# Choice of structural concepts

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**Choice of Structural Concepts**

Choix de concepts structuraux

Wahl des strukturellen Konzepts

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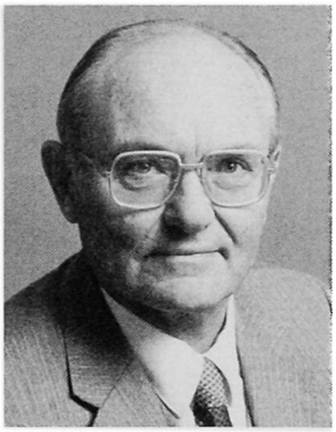

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**SUMMARY**

This paper describes the nature of the processes of conception and selection as important parts of structural design to achieve prescribed objectives in compliance with modern design criteria and practice. Various factors and constraints that influence decision-making are enumerated and the scope and limits of significant innovative progress indicated. The application of optimisation procedures is discussed, as well as the importance of relating simplified deterministic methods to a statistical probabilistic philosophy.

**RESUME**

Cette contribution décrit la nature des processus de conception et de sélection en tant que parties importantes dans le projet des structures pour atteindre les objectifs fixés en concordance avec les critères modernes de conception. Différents facteurs et contraintes qui influencent toute décision sont énumérés et l'étendue et les limites du progrès innovateur sont précisés. L'application des procédures d'optimalisation est discutée de même que l'importance des méthodes déterministes simplifiées par rapport à une philosophie probabilistique.

**ZUSAMMENFASSUNG**

Dieser Artikel beschreibt die Art des Prozesses der Entwicklung und Auswahl von wichtigen Teilen des strukturellen Entwurfs, um vorgeschriebene Ziele zu erreichen, in Übereinstimmung mit modernen Entwurfskriterien und der Praxis. Verschiedene Faktoren und Beschränkungen, die Entscheidungen beeinflussen, sind aufgelistet, und der Umfang und die Begrenzung von bedeutenden neuen Entwicklungen wird aufgezeigt. Die Anwendung von Optimierungsmethoden wird diskutiert sowie auch die Wichtigkeit des Bezuges von vereinfachten deterministischen Methoden zur statistischen Wahrscheinlichkeitsphilosophie.

## 1. INTRODUCTION

The choice of structural concepts is the most challenging and crucial part of the design process. It consists of the conception and selection of structural form and configuration, the determination of the shapes and dimensions of the component members and the arrangement of the fabric or assembly of all the parts to comply with the objectives and overall plan. It provides the structural designer with an opportunity either as principal agent in the case of engineering structures, or as consultant to architects on building projects, to participate in creative design.

After having established his brief and identified the problems, he is faced with the task of finding conceptual solutions which have to be reduced to optimal states by what is generally known as the standard design method. This method in the form commonly used, is based on a deterministic decision model, Fig. 1, which consists of discrete steps commencing with information research and problem identification to clarify the brief. Thereafter the design parameters have to be determined and all necessary assumptions formulated. Conceptual design then proceeds, followed by analysis, checking, evaluation, comparison and selection. This process incorporates feedback with a series of repetitive cycles, or looping, involving the whole or parts of the process, also seeking new information and alternative ideas to converge in a spiralling fashion on a solution to satisfy design criteria and to optimize the product. Creative or innovative ideas are essential to the conceptual stage, but considerable ingenuity and subjective judgement may also be needed to achieve progress at other stages of the process.

The last two decades have seen the development of statistical methods of design which have advanced rapidly from the classical probabilistic theories, to modern reliability theory. The principles of risk theory and reliability analysis related more directly to safety, have been well documented and further research is an ongoing activity. On the basis of this work, first level limit state codes of practice for design, although deterministic in application, nevertheless take account of uncertainty and risk by various partial safety factors, thus providing improved consistency. However, gross errors, mainly of a conceptual nature or due to lack of recognition of problems or negligence, remain the major sources of concern so that adequate checking procedures covering all classes of error remain essential. There has been much debate on this problem[1]. Recent developments[2] in the theoretical treatment of human error may become significant in the application of higher levels of design, but the complexity of the problem is so great that at present there is no satisfactory formalized procedure for eliminating gross errors. It is basically a human problem and the capabilities of the members of a design team are consequently critically important. The shortage of competent engineers exacerbates the situation.

Design criteria can be categorised under functional purpose and requirements, practicability, reliability, durability, cost, aesthetic quality and environmental impact. Under functional purpose and requirements would be indicated the manner of use of building or engineering structures, the nature of the actions to which they might be subjected and the constraints imposed by regulations. Practicability is the essence of engineering which implies the effective transformation of ideas into reality. The importance of relating conceptual design to the site conditions and the envisaged construction methods, is critically important for purposes of practicability and economic construction. The achievement of reliability is the reduction of risk to acceptable levels which in practice is usually prescribed in codes of practice. However, compliance with codes does not necessarily cover all forms of risk. Durability can be expressed in terms of the inverse of the expected costs of maintenance. Cost should be evaluated in relation to total utility as defined later, but in practice is usually reduced to those values that can be expressed in real money. This may not necessarily give the most beneficial results.

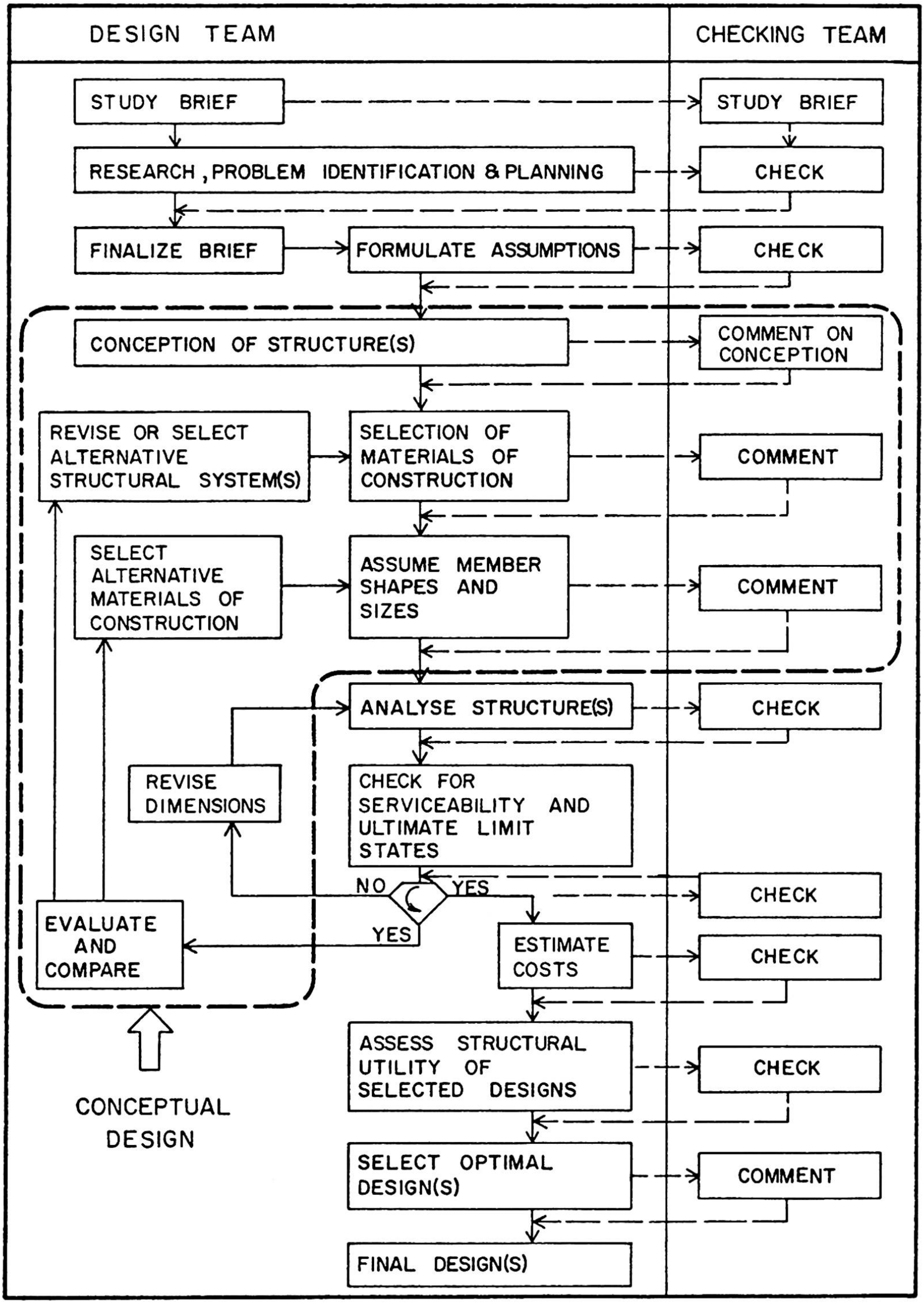


fig. I Simplified flow chart for limit state structural design

Aesthetics[3], being a subject belonging to philosophy and the arts, differs essentially from the disciplines that constitute modern engineering. It follows that an understanding of aesthetics and its importance does not always come naturally to the engineers of today. Generally they develop a predominantly logical approach to design without the intuitive sensibility and judgement that is essential for the appreciation and meaningful evaluation of the aesthetic aspects of their work. Engineers have consequently over the years applied whatever innate abilities they may have had in aesthetic appreciation, with greatly varying degrees of success. There have, however, always been gifted exceptions with a good understanding of the subject and the profession as a whole has during the last decade or two, shown a renewed interest therein.

Various excellent papers and articles have appeared[4] that define the basic principles of aesthetics in structural engineering. Some of the authors attempt to relate these to working rules. It is not the intention to decry the work of those that have in the past and recently produced such design rules, as there is no doubt that they serve a useful purpose, especially for the novice. It must be remembered, however, that these rules or laws have been deduced from past results and do not necessarily have a fundamental basis. They only work to the extent that they define some visual properties of structures which are aesthetically satisfactory and have withstood the tests of time, not unlike classical art. Every design can best be considered to be unique and even where such rules are applied, an imaginative adjustment will invariably result in some improvement. Most artists and architects today appear to agree that there are no rules by which one can create or measure the quality of art or architecture. According to Herbert Read[5] in discussing the meaning of art: 'Many theories have been invented to explain the workings of the mind in such a situation, but most of them err, in my opinion, by overlooking the instantaneity of the event. I do not believe that a person of real sensibility ever stands before a picture and, after a long period of analysis, pronounces himself pleased.'

Since the 1960's, people have become more aware of the need to preserve what is referred to as the 'quality of life', a term which is not easily defined, but amongst other things relates to the attainment of certain social and aesthetic standards and freedoms for mankind, while preserving as much of the beauty of the natural environment and its resources as is feasible and keeping it free of pollution. Likewise, engineers have come to recognise the importance and value of these considerations that extend beyond those more directly related to engineering technology. Unfortunately, many of these considerations cannot be quantified accurately because of their subjective nature. Various procedures have, however, been developed for doing so-called 'impact studies' to assess the effects of a project on the environment and the inhabitants of the affected area. Various authorities require Impact Statements which are usually considered by interdisciplinary committees prior to approval of the project. Environmental impact studies and evaluations should be carried out during the early stages of the site investigation, but subsequent feedback studies may be necessary during the conceptual design of the structure.

Optimization can in theory be best achieved by maximizing total utility expressed in terms of an objective function defined operationally with probabilities and evaluated in monetary terms. The terms of the function should include criteria such as the expected present value of the overall benefits derived from the existence of the structure, initial costs, capitalized normal maintenance costs and expectation of damages. The evaluation of utility can be extended by the inclusion of subjective criteria such as aesthetic quality and environmental impact which require evaluation by judgement. It is not possible in practice to accurately quantify the terms of the abovementioned objective function, but even an approximate evaluation along these lines can serve useful purposes in identifying inconsistencies. Developments of Decision Theory, Operational Research and Mathematical Programming, are paving the way to a better understanding of methods and procedures to realize these objectives.

Design decisions relating to the general form and details of the structure, are greatly influenced by the nature of the loads and actions to which it is subjected, by materials and methods of construction envisaged and by environmental conditions. At a recent IABSE symposium held in London[6], the factors that affect the selection of structural form were extensively discussed. These included the influences of natural and other forces such as dead weight, wind, earthquakes, snow loads, hydraulic forces, man-made loads and materials of construction. Also discussed were the influences of thermal and other environmental conditions, as well as the technical, economic and cultural factors in different design situations.

In spite of the fundamental nature of the improvements in modern structural engineering philosophy, the immediate and visible economic advantages of many of the refinements in design and analysis that are being developed at present, are marginal. This has resulted in considerable resistance to accepting the new ideas from some practising engineers, largely because of the increased complexity. This may also be due to a natural resistance to change, which presumably can be overcome in time. However, even the simplified first level codes of practice have not been readily accepted in all circles, hence the attempts at further simplification. Although there are obvious advantages therein, the dangers inherent in this process require careful consideration. It is important that structural engineers should have a sound understanding of the principles underlying these modern developments in design. Even if simplifications of practical codes are necessary, the qualitative aspects of the probabilistic philosophy and their influence on design decisions should determine the attitude and approach of the individual engineer in his choice of structural concepts. This may have a significant effect on the reliability of the structure.

## 2. THE CONCEPTUAL PROCESS

The conceptual design of engineering structures requires that the designer have a combination of mental attributes consisting at least of the ability to innovate by deductive and intuitive adaptation of existing concepts. In more imaginative cases, the conception of original ideas comes about by creative thinking.Although the nature of the mental processes of creative thinking or invention have largely been taken for granted and are even today not clearly understood, interest therein is not exactly a new development[7]. Initially it had mainly been the philosophers that had struggled with the problem. Some of the reasons for attention to the creative process were however, practical, as insight into the nature thereof can increase the efficiency of almost any developed and active intelligence. Although logical thinking had since Aristotle been exalted as the one effective way in which to use the mind, this conclusion had been questioned for some time. Leibnitz (1646-1716) had expounded the concept of unconscious ideation. The notion of somewhat different mental processes that are not necessarily deductive or intuitive and that involve an unconscious element in the inventive process, had already become well known in philosophical and literary circles in the early 19th century. However, it does seem that mathematicians have spoken of it in the clearest way, probably because in mathematics invention as a process is more easily recognisable.

When at the beginning of the century Henri Poincaré gave his celebrated lecture[7] at the request of a number of Parisian psychologists to explain what in his personal experience invention was, he knew nothing of the findings of modern brain researchers. What he said was that the solution of a problem does not necessarily come about at the conclusion of a lucid and conscious effort, but that on the contrary - especially for the really difficult problems which led him to propose entirely new formulas, creative formulas one might say - the solution had surged forth when he least expected it, at times when he was doing something quite different. The role of what he then called the unconscious, is even more remarkable since, as he said, he was led to address himself without knowing why to a certain element of the problem, or to a difficulty which seemed to be without any relationship to the general problem with which he was struggling, as if for relaxation. Then, after days or weeks, he realized that what he had thought was a contingent phenomenon was in fact precisely an element of the process of discovery which was to lead to the final solution.

The importance of the work of the unconscious in mathematical invention was thus clearly realized by Poincaré. On the topic of inspiration versus drudgery as the source of mathematical discovery, he concluded[8] that mathematical discoveries, small or great, are never born of spontaneous generation. They always presuppose a soil seeded with preliminary knowledge and well prepared by labour, both conscious and subconscious. A similar remark is attributed to Edison to the effect that genius is 99 per cent perspiration and only one per cent inspiration. However, Gauss had a hundred years before said[9]: 'I know that I discover things, but I don't know how I discover them, and when I reflect on it, I think that it can only be a gift from God, since things come to me all of a sudden without my having done anything, apparently, to merit them.' More recently, Professor Joseph Weizenbaum discussing the work of psychologist Jerome Bruner, concludes[10] that we learn from the testimony of hundreds of creative people, as well as from our introspection, that the human creative act always involves the conscious interpretation of messages coming from the unconscious.

Henri Poincaré had also said about creative thinking[9] that: 'The important thing, if you want to find the correct idea, is to begin by thinking off-centre (penser à côté).' More recently Edward de Bono has developed the concept of lateral thinking[11] as an inductive method to develop new ideas and as a problem-solving technique that extends beyond logic. It employs a mix of random and logical procedures involving a certain amount of repetition, a certain amount of imprecision, all of which are inseparable from the process of bringing about a new idea. The complementary 'vertical' logic, which is suitable for deriving or extending rules or algorithms is, however, essential for testing the validity of creative ideas in specific areas of engineering such as those related to the physical and functional aspects that influence structural reliability and effectiveness.

A comprehensive logical system in itself militates against innovation as rules negate the above-mentioned 'random freedom'. History is one long stream of examples that demonstrate this fact as Paul Feyerabend has ably shown in his book titled 'Against Method'[12]. He argues that the most successful scientific inquiries have never proceeded according to the rational method at all. He examines in detail the arguments which Galileo used to defend the Copernican revolution in physics, and shows that his success depended not on rational argument, but on a mixture of subterfuge, rhetoric and propaganda. Feyerabend argues that intellectual progress can only be achieved by stressing the creativity and wishes of the scientist rather than the method and authority of science. Earlier other philosophers like Popper[13] and Thomas Kuhn[14] had produced different arguments in which they demonstrate the limitations of the scientific method. Major advances in science, e.g. Newton's laws and theory of gravity, denied the logic within the accepted paradigm of that time and required ad hoc concepts like force acting at a distance which defied all explanation. Modern science is no different and Max Jammer[15] gives an enlightening account of the conceptual development of quantum mechanics which reminds one in many ways of the discovery of the double helical structure of DNA by James D Watson and Francis Crick, so humorously described by the former in his delightful book 'The Double Helix'[16].

In all these scientific works the importance of lateral thinking is predominant. Innovation in technology is a similar process. Established scientists were still proclaiming the impossibility of sustained flight by heavier-than-air craft when the Wright Brothers made their epoch-making flight at Kitty Hawk in 1903. Goddard experienced a similar resistance to his pre-war research in rocket flight and Whittle to his efforts to develop a jetfighter plane.

The underlying mental process in the innovative design of engineering and building structures is not unlike that in the other fields of creative effort referred to above. It presupposes certain basic levels of knowledge and experience which are essential for the ability to apply the conscious and intuitive procedures and a will to solve the problem, for the subconscious mental processes to culminate in ideas. P R Whitfield[17] has stated that as a mental activity, the moment of creation appears to be largely outside our conscious control, although it is more likely to be stimulated when we have become immersed in a subject. A burning desire to find a solution, concentration, gathering and marshalling of facts and striving for completion by reaching out for still vague ideas, are all activities we can feel and largely control at a conscious level. They mobilize and direct energy to finding a solution, but they are really only precursors to the act of creation, which seems to have a quality of spontaneity making it difficult to track and explain. Harding (1967), suggests[17] that the flash of inspiration often associated with scientific and engineering problems, comes when the scientist tries to rest by turning away from his problem. When thinking or doing something else, the solution suddenly comes to him. Whitfield refers to the mysterious incubation phenomenon, which acts at a time of deliberate withdrawal.

In engineering, the expression of creativity is in part internal and personal and in part dependent on the external opportunities and pressures in an individual's environment. Creative, innovative and entrepreneurial aptitudes seem to need many strengths in addition to special talents in a particular field. Joint efforts by several individuals in the form of "brainstorming" sessions have produced very fruitful results.

The adaptation of existing design concepts, configurations and details in design to achieve the objectives and requirements of specific structural projects, constitutes a very large percentage of the work executed in practice and does not necessarily involve substantive innovation. However much it may conflict with the aspirations of the individual designer for a unique and novel solution, the mere reorganisation of a design along the lines of existing works, does not necessarily detract from the merits thereof. It may be preferable in economic terms to imitate or repeat successful designs, than to invent purely for the sake of diversity.

The history of the design of engineering and building structures does, however, indicate that real progress is very largely dependent on innovative design. There are, however, many aspects of the modern design process as practised that inhibit innovation. The underlying logic which forms the very basis thereof is inherently restrictive on innovation. So also is an obligatory code of practice. The codification of procedures has become essential for good order and the standardisation of methods is an objective that can be rationally justified in terms of sound economics, provided alternative procedures based on proven research are allowed.

Koestler (1964) observed that the act of discovery actually has a destructive and a constructive aspect; it must disrupt rigid patterns of mental organisation to achieve the new synthesis. Only by escaping from the popular frames of reference and critically examining conventional methods and techniques can new ideas be developed and implemented. Disorder appears to be a necessary part of the creative sequence and uncertainty goes with it.

Interesting as they are in suggesting how creative activity occurs, these observations offer little help in describing the actual process. We do not know what goes on at the neurone level, how nerve cells make their individual contribution or act together to form new patterns and insights. But there does seem to be a basic organizing and reorganizing activity going on all the time within the mind, which seems to select and arrange and correlate these ideas and images into a pattern. Innovation in engineering is therefore a complex problem-solving sequence which is not fully understood.

Judgement and approval of creative works by the general public is usually based on the 'common wisdom' of knowledgeable groups giving guidance. Engineering works are largely judged by their usefulness, but in structures aesthetics is important.

## 3. THE LIMITS OF PROGRESS

Although there are apparently limitless possibilities of varying the detail of design conceptions by rearrangement of a particular structural configuration or fabric and changing the type and shape of its members, there do appear to be definite limits to significant progress in a more radical sense.It is almost impossible to give a clear definition of progress in general terms as it can mean many different things to different people depending on circumstances, but in structural engineering it can perhaps be most simply described in terms of the design criteria previously discussed. However, the measure of improvement even for so practical a subject, cannot be absolutely quantified because of the inherent indeterminancy of those criteria.

Much has been written about the nature of progress and of future trends. The dynamics of progress and their importance for the understanding of history, were set forth some sixty-five years ago by Henry Adams in his 'Law of Acceleration'. The acceleration can be explained in terms of reactions involving an element of positive feedback: the further the reaction has already progressed, the faster its further progress. But as Professor Gunther Stent[18] postulates: 'This very aspect of positive feedback of progress responsible for its continuous acceleration, embodies in it an element of temporal self-limitation. For since it seems a priori evident that there does exist some ultimate limit to progress, some bounds to the degree to which man can gain dominion over nature and be economically secure because of our boundaries of time, energy and intellect, it follows that this limit is being approached at an ever-faster rate.' There are many schools of thought on the general implications of this trend, varying from the pessimistic that believe that this limit will be reached soon, to others that optimistically consider such limits merely as thresholds to new developments generated by significant inventions.

In structural engineering there are obvious physical constraints that determine the bounds of the possible at any time. These bounds may be extended with the development of knowledge and new materials, but quite clearly have limits which are related to the physical realities of the earth such as the range of upper limits of the spans of various types of structures as determined by weight and strength of materials of construction. For various forms and configurations of structure, these limits can be calculated using the materials or composites of materials that are available today. Galileo (in about 1600 AD) came to the important conclusion that it was impossible to increase the size of structures to vast dimensions in such a way that their parts would hold together[19]. Super materials may extend these limits, but eventually upper limits will no doubt be reached.

Progress may also be approaching upper limits due to the apparent near exhaustion of ideas within the above-mentioned range of practical configurations. Some of these configurations were already foreshadowed in the earliest primitive constructions. The evolution of structures as a process of sophistication of these configurations, has been largely related to the development and application of materials and methods of construction to meet specific needs.

The rates of progress in the various fields of application in structural engineering, have in the past often been exponential, but usually reducing towards optimal ceilings or thresholds depending on whether or not pertinent ideas are expended, or whether subsequent innovations are of a sufficiently revolutionary nature to initiate new phases of development. New or improved materials and methods, often developing as a result of inventions in other fields, have generated innovation in structural engineering and created eras of rapid development. This happened during the Industrial Revolution and after the world wars. Various benefits have been derived from by-products of space research programmes.

The state of the art or philosophy of structural engineering has played a major role in determining the rate of progress. In the early days of the development of structures prior to 1800 AD, design methods were largely intuitive, being based on experience (often catastrophic) and very elementary and rudimentary theory. In the early part of the 19th century, very significant advances were made in the theory of mechanics of materials by Navier (1785-1836), but it took several decades before engineers began to understand them satisfactorily and to use them in practical applications. This work heralded a new period in engineering and was probably the beginning of modern structural analysis. Navier was the first to evolve a general method of analysing statically indeterminate problems. His work was followed by major contributions of other famous mathematicians, scientists and engineers whose works have been well documented[19] and form the basis of modern structural engineering.

Today we are in possession of greatly enhanced empirical knowledge, coupled with the advanced methods of modelling and analysis provided by modern structural theory with powerful numerical methods used in conjunction with electronic computers, both for analytical work and computer-aided design. The modern design engineer is thus in a better position to evaluate alternatives and take decisions. His scope has widened considerably. Optimization and decision theories are paving the way to a better understanding of methods and procedures to realize objectives. However, there are limits to what computers can do[10] and judgement will retain a most important role in structural design. This fact must be recognised as such in formal design procedures. Whereas the philosophy of cybernetics has had awe-inspiring success in its application to technological systems and in systems engineering, it is patent that the initial optimism with regard to automata with creative ability cannot be realised[20].

Hopefully we are approaching the end of what can be called the period of deterministic methods and striving to achieve greater rationality by the application of statistical (probabilistic) procedures of analysis and design. This has opened the field with almost unlimited prospects of development in applied theory, even if initially only in the form of first-stage indeterministic theories. The practical benefits relate largely to improved reliability, but the direct economic benefits appear to be comparatively marginal at this stage.

## 4. CONCEPTION AND SELECTION IN STRUCTURAL ENGINEERING

### 4.1 General

A study of the historical development of buildings and bridges makes it very evident how various factors have influenced the selection of structural form in the past[16]. The fundamental basis has perhaps always been that of trial and error from primitive huts built of mud, stones, reeds or other natural materials to provide shelter and the use of timber logs or boulders in crude masonry arches and ropes made of creepers or vines in small suspension bridges, to the lofty spires of cathedrals and modern engineering structures.

It is clear that gravity and other forces due to loads and actions have played a major role in shaping structures and determining the configurations. Experience gained in time and lessons learnt from failures, have contributed to the knowledge that we have today. These, in conjunction with the theory of structures that has grown concomitantly with practical experience and experimentation, provide the basis for conception and selection in modern engineering practice. The process has become more sophisticated, but the role of intuition and unconscious ideation, is as important as it was in the time of Leibnitz.

In form and configuration, the vast majority of innovative designs are re-arrangements or adaptations of the fabric of proven designs. Such adaptations are often related to an improved understanding of loads and actions, usually based on theoretical analyses combined with experimentation such as wind forces and earthquakes and the response of structures thereto. Several notable innovations have been apparent such as the improvement of the profiles of bridge decks of suspension bridges to reduce wind effects, methods of damping oscillations in tall buildings, or the elimination of gross movements due to earthquakes by special bearing arrangements and increasing the ductility of shear walls under extreme earthquakes.

The limiting trends referred to above, do not imply that modern structural conceptions cannot be unique, nor that a major invention is not imminent. It only implies that the frequency of such events is reduced in well established fields of structural engineering. I do not believe that structural engineering has reached anywhere near the limits of excellence. In the application of materials and construction methods, there have been a spate of inventions although some of these were foreshadowed in other fields. There is also a definite trend towards improved methods of fabrication and control resulting in better materials and improved structural performance and reliability whereby the designer's scope is increasingly widened. This process is bound to continue in the foreseeable future. The development of standardized designs for economic reasons is not necessarily a limiting process.

Some of the most substantive innovations today are related to the demands for structures in new environments such as the developments in the off-shore industry and sea structures and to a significant increase in scale such as very tall buildings and towers as well as special structures required for scientific and industrial developments.

## 4.2 Conception

Conceptual thinking is not necessarily confined to a single phase of the design process, but is essential to all the procedures for improvement. However, the initial ideas may be critical in setting objectives. Mentally, the designer should be attuned to a way of identifying the problems and seeking conceptual solutions that approximate roughly to the optimum. This comes from experience and a well-grounded understanding of how structures work; the ability to visualize the distribution of forces in structural members; to be able to assess the influence of the relative stiffnesses of members and the response to static and dynamic actions. The more refined that the designer's insight is, the sooner will the design process converge to effective and optimal solutions and the less likely will the occurrence of gross errors be.

A designer who has an understanding of the statistical properties of materials of construction and of the indeterministic nature of the response of structures to random actions, will invariably be at an advantage to attain greater consistency in the reliability of the final product. This understanding should not only apply to the behaviour of individual structural elements or members, but to the assembly thereof and the interaction among various components and the possible modes of failure. Risk is very much dependent on the combinatorial probabilities of failure of elements. Chain structures, with failure dependent on the weakest link, should if possible be avoided. This is mostly not possible, but then suitable adjustment should be made to safety factors where this is warranted. The converse applies where great redundancy is present. Similar arguments apply to single elements where the consequential damages of failure may be high. Such situations often occur during construction. First level codes of practice do not allow for such discrepancies in risk, but a competent designer will take these effects into account.

Although the conception of new structural form is largely motivated by the need to solve engineering problems, the aesthetic aspirations of the designer are inseparably involved. The extent to which he succeeds in imparting visual quality to his works, will depend on his sensibility to aesthetic values. The most successful designers of beautiful structural form clearly have a creative urge not unlike that of a sculptor. On structural projects such as bridges where visual form must come primarily from engineers, consultations with suitably experienced architects may nevertheless be beneficial. The modelling of form and configuration in this manner opens almost unlimited opportunities for aesthetic improvement by variation. This should not be confused with mere ornamentation. The various creations of Maillart and many others bear ample evidence of the ability of creative engineers to sculpt structural forms in a pleasing manner by going beyond pure functionalism in the process of solving specific engineering problems, but staying within acceptable economic bounds. Aesthetic design of a structure and its parts should therefore not be done as an afterthought, but should at all stages be part of an integrated process.

Designers tend to develop various optimizing techniques that either minimize internal energy by for example using configurations or forms of structure that generate resistance by extensional forces in preference to bending, or by minimizing the response to actions, for example by designing shapes to reduce wind effects. Some would minimize materials or relate the design very closely to the construction methods. These objectives should not however be singled out.

The recent advances in methods of theoretical modelling and analysis and knowledge of structural mechanics including the post-elastic and post-buckling phases, have opened new avenues of design and analysis which often extend beyond the reach of intuitive insight. Methods like finite element analyses have become extremely powerful tools to achieve accurate simulation of complex structural behaviour. Conceptual design has thus done a full circle and has reverted to a trial and error process of a nature which would have been impossible at the levels of complexity we are referring to without the modern generation of computers. In design practice things generally happen more crudely, but the benefits of the results of the more sophisticated analyses are usually passed on to set new standards. There is a better perception of the statistical nature of actions such as for example the structure of wind and the nature of earthquakes and the response of structures thereto. However, problems in predicting certain trends, such as the modelling of traffic loading on highway bridges which is not a purely random phenomenon but subject to human manipulation, have once again become evident. Authorities and experts in various countries still differ greatly on modelling of highway traffic. The same problems apply to floor loadings in buildings.

### 4.3 Selection

Selection is a very important part of structural design and consists of a searching for optimal solutions by identification of possibilities, followed by evaluation and comparison, leading to the final choice. Whereas classical optimization procedures have limited application in structural design, numerical methods have opened new approaches. However, judgement still plays an important role in practice. Essentially the decision-making process takes two forms. Firstly there are procedures for finding the best solutions for particular members or configurations of members and which usually consist of the step-wise or incremental adjustment of dimensions or forms in precalculated or random directions to obtain optimal solutions. Classical and numerical procedures can be applied in some of these cases. The other method distinguishes between alternatives that differ discretely or absolutely with respect to the parts or the whole, such as in alternative designs with different configurations or of different materials. The basis of selection should be total utility as defined in chapter 1, even if it can in practice only be partially done by value analysis in terms of monetary costs with a qualitative assessment of other equally important but subjective criteria such as aesthetics and environmental impact.

## 5. CONCLUSION

Although no part of the design process is unimportant, the choice of structural concepts is crucial. It challenges all those inherent and acquired abilities by which a designer takes decisions that determine the essential quality of an engineering or building structure. Although computerisation is reducing the role of human designers in analysis and in the production of documentation, conceptual design will remain the domain of the engineer and well designed engineering structures will therefore always bear the stamp of individual designers.

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