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Main Theme A

The Structural Design Process

Le processus du projet

Der Entwurfsprozess

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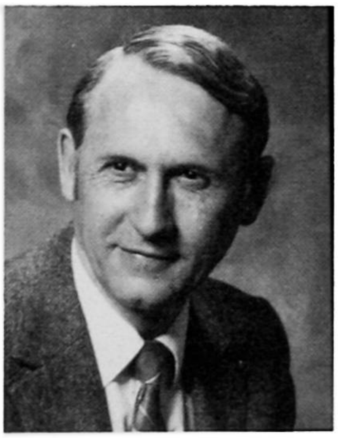

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SUMMARY

This paper studies various aspects of the structural design process and suggests future trends in the fundamental bases of design. Topics discussed include limit states design, plasticity theory, finite element analyses, and the role of codes and computers. This paper is intended as the introduction to a session on such topics as problem identification and planning, choice of structural concepts, modelling and analysis, and feedback from erroneous design and construction.

RESUME

Divers aspects du processus du projet et les développements possibles des bases fondamentales du projet sont présentés dans cette contribution. Parmi les sujets considérés, il y a lieu de mentionner le calcul à la rupture, la théorie de la plasticité, l'analyse par éléments finis, ainsi que le rôle des normes et des ordinateurs. Cet article sert d'introduction à une séance générale sur des sujets tels que l'identification d'un problème et sa conception, le choix du système structural, l'étude et l'analyse par modèle et les leçons à tirer d'erreurs dans le projet et l'exécution.

ZUSAMMENFASSUNG

In diesem Beitrag werden verschiedene Aspekte des Entwurfsprozesses erörtert und zukünftige Entwicklungen in den Entwurfsgrundlagen aufgezeigt. Behandelte Themen sind unter anderem Bemessung auf Grenzzustände, Plastizitätstheorie, Berechnungen mit finiten Elementen, und die Entwicklung im Normenwesen und bei der Anwendung von Computern. Dieser Bericht soll als Einführung zum Thema dienen, und zu Beiträgen über weitere Aspekte wie z.B. Problemstellung und Planung, Wahl eines Tragwerkes, Modellberechnung sowie Lerneffekte aus Fehlern bei Entwurf und Ausführungen anregen.

1. WHAT IS STRUCTURAL ENGINEERING?

The Institution of Structural Engineers of England have defined structural engineering in the following manner [1]:

> "Structural engineering is the science and art of designing and making with economy and elegance, buildings, bridges, frameworks and similar structures so that they can safely resist the forces to which they may be subjected."

In a recent paper on the future of structural engineering Bobrowski [2] has presented this definition:

> "... structural design ought not to be limited to 'merely making forces change direction'. It must aim at optimum resolution of conflicts imposed by gravity, wind, earthquakes and temperature changes, as well as create an open space for whatever activity is required ..."

These definitions emphasize the interplay of science and art or craft, and emphasize that the structual engineer's end product must be buildable, useful and durable.

The engineering design process involves the following stages:

1. Problem identification and planning - A study of what is needed, why it is needed, the objectives and criteria to be used, and the resources available.

2. Generation of conceptual solutions to the problem - This is the crucial and creative stage of the design process. It builds strongly on the data collected in the first stage and on the knowledge, experience and intuition of the designer and his associates.

3. Appraisal of the consequences of the various conceptual solutions - The implications and consequences of each solution are evaluated to determine which solutions are practical, economical, and have the necessary aesthetic or other attributes.

4. Decision - The concept to be used is selected.

5. Checking, evaluation and elaboration - This stage involves:
   (a) definition of the loads and actions to be considered,
   (b) definition of limit states which could constitute failure,
   (c) structural analysis of the concept which has been chosen,
   (d) proportioning of members and fitting the members together into a buildable whole, and, finally
   (e) drawings and specifications must be prepared.

6. Construction

7. Testing and feedback - During construction the structure is monitored to determine whether it is being constructed in accordance with the design. After construction it should be monitored to determine whether its behavior corresponds to that assumed in the design. Maintenance problems constitute a further "test" of the design. Feedback from erroneous design and construction allows refinement of future designs.

The emphasis placed on each stage varies from engineering discipline to discipline and design to design. In the design of a major bridge, the structural designer and his team will carry out or be associated with all seven stages. In building design however, the architect and/or the client frequently assume responsibility for the definition of the problem and the selection of the major components of the conceptual solution, leaving the structural engineer involved only in the fifth stage - checking, evaluation and elaboration of a pre-conceived design. More often than not this leads to a less than optimum solution since the architect is working outside his area of expertise and the structural engineer is required to follow blindly.

In geotechnical engineering, particularly in the case of dams, slopes and deep excavations, the testing and monitoring of the structure during and after construction, and the feedback from this monitoring to the designer and the professional community is an essential stage in the design process. So much so, that a geotechnical engineer who did not monitor a major design would be considered in dereliction of his duties as a professional. In structural engineering, on the other hand, instrumentation and post construction monitoring are almost unheard of. Structural engineers believe implicitly that their analyses and the underlying assumptions are correct and nothing can go wrong. Post construction inspections do not generate revenue and, in addition, are discouraged by many insurers of structural designers.

Structural engineering, as it is taught at many universities and seen by many practitioners, centers around stages 5(c) (d) and (e) in the above list. These steps, particularly 5(c), structural analysis, are amenable to a pseudo-scientific treatment and decisiveness that appeals to many people who enter engineering. If the basic decisions can be made by a computer analysis, the engineer will not have to make them. The reasons for this emphasis on scientific treatment become more evident when we examine the personality characteristics of engineers.

2. CHARACTERISTICS OF ENGINEERS

Dr. Charles Goshen, a psychiatrist who has studied various occupations and professions, has reported a very high consistancy in the character traits of engineers as determined from standard psychological tests. He describes these as:

> "The engineer's most obvious characteristic is his precision, his meticulousness, his attention to detail and accuracy, or his perfectionism. Another striking quality is his intelligence ...[which]... tends to be used in a very specialized way. There is an obvious lack of broadness in point-of-view so that the superior intelligence he has is restricted to a narrow field with the result that he is likely to know a great deal about a little bit but knows only a little bit about the world at large.
>
> "He seems to exhibit an enormous need to be right. Actually, when we get to know him, we find he is primarily interested in trying to avoid being criticized for being wrong. As a result he demonstrates an outstanding sensitivity to criticism.
>
> "... The engineer is most useful to his organization when he has new ideas and develops them in collaboration with other new ideas. ... However the engineer's fear of taking a chance with a new idea, based on his dread of failure and criticism often prevents him from coming up with new ideas his organization needs."

These excerpts have been quoted because they give us insight into a major problem in structural engineering practice - the acceptance of new ideas and new methods. When the seven stages in design listed earlier are considered in light of Goshen's comments we see that the stereotype engineer should be particularly able to carry out stages 3 to 6, especially stage 5, but will tend to be less able or interested to deal with stages 1 and 2, and may be sufficiently concerned about the outcome of stage 7 to overlook it.

3. STRUCTURAL THEORY AND CALCULATIONS

Structural engineering has gone through stages and fads. Prior to the 18th century major structures were conceived by craftsmen who had a great knowledge of materials and construction methods, but little understanding of structural theory. During the 17th and 18th centuries the principles of statics were derived, the concept of elasticity arose, and such things as the theory of virtual work developed. In the latter half of the 18th century these concepts began to affect structual design. During this period Coulomb worked on the theory of earth pressures on walls and later on the strength of vaults. This work was based on "limit states" concepts in which Coulomb postulated modes of failure and used these to derive solutions.

The development of elastic stress analysis gradually, but effectively, displaced other methods of calculating the strength of structures and the concept of limit states design slipped into the background.

3.1 Limit States Design

Limit states design is a process in which the designer:

(a) determines all potential modes of failure. These are referred to as "limit states" since they represent states at which the structure has reached its limit of usefulness.
(b) determines relationships between loads and material properties and each of the limit states, and
(c) uses these relationships, etc. to select a structure which will not reach any of the limit states during its lifetime. This involves judiciously chosen margins against onset of failure, referred to as safety factors.

This is the traditional design process used by Coulomb, as mentioned earlier, and currently used in geotechnical engineering. It should be noted that this definition of limit states design said nothing about probability or partial factors of safety. These are merely "bells and whistles" added to the basic concept.

With the advent of elastic theory, structural engineers gradually drifted to the comfortable point of view that by satisfying the limit state of "no yield or fracture at working loads" they automatically satisfied all others. As a result, structural engineering practice gravitated to the simple, and generally safe, working stress design based on satisfaction of one, or at the most, two or three limit states.

In reinforced concrete, the earliest design procedures were related to observed modes of failure. Further "progress" led to the straight-line theory and further "progress" still, brought design to a pseudo-limit states design where all design was based on avoidance of ultimate limit states with "deemed to satisfy" checks of serviceability limit states.

In the application of limit states design, one limit state or family of limit states is judged to be more important than the others. This "primary limit state" serves as the basis of design. Once the initial choices of member sizes, etc. have been made on this basis, the remaining limit states are checked. Thus, in the design of bridges or buildings, current design codes assume that strength is the primary limit state and serviceability and durability are secondary. In foundation design the limit state of differential settlement will frequently be primary. The resulting designs are then checked for strength and other limit states.

Recently the British Standard BS5337 has proposed a design process for water-tanks in which water-tightness is the primary limit state, serving as the basis of design. Other limit states such as strength are then checked. Here, to quote Hardy Cross slightly out of context: "One might almost say that its strength is essential but otherwise unimportant."

In bridge deck design, resistance to corrosion is of equal importance to strength as the primary limit state. This is recognized in the 1979 Ontario

Highway Bridge Design Code, a pioneer limit states design code for bridges.

Limit states design has been widely condemned, particularly in England, as being too complex. This stems from the introduction of the CP110 code for concrete structures which simultaneously moved in three directions - it moved from a working stress format to a limit states format including load factors, it incorporated much more comprehensive proportioning rules, and it marked the change from Imperial to SI units. Any one of these changes would have brought complaints, to make all three simultaneously brought a storm of complaints. There was no similar groundswell in the U.S. and Canada when ultimate strength design of reinforced concrete was introduced in 1963 because the changes made were the bare minimum needed to implement the new design method. In Canada the limit states design code for steel structures is widely used and respected. Every effort was made in writing this code to avoid complex formulations. This must be the guiding principle for committees writing limit states codes.

The use of limit states design will spread to materials other than concrete in the next decade. This will be accompanied by an increased awareness and understanding of the design process as engineers formally consider the various limit states.

3.2 Safety Provisions

The reintroduction of limit states design into structural engineering practice occurred at the same time as probability based reliability studies were being developed. Modern safety provisions are based on extensive statistical and probabilistic work. In most cases these assume failure is due to variability in loads and member strengths since these are the terms the engineer deals with in his analysis and proportioning.

Increasingly, however, it is being recognized that the incidence of failures due to overloads or understrengths is small compared to that due to "gross errors" - human mistakes in the design office or at the job-site. Although it is fair to say that knowledge is expanding rapidly in this area, we currently do not have adequate procedures for avoiding this type of problem.

Rational treatment of gross errors will develop during the next decade leading to safer designs and fewer structural collapses.

3.3 Plasticity Theory

Material behavior can be idealized as consisting of an "elastic" domain and a "plastic" domain. For almost 200 years structural design has been based on elastic theory which assumes that structures display linear response throughout their loading history, ignoring the post-yielding stage of behavior.

The plasticity theory, on the other hand, disregards the elastic distribution of stresses, substituting an arbitrarily chosen distribution of forces which is in equilibrium with the loads and which corresponds to the kinematics of the structure and the material properties. The plasticity theories are not applicable at service loads but can be used to estimate the strength of concrete and steel structures.

In elastic theory, a given set of members, loads and assumptions leads to a "unique" set of internal moments and forces which may or may not approach the correct values, depending on how well the assumptions represent the real structure. In plasticity theory, it is up to the engineer to choose the desired set of forces and moments within certain constraints. When used as a design tool, there is no unique "correct" solution. If the structural engineer's personality is as characterized by Goshen, it is clear that few engineers will welcome the freedom and understanding gained from using plasticity methods when the "exact" and scientifically pleasing solution available from elastic analysis is considered to be above criticism.

Current design practice for reinforced concrete structures is a curious blend of elastic analysis to determine forces and moments, plus plasticity theory to proportion cross-sections for moment and axial loads, and empirical mumbo-jumbo to proportion for shear and torsion. The combination of elastic analysis and plasticity methods of dimensioning sections can be justified in most cases as a "lower-bound" plasticity solution to the problem.

One of the most important advances in reinforced concrete design in the next decade will be the extension of plasticity based design procedures to shear, torsion, bearing stresses and the design of discontinuities in structures (joints, corners, etc.). Equilibrium (lower-bound) methods of plastic design allow a designer to follow forces through a structure. Major steps have already been made in this direction.

3.4 Finite Element Analysis

The opposite of plasticity theory is elastic finite element analysis. Here by breaking the structure up into small elements it is possible to get an estimate of the internal stresses or strains. Again, the estimate is only as good as the assumptions which, for economic and practical reasons generally oversimplify the problem to cut down on the number of elements or to simplify element layout.

The finite element approach is basically incompatible with modern limit states methods of proportioning concrete structures. The analysis produces elastic stresses, the design methods are based on forces and moments.

In reinforced concrete design, finite element analyses are used when ordinary beam theory breaks down. In these problems, however, the stresses predicted by conventional elastic continuum, finite element analyses are almost meaningless since they neglect the redistribution of stresses due to cracking. It is essential that proper guidance be developed to aid engineers in making the transition from finite element analyses to selection of reinforcement. This must be done by persons who have a first-hand understanding of the response of unusual reinforced concrete members and not by elastic analysts. Professor Schlaich's recent work on this problem bears mention here [3].

3.5 Loads and Actions

The use of probilistically based procedures for deriving safety factors requires a knowledge of the variabilities of the resistances and of the loadings. This, and a number of dramatic failures, has led to attempts to define the true characteristics of wind, snow, live and other loadings. The resulting loadings have become more difficult to understand and more complex to use in design. Thus, the 1937 British Standard BSS 449:1937 covered design clauses, wind and other imposed loadings in the equivalent of 15, A4 size pages. By contrast the section on wind alone in the 1972 British Code of Practice was 49 pages. As another example, the 1980 Canadian National Building Code requires 12 different exterior loading cases when considering the effect of wind on a low, unsymmetrical building.

A major need today is more knowledge on loadings, coupled with attempts to simplify the description of these loadings in codes. Increased definition of imposed deformations is also required along with ways of coping with them in design and appropriate safety factors.

The structural design process copes poorly with interactive soil loadings as encountered on retaining walls, tunnel liners, etc. A part of the problem here is the inability of the geotechnical and structural engineer to communicate. The structural engineer wants a well defined load of well defined probability of occurrence so that he can use load factors and design for ultimate limit states. The geotechnical engineer feels this request is naive in view of all the uncertainties involved. Clarification of this situation is an area requiring significant and well thought out research.

3.6 Calculation Procedure Model

A calculation procedure model is the group of components involved in carrying out a particular structural calculation. It includes:

(a) the existing background of engineering knowledge, such as mechanics and understanding of material properties,
(b) the methods of application of this knowledge in structural analysis and member proportioning and the assumptions necessary in these methods.
(c) the rules of thumb, safety factors, allowable stresses, etc. needed in the proportioning.

When one aspect of the calculation procedure model is changed, other changes may be required also. Thus, if the stress calculations are changed from beam theory to finite element procedures it may be necessary to change the allowable stresses or the way in which these allowable stresses are applied in design. Similarly, when ultra-high strength concretes (70-80 MPa, 10000 to 12000 psi) are used for columns, it is necessary to change the compression stress block constants developed for normal strength concretes. Other changes may also be needed.

Unfortunately, loading descriptions are being developed by one body, analysis procedures by another and structural proportioning rules by still another. This leads to a lack of fit between the various parts of the calculation procedure model. A major role of code writing committees is to minimize this lack of fit.

Beeby and Taylor [4] have pictured the current calculation procedure model as:

> "... the tendency of some engineers to do as much calculation as they can in the design stage. This design approach, used uncritically, leads to the dangerous tendency of which many of us may be accused: if it is possible to carry out calculations for a particular aspect of behavior then we do, if no method currently exists then calculations for this aspect of design are deemed unnecessary.
>
> More simply, we put forward our aphorism for bad engineering practice: I can, therefore I must - I cannot, therefore I need not ..."

This arises from complexities obscuring the true mechanics, from a fear of being wrong and increasingly from a fear of litigation.

4. THE ROLE OF CODES

Codification of structural design has been carried farther than in any other branch of Civil Engineering. Thus, bridge design codes give detailed guidance to all aspects of member proportioning, less guidance on foundation design and little or no guidance about bridge pier scour and hydraulic design even though scour and erosion are the most common cause of bridge failures in some parts of the world. The degree of codification and the increasing complexity of the codes is causing concern among structural engineers. Beeby and Taylor [4] sum up recent trends in codes and design practice as follows:

> "Designers call for a clear statement on every subject so they can get on with their job without wasting their time on research; checking engineers constantly call for comprehensive rules which may clearly be seen to have been obeyed in all possible circumstances. It is nevertheless ironical that these same people often claim publicly that they yearn for the days when 'engineering judgement' was kind and a building could be designed on a few sheets of foolscap. ... despite protestations to the contrary from many engineers, there is a demand for our codes to be more and more comprehensive and, unless very careful attention is given to their implementation, more

> complex."

The complexity of modern codes stems from the rapid growth in structural technology and materials and the concurrent reduction in the size of structures. Codes suffer from a lack of definition of their purpose, inadequate care by code committees, and inadequate study of the changes by users.

4.1 Purpose of Codes

The purpose of a code must be well defined before the code is written. Traditionally codes have been of two types: regulatory documents or "building codes" written to protect public health safety and welfare; and "codes of practice" written to aid engineers in the design and construction of safe, economical structures which perform in a satisfactory manner. While related, these purposes are quite different, a building code need not concern itself with serviceability limit states (deflections, vibrations, etc.) except when these endanger the public. A code of practice should deal with such items. Frequently a building code will recognize a particular code of practice as being "deemed to satisfy" its requirements concerning structural safety. When this occurs, the code of practice becomes a regulatory document even though portions are outside the scope of public safety.

Closely related to the purpose of a code is its audience. Should codes be written for the building inspector, the designer, the contractor, the researcher, university students? It would appear that the building code should be written for the building inspector and the designer in that order. On the other hand, the code of practice should be written first and foremost for the competent designer. Horne [5] discusses the degree of competence required:

> "... A Code need not - and should not - explain how such fundamental calculations [plastic collapse load, elastic frame analysis and elastic critical load] are to be made. ... A sound and up-to-date knowledge by all structural engineers of structural theory is the first essential if we are to have technically effective and progressive codes. ... The result [of the lack of such knowledge] has been the necessity to transform Codes into recipe books. This I believe to be the ultimate reason for the apparently complex and unsatisfactory nature of some of our structural Codes."

4.2 Bases of Codes

Three rules should be followed in formulating code clauses:

1. Wherever possible, code provisions should be based on mechanical models. Thus, for example, the American Concrete Institute Code and other modern codes clearly set out a physical model for flexure - a beam is a tension force and a compression force which form a couple. Strain compatibility and equilibrium are invoked. Similarly, this code requires that the total moments in a slab panel must equal the statical moment. On the other hand sections of this code dealing with shear and torsion offer little insight into the mechanical workings of beams subjected to shear and torsion. In general, those code sections dealing with mechanisms which are fully understood (flexure, short columns) are short and to the point. Sections dealing with poorly understood concepts are long, tedious and complex. In my opinion the most important value of plasticity theory will be to offer simple, equilibrium based models of shear and other actions.

2. If it is necessary to introduce empirical constants or simplifying assumptions, the end result should be as simple as possible. However, "simplification" should not be taken so far that the mechanical model is lost. The derivation of simple rules may take considerable effort on the code-writers' part. The rectangular compression block used in concrete design is a simple approximation compared to the Hognested stress block, the Jensen stress block,

the parabola-rectangle and others. This simplicity is based on extensive and thoughtful research, based in turn on a professional understanding of the degree of complexity which could be tolerated in a design office. In selecting empirical constants, the sensitivity of the problem to each variable should be examined with an eye to omitting those variables which have insignificant effect in relation to the general uncertanties involved.

3. When design shifts from one range to another (say from deep beam design to normal beam design) the appropriate design rules should meet at a common point unless there is a mechanical reason why they should not. In the American Concrete Institute code, there is a 100 percent jump in the efficiency of vertical stirrups when one passes the empirical code boundary dividing "deep beams" from normal beams. This is clearly unacceptable. Codification based on mechanical models avoids such problems in most cases.

Current codes suffer in part because these concepts have not been considered in the code writing process. This is due in part to a tendency for codes to adopt the formulations of a particular researcher rather than general principles. This comes in part from the presence of researchers on code committees (although such persons frequently are more able and willing to devote time to code work than others), and in large part because of the voluntary nature of code developmental work in many countries which limits the amount of time which code committees can spend rethinking complex expressions.

4.3 Code Format

As a reaction to the complexity of modern codes, different means of presentation have been suggested. These include: two-level codes (a master code and a simplified code), moving detailed rules to handbooks or data sheets, the use of performance codes rather than prescriptive codes, the preparation of omnibus codes covering all uses of a given material, and finally, rearrangement of material in the most usable fashion. The pros and cons of these various possibilities are discussed in an earlier paper [6].

The development of a two-tier code with a separate section or document presenting only those clauses required in the design of conventional buildings shows some promise as a means of simplifying the everyday design process while retaining the ability to handle a multitude of cases. In preparing such a code the "simplification" should not be carried to the extent that equations no longer appear to be related to the mechanics of the problem. To do so removes the engineer one step further from the design process. Two-tiered codes introduce potential legal problems, however. In the case of a lawsuit about a structure designed using the simple code, the designer's legal defense would have to be based on the lack of more stringent requirements in the complex code for the problem at hand rather than whether the building met the code definition of simple building. This, then, controls the scope of such a code and, in effect, requires that designers must be completely familiar with the complex code before using the simple code.

The use of the performance code format accompanied by a non-standardized recommended practice introduces uncertainties as to the relative acceptability of the various clauses in the recommended practice. Once a recommended practice was recognized by a building official, it would then become a mandatory document for all intents and purposes, thereby removing many of the perceived advantages of the performance code.

In recent years, the structure and arrangement of building standards has been studied and means are available for optimizing the organization of clauses. Rearrangement of code clauses according to such a scheme will not remove the technical complexity but may ease the task of moving from clause to clause.

The greatest simplifications will come, however, from clarification of the mechanical models to be followed in design and the use of these models as the framework for drafting of the code.

5. THE ROLE OF COMPUTERS

Computers have had, and will continue to have, a dramatic effect on structural design practice. Changes have occurred so rapidly that the profession has yet to assess and allow for the implications of these changes. In the calculation phase the computer reduces the drudgery of engineering computations and allows these to be much more extensive and "accurate". It assists in preparation of drawings and specifications and can be used to do material take-offs, etc. directly from the data files for these drawings. Specifications can be stored, amended and produced semi-automatically.

Because structural analysis and detailing programs are complex, the profession as a whole will use programs written by a few. These few will come from the ranks of the structural "analysts" referred to by Tedesko and Billington [7] and not from the structural "designers". Generally speaking, their design and construction site experience and background will tend to be limited. It is difficult to envision a mechanism for ensuring that the products of such a person will display the experience and intuition of a competent designer.

In the design office the reduction in computation time will free the engineer to spend more time in creative thought - OR it will it allow him to complete more work with less creative thought than today. Because the computer analysis is available it will be used. Because the answers are so precise there is a tendency to believe them implicitly. The increased volume of numerical work can become a substitute for assessing the true structural action of the building as a whole. Thus, the use of computers in design must be policed by knowledgeable and experienced designers who can rapidly evaluate the value of an answer and the practicality of a detail. More than ever before, the challenge to the profession and to educators is to develop designers who will be able to stand up to and reject or modify the results of a computer aided analysis and design.

Co-ordination problems arise in computer-aided design and drafting unless all consultants on a given project use the same software. If, for example, the architect updates his files and the mechanical or structural engineer's files remain as they were, some of the advantage of computer-aided-design is lost. In today's rapidly expanding computer market it seems unlikely that all consultants who might interface on various jobs will have the same hardware. Steps must be taken therefore to standardize the software so that interchangeability is possible.

To close this section, I wish to quote from Tedesko and Billington [7]:

> "We are fully convinced that better design depends upon the human interaction between analysts and designers. The computer certainly can help but it cannot replace the analyst who directs it. No one has been able to show that the computer has led to better structures. The computer played no role in the major new design ideas in concrete structures, such as Finsterwalder's segmental prestressed cantilever bridges, Isler's thin shell concrete roofs, and Khan's expression of concrete structure in tall buildings. It was the personality of the individual designer which led to the new forms."

6. ROLE OF RESEARCH AND DEVELOPMENT

About 0.35% of the turnover in the construction industry in England is spent on formal research and development, compared to about 36% spent on repair and maintenance [8]. Although this probably underestimates the fraction for research and development if one includes innovative design as "research", the percentage is still well below that spent in more innovative industries.

Frequently, developments in structural engineering are accepted in practice with little consideration of the long term effects. Examples have been the problems with High Alumina Cement, with certain types of glue-laminated timber beams, or more recently the increased incidence of corrosion failures of unbonded tendons in prestressed concrete structures. Reinforced concrete parking garages and bridge decks have proven highly susceptible to the de-icing chemicals used on roads. These members all behaved well in short time tests. It is difficult to visualize acceptance procedures which could adequately account for time effects - manufacturers will not sit around for 20 years waiting for approval, and frequently when long duration tests have shown one product to be better than another, the manufacturers have changed their processes during the interim so that the results are meaningless. One alternative would be a more intensive application of the spirit of limit states design by implicit consideration of the "limit state of long time chemical or physical stability" during the acceptance of new materials.

The results of research affect structural engineering practice primarily through inclusion in building codes and practitioners are, rightly so in most cases, hesitant about acceptance of research results without the screening of a code committee. As stated earlier, the code committee must very carefully screen new ideas, modifying them in light of past experience, simplifying them, generalizing them and making sure they are not in conflict with existing code clauses. A code does not exist to immortalize researchers and very seldom can a researcher stand far enough back to see all the implications of his work.

As stated at the beginning of this paper, the last stage in engineering design is to monitor the behavior of the completed structure. If properly carried out, this monitoring leads to ideas for future research and tempers the acceptance of new research.

7. SUMMARY

The next decade will be a period of great change in the structural engineering field. These changes will arise form expansion of our knowledge and introduction of computer aided design. The major changes will include:

1. Introduction of the true concept of limit states design - that design should itemize and consider all potential modes of failure.
2. Design methods based on plasticity theory will improve our design of concrete structures, particularly for shear, torsion, and localized loadings.
3. Widespread acceptance of computer aided design will reduce the drudgery, allow more time for proper review and improvement of designs.

At the same time, however, the profession will have to cope with problems arising from the rapid changes in our practice:

4. Means must be found to develop structural intuition in the increasingly inhibiting environment of computer aided design. This is a major challenge to engineering associations and educators but even more so to organizations engaged in structural design.
5. The incompatibility between finite element analyses and modern limit states design must be bridged, particularly in the case of reinforced concrete.
6. Codes should be based where possible on clearly explained mechanical models of structural processes. Code committees must work to express

research results in terms of generalized models. Code users must update themselves to the current technology.

7. Industry wide standards should be developed for computer-aided-design and drafting software to minimize problems of interchange of design information between architects and engineering disciplines.
8. Mechanisms must be developed to monitor structural behavior and to feed this information back into the codification and design process.

REFERENCES

1. EVANS, C.J., "Structural Engineering - What and Whither", The Structural Engineer, Vol. 60A, No. 12, December 1982, pp. 379-382.

2. BOBROWSKI, J., "The Future and Selection of Structural Form", The Structural Engineer, Vol. 59A, No. 2, February 1981, pp. 43-48.

3. SCHLAICH, J. and WEISCHEDE, D., "Detailing of Concrete Structures", Bulletin d'Information No. 150, Comite Euro-International due Beton, Paris, March 1982, 163 pp.

4. BEEBY, A.W. and TAYLOR, H.P.J., "The Use of Simplified Methods in CP110 - Is Rigour Necessary", The Structural Engineer, Vol. 56A, No. 8, August 1978, pp. 209-215.

5. HORNE, M.R., Discussion of "Simple Codes can Stiffle Structural Technology", The Structural Engineer, Vol. 60A, No. 10, October 1982, p. 328.

6. MACGREGOR, J.G., "A Simple Code - Dream or Possibility?", Significant Developments in Engineering Practice and Research, American Concrete Institution Publication SP72, Detroit, 1982, pp. 199-218.

7. TEDESKO, A. and BILLINGTON, D.P., "The Engineer's Personality and the Influence it has on His Work - A Historical Perspective", Concrete International, Vol. 4, No. 12, December 1982, pp. 20-26.

8. FORDE, G.R.D., Discussion of "Structures for the Future", The Structural Engineer, Vol. 60A, No. 7, July 1982, p. 223.