# THE PRODIGIES OF STRUCTURAL ENGINEERING

BY

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*To Truth Indestructible*

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"Materials science has become recognised as a field of study and research capable of yielding great dividends".

R. W. Nurse (1972)
*Philosophical Transactions Royal Society*, London,
Volume 272, Number 1229.

1. It is common practice for academics with full professorial rank to be called upon to deliver inaugural lectures since 1708 when Thwaites, an English Professor of Greek delivered the first inaugural lecture. Eminent personalities in the society are usually invited to join the academics from various disciplines. The duty of an inaugural lecturer, therefore, is to address a general audience with varied experience and interest.

The inaugural lecturer may choose to discuss the special field in which lie his main interests and in so doing he would regard the occasion as one on which the audience might expect to get a fair idea of his research work. In the alternative, the inaugural lecturer may discuss broader features of his profession. This evening, Mr. Vice-Chancellor, Sir, I will tread the middle road, which will give the eminent audience an opportunity to identify Structural Engineering as a discipline which makes most of the wonders of this century a reality. To do this, inference will be drawn from history to explain the various stages of development through which Structural Engineering has passed, before it was given the singular right to lay claims on the wonders of the world.

2. Karl Marx (1818-1883) propounded a most imaginative technological theory of history. To Marx, society consisted of a *'basic structure'*, which is technology, and a *'super-structure'*, which is made up of the various activities of man such as business, politic, social organisation, philosophy, etc. His key idea: *the super-structure is determined by the*

*basic structure.* If Marx was right, the engineer, as the creator of technology, is the major propelling force behind civilisation. The Structural Engineer, unknown to everyone, including himself, is society's most radical revolutionary. There is no doubt that the eminent audience and learned colleagues will agree with Marx that technology is a propelling force behind civilisation. In doing so you are not being unjustly agreeable but justly honouring what is honourable.

3. Perhaps we should pause a little bit to examine the Stone Age man. This earliest man wandered round the surface of the earth in search of comfort in similar manner as we still do today but his horizon was not so wide. He lived in caves and various types of shelters. During his endless journey, he unwittingly developed the art of construction. His future therefore began to unfold. He then became concious of the limits of cave life; he desired changes. Changes in his food, changes in his life style, and, much more, changes in the totality of his environment. Necessity forced him to search for change and his first action in this direction gave birth to technology.

The earliest technologists were the builders of yesteryears, who in modern language are referred to as Structural Engineers. They are the pace-setters of the existing and future civilisations. Imagine yourself to be in a space ship on a journey to a new world. Your imagination on the ship would be to see beautiful houses, civilised people and well-developed environment. If on arrival all these things are not existing, you may define civilisation in terms of environmental development. Your definition may not be far from truth, bearing in mind that civilisation and environmental development are one and the same thing.

There is a body of evidence to suggest that the rate at which our environment develops is a measure of the rate of the growth of civilisation. But Structural Engineering is the backbone of all environmental developments and creations. Structural Engineering affords man the very rare opportunity for creativity and elegance and it happens that these are the requisites for civilisation. Like the ancient builders, the Structural Engineers of today are producing enviable monuments which should serve as challenges for the future. In spite of these achievements, Structural Engineers need to take new strides, with a confidence to succeed. Without this confidence, they will not have the necessary inspiration to do great things. But great things they will *have* to do, if the world is to be saved from the looming dangers of soaring population, diminishing natural resources and biting international inflation.

So much has been said and done to determine the best way to combat world-wide shortages of houses. The need to develop new construction material becomes obvious, but the inhibiting energy crisis and the accompanying financial restraints are clogs in the wheels of progress.

It, therefore, appears to me as if the hostility of this planet to man increases daily as man makes determined efforts to conquer it. If, however, the hope to house the world population is abandoned and arms races and adventures to other planets are given preference, then *Man* must have failed in its mission.

4. It was the Egyptian, the Greek and the Roman civilisations that gave man bricks, mortar, concrete, etc. Those earliest Structural Engineers learnt and understood the properties and the limitations of bricks, concrete and other materials of their time. There is no evidence that they knew the theory of structural concrete. Nothing was known of structural concrete, at least as we know it today, until 1854 when the first true structural reinforced concrete was introduced by William Boutland Wilkinson of Newcastle-Upon-Tyne, England. Earlier, in 1824, an English stonemason, Joseph Aspdin, had perfected a method of producing cement from burnt mixture of limestone and shale. Wilkinson took

advantage of the quality of Aspdin cement, and took a patent on the 27th October, 1854, in which concrete was reinforced for the first time ever with flat bars and wire ropes which he got from nearby collieries. There is no argument as to who first introduced structural concrete, since Wilkinson's patent was a year earlier than the patent taken by Lambot and the British patent of the Frenchman Coignet. Wilkinson described in his patent how the reinforcement should be placed to take tension – just as the practice is today.

Concrete is a mixture of graded stone, sand, cement and water in known proportions. The cement reacts with water to form a cementitious paste which binds the sand and stones together to form concrete. Concrete has a considerable compressive strength but is weak in tension. In some structural elements like beams, compressive and tensile stresses can be developed under load. It is, therefore, certain that concrete alone cannot resist tensile stresses. This makes it necessary to introduce steel reinforcement to assist concrete to sustain all the tensile stresses and also to supplement the compressive strength of concrete.

In order to enhance the progress of civilisation beyond the point at which the Romans left it, many structural engineering concepts have been developed and new materials have been invented. The searches still continue, however, and the appetite of the structural researchers remains instatiable, inasmuch as civilisation appears to be without end.

5. The achievements of Structural Engineers to-date have left us in no doubt that the old days are gone, when some natural phenomena were accepted by a majority of the people as *Acts of God;* – a picturesque term for calculated risks. This attitude on the part of the public has changed, particularly in this century. Engineers have been more zealous and more dynamic in striving to provide structures that can endure when struck by acts of nature or man-made acts.



The Structural Engineer is, therefore, concerned with the development of structures which would successfully resist the forces of nature and the loads imposed on them by man. In order to accomplish his task, the Structural Engineer must know how to calculate the effects of loads and forces on structures and their components. He must know how to search for the truth to enable him to select materials which have sufficient strength, either alone or in combination with other materials and other units of the same materials. This is not the end. He must be able to design buildings of all types, sizes and shapes; bridges and other forms of structures such as docks and stadia, as well as to handle the supervision of actual construction and the maintenance in later years of service.

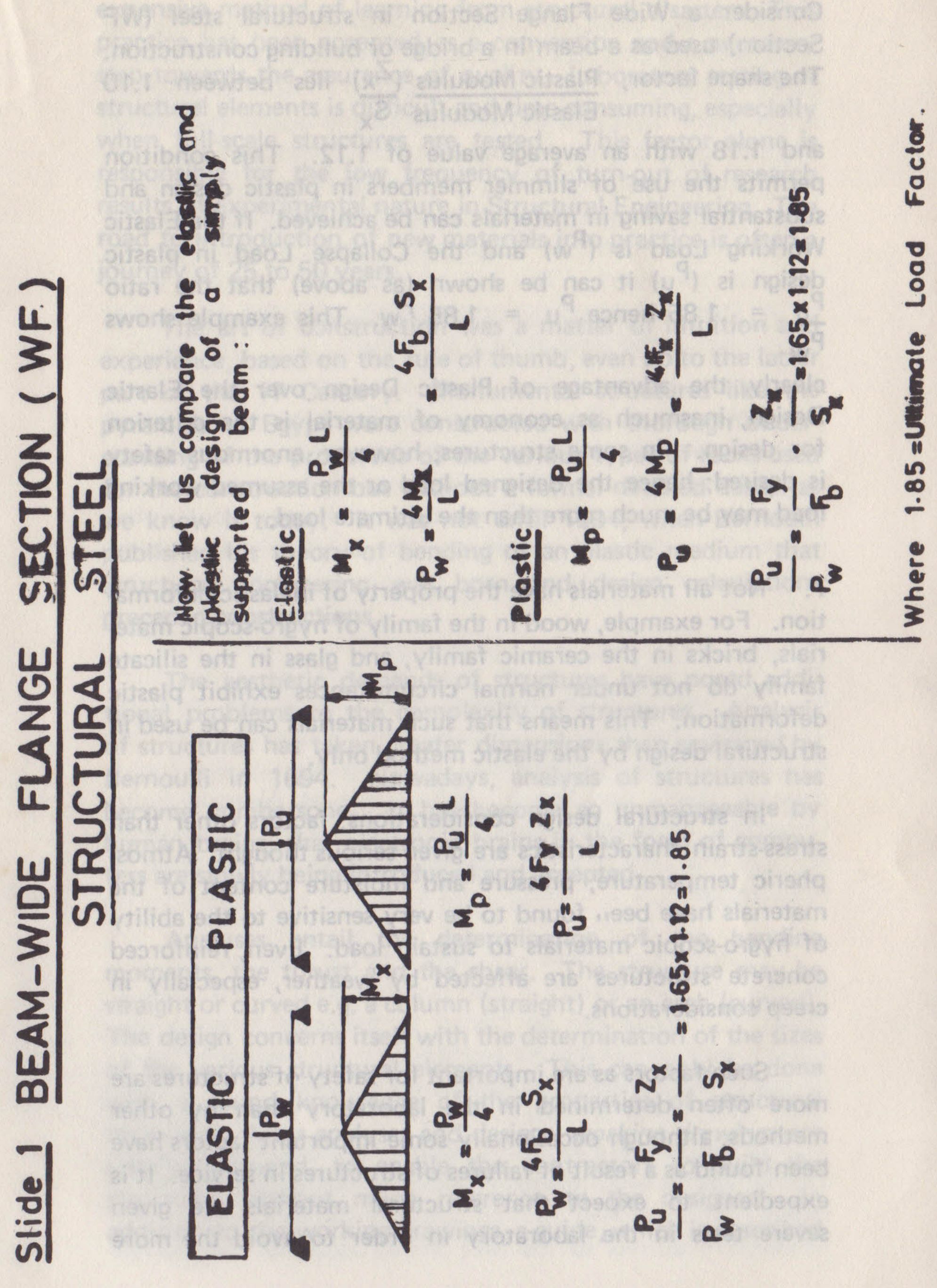
When a load is applied to a material, a balancing force is set up within the material. This internally acting force is known as *stress.* This stress may be due to dynamic or static load or a combination of the two. The applied load may produce bending, thrust or shearing stresses in the loaded member, depending on the type of structures and the loads. Any member that is capable of carrying one or a combination of these stresses is a structural element. To illustrate, a beam, a column or a wall are a few examples of structural elements.

Structural materials are materials which can safely be used to make structural elements. A material cannot be described as a structural material until it has been proved suitable for the manufacture of structural elements. Most, but not all structural materials obey *Hooke's Law of Elasticity.* In 1678, Robert Hooke enunciated a law stating that the strain developed in a loaded member is directly proportional to the stress producing it. This law holds within certain limits for most structural materials. Beyond Hooke's *limit of proportionality,* the strain is not directly proportional to the applied stress. The zone beyond Hooke's limit is known as the *plastic zone.* The behaviour of materials beyond Hooke's limit varies. Some materials do not sustain load after Hooke's limit, while other materials can still carry more loads.

6. According to the theories of plastic flow, the plastic deformation in steel is due to the movements of dislocations, which are structural defects in crystals, across the slip planes under the action of applied stress. The significance of plastic deformation of some structural materials is best demonstrated by considering the behaviour of steel when loaded. The stress-strain curve for steel can be idealised to the inclined linear part which is the elastic range, the almost horizontal part which represents the plastic range and the strain hardening part followed by necking and failure. In elastic design considerations, the material is never utilised to its maximum advantage. This phenomenon, which is inherent in the elastic design, may become advantageous only where heavier loads than the assumed loads in the design have to be placed on the structure. A good example is the Carter Bridge which joins the Lagos Mainland with the Island. It is obvious that the volume of traffic now using the bridge is much more than was assumed when the bridge was designed during the early part of this century. There is an assumed limit of usefulness for structures which are designed by the elastic method and it appears that Carter Bridge has not reached this limit; however, the new bridge beside the Carter Bridge is in anticipation of this limit.

In the modern method of design, the plastic as well as the elastic parts of the stress-strain curve are utilised. There is also a limit of structural usefulness in plastic design. Let us consider the following diagram:





Consider a Wide Flange Section in structural steel (WF Section) used as a beam in a bridge or building construction. The shape factor, $\frac{\text{Plastic Modulus}}{\text{Elastic Modulus}} \left(\frac{Z_x}{S_x}\right)$ lies between 1.10 and 1.18 with an average value of 1.12. This condition permits the use of slimmer members in plastic design and substantial saving in materials can be achieved. If the Elastic Working Load is ($P_w$) and the Collapse Load in plastic design is ($P_u$) it can be shown (as above) that the ratio $\frac{P_u}{P_w}$ = 1.85 hence $P_u$ = 1.85 $P_w$. This example shows clearly the advantage of Plastic Design over the Elastic Design, inasmuch as economy of material is the criterion for design. In some structures, however, enormous safety is desired; hence the designed load or the assumed working load may be much more than the ultimate load.

7. Not all materials have the property of inelastic deformation. For example, wood in the family of hygro-scopic materials, bricks in the ceramic family, and glass in the silicate family do not under normal circumstances exhibit plastic deformation. This means that such materials can be used in structural design by the elastic method only.

In structural design considerations, factors other than stress-strain characteristics are given serious thought. Atmospheric temperature, pressure and moisture content of the materials have been found to be very sensitive to the ability of hygro-scopic materials to sustain load. Even, reinforced concrete structures are affected by weather, especially in creep considerations.

Such factors as are important for safety of structures are more often determined in the laboratory than by other methods, although occasionally some important factors have been found as a result of failures of structures in service. It is expedient to expect that structural materials are given severe tests in the laboratory in order to avoid the more



expensive method of learning from structural disasters. This practice has been accepted as a convention and a necessary step towards the assurance of quality. Laboratory testing of structural elements is difficult and time-consuming, especially when full-scale structures are tested. This factor alone is responsible for the low frequency of turn-out of research results of experimental nature in Structural Engineering. The road to introduction of new materials into practice is often a journey of 25 to 50 years.

The art of construction was a matter of intuition and experience, based on the rule of thumb, even up to the latter part of the 17 Century. Monumental structures like the pyramids of Egypt were constructed with thorough understanding of the properties of the various types of rocks used for the construction but without a formal detailed design as we know it today. It was not until 1694, when Bernoulli published his theory of bending of an elastic medium that structural engineering was born and design calculations preceded constructions.

The aesthetic demands of structures have posed additional problems to the complexity of structures. Analysis of structures has taken greater dimensions than envisaged by Bernoulli in 1694. Nowadays, analysis of structures has become cumbersone. It has become so unmanageable by human brains, that electronic brains in the form of computers are slowly being introduced and accepted.

Analyses entail the determination of the bending moments, the thrust and the shear. The structure may be straight or curved e.g. a column (straight) or an arch (curved). The design concerns itself with the determination of the sizes of the various structural elements. This can only be done with a sound knowledge of the properties of structural materials. After analyses and designs, *working drawings* are usually prepared, to enable the contractors to build the structures without much reference to the designer. In addition to the working drawings, a guide, which is described as the *specification,* is normally prepared. It is a type of explanatory note, which sets out in detail the type and properties of the material to be used, the expected strength of the material during and after construction, the supervision and storage and other matters which are relevant to a successful construction and utility of the building. The *bill of quantities* is another document, which is usually prepared to support other contract documents. It is prepared by the quantity surveyors. The bill of quantities contains a list of all items of construction materials with the prices that are current at the time of data collection.

The working drawings, the specification and the bill of quantities are often referred to as contract documents. The three documents must be given to the contractors at the tender stage and must be embodied in any contract agreement. The contract documents are important documents which are often used in cases of hazards or disagreement.

*Local Materials – the Termite Mound:*

8. The use of local materials for construction has been universally described as the surest way to achieve an economic mass housing programme. In recognition of this fact a research study was begun, while I was at Ahmadu Bello University, on the chemical stabilisation of soils. The research revealed that laterite is the most amenable soil to any form of stabilisation.

Laterite is a typical soil, which to the ordinary man is a reddish soil used mainly in road construction. The geological origin of laterite can be traced to hydrated ferric oxide, usually with some alumina and silica. It is a deposit of mineral matters of decomposed igneous rock origin.

Attempts were made to improve the structural properties of laterite with various types of chemicals, but unfortunately, first attempts did not yield interesting results. It suddenly occurred to me that the structure of *submarines*



was derived from the *fish* and that of the *aeroplanes* from the *birds.* The investigation of *termite mounds*, therefore, came to mind. Earlier to this work, there was no research record on the structural strength of termite mounds. The ecologists had only reported that the mounds are built of earth particles which are cemented together to form hard bricklike materials which are very resistant to weathering and also very difficult to chip with a sharp pick.

These characteristics of termite mounds are some of the essential properties of good materials. The structural strength of termite mounds was therefore evaluated, in order to establish whether or not the soils in the surrounding of the mounds were stabilised by the termites before use. Extensive study has confirmed that *termites do actually stabilise the soil before use.* The chemical stabilisation process used by the termites is therefore worthy of determination.

The soldier termites which are responsible for the construction of mounds were studied. A brown acidic organic substance was extracted from a collection of soldier termites. The organic substance was obtained as the petroleum ether extract of live soldier termites. Analysis showed that the organic substance was a mixture of acetic acid, 2-amino glucose protein (both being hydrolysis products of chittin) and proctodael matter. This substance appeared cementitious and appeared to be similar to the acidic secretion with which the soldier termites invariably defend themselves.

It was therefore established that not all species of termites secrete formic acid, as ecologists had led us to believe. In confirmation of this finding, test specimens prepared with weak solutions of formic acid did not yield appreciable increase in structural strength, whereas specimens prepared with solutions of glacial acetic acid showed definite increase in structural strength. Other findings are that (a) the geographical locations of termites and termite mounds are functions of silica and clay, (b) the quantities of clay and silica that are available in a given sample of soil deposit are also important in mound construction. It is the combination of clay and silica that made it possible for calcium aluminates to be formed; and this family of aluminates is responsible for the stabilisation of laterites by the soldier termites in similar manner as calcium is the dominant element in the manufacture of cement. The results of this research were used to formulate a process of successful stabilisation of laterites. Structural strengths which are comparable with high quality bricks and even concrete were obtained at ambient temperatures and pressures. The secret of the soldier termite was therefore for the first time unfolded for the use of man.

9. The characteristic properties of laterite, that is the low organic content and high content of sand in some cases, suggested that laterite could be successfully used in concrete in the absence of sand. There are some parts of the world, such as Sierra Leone and Gambia, in which sharp sands are either not available or are available in diminishing quantity. The diminishing availability may be due to massive extraction of it may be due to environmental developments.

The need may therefore arise to introduce various types of aggregate into concrete mixes. However, the technology of concrete is not restricted to the use of conventional materials — sand, gravel, cement and water — only. Industrial wastes have found uses in the making of reinforced concrete. The following are a few of the unconventional materials that have been successfully used in reinforced concrete:

*Aglite* — expanded clay from sintered strand

*Bragg* — sintered colliery wastes

*Foamed Slag* — molten blast-furnace slag treated with cold water.



*Leca* — expanded clay from rotary kiln.

*Lytag* — sintered pulverised fuel ash.

*Solite* — expanded slate from rotary kiln.

Furthermore, the structural properties of concrete can be improved by the addition of fibres. During the last decade, material technologists and scientists in advanced countries have intensified efforts on two important structural materials. One is *Fibre Reinforced Concrete* and the other is *Fibre Reinforced Plastic*. Fibre Reinforced Concrete is concrete to which fibre of various diameters and lengths are added in controlled quantity and uniformly distributed in the mortar matrix. Fibre Reinforced Plastic is a matrix of epoxy resin into which various diameters and lengths of various types of fibres are added in controlled quantity and uniformly distributed in the epoxy resin matrix. The fibres may be glass strands such as Silenka E-glass, carbon such as Grafil HT-S type of carbon, polypropylene or the most common steel fibres.

The search for alternative structural materials and the improvement of the structural properties of the existing ones are the paramount objectives of structural engineers. In this direction, I have recorded two personal achievements. The first was the chemical stabilisation of laterite fines (or laterite in powder form), on which literature is available, and the second is the very young pioneer work on the introduction of laterite fines into concrete mixes.

It all began with the awareness that there is very close similarity between laterite and sand. Laterite is similar to sand except that sand does not contain clay which forms a large portion of the fine materials in laterites. Although any form of clay is undesirable in concrete mixes, clays of the class of kaoline can be tolerated. Kaoline is the pottery clay which lends itself to hardening by chemical or physical burning. The introduction of kaoline into concrete, therefore, raises on anxiety, since kaoline will react with cement to produce very hard material.

Comparative experimental work began by comparing various mixes of the conventional concrete with the new type of concrete in which sand is replaced with laterite fines. I have christened this new concrete, in which laterite replaces sand, *laterized concrete.* Observations showed that laterized concrete required less water and about 10-15 per cent of cement more than similar mix of conventional concrete. Fire resistance of laterized concrete was compared with that of normal concrete. The results were in favour of laterized concrete, which notably retained not less than a third of its strength after firing to 100$^{o}$C. It appears, therefore, that laterized concrete is a better material in fire hazards. The superiority of laterized concrete is due to the further hardening of the kaoline content of laterite.

After a few basic tests, the results of which were published in international journals, comparative tests were carried out on beams and columns made with normal concrete and those made with laterized concrete. Here again, the results showed that laterized concrete is a suitable structural material. Altogether, four papers have been published in international journals on the new concrete. Feedback from readers and comments in international reviews of research are encouraging. The need to do more work has been emphasized and efforts to learn more of laterized concrete have begun in Brazil, Sierra Leone, England and Belgium. At the same time, the work in the University of Lagos continues. As a sign of recognition of my pioneering work, I have been invited by Applied Science Publishers Limited to write a chapter on Laterized Concrete for the second volume of a students' series on new developments in Concrete Technology.

10. In almost every pioneer work, the goal is not immediately in sight. In the case of research for new structural materials, the adoption of the material for use is generally delayed. This delay is born out of fear of structural disasters. In most structural failures, causes are due to one or more reasons, such as foundation failure, construction error,



error in design, Acts of God like earthquake or subsidence, explosion, excavation of adjacent buildings, car impact and many other causes, to mention a few. The mere mention of these calamities is sufficient to create fears in some people. For example, the collapse of the footbridge at Western Avenue Lagos, is one of the factors which can be responsible for the refusal of many people to use other footbridges in Ikorodu Road, even with the risk that is involved in crossing the traffic lanes.

Although the structural engineer is not much known in the society, he is never pardoned for responsibility in structural disasters. No structural engineer likes to think about, much less talk about, failures of structures in his practice. Yet these are the times when we realise how the complex assemblages of components that we refer to as structures actually perform under the situations to which they are exposed. The human side of structural failures is also important, because those apparently remote from the occurrence of disasters may have financial responsibility.

The diagnosis of structural failures is usually carried out with three points in mind. These are: (a) *modes* of failures; (b) the *causes* of failures; and (c) *responsibility* for failures. Modes of failure concern structures that are similar in the manner in which they fail. Causes of failure concern structural logics based on the pathological studies of failures. Responsibilities for failures concern parties involved with the design and construction of the structure from its inception to the time of its failure. The designer and the contractors may be legally or professionally liable for the failure.

Examples of structural failures outside Nigeria can be quoted; unfortunately a great portion of the results of investigations of structural failures in Nigeria are buried in the files of investigating engineers, insurance companies and building owers. The result is that lessons learnt from such investigations are not available to practising engineers and engineering teachers who could apply the knowledge to avert similar happenings later on. Consequently, some of the more common causes of structural deficiencies are repeated in design and construction, resulting in multiple collapses. The government, through its appropriate agencies and ministries are, therefore, implored to play a leading role to educate us on the modes and causes of structural failures without apportioning blames or responsibilities. Learned and professional societies are also implored to please arrange lectures and seminars on structural failures in the country, to avert future mishaps. The intervention by government functionaries is mainly to guarantee immunity against libel and similar litigations and thus permit free discussion on the chosen structural failures. I would like to emphasise at this juncture that analysis of structural failures invariably produces an insight into structural behaviour. The expected insight cannot be gained through syntheses of data and knowledge derivable from any engineering institutions.

Finally, Mr. Vice-Chancellor, Deputy Vice-Chancellor, academic colleagues, distinguished guests, ladies and gentlemen, it is gratifying to note that the Seven Wonders of the old World were the most impressive of the prodigies of Structural Engineering. Today, only the pyramids of Egypt remain. All the remaining six have disappeared, destroyed by wars, by Acts of God or by disintegration through neglect. We cannot tell what these wonders meant to the people of ancient times; but there is no doubt in our minds this evening that these monumental achievements of Structural Engineering should always be the highlights of the wonders of human endeavour.