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EVEN METALS SUFFER HYPERTENSION

BY

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EVEN METALS SUFFER HYPERTENSION

An Inaugural Lecture delivered at the
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DEDICATION

To my Father

Chief Anastasius Okotako Enahoro

A Dedicated Educationist

and to my Mother

Fidelia Inibokun Enahoro

with loving memory

EVEN METALS SUFFER HYPERTENSION

Vice-Chancellor, Deputy Vice-Chancellor, honoured guests, colleagues, ladies and gentlemen, it is always an honour to be requested by this University to give an Inaugural Lecture. I would like to acknowledge, on my own behalf and on behalf of my very hard-working colleagues in the Mechanical Engineering Department, the honour of giving this last inaugural lecture in this George Orwell's uneventful academic year of 1984.

I would like to dedicate this lecture to my parents, to my father, a very dedicated educationist who decided, a very long time ago, that education was the best legacy that he could leave behind for his children and worked very hard to ensure that he gave all of us a good educational foundation; and to my mother, of whom we all have the fondest memory. Having used the term "we", I would like to crave your indulgence to recognise the presence of my brothers and my sister and, of course, my wife.

When I was asked to give this lecture and was requested to provide a title, I had the option of giving a lecture on a topic with which I was very familiar or one that would involve research. I chose the latter, so that we may all, together, learn something new.

I have been struck, for a very long time, with the similarity of the terms used in Medicine and Engineering and with the similarity of the approach of engineers and doctors towards the solution of problems that confront them. They both try to diagnose faults, suggest cures, find the causes of the problems and recommend ways to prevent recurrence.

It did not take very long, therefore, to decide to relate the collapse of engineering structures to the failure of the human system, hence the title, "*Even Metals Suffer Hypertension.*" Various people have intercepted me in the past few days and said how anxiously they were looking forward to this lecture. I have felt like telling them that one should not become a hypertensive case through worrying over something that occurs, as inaugural lectures do, as frequently as the new moon.

Metals

The first step in dealing with this topic is, I believe, to define the word "Metal". Before that however, I would like to apologise in advance to the specialist engineers and doctors in the audience here today if I am not as technical as they would like; this is because the audience is made up of people with diverse interests.

In defining "Metal", I have to refer to Chambers Twentieth Century Dictionary[1] though the Metallurgists and Chemists may prefer more exact definitions. According to Chambers, a metal is an "opaque, elementary substance possessing a peculiar lustre, fusibility, conductivity for heat and electricity, readiness to form positive ions etc, such as gold etc; an alloy, that which behaves chemically like a true metal etc. . ." There are very many materials that qualify to be called metals. Perhaps I should mention first some that occur naturally before going on to the alloys.

First come, obviously, the noble metals, Gold and Silver. They were called noble[2] because they did not tarnish when exposed to the atmosphere for long periods and, furthermore, did not lose much weight when melted repeatedly. These properties caused them to be used for making jewellery and, later, coins. By contrast, all other metals were called base metals.

Gold is the most ductile and malleable of metals and, in the pure form, is too soft to be used alone hence it is often alloyed with such other metals as silver, in which case you have white gold, or alloyed with copper, in which case the result is red gold. Other alloying metals may be zinc, cadmium or nickel. The word carat, which is used to describe the quality of gold, means a 24th part. Thus 9 carat means 9 parts gold and 15 parts alloying metal to make up the whole 24 parts. 18 carat means 18 parts gold and 6 parts alloy. Since 9–24th is 37.5% or 0.375, 9 carat gold is often

hallmarked 0.375 beside the 9 carat or 9c markings. The obvious conclusion is that if somebody offers you jewellery and says it is pure gold, he or she is either having you on or is selling you something that will dent or mark very easily because it is very soft.

Silver is the other noble metal. It can resist many corrosive agents except sulphur which tends to attack it. It is very resistant to acetic acid hence it is used widely in the following industries: vinegar, brewing and milk. It is also used extensively in the photographic industry in the form of silver bromide because of its sensitivity to light.

Mercury or Quicksilver is also of particular interest today. It is the only metal that is liquid at room temperature. It is used in wartime to make Mercury Fulminate, $Hg(ONC)_2$, one of the initiators used to detonate explosives. It is, however, more commonly used in scientific instruments such as thermometers, barometers, manometers (which are used for measuring pressures such as blood pressures), discharge lamps, vacuum pumps etc. Metals such as gold, silver and tin dissolve in liquid mercury to form alloys or amalgams which are widely used in dentistry. Because of the way that the liquid flows quickly and moves around, it was named after the fast moving messenger of the gods in Greek mythology Mercury.

Other natural metals that may be worthy of mention are Nickel and Cobalt. Nickel is often used as an alloying metal. It was named after the devil or Old Nick by the early miners who found an ore that they thought could be copper-bearing but which they found the greatest difficulty in reducing to copper in those days because, they thought, of the influence of Old Nick himself. On the other hand, Cobalt, often used as an alloy, was named after the friendly spirits, Kobolds.

Also worthy of mention are Osmium, the heaviest of metals and Lithium, the lightest. Then, of course, there are the other common metals that occur in nature, Aluminium, copper, lead, tin, zinc etc, each with its own peculiar properties that are applied either in the natural form or as alloys.

Man has, of course, gone one step further than nature and produced a wide range of metals by combining, or alloying, these natural metals to obtain any desired behaviour. Examples of such man-made metals are Brass, Bronze and many other combinations. Then there are the Rare Earth metals which are very scarce, very expensive and are produced in very small quantities. They range from Cerbium, through Praesodymium to Yttrium.

I have not forgotten that most common of ores, Iron. In fact, there is supposed to be more aluminium than iron in the earth's crust, about as much as 8 parts aluminium to 5 parts iron in 100, with Silicon and Oxygen taking up as much as 74 parts. However, the exploitation of ores depends on the ease with which they can be mined and smelted and iron is particularly easy to exploit. I shall not talk so much about iron as about its man-made version which could be called the ultimate metal or the universal metal, Steel, which is supposed to have derived its name from the German form, stahl. Steel is an alloy primarily of iron and carbon though such other alloying metals as nickel, cobalt, molybdenum, chromium, vanadium etc are added to give it special properties.

I do not intend to go into the methods of manufacture of steel. Steel is the most common structural material and appears directly in the manufacture of products or in the machinery used in manufacturing them. Steel appears in buildings, vehicles ~~of all~~ types, lifts, even in microphones, in your spectacle rims, the tips of your shoe laces and in the machines used in making the chairs you are sitting on. Steel, therefore, is the most common metal in use today and I shall, accordingly, concentrate my attention on the metal, steel.

I shall use the term "steel structure" to represent anything built of steel whether it is a car body or engine or steel

table. What we are interested in is the method of failure of these structures. First of all, we must examine how we can determine the load on a specimen of material. The analytical and practical methods are different though they yield the same results. Theoretically, we consider an infinitessimal element of the material which is represented diagrammatically in two dimensions as a square, or, in three dimensions, as a cube. We shall consider the simpler, two-dimensional form which is shown in Fig. 1. Stress is defined in engineering as the load on a member divided by the relevant cross-sectional area of the member or, in this case, the element. There are three types of stress which can act on a structure; these are tensile, compressive and shear or torsional stresses. The corresponding forces are tension, compression and torsion. An element can be acted upon by these stresses singly, in a combination of two or three.

When they act in combination, their joint effect on the element can be determined by adding the stresses vectorially or graphically. The graphical solution has been named after Otto Mohr. This is shown in Fig. 2 for the combined stress case. The resultant stresses are called principal stresses shown by σ_1, in this case tensile and σ_2, compressive and the maximum shear stress, τ_{max}.

What happens in practice is that a tensile specimen is prepared and tested in a universal testing machine. The tensile specimen is shown in Fig. 3. The gauge length, usually 50mm in length, is the straight part of the specimen. It is within this part that the specimen ultimately fails. The type of result obtained when the specimen is thus tested is illustrated in Fig. 4 which shows the tensile test curves for two materials, A, which is ductile and B, which is brittle. Ductile materials are those that can be pulled or bent extensively without breaking; a typical example is mild steel whose curve is represented by A. Brittle materials, shown by B, on the other hand break easily when pulled or bent. Another way of putting it is that ductile materials exhibit plasticity beyond the elastic region. In the curve for the ductile material, the region OC is the elastic region which is a straight line where stress is directly proportional to strain. The point D is the ultimate tensile stress, E is the fracture stress and the region CE is the plastic region. In material B, on the other hand, fracture occurs at F with no clear yield point or plastic range; such materials are said to behave as though they were perfectly elastic.

The vast majority of engineering structures are made of ductile metals or consist of brittle materials like concrete which is not a metal but which is often reinforced with steel. Engineering structures generally do not operate beyond the elastic region though nowadays some design is based on the plastic strength of some metals. When the stress at any point in a structure exceeds yield stress, the structure is generally considered to have failed.

Hypertension

Tensile stress is the most disastrous of the three stresses to which structures can be subjected; it can arise from a direct tensile load or may be derived from a bending load. If you bend a stick over your knee, the fibres on the upper side tend to be stretched thus indicating that the stress there is tensile and if the stick breaks, it usually breaks there first.

Stresses can be accentuated by the presence of holes or sharp corners or any sharp changes in cross-sectional area. This is due to stress concentration at the section of sudden change or discontinuity; the sharpness of the change will determine the magnitude of the increase in stress. Thus a member with no hole in it can bear a lot more tensile load safely than a similar member of the same material and the same overall dimensions that has a hole or, as it is called, a stress-raiser, in it. In either case, if failure occurs, the structure may be said to have failed because it has been called upon to bear an excess of tensile stress or, alternatively, an excess of tension.

I have already stated that tensile stress and the resulting force, tension, tends to be the most damaging of the different

types of stress. This is why the most common materials testing method is to measure the tensile strength of a material. To define tension, I have to refer again to Chambers[1] It defines tension as "stretching: a pulling strain: stretched or strained state: strain generally: formerly, pressure in gases or vapours: electromotive force: a state of barely suppressed emotion, as excitement, suspense, anxiety or hostility: a feeling of strain with resultant symptons: strained relations (between persons): opposition (between conflicting ideas or forces)."

This definition satisfies everybody, it satisfies the scientists who include engineers and doctors and satisfies sports like soccer or boxing where it is often said that there is a lot of tension between the protagonists.

I would like to draw your attention to the part of the definition that refers to "pressure in gases or vapours". Again, Chambers[1] tells us that "hyper–" means excessive, more than normal and hence that hypertension means "blood pressure more than normal". In Medicine, a patient suffering from hypertension is said to have high blood pressure, HBP.

Blood pressure is best measured with a mercury manometer with a cuff wound round the patient's upper foreman. There are regulations about the size of the cuff to ensure reliable readings. In general, the width of the cuff should be about one third of the length of the upper foreman; for adults, this works out to something about 130mm wide and 300mm long[3]. Errors can also arise if the patient tightens his fist or arm muscles instinctively or if the rate of deflation of the cuff is too high.

Blood flow in the body is related to the flow of blood in the arteries and is dependent on the way the heart pumps blood into the system as it contracts and expands. It pumps about 70ml of blood into the arterial system each time it contracts.[4] Since the system already contains blood, this new inflow sets up a pulse in the arteries which are, in a normal system, reasonably elastic. The height of the pulse is called the systolic pressure which is recorded as the heart contracts. When the heart expands or, as the doctors would prefer, dilates, the pressure drops and the trough of the pressure is called the diastolic pressure. Thus, whenever your blood pressure is taken, two values are recorded, the systolic and the diastolic.

In a young person whose health is good, blood pressure values of $\frac{120}{80}$, systolic/diastolic, may be recorded. During periods of great physical activity or high emotion, both figures may rise without causing any concern. As the body grows older, the arteries also grow older and, naturally, do not retain the amount of elasticity as they did in youth. The older person, therefore, exhibits rather higher systolic pressure and diastolic pressure values which may go up to $\frac{140}{90}$, the systolic rising rather higher than the diastolic. Again, in the case of the older person who is in a healthy state, these figures may rise up to $\frac{160}{90}$ or $\frac{160}{95}$ during periods of abnormal activity, physical or emotional, without disaster. The engineer would call $\frac{140}{90}$ no-load pressures and $\frac{160}{95}$ the pressures measured under load which, in this case, may not necessarily be a physical load.

From the above figures, it can be seen that the diastolic pressure does not rise very much under normal circumstances. When it does, there is cause for worry. The system may fail when the pressures go up to, say, $\frac{140}{120}$, with little rise in the systolic from a normal of about 120 but quite an abnormal rise in the diastolic from the normal figure of about 80 to 120. How does this happen?

It will be necessary to describe one of the mechanisms of hypertension by, first of all, looking at the structure of

an artery. This is shown in Fig. 5. The arterial system is like a river except that the direction of flow of blood is opposite to that of the flow of water. In a river, the source may be made up of a series of rivulets that combine to make up a large river as it approaches the sea. Similarly, at the termini of the arteries, they become small blood vessels and are called arterioles. Near the heart, the lumen or cavity or bore of the artery may be as large as 25mm or 1 inch.

Under normal conditions, the inner wall of the membrane of the artery is smooth and permits easy flow of blood with little frictional resistance. However, conditions may arise, either with age or some form of illness which cause deposits to form on the membrane. The effect of these deposits is three-fold. In the first place frictional resistance to the flow of blood increases because the deposits are not as smooth as the original wall. Secondly, it reduces the bore of the artery and thirdly, it reduces the elasticity of the wall of the artery. All these make it more difficult for blood to flow easily and may encourage a rise in blood pressure.

The packing surrounding the media may also begin to harden and tend towards brittleness and this will also reduce the elasticity of the arterial wall. It is possible for the deposits to extend to the stage where they close up the artery then a blood clot would form at that point. Depending on where it is, it may or may not be disastrous.

Now, the arterioles are surrounded by muscles and, during periods of stress, the muscles tend to tighten and put pressure on the arterioles. The pressure is transmitted upstream and, in a healthy person, the pressures recorded would show a slight increase and no harm would be done. However, if there is a point in the system where the artery is weak, particularly where the packing is no longer effective and the muscles can, therefore, no longer support the membrane, failure of the artery would occur, the artery would burst and an internal haemorrhage would take place. In common parlance, the patient would be said to have burst a blood vessel. Since the open spaces of the brain are not particularly rich in muscles, it is not surprising that the haemorrhage often occurs in the brain. The patient is usually said to have had a stroke. If it is a mild stroke it may only cause disability in a part of the body. The engineer would say that this is proof of the saying that a chain is only as strong as its weakest link.

Hypertension, though not an infectious disease, has been classed as an epidemic in the United States of America because of the fact that an estimated 20 million people suffer from it. Similar statistics do not exist in this country but it is accepted that hypertension attacks the young and the old and the urban and the rural dweller without prejudice. It is known to be hereditary, though it may sometimes need favourable conditions to make it surface.

Hypertension is not a disease that attacks a perfectly healthy person suddenly. The conditions build up gradually, even though they may not be detected because the person suffering from it may not have been to see a doctor. So, even though news that a person who was apparently healthy has had a stroke may come as a surprise to some people, the events that may have caused the collapse could, in fact be quite minor and not have had much effect on a normally healthy person. This means that the stress conditions that result in hypertensive collapse need not necessarily, in themselves, be particularly severe.

Other Causes of Failure in Engineering Structures

The failure conditions in engineering structures that I described earlier are in fact very rare. Such conditions where a force is applied to a structure once or infrequently are called static stress conditions. If a structure has been properly designed, no such failure should, under normal conditions, occur. This does not mean, of course, that engineering structures do not fail under static conditions; they do, but such failures are so rare that they come as a surprise when they do.

Impact Failure

There is another form of failure which is much more common and which may arise from a suddenly applied load which is called an impact load. A static load is assumed to be gradually applied. A load of the same value when applied as an impact load to the same structure may cause collapse of the structure.

Fatigue Failure

The most common form of failure that occurs in engineering, however, is fatigue failure. Rotating parts of structures, which may be shafts or axles, are subjected to repeated cycles of stress during each rotation going from maximum tensile down to zero and then to a maximum compressive stress at the outermost fibres of the member; the stresses are reversed halfway through the next rotation. The destructive action of repeated stresses on metals is far more damaging than that of static stress and the material breaks at a stress much lower than its ultimate tensile strength. Failure of a metal under repeated stress conditions is called Fatigue; the maximum stress level that a metal can bear without fracture for a specific large number of stress cycles is called the Fatigue Limit or Endurance Limit of the metal. For steels, this is about 35% to 55% of their ultimate tensile strength. If the member has a hole, fillet, scratch, notch, crack, inclusion or any other form of discontinuity in it then the fatigue limit is considerably reduced to a proportion depending on the severity of the discontinuity.

Fatigue may be caused by different kinds of stresses, tensile, bending (which also provides tensile stress) or torsional. Investigation has shown that there are many conditions in a metal or in its service that could give rise to fatigue failure. There are as many as a dozen such conditions,[5] ranging from inclusions, scratches, improper shapes to the effect of temperature. Thus the very high speed aero-engines operating at high temperatures that exist nowadays need scratch-free members and many of these members, even so, have limited working life and have to be taken out and replaced at the end of their design life.

A typical stress-cycle fatigue curve for a plain un-notched specimen is shown in Fig 6. It can be seen that the curve flattens out at a stress value at which the member can be loaded indefinitely without failure. At a higher stress, the member would have a limited life. This limiting stress is the Endurance Limit. The dotted line indicates the curve for a notched specimen of the same material; the stress level at which this can be safely loaded is much lower because of stress concentration.

Creep Failure

Another phenomenon that causes failure in structures and that was not diagnosed for a long time, even after large ocean liners were being built of steel is Creep. Creep may be defined as a time – and temperature – dependent permanent strain under stress. The creep strength of a material may be determined by loading the material at constant temperature and measuring the deformation over time. This can be demonstrated dramatically with a lead specimen which will fracture within a few minutes under suitable conditions of load and temperature.

A typical creep – rupture curve is shown in Fig.7 [6]. The strain ϵ_0 is obtained immediately after the specimen is loaded. Between ϵ_0 and ϵ_1, called the primary creep region, the creep rate decreasees continually. Between ϵ_1 and ϵ_2, the secondary or steady state creep region, the creep rate remains constant. From ϵ_2, onwards, the creep rate increases gradually till rupture occurs at strain ϵ_r and time t_r. This last region is called the tertiary creep region. Again, in this case, as with fatigue, tension is the critical stress condition. Creep has created problems in the past in pipe joints where bolts have lengthened, apparently for no reason at all, under creep strain over long periods and hence caused leakages at the joints. Welded ships have inexplicably split apart as they were being launched, again because of creep strain.

Stress Analysis Techniques

The tensile testing method that I described earlier was merely a material testing method, to determine the strength of a material, or how much load a material can carry under a simple tensile testing condition. It does not help when one wishes to determine how much load a member in a structure is actually carrying because the member is usually of a peculiar shape and is, quite often, joined to other members to make up the structure. Experimental techniques have been developed which have proved to be very useful in the determination of the safety or otherwise of existing structures or in assisting to ensure safe and economical design of new and complex structures. The two best known of such techniques are the strain gauge and photoelasticity, both of which will be described briefly.

Strain Gauge

In simple terms, the strain gauge technique depends on the properties of a ductile wire. It has been found that when some metals are stretched, their electrical behaviour changes by an amount proportional to the extension. Thus an electrical measurement can be made instead of the physical extension which is of infinitessiomal dimensions. When one wishes to test how much a material under strain will extend, therefore, this particular wire, called a strain gauge, will be glued firmly to the material to be tested so that it forms, so to say, a second skin. Thus, when the material is stretched under load, the strain gauge will stretch to exactly the same amount and the extension can then be monitored electrically. Since the behaviour of the gauge is dependent on its ability to stretch, the load must be applied along the axis of the gauge. Some preliminary analysis must be carried out, therefore, to determine the direction along which the operating loads act, otherwise the resulting calculations become very complicated.

The measure of the sensitivity of the gauge is called the "gauge factor", F. It is, mathematically, the ratio of the unit change in resistance to unit deformation:

$$F = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = \frac{\frac{\Delta R}{R}}{\varepsilon}$$

The most common gauge material is Constantan or Advance[7] consisting of 45% Nickel and 55% Copper. Strain gauges vary in active grid length from about 0.375 mm to well over 50mm.

If there is more than one loading direction then, of course, there must be as many gauges as there are loading directions. In addition, because the same magnitude of error in measuring a small length is proportionally higher than the same error in measuring a much larger length, the strain gauge wire should be as long as possible, within reason. As a result, strain gauge wires are usually looped so long as the wire does not overlap so as not to cause a short circuit.

In practice, the application of the strain gauge technique is much more complicated than the theory suggests. It is necessary for a structure to be tested under its actual working conditions. Thus if a structure operates at high temperatures then the gauge used must be a high temperature gauge, the glue used and the wires connecting the gauges to the measuring instruments must also be able to withstand the high temperatures. If the operating temperature is below zero then the gauge and glue must be such that they do not become brittle and fracture at such temperatures. If the gauges are to be used outdoors for a long time then they must be protected from the elements.

Photoelasticity

Photoelasticity is a much more visually dramatic technique than the strain gauge though the principles are rather similar. Photoelasticity depends on the property of some transparent materials to exhibit a change in optical properties to the proportion of the load applied. Such materials are called photoelastic materials. In this technique, a specimen is prepared out of photoelastic material similar in shape to the structure to be investigated. The equipment used in carrying out the investigation is called a polariscope or an optical bench. This is shown in its simplest form in Fig. 8[7]. The simplest optical bench consists of a light source, then a polariser which controls the rays of light, then the specimen which, under load, scatters the light rays to an extent depending on the nature of the load. Next comes the analyser which analyses the resulting stress pattern. The bench is completed by a lens and screen or polaroid camera.

Once more, in practice, the simple bench just described is not much use for quantitative analytical purposes and is used only for qualitative work. The complete bench used for quantitative work is much more complicated.

There are variations of the standard optical bench. One such variation is the Teaching Polariscope which we have here today. Instead of being stretched out on a horizontal bench, the elements of the teaching polariscope are arranged vertically.

In the photoelastic technique, the stress level is determined, in simple terms, by counting the number of stress lines, or fringes, that occur at any point on the specimen. The greater the number of lines, the higher the stress. The specimen on the teaching polariscope today has a hole or stress raiser. It can be seen that the fringes are closer together near the hole than in the area far from the hole. It may be predicted, therefore, that if the load were gradually increased, the specimen would break where the stress is highest, that is, across the section where the hole is.

Another variation is the reflection polariscope which is used to investigate stress distribution in working or loaded structures rather than in specially prepared specimens. A thin pliable sheet of photoelastic material is prepared from the liquid form and wrapped on to the structure so that it becomes, as in the case of the strain gauge a second skin. It will distort just as much as the structure does under load and acts as a mirror to reflect the beam of light from the light source after it has passed through the polariser. The system is shown in Fig. 9. It can be seen that all the elements of the standard polariscope are there except the transparent specimen. This variation of the standard polariscope can be used to investigate sections of really large structures or machines.

What I have described so far refers to two-dimensional or single-plane analysis. Structures are, however, generally three-dimensional and photoelasticity can also be used to analyse them. Since such structures are either too thick or are non-uniform in shape to be used effectively on a standard optical bench, it is necessary to use another property of photoelastic materials and that is that it is possible to "freeze" a stress pattern in a loaded scale-specimen of the structure provided the specimen is not too large because the freezing is carried out in a special type of oven. It is as if when you stand in front of a mirror, your image would be frozen in the mirror so that even after you have walked away, anybody who comes along can see your image in the mirror and it would stay there for a long time afterwards.

The specimen is placed in the special oven and loaded as necessary. The temperature and length of exposure to the conditions depend on the properties of the specimen material. These are controlled by the person who prepares the solid specimen from the liquid. After the specimen has been removed from the oven, it is sliced into thin specimens which can then be analysed as two-dimensional pieces in the x and y (or horizontal and vertical) directions. The variation

of the stresses from one specimen to another then gives a measure of the stresses in the third dimension. The three-dimensional technique has also been used by teams of engineers and doctors to investigate the behaviour of bones under load, the "bones", for example, the knuckle joint at the hip or the complete hip-bone, being made out of photoelastic material.

The engineer does not need to investigate all parts of a structure since very few structures, either human or man-made, fail because all parts have collapsed simultaneously. It would be far too tedious to place strain gauges on all parts of many structures but this is what an engineer would need to do if he did not know where the stresses in the structure are most severe. Even when he does determine the area, he would still like to know in which directions the stresses act so that he can align his gauges in the same directions. If it is not possible to determine the major stress directions, then there are combinations of strain gauges known as rosettes (or small roses, because of their appearance) which can be used to determine the magnitudes of two or three stresses from which the major or principal stresses may be calculated.

However, the engineer can use a liquid, "brittle lacquer" or "stresscoat", to coat the sensitive area. The liquid is brittle when dry and will crack when the specimen is stretched, showing lines at right angles to the direction of loading. As in the case of photoelasticity, there will be more lines and they will be closest in the area of highest stress. This is the place where the strain gauges must be applied. Photoelasticity is also often used in the same way to determine where best to apply strain gauges.

Case Study of Application of Strain Gauge Technique

I shall now proceed to describe briefly a research project in which I was involved some years ago which will demonstrate both the application of the strain gauge technique and also the damaging effect of tensile stresses or the corresponding force, tension. An aircraft carrier, as you know, carries several fighter aircraft which may be used for defence or attack. It is, in effect, a mobile mini-airport. The runway is too short for normal take-off by aircraft which, therefore, have to be catapulated into the air from the deck. Once in the air, the engines take over and the planes fly away. The principle of the catapult is shown in Fig. 10

In simple terms, the catapult operates as follows. Steam is generated in the usual way in a boiler and fed into two large cylinders known as the forward steam receivers. From the receivers, the steam operates a catapult device through a steam engine. The steam operates a hook which pulls one end of a chain at great speed. The chain goes round a pulley; at the other end of the chain from the hook is a platform on which the aircraft rests. Thus, one end of the chain goes in towards the steam engine while the other propels the platform outwards and throws the aircraft out to sea.

The receivers were each about 6ft in diameter and 29ft long and operated at 400 p.s.i. and 700°F. Both were heavily lagged with about 6in of lagging to maintain high steam temperatures and keep the surrounding temperatures down. The receivers, which were originally circular in cross-section, had assumed roughly oval shapes; each one squashed in at the north and south poles.

The problem was to determine whether the receivers would last out their design lives or whether collapse was imminent. Failure might mean an explosion and the release of high pressure steam into a confined space which would be catastrophic. We were also to try to find out what had caused the change in shape so that if the reasons were due to human error, steps could be taken to avoid any recurrence.

Despite the thickness of the walls of the cylinders, the problem was treated essentially as a thin cylinder problem because of the very large diameter involved. The system of loading was considered as fatigue or repeated stress loading.

The solution, therefore, was to determine theoretical values for the stresses that should obtain at the critical sections of the cylinders, the theory being applied to a cylinder of the peculiar shape that the vessels had assumed. The actual working stresses were then to be determined experimentally at the same sections. These values were then to be fitted onto the fatigue curve for the material of the receivers to determine the actual cycle age and hence the remaining life of the receivers. If this agreed with the estimated number of years that the carrier was supposed to last, then it was still safe to continue using it and operating the steam catapult.

The tests were carried out under dynamic load conditions, with the steam receivers loaded to full working pressure at working temperature and with dead loads catapulted repeatedly into the harbour. Dynamic strain readings were recorded by means of pen recorders, and photographic records were kept of the fluctuations of pressure at the moment of opening and closing the discharge valve[8].

It was concluded that the high tensile stresses measured near the front foot of the receiver may have been due to the presence of welds which restricted free expansion of the vessel and tended to pull down on it and elongate its horizontal diameter. The stresses measured were above design value but not beyond yield stress. Secondly, because of the arrangement of the feet of the receiver and the slide beds, it was possible that during heating up of the vessels and the resulting expansion, the feet would tend to move apart circumferentially. It was also suggested that the effect of sudden heating of the vessel could be to cause a large temperature difference between the two surfaces of the wall. Furthermore, it was suggested that the ovality of the receivers could have been caused by severe thermal stresses due to transient conditions which may have occurred accidentally. These stresses, added to the working stresses due to the working pressure, may have been large enough to cause permanent or plastic deformation in the vessels which then assumed their present free shape.

The tests lasted over a period of months and subsequent measurements of the oval shape of the vessels despite frequent use of the catapult showed no change. This confirmed the conclusion that the ovality was not the result of a gradual effect but rather that of a phenomenon that probably occurred once.

It was recommended, therefore, that the steam receivers could be used for their remaining design life so long as periodic checks were made of their ovality and every effort was made to avoid any conditions that would cause high thermal stresses in the walls of the vessels. In addition, the welds at the feet of the vessels and the areas around should be checked periodically for possible initiation of cracks.

However, it would seem that there would soon be no need to have to solve this type of problem, because a new method of collecting and despatching aircraft is being developed for use on aircraft carriers. In Britain, a new type of vertical take-off plane which can also hover will make it possible to eliminate the small runway on carriers. The "Sky-hook" idea is shown in Fig. 11. I sometimes wonder if we are being serious when we talk about catching up technologically with the developed countries. We seem to want to make our omelettes without breaking any eggs.

I have, of course, not described all the methods of non-destructive testing; this is the type of test where the specimen being tested is not destroyed as in the case of the tensile test I described much earlier. Many other types of non-destructive tests exist apart from strain gauge, photoelasticity and stress-coat but they are generally more exotic and more expensive to apply than the ones I have selected.

Conclusion

I hope I have shown that by various methods of analytical and experimental investigation, the engineer can determine the magnitudes of the stresses which act on various members of a structure. The majority of engineering failures

are due to fatigue loading which may be a direct or bending load. Creep also contributes to the number of structural failures in engineering. In both cases, the most damaging stress is tensile stress and failure occurs when the stresses in the structure exceed yield stress or, to put it in other words, when the tension in the structure becomes excessively high. This, as the doctors would put it, is a condition of hypertension.

Sometimes, both doctors and engineers can do something about their "patients" if it is not too late and total collapse has not yet occurred. If collapse has already occurred, in both cases, an autopsy is performed. The doctor would wish to find out the cause of collapse whereas the engineer would wish not only to find out the cause of collapse but also to see if he can use the knowledge to make his next design safer. Unfortunately, the doctor cannot do anything about making the next human structure safer or better though he can, perhaps, by therapy, if he cathches a similar patient earlier next time, prevent conditions from deteriorating to total collapse.

The engineer, had he been responsible for designing the human body would have, by now, eliminated such apparently superfluous organs as the tonsils and the appendix and used the material saved to strengthen other parts of the body. Perhaps he would have built a second heart or a third kidney although it does not seem as if nature appreciates stand-by organs. Such organs would tend to become weak and flabby from disuse. This is unlike the engineering structure which usually remains new when stored away.

The engineer also has much to learn from the doctor whose patients go to him for periodical check-ups. This is what the engineer would call preventive maintenance; if the engineer uses the various methods available to him to keep frequent checks on his structures, minor faults could be corrected quite early and the incidence of total collapse reduced.

Finally, I would like to recommend that more effort should be made to bring doctors and engineers together, particularly in the universities. Engineers would have a lot to offer in such team work and I am sure that doctors, surgeons in particular, do have tools that they would like to improve upon. In addition, they may have ideas about new tools that they feel would make their work easier. Engineers could help to design and produce such tools. Perhaps it only needs a push. Such teams have done very useful work in other places and there is no reason to imagine that they will not be equally successful here.

Vice-Chancellor and Chairman, ladies and gentlemen, I have now come to the end of my one and only inaugural lecture. I would like to express my gratitude to the medical doctors who, through discussions, helped to impart some knowledge of hypertension to me. I refer to Professor Lesi and Dr. Fadahunsi and particularly Dr. George who also gave me access to his library. Finally, I wish to thank the University again for asking me to give this inaugural lecture and all of you for coming to listen and staying to the end.

Thank you.

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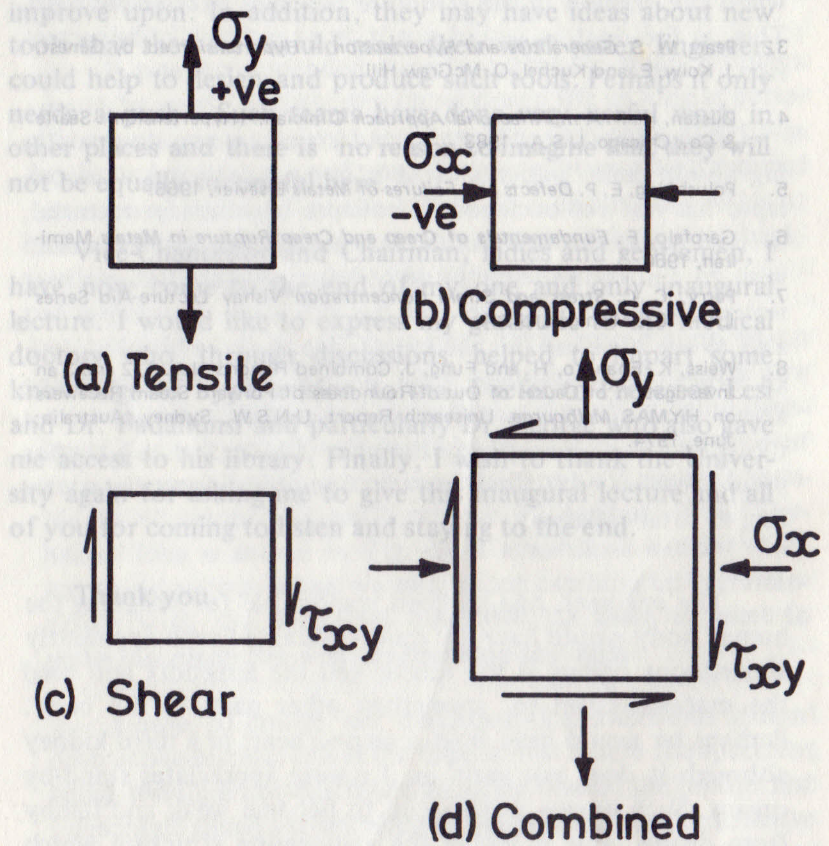

FIG.1. STRESSES ACTING ON AN ELEMENT

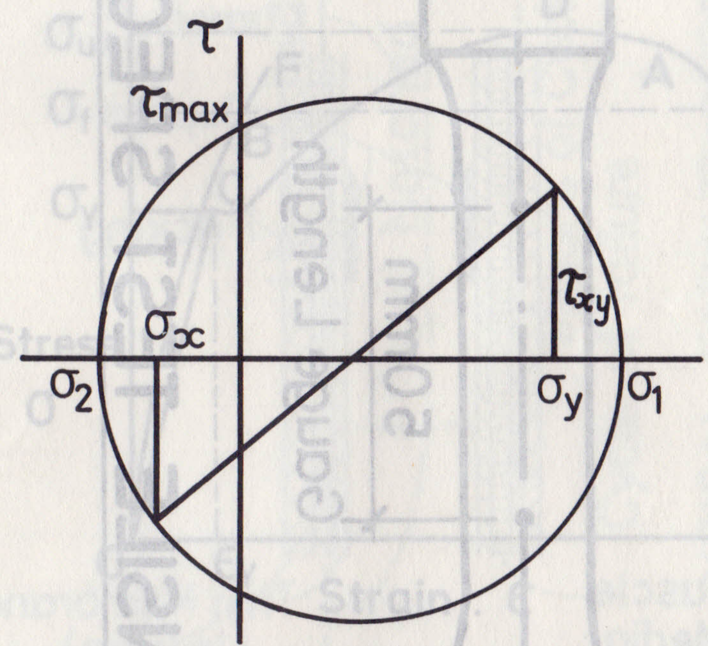

FIG.2 MOHR'S CIRCLE OF STRESSES

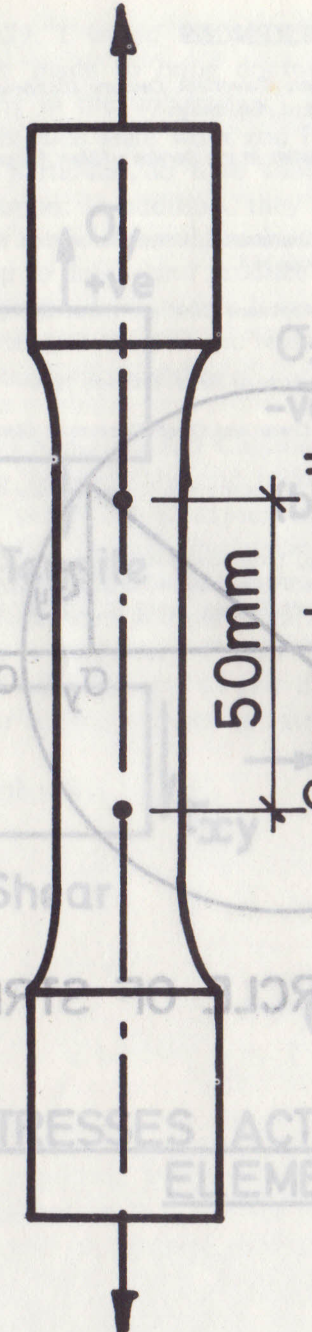

FIG.3 TENSILE TEST SPECIMEN

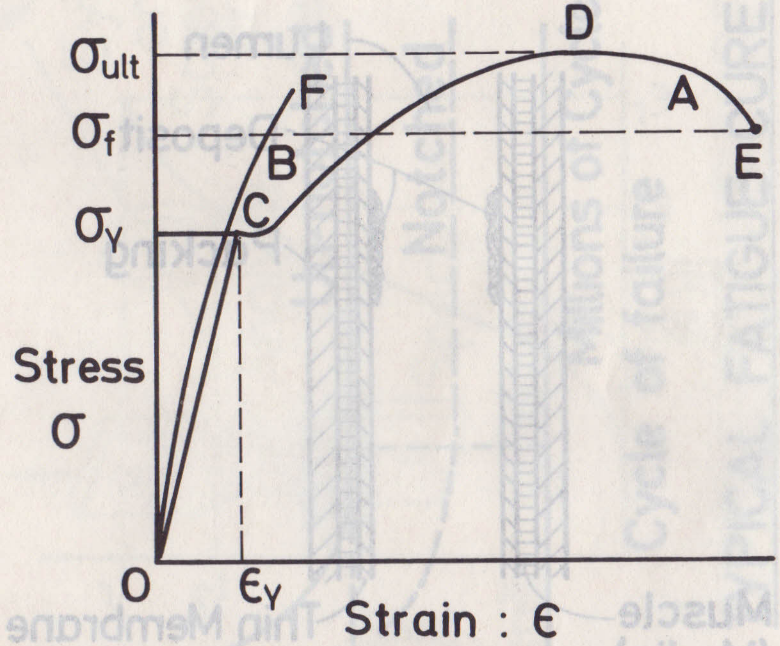

FIG.4 STRESS-STRAIN CURVE FOR ELASTIC AND BRITTLE MATERIALS

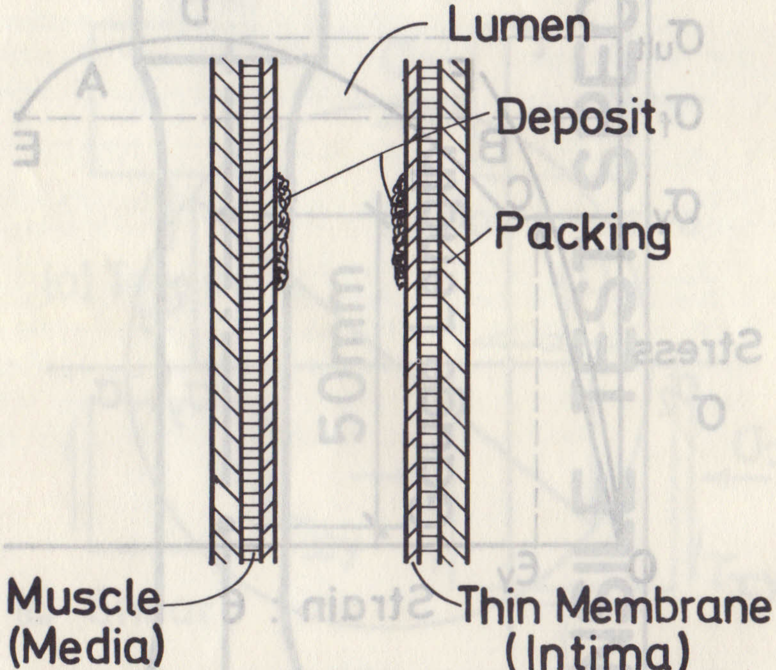

FIG. 5 STRUCTURE OF ARTERY

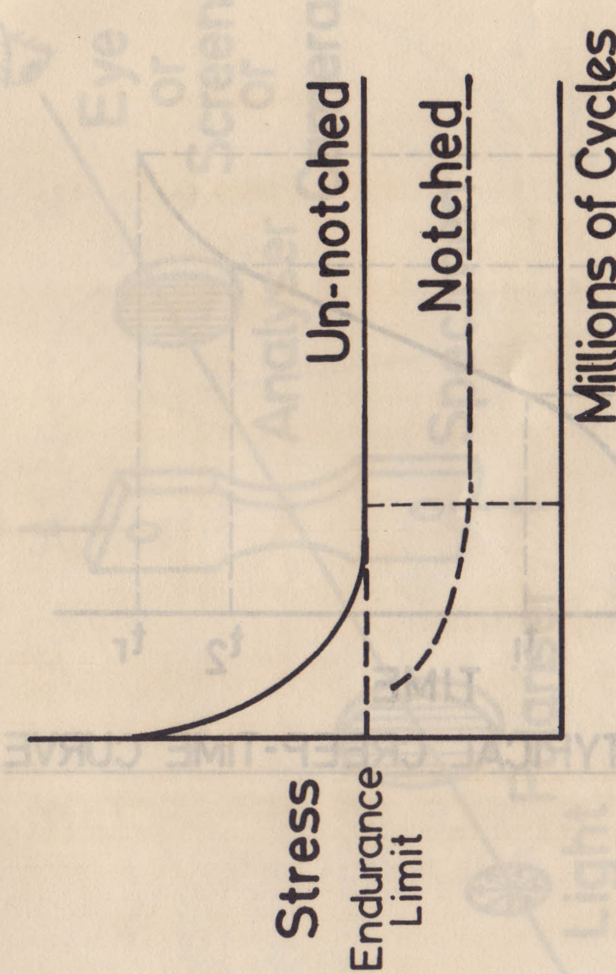

FIG. 6 TYPICAL FATIGUE CURE

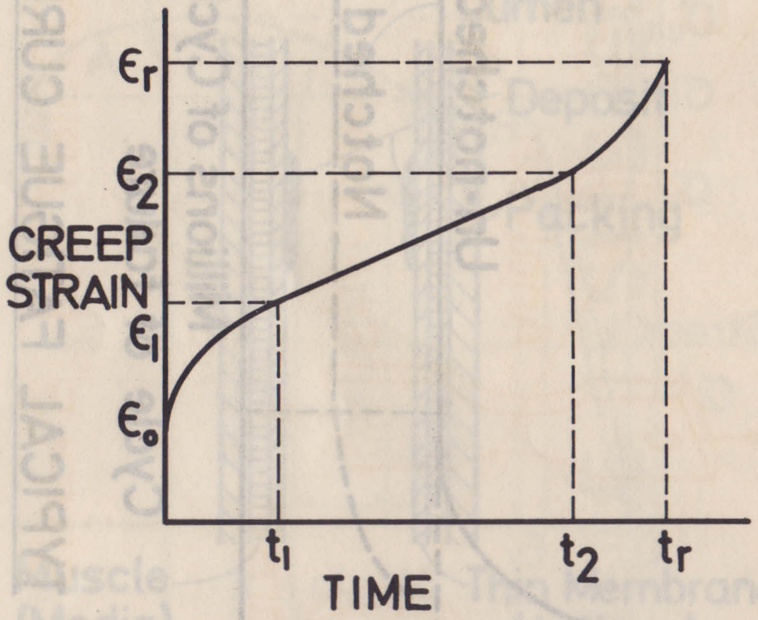

FIG.7 TYPICAL CREEP-TIME CURVE

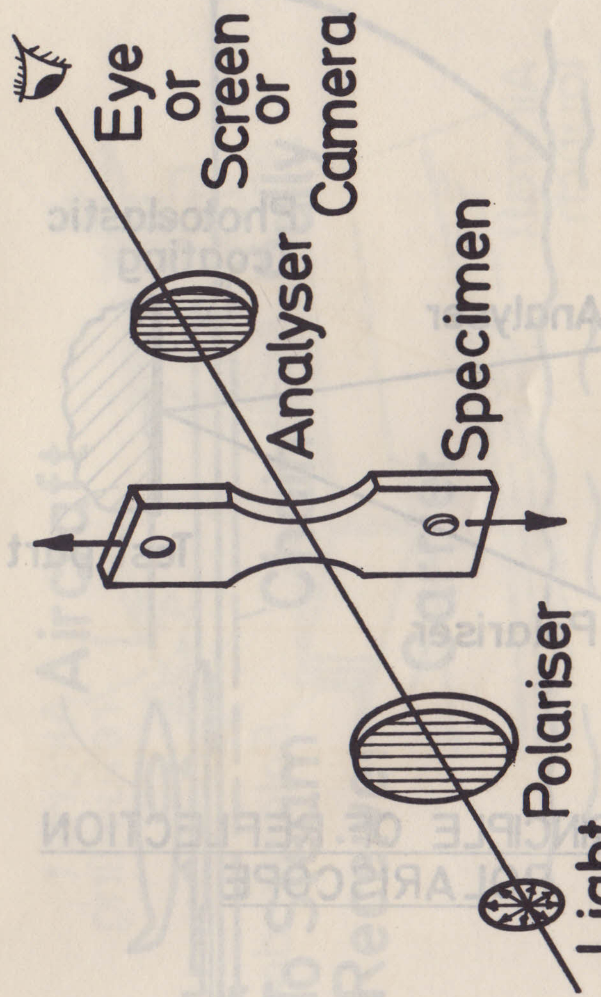

FIG. 8 SIMPLE POLARISCOPE

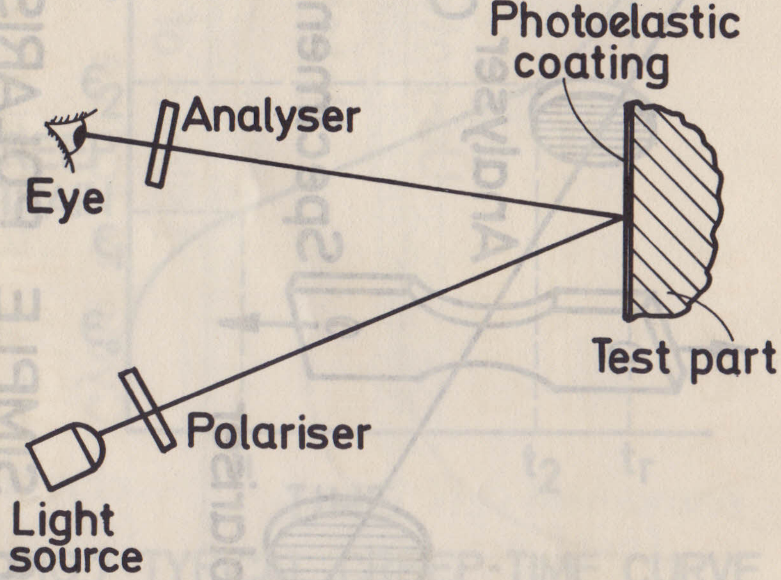

FIG.9 PRINCIPLE OF REFLECTION POLARISCOPE

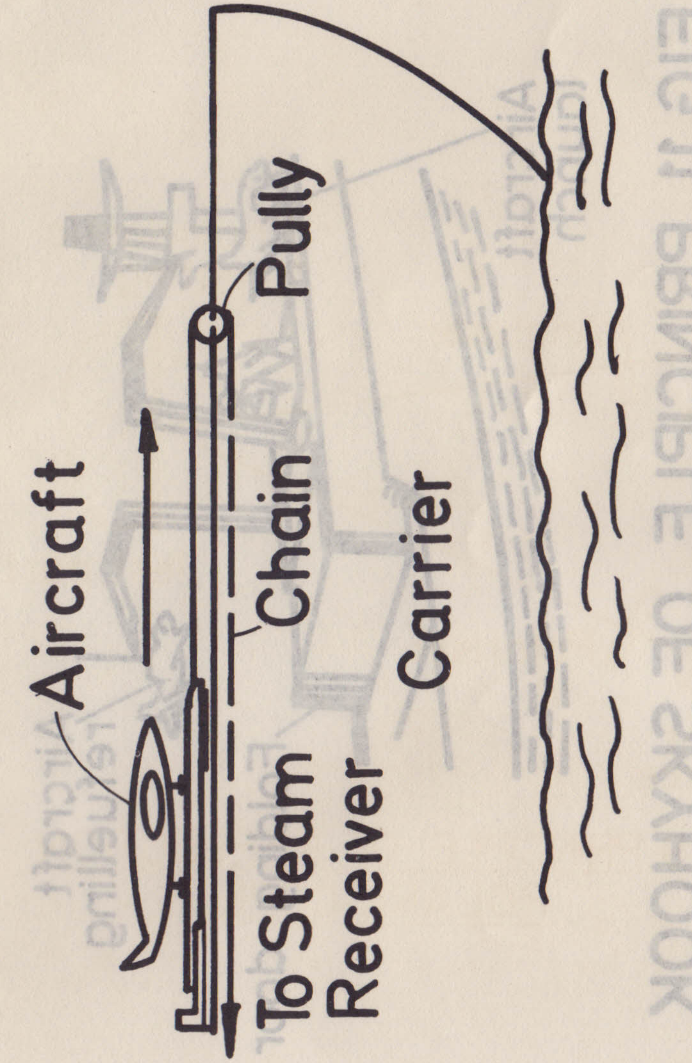

FIG. 10 CATAPULT IN ACTION

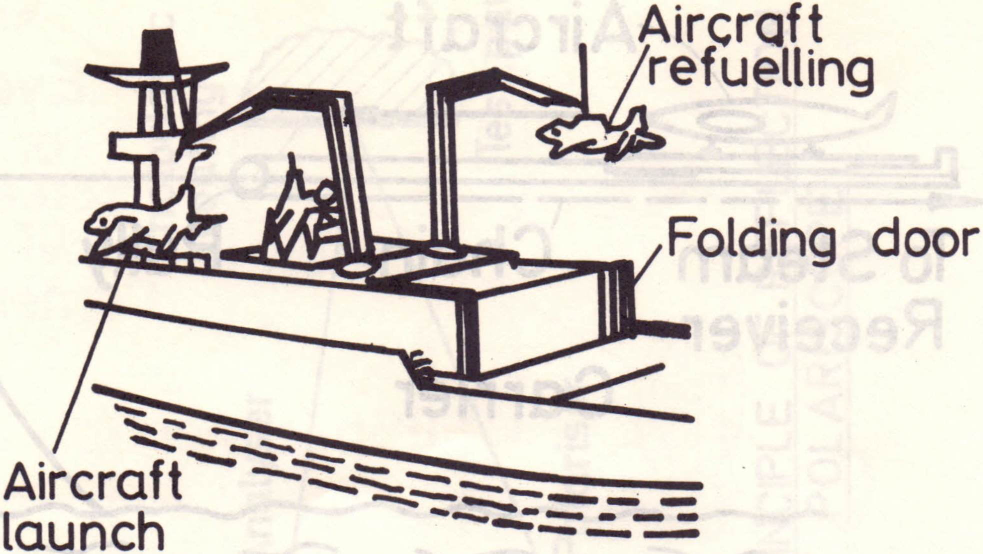

FIG.11 PRINCIPLE OF SKYHOOK
(From Nigerian Tribune)