being performed and the meaning of the design checks. But this has always been true of any type of design. The computer software must have proven reliability. The engineer has to trust the accuracy of the numerical calculations, but only to a point. He should look at them critically and apply the simple common sense, equilibrium and upper and lower bound checks which have always been wise practice.

I suspect that by now I have tipped my hand as to factors I believe important to future progress: research, education and discriminating assimilation of new technology into practice. They deserve scrutiny, for there are problems in each.

RESEARCH

Earlier, I mentioned a few problems that are either unsolved or inadequately solved. The list could extend almost indefinitely: wind effects on structures, plate girder web resistance, strength of complex weldments, socketing for bridge strand etc. The question is whether the outstanding problems are addressed with the vigor they deserve. I think not. Again, it is illuminating to recall the recent past.

From the end of World War II to the late 1960's, there was intense activity in structural steel research throughout the western world. All aspects of the subject were covered: columns, materials development, cold-formed steel, fatigue, connections etc. America was a leader. Many investigations were conducted in American universities with support from the steel industry and government agencies. Much of the work in this period was focused on plastic design, and at least 80% of the funding for the research came from the AISI and AISC. The climax of that effort came in 1965 with the Lehigh Multi-Story Frame Conference. Research did not come to an abrupt halt after that. But the excitement of those times has been lost and the level of activity has declined. This is cause for concern, for the needs and the promise of reward to practice are at least as great as they have ever been.

A number of things contributed to the decline, among them a feeling the goals in steel had been reached and it was time to turn to something different; the enticement of work on a broad range of problems made accessible by the computer, the growing competitiveness of other materials; and even such non-technological factors as the disruptions by the Vietnam War. Two I would comment on: conceptions—and possible misconceptions—regarding the conduct and products of research, and the present roles of the basic steel industry and government.

In applied research, there often seem to be misunderstandings about what is being done and the significance of the end product, among both those who are interested in using the research and those who actually do it. For instance, it would be very easy to conclude the massive effort in plastic design research was a failure. Since construction of the Stevenson Apartments, an 11-story building near Washington, and a few other structures, plastic design as such has not been used to any extent. But that conclusion would be false. The research that Lehigh, Cambridge and other institutions conducted under the rubric ''plastic design'' contributed enormously to the understanding of steel structures. It continues to have a profound influence on much done in design today. Several of my suggestions for using interactive computer graphics represent ideas for putting into practice concepts developed in that research.

There is also, still, an unfortunate tendency to place research and researchers in two extreme categories. One, ''practical research'', is believed to be the province of men who can solve to a schedule a problem which has surfaced in production or practice and is beyond the ken of the design engineer. The other, ''academic research'', is believed to be the domain of remote individuals supported in industrial or university ivory towers to conceive new directions, with the uncertain hope they may produce something useful.

These are caricatures of course. The flavor of the more scientific side of research may be found in words C. P. Snow, a scientist turned author, expressed through one of his fictional characters, Walter Luke, a scientist turned politician. In summing up his eminent political career, Luke said, ''What difference should I have made if I'd stayed in a physics lab every blasted minute of my life? The answer is damn all. There aren't more than five or six men in the whole history of science who've made a difference that you can call a difference.'' Then, in thinking of an equally successful friend who did stay in scientific research, he added, ''Well, if old Francis had never existed or had gone in for theology or stamp collecting or something of the sort, someone else would have come along and done the same work within a matter of months. All that happens is that the old boy gets a hell of a lot of satisfaction. I suspect I might have got that too.''[10]

Even more than in science, good applied research in technology, which is what we are interested in, is hard, unglamorous work on a difficult task requiring some intelligence and a modicum of creativity, and that, with good fortune, will contribute a little bit to progress. It is very much like any other business or professional activity—if things work out well, the ultimate reward is personal satisfaction. But it is inherently a speculative business, even more so than drilling for oil. Its goals, and even its end result, may not be clear, and the dollar value is seldom clear. Unfortunately, this elusive fiscal quality and its detachment from line operations makes research vulnerable in times of stress.

Stress in American industry today is obvious. Dr. Keyworth's recent analysis is relevant: ''Our self-esteem has taken a beating, and I think it reached its low point a year or so ago when there was a great moaning throughout the country about how the Japanese were overhauling us and how we had to take drastic steps to protect our battered American industries and American workers. . . . That rapid embrace of defeatism was hardly what we would have expected from an industrial community that was born in competition and which led the world for decades. . . . Happily, we've now been largely restored to our senses. . . . We see much more clearly today that while many of our industries are being challenged by foreign competition they've hardly been beaten. And, unlike those panicky times a few years ago, when many of those challenged industries were turning to Washington for help, most of them today have rekindled that competitive spirit and are charging aggressively back into the market place.''[7]

As an example, Dr. Keyworth cites the RAM market. Just three years ago, there were fears Japan was preempting the field by capturing the initial market for 64K RAMS. A.T.&T. was getting ready to produce 256K RAMS, and American industry now talks about marketing a four-megabit RAM by 1986. He picked an easy one, of course. There is little similarity between the young semi-conductor industry and the mature steel industry. No pep talk by a scientist-statesman will solve the almost infinitely more comlex problems of the American steel industry. Nevertheless, Dr. Keyworth stated a simple truth: ultimate success in the marketplace requires a competitive spirit.

AISC shows the revitalized spirit Keyworth called for. Steel fabrication is, however, only a relatively small part of the American steel industry. Fortunes of the fabrication industry are still linked to those of basic steel, but major corporate ties and financial support existing during the postwar period have been lost. We university people

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[10] Snow, C. P., *Last Things*, C. Scribner, New York, 1970.

who have an interest in the future of structural steel see the cutbacks in the laboratories and the engineering staffs of the major producers and the decline in support of university research through AISI. The message we get is of a lack of concern for steel as a construction material. Whether the reductions are a result of misconceptions of the nature of research, a manifestation of the defeatism Keyworth mentioned or a shrewd business decision in response to a permanent change in the world steel market, I do not know. But the end effect is the same, a curtailment of the research needed for progress.

There is no reason to believe the government will take up the slack. The major government agency providing support for research in civil engineering structures is the National Science Foundation. Less than 10% of its approximately one billion-dollar budget is allocated to all of engineering. Of this amount, a very small part trickles down to steel. Figures are hard to come by because a number of projects cut across disciplines and funding comes through several sections, but $1,000,000 a year is a liberal estimate of the amount assigned to structural steel. Although the unsolved problems in steel are as fundamental and intellectually challenging as those in reinforced concrete, the NSF support for research in steel structures is, at best, less than one-fifth of that for concrete. There is no indication these figures will change. Further evidence of the government's attitude toward structures research can be found in the attempts of the administration, both last year and this, to eliminate the Center for Building Technology of the National Bureau of Standards.

It seems to me to be a truism that a vigorous, speculative research program is an essential ingredient of competition and that, without one, an industry will atrophy. I would only hope that the spirit we find here in AISC can be infused into the rest of the industry.

EDUCATION

Contrary to what may be said in the popular press, the computer does not simplify teaching. Rather, it creates new demands. Education for the intelligent use of high technology is difficult. I am not referring to preparatory skills such as programming and terminal operation. These are reasonably well in hand and should be increasingly so as basic instruction spreads throughout the secondary schools. It is the demands upon professional education that concern me.

For example, the advent of the computer did not result in additions to the laws of mechanics. But it is much more than another tool for the use of these laws. It has changed how they can be applied in a number of major ways. I am convinced the engineer who truly understands the methods of structural analysis developed in response to the computer's operational requirements has a broader insight into structural behavior than his forebears, whose perception was restricted by the limited power of older methods. But "truly" is a key word here, for less than a thorough understanding can leave us worse off than our predecessor, who had a C+ appreciation of the method of moment distribution. The laws of mechanics must still be mastered, and it is not wise to drop all the classical methods from the curriculum. As an addition, therefore, education for modern structural analysis should include study of matrix and finite element methods, numerical methods, what I will call the mathematics of handling large quantities of numbers and data analysis methods.

To consider how education is coping with these and similar demands from other disciplines, it is once again useful to start with the recent past. In this case it will be the monumental study of civil engineering education conducted in the 1950's, culminating in the Ann Arbor Conference of 1960.[11]

In his opening address at the Conference, Prof. Nate Newmark stated, "In my opinion, a major change in civil engineering education is long overdue. This change must be of such a nature as to increase the technical as well as the professional competence of civil engineers and thereby to prepare them for truly professional careers."[11]

He also introduced a resolution, prepared by a planning group, which "favors the growth in universities and colleges of a pre-engineering undergraduate, degree-eligible program for all engineers, emphasizing humanities-social studies, mathematics, basic and engineering sciences with at least three-quarters of the program interchangeable among the various engineering curricula, to be followed by a professional or graduate civil engineering curriculum based on the pre-engineering program and leading to the first engineering degree, with a civil engineering degree awarded only at the completion of the professional or graduate curriculum."

In assessing this resolution, and in looking ahead, Newmark offered his opinion that it "seems likely undergraduate engineering in the future will be devoted primarily to pre-engineering with emphasis on an engineering science preparation for professional study." He also commented, "If engineering is to develop as a true profession, in terms of the concepts defining the medical and legal professions, a reorientation of the educational process, in terms of professional schools following undergraduate degree programs in engineering science, seems desirable."

The resolution was approved by the delegates, who represented almost all of the 138 civil engineering programs accredited at the time. It had a lasting effect on

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[11] *Civil Engineering Education*, A Study Sponsored Jointly by the Cooper Union, ASCE, and ASEE under a grant from NSF, 1959-60, ASCE, New York.

curricula, but the precise nature of that effect is difficult to pinpoint, as presaged by Newmark in a wry comment on a preliminary planning meeting: ". . .no change was made in this resolution, although the interpretation of it aroused considerable discussion." It admits of at least 138 interpretations and there have, indeed, been more than that over the years as the number of accredited programs passed that figure.

If one could find the mean of today's undergraduate curricula, it would probably not be far from the planning group's idea, with perhaps a bit less engineering science and a bit more technology, although certainly not the old elementary skills of drawing and surveying. I would call most programs "pre-engineering" in the sense used in the resolution. The other half of the proposal, a first engineering degree coming only after a professional or graduate program, simply has not caught on. Graduate enrollment has increased, and a few of us have professional masters' programs of which we are rather proud, but the norm for entry into the profession is still a four-year baccalaureate degree. Of course, these graduates go out and do the job, just as engineers have always done. That is the nature of our calling. But many of them are going out without the education that enables them to do a really proper job now, and prepares them for wise use of emerging technology.

I am not alone in being less than satisfied with today's engineering education. Again, AISC has taken initiative and, under the leadership of Albert Wilson and Lynn Beedle, it has made a number of suggestions for improving education for steel design.[12] 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 in the future if the present scheme of things continues.

Computer-driven technology has made ever more pressing the need to increase the technical and professional competence of civil engineers through changes in education of the sort Newmark said were long overdue 24 years ago! The technical and intellectual demands upon structural engineers are at least as great as those in any learned profession, yet our education is still not a true professional one. Given the outcome of the last attempt to effect a change, another effort could turn out to be a quixotic venture. However, by now there may be sufficient recognition of the complexities of technology to have changed the climate among the decision makers in education. I urge the professional and education societies to have another go at it. It is worth the try.

TECHNOLOGY ASSIMILATION

Research that develops the potential of high technology, and education for its use, are important, but they will not result in progress unless they are assimilated into design and production. This means more than just buying computers and putting them to work. It involves the much more complicated process of finding out, in each business, what men can do best and what machines can do best, then establishing an environment in which they can work together naturally and effectively.

The process can be facilitated by suppliers of computerized design and manufacturing aids who make their hardware and software reliable, readily accessible, easy to understand and convenient to use: "user friendly" in the current jargon. I have suggested some ways this may be done. But the problem of assimilating technology is the user's, and not an easy one to solve.

For example, although I have not visited a major American fabricating shop recently, my impression is that automated drafting and process control are used increasingly, and this trend will continue and spread as hardware and software become more refined and versatile. This seems inevitable. It also seems good, provided the human element is not lost. I had a personal reminder of the importance of the individual when, as I prepared this talk, I heard the Elmira plant of American Bridge is closing. I had the good fortune to spend a summer in the Elmira drafting room right after World War II, assigned to the bridge squad, a small group in those days: Tommy Thompson, George Westra, Tom Kerwin, Carl Nash, and Abe Abrahamian. They were professionals. They knew what could be done with steel, they were devoted to their work, and were great teachers. They did not have their names on technical publications, but their initials on thousands of drawings were symbols of the quality of product and the integrity of the profession. It seems that as automated technology invades the drafting room, ways must be found to provide the common sense and critical eye these men once furnished, and the computer cannot.

The object is to utilize the enormous power of modern technology without surrendering to it, without hiding behind the computer when things go wrong. Errors will always be made. But it should be possible to eliminate the little blunders that can result in tragedy, and tell us nothing.

CONCLUSION

In this paper, I have tried to establish the point research and the intelligent use of the best technology can lead to progress by continuing to narrow the gap between anal-

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[12] AISC Partner in Education, 1982 Workshops, AISC, Chicago.

ysis and test. I also argued that unless the basic steel industry increases its interest in research, and the educational process improves, the rate of progress will be disappointing. Lastly, I have emphasized that after all is said and done, or not done, the individual remains the key to good construction, just as in Cross's time, when the Roeblings built the Brooklyn Bridge 100 years ago, and when Richard of Farleigh built the spire of Salisbury Cathedral 600 years ago.

The 1923 AISC Specification contains a statement which, except for minor dating, remains a guide for today and the foreseeable future: "The question of design is all-important. This Specification necessarily presupposes that the design is good, made by and executed under the supervision of competent structural engineers; that proper provision is made for secondary stresses, eccentric loads, unequal distribution of stresses on rivets, etc.; that the details are suitable and that the workmanship is high grade."[1]