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Seminar II

Computer Aided Structural Engineering

Génie des structures assisté par ordinateur

Computergestützter konstruktiver Ingenieurbau

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SUMMARY
Computers and computer-based methods have already significantly affected the practice of structural engineering. New developments in computers, computer graphics, databases, expert systems and intelligent construction equipment promise even bigger changes. To benefit fully from these developments, existing disincentives have to be removed.

RESUME
L'ordinateur et les méthodes basées sur l'ordinateur ont déjà influencé profondément la pratique du génie civil. De nouveaux développements dans le matériel, l'infographique, les systèmes de bases de données et le contrôle numérique de l'équipement de construction promettent encore de plus grands changements. Pour bénéficier pleinement de ces développements, il est nécessaire de faire disparaître tous les éléments décourageants encore existants.

ZUSAMMENFASSUNG
Computer und Computermethoden haben die Praxis des konstruktiven Ingenieurbaus schon tief beeinflusst. Neuere Entwicklungen in der Computer-Hardware, in der Computer-Graphik, in der Datenbanktechnik und in den digital gesteuerten Konstruktionsverfahren versprechen sogar noch grössere Einflüsse auszuüben. Um von diesen Entwicklungen ganz zu profitieren, ist es notwendig, alle noch vorhandenen entmutigenden Faktoren aus dem Wege zu räumen.

1 Introduction

Over the past 25 years, computers have taken on an increasing role in structural engineering practice and research. Computer programs have been developed to assist in every phase of structural design, analysis and construction. Yet we are only a short distance into the "computer revolution". The emergence of powerful personal computers, vastly expanded computer graphics, widely accessible distributed databases, microprocessor-controlled "intelligent" construction equipment (soon to be augmented by a wide range of construction robots), and knowledge-based expert systems will all drastically change structural engineering design and construction practices, and even the nature of the structures we design, build and operate. In order to take full advantage of these developments, the structural engineering profession must remove many of the existing disincentives due to the professional, organizational and regional dispersion of the profession.

The purpose of this general report is to provide a focus for the Seminar and Poster Session on Computer-Aided Structural Engineering. To set the scene, the processes of the structural engineering profession are modelled as a four-level nested hierarchy of "programs" in Section 2. The potential contributions of informatics, incorporating computer-aided and computer-based methods in the broadest sense, are presented in Section 3. The present status of computer-aided structural engineering is summarized in Section 4. Section 5 present a tentative list of further potentials, while Section 6 deals with some of the barriers and disincentives to overcome. A brief summary and conclusion is given in Section 7.

2 The Structural Engineering Process

In a general report dealing with computer-aided structural engineering, it is appropriate to model the structural engineering process by computer "programs".

At the innermost level, the activity of a design organization designing a structure may be represented by the procedure Design.

```
PROCEDURE Design;

   BEGIN

      {input:  standards, design specifications;
               client needs, program, constraints;
               knowledge of construction practices;
```

```
            office design experience}
      conceptual design {synthesize structural configuration};
      analysis {predict response};
      detailed design {proportion components};
      evaluate constraints;

      IF design unsatisfactory THEN

           REPEAT

           modify structural parameters;
           redesign;
           re-evaluate constraints

      UNTIL design satisfactory;

      produce design documents;
      record/modify design experience;

   END design.
```

The extend of redesign and re-evaluation is highly variable, and may range from a full iteration starting from a new conceptual design to minor parameter adjustments.

At the next level, the activity of a design-build organization is represented repeated by the procedure Design-build.

PROCEDURE Design-build;

```
   BEGIN
      {input:  standards, design specifications;
               client needs, program constraints;
               construction experience}

      Design;
      evaluate buildability;

      IF design not buildable THEN

         REPEAT
              modify construction practice knowledge;
              redesign;
              re-evaluate buildability
         UNTIL design buildable;

      build;
      record/modify construction experience;

   END design-build.
```

It is to be noted that if design and construction are contractually separated (as in public bids based on completed designs), much of the feedback indicated by the model cannot take place. The activity of a major owner is modeled by the procedure Commission-Operate.

```
PROCEDURE Commission-operate;
   BEGIN

         {input:  standards, design specifications;
                  operating performance experience}
         formulate needs, program, constraints;
         Design-build;
         evaluate operating performance;

         IF building not operable THEN

            REPEAT
                 modify building;
                 re-evaluate operating experience
            UNTIL building operable;

         record/modify performance experience;

   END Commission-operate.
```

The overall process of the profession as a whole is represented by the program Structural Engineering Profession.

```
PROGRAM Structural engineering profession;
   BEGIN

         {input:  collective experience represented by standards
                  and design specifications}
         Commission-design-build-operate;
         evaluate performance;

         IF performance inadequate THEN

            REPEAT
                 modify standards;
                 re-evaluate performance of buildings
            UNTIL performance adequate;

         record/modify standards

   END profession.
```

The salient points of these models are:

- there are multiple iterations at each level - the amount of iteration can be substantially reduced if the inputs are correct and are fully understood;
- there are two "outputs" at each level: the tangible "deliverables" (the

design documents, the completed building) and the intangible increment of knowledge or experience, which provide the feedback that influences future activities; and

- at the outermost level, standards and design specifications represent the "collective memory" of the profession as a whole, in terms of empirical evidence that the requirements, methods and practices incorporated in the standards produce safe and serviceable structures.

3 Potential Contributions of Informatics

Computers and computer-based techniques can contribute significantly to the improvement and expansion of the processes sketched in the preceding section. The contributions can be grouped into four major categories.

Procedures. Undoubtedly the most common contribution is in the development of procedures, implemented as computer programs, for the many aspects of design, analysis and management. Programs of various levels of completeness and generality have been written for essentially every phase and aspect of structural engineering. The development of these programs has a two-fold benefit: the practical one of providing a computational tool, often for tasks and levels of modeling prohibitively expensive for manual processing, as well as the intellectual one of forcing the program developer to explicitly and critically examine and evaluate the procedures, limitations and assumptions used in manual processes.

Up to the present, all procedures implemented as computer program has to be algorithmic, implying that the program produces a unique and correct solution for every possible combination of conditions within its scope. As will be discussed in Section 5, the recent development of expert systems based on artificial intelligence methods provides a way to represent and process heuristic knowledge, consisting of the empirical knowledge and "rules of thumb" which characterize much of structural engineering expertise.

Interfaces. The growth in complexity of programs, and the desire to integrate programs initially developed for separate tasks, both contribute to the attention being paid to interfaces between programs and their users. Man-machine interfaces, in the form of "user-friendly" programs and particularly computer graphics, contribute significantly to raising the man-machine dialog to the level of the engineer, and to the visualization, understanding and "internalization" of the complex phenomena manipulated by the programs.

At the same time, the need to interface separate programs provides the impetus for the development of design databases, which can serve as the active repository of the highly dynamic data that emerge in the design process. Thinking about and attempting to structure this collection of information has the same intellectual benefit as the process of procedure development.

System Concepts. The increased integration of procedures, programs and data naturally leads to a system view of structures, with the goals, environment and hierarchical constraints among components and their responses defined much more explicitly than in the past. Equally important, these concepts lead to viewing the design process itself as an operational system, with the individual activities coordinated and managed in a consistent fashion. This systems viewpoint permits considerably tighter integration in breadth (among the participating design professionals) and in depth (across the design, construction, regulatory approval operations and management phases).

Sensors and Controls. The sensors used throughout structural engineering for data collection, for performance and environment monitoring and for fabrication and construction control are becoming increasingly sophisticated, and many of them now produce "on-line" digital signals that can be directly integrated with analysis and control processes. Similarly, fabrication and construction equipment is increasingly digitally controlled, and can accept their control information directly from the output of design programs.

4 Present Status

The following subsections summarize the perception of the present status of computer-aided structural engineering.

The Computing Environment. In computer hardware and access mechanisms, it is clear that the trend is increasingly towards powerful personal computers, providing substantial local processing capability for the individual engineer, but networkable to access special resources, such as large databases, large processors for occasional big computing jobs, plotters, etc. Software engineering tools and methodologies, initially developed for large programming projects, are being adapted to the more distributed environment of structural engineering practice. A variety of robust software components, including computer graphics, geometric modeling, database management systems, word- and text-processing are increasingly being integrated into structural engineering software and systems. Commercial CAD systems are also finding increased use. The first generation stations were purely drafting tools, requiring digitized or other manual graphic input, and were intended only to produce plotted output. These systems are being rapidly extended by "downstream integration" to produce bills of materials, parts lists and other derived information. Increasingly, these systems are also undergoing "upstream integration," so as to receive some or all of their data from preceding design operations.

The Professional Environment. There are some disturbing indications that computers are adding directly to the pressures of practicing professionals. Inclusion fo computer capability evaluation in the selection of consultants, contract requirements to use specific programs or systems, and insistence on refinements and tolerances achievable only by computing may be justifiable in specific instances, but their indiscriminate application by clients or regulatory agencies can be counter-productive and can restrict the range of the engineer's professional responsibilities.

Second, there is an increased disparity between analysis and design. Curiously, this phenomenon has two different manifestations.

For relatively simple structures, primarily framed structures, it is now common practice to produce a fully stressed design, i.e., iterate a few times on analysis and proportioning until every member is at the maximum allowable limit (stress, strength, deflection or other appropriate specified constraint) in at least one loading condition. We tend to forget that the limits embodied in our specifications and standards have been historically "calibrated" in a manual design environment where reanalysis was prohibitively expensive, and the design was considered satisfactory when a few key members were at their allowable limit in one loading condition. In the terminology of reliability-based design, the analysis error and its variance have been drastically reduced. Yet, we have not seriously questioned the impact of this development on the central safety factor.

In relatively complex structures, such as tanks and pressure vessels, the opposite occurs. The detailed computer model - practically always a finite element model - is so time consuming to construct and interpret that analysis is used primarily as a post-facto evaluation tool of design decisions previously made. In effect, for these structures, detailed analysis has largely been removed from the design cycle. This trend has been aggravated by the ease with which geometric design can be performed on CAD systems; it appears to have been migrated, but not eliminated, by the closer coupling to Design Analysis supported by the newer CAD systems.

Furthermore, the ready availability of complex analysis tools, especially those for nonlinear conditions, have presented many structural engineers with models and solutions which they cannot adequately comprehend. There is a general lack of guidelines and comparisons for using these advanced analysis tools.

As a counterpoint, many positive effects can also be identified. Certainly, new applications, new models and new methods continue to proliferate, and some are gaining increased usage.

A very significant positive factor has been the emergence of a healthy civil engineering software industry. Every issue of Civil Engineering, ASCE News and Engineering News-Record carries columns of ads for civil engineering software products. Hardware vendors and service bureaus are providing an increased range of civil engineering software produced and maintained by independent developers.

There is a genuine interest across the profession for closer integration of design processes both in breadth and depth. The technical feasibility of such integration is vastly improved by the availability of the appropriate support facilities, primarily those for database management and geometric modeling.

There is equal professional interest and concern for redressing some of the unbalances discussed above. This is evidenced by the increased interest in synthesis and optimization, intended to provide computer aids to the early stages of design, and in updating of standards and specifications so as to bring them more in line with computer-based techniques.

Finally, there is some renewed and broadened interest in cooperation and information sharing among computer users. In the US, NICE is incorporated as a non-profit organization. In other countries, notably Great Britain, Holland, Japan and Australia, there are much more active civil engineering users' groups, undertaking on a cooperative basis a number of research, educational and development activities. An international "umbrella" organization, FACE, is emerging as the top node of this network of cooperative activities.

5 Potentials

The new computer revolution promises to have a wide-ranging impact on the future of structural engineering practice and research. The following sections outline some of the expected developments. It is hoped that the papers in this Seminar and Poster Session will address in more detail some of these areas.

Practice. It seems clear that the personal computer will become the dominant mode of computer use in practice as well as in education. The personal computer of the 1990's will cost no more than its 1980 precursor, but will have 10 times the storage and 100 times the speed. It will also be flexibly linked to other processors, databases and output devices.

Graphics and CAD will be vastly expanded, supporting and augmenting the entire range of design activities. Designers will be able to visualize and "feel" the effect of all design decisions, and will be able to control graphically most aspects of the design process.

Integration of design activities through shared databases will become common, even among multiple organizations involved in a design project. The advantages of this approach will become so self-evident that major institutional and organizational changes will result. In particular, the traditional design-construction separation will begin to disappear; in a few years all prospective bidders will have access to the design databases in "machine-processable" form.

Finally, a much wider and more viable civil engineering software marketplace will develop.

Research. The mathematical modeling of physical phenomena will continue to be the "mainstream" of computer-based structural engineering research. There is pressing need to develop models of increasingly complex phenomena, such as fracture, non-linear problems of a great variety, coupled phenomena between the structure and its environment, and many others.

Closely allied to model development is research to provide experimental validation of analytic models. At the present, our analytical modeling capabilities exceed our understanding of materials and real structural behavior, especially in the inelastic range. This unbalance must be redressed, eventually leading to a new generation of reliable analytical simulation capabilities.

In parallel to the above research streams, deeply rooted in the traditional engineering research tradition, there will be increased research activity in more specific computer-related issues. Among these are: exploration of novel computer architectures, such as highly parallel processors, for modeling engineering problems; research on the role of graphics, geometrical modeling and design databases; and research on user interfaces for engineering users and engineer application developers. The profession's increased dependence on these tools have by now demonstrated to the academic community that research in these areas contributes as much, if not more, to the growth of the profession as traditional research in modeling.

Promising Areas. There are at least three computer-related areas, presently in their infancy in structural engineering, which promise to have an explosive growth in the next decade.

First, structural engineering, dealing with relatively static objects, has been barely touched by the microprocessor, which is already supplying large amounts of distributed intelligence and processing capabilities in many other civil engineering areas (e.g., traffic control, building environmental control, manufacturing, etc.). It is not yet clear how this inexpensive, sensor-based distributed computing capability will manifest itself in structural engineering, but it is bound to have a major impact, at least in new construction tools and methods, which will then affect design options and methods. Beyond that, the possibility of self-diagnosing buildings and bridges is conceivable, and eventually even dynamic control of structural response.

The second promising area is that of expert systems, computer programs which perform intelligent tasks currently performed by highly skilled persons. This area has recently emerged from computer science research in artificial intelligence to the point where it is becoming practical to think about expert systems in structural engineering, incorporating the heuristic knowledge acquired by experts through experience. Most of the practicing structural engineer's mental processes are not algorithmic, but heuristic. Potential applications of expert systems range from generative processes such as synthesis and preliminary design to interpretive processes such as design evaluation or failure diagnosis.

Distributed computing, sensing, control and expert systems combine with mechanical devices to produce robotics. This is another rapidly growing area which has not yet affected structural engineering. Certainly, today's robots do not have either the requisite mobility to "navigate" around a changing construction site or the versatility to handle the large number of "one-of-a-kind" components that comprise most structures. Yet robotics will clearly affect the way structures are built, by providing a way to reduce costs, increase construction safety and extend the construction "workplace" into hostile or dangerous environments. It is time to begin thinking about the problems and opportunities that will arise. In particular, thought must be given to the radically different structural schemes made possible by robotic construction.

6 Disincentives to Overcome

The realization of the full potentials of computer-aided structural engineering will require some serious thought by the profession as a whole, its clients, partners and regulators to remove some of the present disincentives. The major impediments seem to fall into three categories.

Program Development and Sharing. The diversity and dispersion of the structural engineering profession has so far prevented us from sharing program development effort and costs in a meaningful fashion. Admittedly, this is a difficult task which presents an interesting paradox. In software engineering, the value of utility programs is measured by their portability, that is, how easily they can be transplanted to a new environment. In structural engineering the measure of the design program's value is just the reverse: if the program truly reflects the design style of the originating organization, it is bound to fail when used by another organization, in that it may yield results in variance with that organization's assumptions and design style. Nevertheless, the profession, the emerging software industry and the various cooperative user groups must attempt to develop mechanisms to improve the program development and distribution process.

Project Information Sharing and Feedback. As illustrated in the first two procedures in Section 2, large volumes of information about the emerging design, as well as about its suitability and buildability, circulate among the design and construction organizations cooperating on a project. The horizontal and vertical divisions among the participating organizations often impede the natural flow of up-to-date information and the necessary feedback. As a minimum, standards for format and contents of "machine-processable" design and construction data are needed. Beyond that, computers and information processing techniques are needed to communicate back to designers the results of construction experience so as to guide future designs. A similar information flow needs to be established at the next outer level, to provide feedback on the operability and maintainability of completed structures.

Professional Information Sharing and Standards. Moving to the outermost "program" discussed in Section 2, mechanisms must be found to record and make accessible "on-line" information about past building performance, to serve designers directly as well as to provide the basis for the development of improved standards and design specifications.

7 Conclusions

Computers and informatics have already profoundly affected structural engineering, to the point where the qualifier "Computer-Aided" in the title of this Symposium is almost redundant. The foreseeable new developments in computers, information processing technologies, monitoring and control equipment, and in robotic construction methods will produce even more radical changes. It is hoped that this symposium will clarify the issues involved and provide a glimpse on an exciting future.