THAT STRUCTURES MAY BE SAFE, SOUND AND ECONOMICAL

BY

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UNIVERSITY OF LAGOS PRESS - 1989
INAUGURAL LECTURE SERIES
Erratum

P. 23 Minimize, or Maximize \( f_i(x_i), \ i = 1, \ldots, N \)

Subject to constraints \[ f_j(x_j) \begin{cases} < & 0, \ j = 1, \ldots, M \\ > & 0, \ j = 1, \ldots, M \end{cases} \] (1)

\( x_i \geq 0, \ i = 1, \ldots, N \)

That structures may be safe, sound and economical

An Inaugural Lecture delivered at the University of Lagos on Wednesday 22\(^{nd}\), February, 1989

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My choice of subject for this lecture has been influenced by the following reasons. The first is my awareness that the profession of engineering is still not properly understood in this country. Secondly, that the recent cases of structural collapses have often bedevilled our views to the successes of structural engineering. Thirdly, that most of us in our individual capacity or as representatives of private sector organisations or of government institutions often have to interact with structural engineers and it will be useful to know how and why structural engineers function as they do.
It is indeed a great honour for me to have been invited to deliver the first lecture in the series of Inaugural Lectures for the 1988/89 session. I can think of many reasons why this event is significant and I believe two of these reasons are worth mentioning. This is the first time that a former student of the Faculty of Engineering of this University is delivering an Inaugural Lecture here. It is a very pleasant thing for me because this happens to be the Silver Jubilee Year of the Faculty and I was one of the foundation students of the Faculty. Secondly this is also the first time that an Alumnus of this University is presenting an Inaugural Lecture.

I do not consider this event as a personal achievement, rather I see it as representing a conspicuous landmark, in the voyage of our university to maturity. One of the major functions of a university is concerned with the production of high level manpower for all sectors of the national economy. It is my view that a university's success in this task can be assessed partly by how effective it performs its role of producing the high level manpower it requires to sustain itself particularly in the academic cadre. In this respect the University of Lagos is on the right track. I consider myself lucky to have had the privilege of being one of the first set of students of this university to fully join the academic staff and I consider it a great honour that I have this unique opportunity of presenting the first Inaugural Lecture to be given by an Alumnus of the university.

My choice of subject for this lecture has been influenced by the following three reasons. The first is my awareness that the profession of engineering is still not properly understood in this country. Secondly, that the recent cases of structural collapses have often beclouded our views to the successes of structural engineering. Thirdly, that most of us in our individual capacity or as representative of private sector organisations or of government institutions often have to interact with structural engineers and it will be useful to know how and why structural engineers function as they do.
My intention in this lecture is therefore to broadly discuss the fundamental principles of modern structural engineering science. Since structural design is the heart of structural engineering, I will concentrate on the nature of structural design or what one may call the philosophy of structural design. Philosophy is used here to denote the system of theories and general intellectual framework within which structural engineers operate. Baker (1974) neatly summed up the salient points of this framework in the James Forrest Lecture delivered at the Institution of Civil Engineers, London and I quote,

"A modern designer, if he is creative conceives for a particular requirement many designs in his imagination. He then eliminates the superfluous and in fact by using intuitive judgement, common sense and experience, in conjunction with calculations of strength and cost. Safety is uppermost in his mind if he is concerned with tall or large span structure."

Hence structural design is involved with the provision of structures that are safe, sound and economical through the calculation of strength and cost and the use of common sense and intuitive judgement. I shall therefore be discussing some events and discoveries which have contributed to the growth of structural engineering design knowledge. I find it convenient to present the discourse under three broad headings which are by no means mutually exclusive.

These are:
(i) Structural Safety and Reliability
(ii) Structural Strength and Integrity
(iii) Structural Optimization.

It is hoped that in the process of the presentation some of the intrinsic strengths of structural engineering will be highlighted, some of the weaknesses will be exposed and relevant recommendations for improvement will be put forward.

However, it would be useful to start by answering the question:

What is a Structure?

A structure is popularly defined as any assemblage of materials which is intended to sustain loads. Structures abound in nature. Indeed since every plant and animal and nearly all the works of man have to sustain some forces, in a way they are all structures.

This lecture is concerned with engineering structures which are man-made contraptions designed to resist loads. The answer to the question of how an inanimate solid, like steel, stone or timber, is able to resist a mechanical force or indeed sustain its own weight, lies at the root of the study of structures. This was an intellectually difficult subject which proved too difficult for even Galileo (1564-1642), philosopher, mathematician extra-ordinary and in a sense the first modern physical scientist. That we now understand the problem as we do today goes to the credit of Robert Hooke (1635-1703).

Hooke established the relation between the forces on elastic bodies and the deformations they produce. He argued that a material or structure will resist a load by pushing back at it with an equal and opposite force. Each time we push down on the floor with our feet, the floor must push back on our feet. This auditorium in which we are all seated exerts some pressure on the earth through its foundation. The total force exerted is the sum of the weight of the auditorium and the weight of all the objects inside it including the weights of all of us. The earth in turn must exert an equal and opposite force on the foundation. This phenomenon is implicit in Newton's third law of motion on the fact that action and reaction are equal and opposite.

What this means is that a force cannot be lost. Every force on a structure must be balanced by an equal and opposite force within the structure. This is true of all structures and for all points on a structure, no matter how simple or complicated. It is true for floors or roofs of residential buildings, offices, factories, gymnasia, churches
and mosques. It is true for bridges, motor vehicles, ships and aeroplanes.

If the condition is not satisfied, that is if the forces on a structure are not in equilibrium or balanced by the forces within the structure the structure becomes unsafe, it will either break or set off in motion. In the case of our auditorium, if the total force with which the auditorium pushes on the ground is greater than the force exerted by the ground on the auditorium, it will begin to sink. If however the ground were to push with a greater force the auditorium can crumble or take off like a rocket. This is what happens during an earthquake.

By about 1676 Hooke was not only convinced that solids resist weights or mechanical loads by pushing back at them but also made two important observations on the subject. The first is that every kind of solid changes its shape either by stretching or contacting when a mechanical force is applied on it and secondly that it is this change of shape which enables the solid to push back. The deflection or change in shape which occurs when a weight or mechanical force is applied on a solid varies enormously in practice depending on the size, geometrical shape and the type of material from which it is made. Whilst rubber or flesh can be deflected by small forces which can be applied by the finger, other materials such as wood, stone and most metals are considerably stiffer.

Hooke tested a variety of objects made from obvious geometrical forms and found that some materials recover their original shape when the load was removed. He found that the loading and unloading could be repeated indefinitely without causing any permanent change of shape. Such behaviour is called elastic. Certain materials like putty and plasticine do not recover completely but remain distorted when load is applied on them and then taken off. This behaviour is called plastic.

Although many of the materials which Hooke considered to be elastic were later found to be imperfectly so after more accurate and sophisticated methods of testing were adopted. In spite of this fact, Hooke's observations remain true in a broad sense and still provide the basis for modern science of elasticity. Indeed, the idea that most materials and structures behave very much like spring may seem very obvious today but it is clear from Hooke's diary that to get to the conclusion cost him great mental effort and many doubts.

After trying the ideas in series of private arguments, Hooke published the results of this experiments in 1679 in a paper called 'De potentia restitutiva or of a spring'. It contained Hooke's famous statement 'ut tensio sic vis' which translates thus 'as the extension, so the force'. This principle which has now been known for over three centuries is called Hooke's law and is definitely one of the great intellectual achievements of the history of structural engineering.

STRUCTURAL SAFETY

From time immemorial safety has been an important factor in the design and construction of structures. As far back as 1700 B.C. Hammurabi, the great ruler of the ancient city of Babylon realised the importance of the safety of structures and therefore enacted a severe law to control speculative builders who would otherwise have sacrificed safety for other considerations. Hammurabi's law states (Baker 1974) "If a builder builds a house, but his work is not strong enough and it happens that the house he has built collapses causing the death of the owner of the same, the builder will be condemned to death".

The Bible emphasizes the importance of the safety of structures by using it figuratively to illustrate some aspects of Christian ethics. In Matthew 7:24-27 and Luke 6:46-49 reference is made to the safety of houses built on good and bad foundations to illustrate the consequences of good and bad conducts.

The general public is sensitive to matters connected with the safety of structures and reacts with concern to news of structural failures and accidents. One is therefore not surprised at the public outcry that accompanies the news of a structural failure. The latest of
such in this country occurred when the Bagauda Dam collapsed in August last year.

Compared with the manufacturing industry, civil and structural engineering tend to be primarily concerned with the design and construction of large scale structures using readily available and relatively cheap materials. As a result there is very little duplication of design solutions and prototype testing is restricted to component of structures. It is inconceivable for one to think of testing to failure a multi-story building complex or a dam. In spite of the fact that no structural engineer would wish his name to be associated with a collapsed structure, the rare occasions when structures collapse provide opportunities for engineers to learn some new lessons.

Blockley and Henderson (1980) compared the growth of scientific knowledge to growth of engineering knowledge. They adopted the postulates of Popper (1976) and Kuhn (1962) to the effect that the scientist's primary aim is to falsify his conjectures as ingeniously and as well controlled a manner as he is able. The engineer's method, Blockley and Henderson argued, involved cautious conjectures which will not be falsified. Engineering failures represent instances when the engineer's conjectures are falsified and are therefore central to the growth of engineering knowledge.

Structural failures have contributed immensely to the growth of structural engineering knowledge. A classic example of this is the failure of the Tacoma Narrows Bridge in November 1940. The Bridge failed due to aerodynamic instability for which suspension bridge design theory at that time made no provision. The design of early suspension bridges were done intuitively and empirically until 1850 when Rankine's approximate method was available. Melan's theory was developed at the end of the 19th century. The report of the investigation on the Tacoma Narrows Bridge concluded that the bridge was well designed and built to resist safely all static forces. The designer Moiseff, who was a leader in the profession in his time, appeared to have been unaware of the possibility of large vibrations and for the purpose of economising on materials had chosen plate girders instead of the usual truss. Ever since the failure of the Tacoma Narrows Bridge, increased attention has been given to the dynamic behaviour of long span bridges and the understanding of the damping capacity of light and flexible structures.

Similar cases of structural failures which have drawn attention of engineers to weaknesses in design and/or construction practice abound. I shall however illustrate the point with three more cases, two of these I have some direct and indirect personal experience of and the third is a case which many engineers in this country are familiar with. These are:

1. The Failure of Cooling Towers
2. The Failure of Steel Box Girder Bridges
3. The Barnawa Flat Disaster

Failure of Cooling Towers

On 1st November 1965 three cooling towers collapsed from a group of eight towers at Ferrybridge, Yorkshire, England during a severe westerly wind which was subsequently estimated to correspond to a return period of about 5 years. The towers, built for the Central Electricity Generating Board in England in 1962, were 114.3 metres high and had the largest shell diameter and greatest shell surface area ever built at that time.

The shell was designed using conventional membrane theory to determine the static structural response. A basic wind speed of about 100km/h at 12 metres above ground and a power law exponent of 0.13 for the variation of speed with height were assumed. No reference was made to the code of practice C.P.3 Chapter V (1952) for wind loading. The wind distribution around the shell was required to be in accordance with the data provided by the National Physical Laboratory report for work at high Reynold's number.

The Committee of Inquiry found that the wind loading was greatly underestimated. The aerodynamic effect was not taken into consideration as the National Physical Laboratory report was based...
on mean wind pressure on a model of an isolated tower in a wind tunnel. The effect of grouping was to create a turbulence on the leeward towers which collapsed.

In addition to this point, the Ferrybridge cooling tower collapse directed attention at the need for structural engineers to carry out accurate dynamic analysis of thin shell structures like cooling towers. It became clear that data on the natural frequencies and modes of free vibration of the shells will help engineers to design shells in which the possibility of catastrophic resonant vibrations during severe wind gusts are eliminated.

In the thesis which I submitted to the University of London and for which I was awarded a Ph.D degree in 1972, a finite difference solution of the equations of motion was used as the basis of a versatile computer program for determining these dynamic characteristics for shells of revolution of various meridional shapes. Some aspects of this work were presented in Akeju and Munro (1974). The same results were confirmed through the use of a semi-analytical finite element formulation in Akeju et al (1981).

The Failure of Steel Box Girder Bridges

A box girder bridge in Milford Haven, South Wales, U.K. collapsed during construction in June 1970. Collapse occurred when a side span which was being cantilevered out from a completed anchor span hinged over its supporting concrete pier. Four months after the collapse of the Milford Haven bridge, one of the side spans of the West Gate bridge in Melbourne, Australia over the River Yarra failed.

These two collapses together with the buckling failure of another box girder bridge in Coblenz, Germany focussed attention on many aspects of steel box bridge practice. It became clear that there was need for appraisal of the contractual procedures, design rules, research methods and recommendations of codes of practice. The Merrison Committee which was set up to look into these matters specifically investigated the collapse of the Milford Haven and West Gate bridges.

Following the release of the report of the Merrison Committee, the Department of Environment in the U.K. commissioned a number of consulting engineering firms to carry out design appraisal of all existing box girder bridges in the United Kingdom. From November 1971 to November 1972 I worked in London for Messrs G. Maunsell and Partners on this project. Using the Merrison rules, we carried out the design appraisal of many bridges including the ill-fated Milford Haven Bridge.

The Merrison rules set the pace for far-reaching strides in bridge design practice. Research work into loading, safety factors, aerodynamic effects and strength of welded members and connections were encouraged. Some of the findings of the research efforts have now been incorporated in the code for steel bridges BS 5400. In Part 3 of this code partial safety factors to provide a balance between safety and economy are selected through procedures, which for the first time ever in a code, were based on reliability theory. Assessment of fatigue life treated in Part 10 of the same code incorporates results of extensive research and is more thoroughly treated than in previous documents. Thus the panic resulting from the collapses of box girder bridges have yielded some dividends in that now designers can make the fullest use of the potential strength of plated construction to produce highly competitive structures.

The Barnawa Flat Disaster

On the night of 23rd September, 1980 a three storey block of flats at 20, Congo Street, Barnawa Low Cost Housing Estate of the Kaduna State Housing Authority collapsed resulting in loss of life and property.

The report of the committee of experts set up to investigate the circumstances leading to the disaster cleared the architectural design but considered the structural design suspect. The report argued that the foundation which consisted of combination of an in-
filled block wall and reinforced slab could not reasonably be considered to represent a cellular raft foundation because it did not provide sufficient stiffness required of a monolithically cast cellular raft foundation. The committee recommended amongst others that raft for the type of building encountered at Barnawa should be made fully cellular with beams cast monolithically with the raft slab and ground floor. It also recommended that the use of block walls as load bearing walls for buildings of more than two storeys be abolished and that in the case of two storeys the blocks must conform to necessary specifications in practice.

The report was highly critical of the degree of supervision given by the client Ministry and found the contractor's supervisory staff to be technically inadequate. There did not appear to be a proper definition of the exact role and responsibilities of the various groups of supervisory staff on the site. It recommended that the contractors and clients on projects should ensure that the various groups of supervisory staff are adequately qualified and are able to carry out their duties as defined in the contract documents.

The purpose of discussing these cases of structural failures is mainly to illustrate the way in which they have contributed to the growth of structural engineering knowledge. The study of structural failures can be likened to pathology in medicine where a specialized group of doctors study diseased tissues so that the entire profession can benefit from this knowledge. The profession has benefited immensely from the Ferrybridge Cooling Tower collapse and the Box Girder Bridge failures in that the research works carried out as aftermaths of the collapses, have their results incorporated in codes of practice. There is no evidence that in this country we have benefited in a similar way from carefully conducted investigations like that of the Barnawa Flat Disaster. More often the reports of the investigations are not available to practising engineers, not to talk of influencing the development of codes of practice.

For a structure to be safe, certain undesirable events must be avoided. These events can be categorised into three groups:

(i) Exceeding the various limit states of structures.
(ii) External random hazards which threaten the safety of a structure for example fire, floods, vehicle impact and explosion.
(iii) Human errors in design or construction.

A number of researches such as those of Sibly and Walker (1977), Mataousek (1976), Blockey (1977) and Akaju (1981) have reported the preponderance of structural failures due to human errors. Hauser (1979) and Fraczek (1979) who analyzed over a thousand failures of concrete structures in North America and Europe also found that the central problem in structural safety was the gross errors committed by the individuals involved. Human errors cover a wide range of mistakes and misdemeanours varying from obvious cases caused by inexperience and/or negligence to the more subtle cases involving for example new material, new structural form and new construction procedure. The demarcation between these categories of errors cannot be clearly defined. The view is generally held that obvious human errors can be detected by good project control and management procedures whilst the errors of the subtle type are impossible to predict and difficult to detect or prevent. The most difficult type of subtle human error to detect is the type first identified and described by Pugsley (1969) as errors associated with the engineering climate. He identified the parameters which affect structural safety and compared them to the way in which the parameters of climate such as temperature, humidity and rainfall affect human health. The parameters which Pugsley suggested for consideration in this situation are political, financial, scientific, professional and industrial pressures. Whilst the interrelationship of the parameters is easily recognised, it is instructive to examine the engineering climate within these broad divisions.

For example, the last civilian government of Lagos State initiated the construction of a mini-sport complex at Joel Ogunnaike Street, G.R.A. Ikeja. The complex was to have accommodated two grandstands, a swimming pool and pitches for various games. A lot of political pressures was imposed on the project. It was to have been
commissioned in time for the Independence Anniversary celebration on 1st October, 1983. Closely related to this was the fact that both the consultants and contractors on the project were in-house. The policy was meant to save cost but nonetheless it imposed considerable financial pressures on the project. The initial tender bid was too low and had to be increased drastically. The professional climate was inadequate for a project of its magnitude in that the orders of the consultants were constantly challenged and at times flouted by the contractors as both of them were responsible to the same higher authorities. Consequently standard contract procedures were not utilised and grave errors were committed.

In spite of the fact that a lot of money had been spent on the superstructure of one of the two grandstands and substantial amount of work had been done on the other grandstand, the Akeju Capital Project Review Committee, which was among others set up to advise the Government on the integrity and safety of the structure, recommended the demolition of the grandstand. This decision was very painful but was taken after careful consideration of all the possible remedies to salvage the structure. We should consider ourselves lucky if our errors can, as in this case, be reckoned in terms of naira and kobo but not in terms of number of lives lost and people maimed.

The avoidance of human errors depends on many factors: proper demarcation of responsibilities, setting up an effective channel of communication, charity of thought and above all a thorough understanding of the way a situation develops before a structural failure.

Conceptual Model of Structural Failure

One possible model (Blockley, 1980) to help visualise the way a situation develops before a structural failure is provided by the application of the Catastrophe Theory of Rene Thom (1975) and Christopher Zeeman (1977). The principle used in the Catastrophe
Theory falls in the branch of mathematics called Topology. The theory was introduced to enable one to model situations in which sudden jumps, or changes in state or catastrophes occur. Situations of this kind abound in nature and it has not been possible to model them by conventional mathematics. The model consists of a folded surface called a cusp catastrophe. It is a three dimensional graph with axes of time, some measure of project success and some measure of the pressures on the project. The process of design and construction of a structure may be imagined to consist of a path on the surface of the three dimensional space with a fold. The surface is normally not smooth. There are irregularities in the form of steps and reversals which can only be defined in a fuzzy sense. Three typical paths can be identified and these are labelled A, B, and C. Path A represents a successful project in which the pressures are not above normal and do not threaten the safety of the structure. Path B is the route of a troubled project with pressures above normal and therefore creates problems for those involved in its construction. As the pressures increase the path is pushed out towards the fold of the surface but eventually the disputes are settled, the problems solved and consequently the pressures diminish and the structure successfully completed. Path C represents a project where failure occurs. The pressures become so great that some incident triggers the path over the fold. A sudden jump results giving rise to a sudden steep change in the state of the system from a state of success to a state of chaos.

Very deep and stimulating parallels have been shown to exist between engineering phenomena and these topological models. Thompson and Hunt (1975) used it as the basis of a unified static bifurcation theory. A splendidly clear account of the delineation between the static ingredient of catastrophe theory and the dynamic instabilities that arise in the wind induced flutter of aircraft and suspension bridges where the response is not governed by an energy potential, is contained in the book by Thompson (1982). One of the many interesting examples discussed by Thompson is a theory that the Tacoma Narrows suspension bridge failure was due to a combination of more than one of the three possible distinct mechanisms of aeroelastic excitation.

In the context of structural safety however it is Zeeman's many interesting applications of cusp catastrophe in the social sciences that are directly relevant. One of these applications is in psychology where Zeeman used Catastrophe Theory to describe the conflicting drives of rage and fear. This application has provoked some critical comments and controversies because of the introduction of spurious quantification. The modelling of structural failure using Catastrophe Theory is also capable of being criticised in the same way. For this reason it can only be regarded as an aid to conceptual understanding of the phenomenon.

### Fuzzy Set Analysis of Safety

The current formulation of structural reliability problem leads to the calculation of a notional probability of failure in which the uncertainty due to human error is not included. This is because the notional probability of failure is concerned with the variabilities of load and strength parameters which can be quantified with some degree of clarity whilst the effects of human error are not so clearly defined. There is therefore a need to deal with this problem through some kind of mathematics which is different from the conventional type.

Blockley (1981) has suggested the application of the mathematics of approximate reasoning for this analysis. The concept is based on the principle of fuzzy sets which was first proposed by Zadeh (1965), an American system scientist working in the area of control engineering.

Zadeh put forward the notion that human beings are able to summarize masses of information and then extract important items relevant to their particular problem because we think approximately: that is in terms of classes or sets of objects where the transition from membership to non-membership is not abrupt but gradual. The implication of this notion is simply that human reasoning is not based
on two valued logic or multi-valued logic but on fuzzy logic. As the complexity of a system increases our ability of making precise and yet significant statements concerning its behaviour diminishes. Consequently the closer one looks at real world problem which is usually complex, the fuzzier its solution becomes. This problem was soon found to be relevant to many subject areas such as economics, medicine, management science, psychology and sociology, where mathematics has so far not had very significant impact. This led to an explosion of research work on fuzzy sets and the mathematics of approximate reasoning.

In the application to structural analysis the value of certain parameters are subjectively estimated in two ways using linguistic variables such as large and small with suitable operators, first in size and second in importance or weighting. Blockey’s (1976) checklist consists of eleven parameters which are grouped into six broad heading as follows:

**Materials**

1. The degree of confidence in the analytical model used to described the behaviour and variability of the parameter (e.g. elasticity).
2. The size of uncatered for effects (e.g. residual stresses).

**Type of structure**

3. The degree of confidence in the analytical model used to analyse the structure (e.g. so called fixed beam column connections).
4. The complexity of the calculations (arithmetic errors).

**Design experience**

5. The amount of experience of the design organisation in similar type of structure.

**Time**

6. The amount of pressure on the designers due to shortage of time.

**Construction**

7. The degree of confidence in the construction methods to be used.
8. The amount of experience of the various contractors on similar types of structure.

**Externals**

9. The industrial climate
10. The financial climate
11. The political climate

There are difficulties in the use of the method to assess future projects rather than historical projects. The past projects benefit from historical perspectives whilst future projects do not have this benefit. Judgement about the future can only be made on the basis of experience of the past plus the ability of the analyst to organise his experience into hypotheses.

In addition the use of fuzzy logic model of safety to monitor the safety of a structure during its design and construction may raise ethical problems if subjective assessment of the competence of other personnel are being made.
STRUCTURAL STRENGTH AND INTEGRITY

In spite of the promising start, the science of elasticity witnessed very little progress in the eighteenth century. Hooke had broadly explained the manner in which structures worked, however he dealt with forces and deflections by considering the structure as a whole instead of investigating the forces and extensions at any given point. Hooke was concerned with the deflection of a spring or a bridge or a dam or a tree when load is applied to it. This reasoning set the pattern for the few scientists who tried to study the subject in the eighteenth century and well into the nineteenth century.

The concept of the elastic conditions at a specified point inside a material is embodied in the concept of stress and strain. The pioneering work on this concept is credited to Augustin Cauchy (1789-1857), who put forward the ideas in a generalized sense in a paper to the French Academy of Sciences in 1822. Stress is a measure of the magnitude of the force that is pulling the atoms apart or together at any point in a material which is resisting an external force whilst strain is a measure of the proportion by which the bonds between the atoms are stretched or compressed. Thus, stress indicates how hard the atoms at any point in a material are being pulled apart whilst strain tells us how far they are being pulled apart. The concept of stress and strain removed the confusion created by Hooke's law in its original form between the strength of materials and the behaviour or strength of a structure.

The strength of a structure is the load which will break the structure. It applies to some specific structure. The strength of a material, on the other hand, is the stress required to break a piece of the materials. Some materials have standard sizes and shapes for determination of such strengths for example the steel test-pieces used for determination of ultimate tensile stress in tensile testing machine and the concrete cubes and cylinders.

The object of many strength calculations and of many tests on specimens of materials is to predict the strength of a structure from the known strength of its material. Thus, an engineer's involvement with stresses and strains is only as a means to an end, that is to enable him design safer and more effective structures and to give him a better understanding of how structures behave.

Structural engineering is based on two hierarchy of hypothesis. These are analysis and design. The highest level hypothesis used in structural response analysis is that of Newtonian mechanics with its notion of space, time, force and mass. Considerable progress has been made by structural engineers in the use of Newtonian mechanics for analysis of structures. Such progress has, however, been limited by the type of tool available for carrying out the numerical work involved. Hardy Cross moment distribution method was an outstanding contribution in this respect for it opened up avenue for structural engineers to handle more complex problems than they could handle before its discovery. For many years the moment distribution method was the favourite tool for analysing continuous beams and rigid frame structures. There were, of course, other variations of this scheme but they all have a common denominator in that they are all based on an iterative solution of the slope-deflection equations.

The finite element was developed intuitively in the middle of the fifties as an offspring of matrix frame analysis. The intuitive process was later found to be justifiable within the context of Newtonian Mechanics. This discovery contributed to the rapid growth of the finite element method.

The finite element method is now being freely applied to solve many types of problems in engineering analysis. It has been extremely useful in modelling problems of fluid flow, heat transfer, soil mechanics and magnetic field analysis. Both linear and nonlinear behaviours can be modelled by the finite element method. It has also been successfully applied to time dependent problems.

Recent developments in microcomputer technology have further emphasized the promising future of the finite element method.
An argument against the method was that it needed large frame computer hardware for its implementation. It is a great consolation that microcomputers are now not only supplying the type of memory required for finite element implementation, they are also within the reach of many more users. Another plausible criticism of the finite element method is its need for laborious data preparation for most practical applications. The use of automatic mesh generation programs coupled with the improved interactive and graphic capabilities of present day computers has ameliorated this problem.

One of the major reasons for the versatility of the finite element procedure is its ability to model irregular structures accurately. In addition, the use of numerical integration technique has opened up a wide area of research for plates and shells in particular. Very simple elements have been developed whilst complex elements have also been developed. We have operated at the two ends of the extremes. In Akeju (1986) a simple axisymmetric element has been used to study the effect of the reduced and selective integration techniques on the vibration of thin circular plates while in Akeju, Kelly, Zinkiewicz and Raju (1981), the dynamic characteristics of a complex structure in the form of the spool of the Rolls Royce RB 211 Jet Engine was modelled with success.

Another important measure of structural integrity is concerned with the assessment of the stability of structure. About fifty years after Sir Isaac Newton laid the foundation of mechanics in his *Principia* of 1686, a famous Swiss mathematician, Leonard Euler in 1744 used his newly invented Calculus of Variation to investigate the equilibrium configuration of a compressed elastic column. This solution gave birth to the classical Euler strut.

The development of the analytical energy approach in mechanics is credited to Lagrange. Through this method important generalization that could not be established by Newtonian vector method were conveniently determined. One major conclusion from this is the fundamental energy theorem that a minimum of the total potential energy is sufficient for stability of a structure. It was, however, the French mathematician, Henri Poncaire, who later sketched a general bifurcation theory and created the global quantitative dynamics in which much of stability theory is now viewed. In his memoir of 1892, Liapunov defined stability with mathematical precision and introduced the generalized energy function that now bears his name. In one of the two methods proposed by him and referred to as the direct method of Liapunov, stability information is obtained by investigating the nature of certain constructed functions or functionals.

This qualitative method possesses a great advantage especially for fairly complex problems in that explicit solutions of the governing differentials equations are not sought. However, the approach has inherent limitations. There are no known universal methods for constructing Liapunov functions or functionals and sometimes stability information obtained by a particular investigator solving a specific problem depends to some extent on the ingenuity or sharpness of the analyst. Although some innovative techniques for constructing Liapunov functions have been reported in the literature, these innovations do not appear to be extended fully to the problem of continuous dynamic systems. The major reason for this is the Lagrange (Dirichlet) theorem which relates stable equilibrium to a minimum potential energy, whilst being valid for all discrete systems, has no rigorous counterpart for continuous systems.

In Akeju (1982) the stability of lateral buckling of I beams subjected to pure bending is investigated by means of Liapunov’s direct method. Akeju (1985) presents another application of Liapunov’s direct method to problems of torsional - flexural buckling of columns.

### STRUCTURAL OPTIMIZATION

The history of architecture and structural design has from the earliest times been characterized by efforts to produce structures which are better than their predecessors. Such structures were...
expected to be more efficient in the use of materials and in the performance of the functions expected of them. This process of continuous search for better structures is termed structural optimization. With the development of fast computing facilities and corresponding computation techniques, structural optimization can now be defined as follows: The development and application of automated techniques for improving designs within the context of well defined cost and specified constraints. This definition therefore implies that structural optimization is an aid to designers for quantitatively choosing an economical design from an array of acceptable conceptual designs. The computer is the central tool for implementing structural optimization. It is used for searching and sorting through the various alternative designs. It arrives at a design which the engineer would of course have obtained, were he able to compare the time and effort. Saving in design time and cost are the principal advantages of optimization. The method also reduces much of the effort in the input output process and costly data handling procedures.

Developments in the field of structural optimization have helped in raising the hierarchy of design. It is now possible to introduce into the optimization process design variables which in the past, were thought to be in the realm of creative decision making and hence difficult to program. Processes that can be identified in this respect include description of geometry and shape of structures, choice of materials, complete design including comparison of element types, overall fabrication and erection costs and material availability.

By far the greatest achievement of structural optimization is the demonstration that the largely ad-hoc processes of structural design, which seemed to have little mathematical logic, could now be expressed formally in mathematical terms with much rigour and logic. Thus, an otherwise fragmentary subject has been unified under a formal mathematical basis.

Definition of the Structural Optimization Problem

Minimize, or Maximize $f_i(x_i) \quad i = 1, \ldots, N$

Subject to constraints

$\sum_{j} g_j(x_i) < 0 \quad j = 1, \ldots, M$

where the variable $x_i \quad i = 1, \ldots, N$ usually represent physical parameters of the structure which is being designed such as dimensions, spacings, bar sizes, plate thicknesses. The objective or merit function $f_i(x_i)$ is the efficiency criterion in the form of minimum structural weight or minimum cost which is to be optimized. The M constraints $g_j(x_i)$ which may be equalities or inequalities specify all the relevant restriction like for example known material properties, requirements of code of practice, fabrication requirements and general shape requirements. The N non-negativity conditions specify the practical nature of the problem in that all the engineering variable must be real and feasible.

Solution Methods in Structural Optimization

The most general structural optimization problems are large and highly non-linear. That is, all or some of the governing equations or inequalities are non-linear. The most direct method of solution is therefore through the use of mathematical programming method. The most popular amongst these for non-linear problems are dynamic programming and geometric programming.

There are two indirect ways of handling non-linear optimization problems. One of this method is by sequential linearization. In this case each of the function $f_i$ is replaced by a linear approximation which has the
same value and gradients as the trial function and then solved as a linear programming problem.

A second group of simplification consists of the use of penalty function methods. Here the constrained optimization problem is converted to a sequence of unconstrained problems by defining a function composed of the original objective function and each of the constraints multiplied by a penalty factor $\lambda_i$.

A lot of work has been done on the penalty function methods in both the interior and exterior methods where the search involves starting from the feasible and infeasible regions, respectively. By far the most popular algorithm in this approach is the Sequential Unconstrained Minimization Technique of Fiacco and McCormick (1968).

In linear programming problem all the functions $f(x_i)$, $i = 1, \ldots, N$ are linear. Linear programming problems are fairly simple and well known. It is this simplicity which has contributed to its use sequentially in solving nonlinear problems.

In all the problems described so far no assumptions are made about the location or nature of the problem. The optimum is obtained by some search procedure based on the mathematical nature of the equations defining the functions $f(x_i)$, $i = 1, \ldots, N$. In contrast to this procedure one may solve a structural optimization problem through a knowledge of some characteristics of the optimum.

The optimality criterion approach involves an investigation of the nature of the optimum for the purpose of determining the conditions, if any, governing the optimum problems. The conditions are then used to develop a search scheme for the solution of the problem.

A set of mild simplifying assumptions which aided the definition of the optimum design of a composite bridge deck was presented by Akeju (1976). With these assumptions, Orangun and Akeju (1977) carried out a parametric study of the characteristics of the optimum design of composite bridge deck. Akeju and Orangun (1979) employed the results of the last work to develop an automatic scheme involving a three stage direct search algorithm for the selection of girders for the optimum design of simply supported composite highway bridge deck from a list of universal beam sections.

In spite of the progress made in the past two decades or so in the field of structural optimization, the method does not seem to be popular with engineers in the field. This is partly because of the fact that most structural optimization techniques only determine local optimum. Many factors which are not often considered influence the global optimum of a problem. It may be necessary to consider factors like initial costs, demolition costs, maintenance costs, chances of failure, direct cost of failure and indirect cost of each type of failure for one to be able to realistically assess the global optimum of a problem.
RECOMMENDATIONS

I now wish to reflect on some of the concepts discussed earlier on in the course of this lecture and make some recommendations, not on calculation techniques and design procedures but on education and training, research and codes of practice which are also considered to be relevant to the well-being of the engineering profession in general and the structural engineering profession in particular.

The engineer often has to handle information of widely varying type and dependability. There is a tendency to put a lot of effort into the information which can be tested whilst relatively little effort is devoted on other equally important information which is difficult to test. For example, a vast amount of effort is devoted to structural response analysis in contrast to the effort put into analysis of loads on structure and their safety. There is no doubt that structural response analysis plays a primary role in the design of structures but that does not mean that it should be the only factor to receive attention in the process of designing structures. We require to put more effort than hitherto into load and safety analysis.

The use of the elastic theory in the nineteenth century led to the development of limiting stress philosophy as a criterion of failure and seemed to have taken attention away from ultimate failure as a criterion. However, subsequent development of the plastic theory brought attention back to ultimate failure as a criterion of failure although the two ideas were not brought together until the introduction of the limit state design philosophy. With the various subdivisions of the ultimate and serviceability limit states, a first attempt was made at categorising failure types and more comprehensive criteria of safety were established.

Through the use of a probabilistic approach, recognition was given to the variable nature of the phenomenon with which design had to cope. Reliability theory is now being used to choose the partial safety factors although it must be stated that conventional reliability theory as now used in other applications into structural engineering has not been able to address the actual uncertainties which the structural designer has to cope with. This is because it relies principally on the probability theory of precisely defined events. The point has been made in the course of this lecture that events for defining the safety of structures have a measure of uncertainty associated with them. It is therefore necessary that the structural engineer build a model of structural safety which could be updated during the progress of a project as more information becomes available. The mathematics of approximate reasoning has been recommended as a good tool for this task.

The complexity of human involvement in the case studies of structural failures that have been carried out makes it mandatory for the engineer to give greater recognition to the Social Science of Engineering. The discipline will examine the psychological and sociological influences on people concerned with structural engineering be it in the design office or on the construction site. The object will be to identify the factors responsible for human errors. There is a need to correct the widely practised concept of engineering science as a discipline of only physical sciences in which the bulk of the engineer's training is quantitative and technological. Whilst it is recognised that developments in construction management studies have been made as a result of the need to develop proper methods of financial and production control and site management, it would be desirable to undertake social scientific studies of this projects with a view to determining how they affect the safety of structures.
With regards to structural optimization, it has been emphasized that information on global optimum of structures would in most cases be more useful than local optimum. The structural engineer has a paramount duty to his client and to the society at large. In a given situation, he must ensure that the design he has chosen is the optimum and he must realise that he can only do this if he takes advantage of the latest technology in his field.

**Codes of Practice**

In order that our structures may be safe, perform adequately the tasks for which they are designed and cost reasonable amount of money, we must gear up all our resources to develop our own Codes of Practice. These documents must address our own special environmental and climatic conditions as well as take into consideration the state of professional practice prevailing in the country. Whilst codes should always attempt to incorporate new research data and the latest information, concerted effort should be made to avoid complications as they may lead to increase in cost as a result of increased design time and effort. There is also the possibility of human error occurring through engineers misinterpreting complex clauses which they do not fully understand or appreciate.

Engineers should be free to adopt whatever level of complexity they wish to use for their calculations. It is sufficient for the Code of Practice to prescribe simple approximate procedures for the design of fairly straightforward structures at reasonable safety level. The codes should not prevent engineers from adopting more complex and less conservative methods of analysis and design but they should do so with the understanding that they accept full responsibility for the correctness of these methods.

Codes and local authorities must continue to require that structures be designed by COREN (Council for the Regulation of Engineering in Nigeria) registered engineers and in some cases continue to insist that the design be checked by local authorities before approval is given for construction.

In addition to dealing with failures affecting structural safety, we should also show concern for failures in performance particularly in connection with achieving work of required quality within a prescribed time and a prescribed budget.

The Tacoma Narrows bridge failure is a good case of a mode of behaviour which was not understood by the technology of the day. There were warnings because many suspension bridges had suffered vibrational problems, their importance was missed by engineers of the day. We should ask ourselves if we too are not missing similar warnings about structures which are presently being designed and built. In particular, are we not missing warning signs on our dams?

The strength of the Finite Element Method as a tool for structural analysis has been demonstrated. For this reason we need to adopt a new approach to the way in which Structural Analysis is thought. I submit that we need to concentrate more on principles than on methodology.
ACKNOWLEDGMENT

The quality of a person's education depends on many factors. The first is his interest in learning. Close to this is the quality of the institutions he attended and the quality of his mentors. I have been a particularly lucky man. In my career, I have had the opportunity of interacting with very good people, and I do not say this just for this occasion.

In this University, I was lucky to have as my lecturers, three of the best engineers that this country has produced. Professor A. O. Adekola was my first lecturer on Elasticity. Professor I. O. Oladapo lectured almost all of my courses on Theory of Structures whilst Professor C.O. Orangun who took some aspects of my Structural Design has remained a great mentor and a man I wished I could emulate fully. I want to thank them and wished them well. I think the three of them and others who lectured me or influenced my career need to be congratulated on this occasion.

I need to mention on this occasion the late Professor John Munro, former Head of Department of Civil Engineering Imperial College, London. I owe my varied interest in the field of Structural Mechanics to him. May his soul rest in perfect peace.

I have also been lucky to be associated with that great exponent of the Finite Element Method, Prof. O. C. Zienkaewicz, now retired from Department of Civil Engineering, University College of Swansea.

I want to thank all members of my family in particular my two sisters Mrs. J. A. Adekanbi and Chief (Mrs) D. M. Rotimi for their support and interest in me. Finally, I thank my wife, Mrs. Bisi Akeju and my children, Titilola, Folashade, Olugbenga and Abisola for their love and understanding at all times:

CONCLUSION

The successes and triumphs of Structural Engineering are great. We should not by any means allow structural failures and collapses to overshadow them. However, when failures occur we must be prepared to re-examine our ideas and methods and pick up whatever lessons are there for us. It is hoped that the present discourse on the basic assumptions of Structural Engineering Science and some aspects of modern research on structural safety has exposed the strengths and the weaknesses of Structural Engineering Practice.

I thank you for your attention.
REFERENCES


