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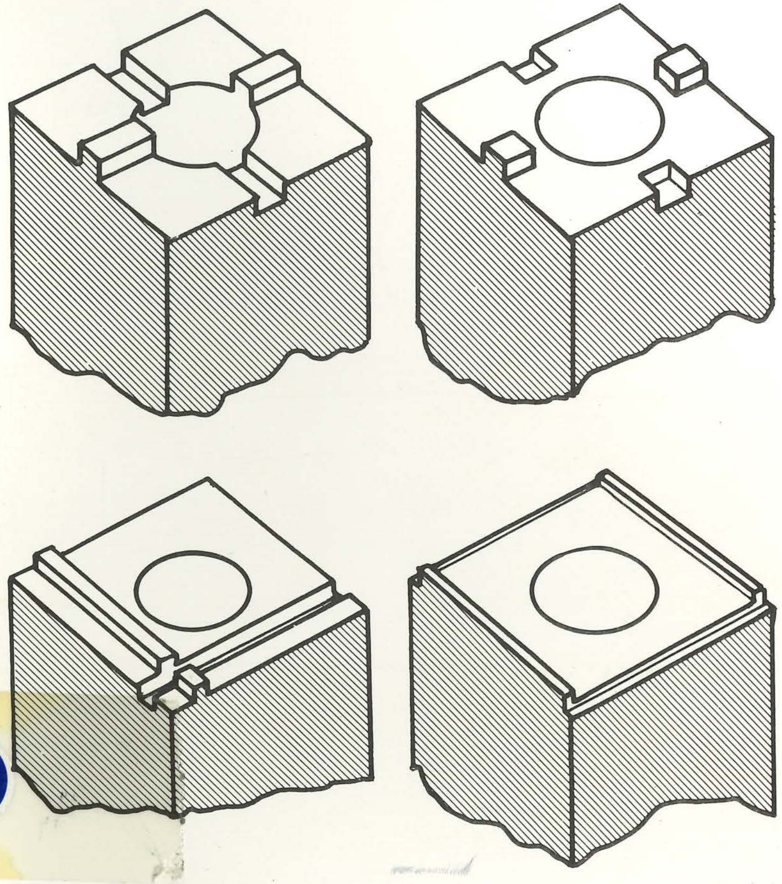
J. M. ALEXANDER

Design—A Continuing Challenge to the Mechanical Engineer



University College of Swansea

UNIVERSITY COLLEGE OF SWANSEA

DESIGN—A CONTINUING CHALLENGE TO THE MECHANICAL ENGINEER

Inaugural Lecture

Delivered at the College on 6 November 1979

by

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DESIGN—A CONTINUING CHALLENGE TO THE MECHANICAL ENGINEER

INAUGURAL LECTURE

TUESDAY 6th NOVEMBER 1979

by

PROFESSOR J. M. ALEXANDER

Mr. Vice-Chancellor, Principal, Colleagues, Ladies & Gentlemen,

One of the penalties of being made a Professor is that one has to deliver an Inaugural Lecture. A full timetable for other Inaugural Lectures at the University College of Swansea gave me a year's grace, however, so I have no grounds for complaint. Also, alas, no excuse for using again my first Inaugural Lecture,[1] entitled "Engineering Plasticity" and delivered in 1964 at Imperial College when I had the title of Professor of Engineering Plasticity conferred upon me. In 1969 I took over the Chair of Applied Mechanics at Imperial College but somehow escaped giving an Inaugural Lecture then.

Having read previous Inaugural Lectures on Engineering topics in our Faculty of Applied Science here I see that I have to maintain a very high standard. I was particularly impressed by Professor Kastner's in 1950 entitled "Education, Tasks and Outlook of the Engineer".[2] Of course, at that time we were just emerging from the last war and on an upward trend in respect of the application of science and engineering for the benefit of Society. Nowadays the roles of scientists and engineers have become even more important mainly, I suppose, because of the incredible advances which have been made and which have sometimes had disastrous consequences. In science, for example, we have seen the difficult ethical and moral problems introduced by genetic engineering and in engineering the adverse effects of the energy crisis, of various forms of pollution by oil and chemicals and buildings such as the high rise apartment blocks in Manchester. Also the spectre of mass-unemployment from robots and micro-processors. The lessons to be learnt from all these developments we have made are fairly obvious. The most important one is that scientists and engineers have to be responsible, mature citizens with common sense and an ability to mix in and work with other people for the benefit of society as a whole. It has been suggested by Professor M. W. Thring, Head of the Department of Mechanical Engineering at Queen Mary College in London University, that there should be a form of Hippocratic Oath for all engineers. I suppose anything that can engender a greater sense of responsibility in our future professional technologists is important and useful. What is clear is that the remedies for the anti-social consequences of some of our technological advances can probably only be found by the scientists and engineers themselves and their role in society is now much more important than ever before. Having brought about the technological advances which have greatly improved our living standards in general, we must now set about remedying the undesirable side-effects which have accrued from them.

How does all this redound on the traditional mechanical engineering course given in the University? By and large, most Departments of Mechanical Engineering offer similar curricula throughout the country, based on the traditional fundamental topics of mechanical engineering. Most academics are best at teaching these basic subjects such as strength of materials, stress analysis, dynamics and control, thermodynamics, fluid mechanics or heat transfer but less good (understandably) at teaching the more applied subjects such as those involved in design, management studies, and other forms of system analysis. It is just those latter subjects which are of most importance in my view and I have been most heartened to find here in this Department of Mechanical Engineering at the University College of Swansea that the staff are all interested in and expert in design. They have all worked at some time or other in Industry (not always the case with academic staff in Universities) and are therefore well able to supervise design projects and give supporting lectures. My predecessor, Professor F. T. Barwell, had close contacts with industry both in this country and all over the world (in the field of transport and tribology) as did his predecessors, Professors MacMillan and Kastner before him, so there has been a history of real industrial involvement by the staff of my Department which I intend to nurture and foster as much as I can in the future.

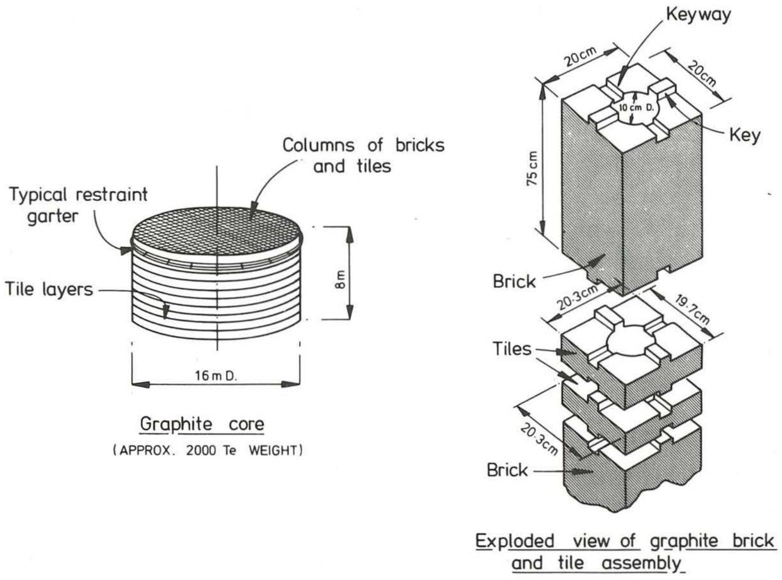
Since I am sure that there are many people in my audience who will not be familiar with what is meant by design in the context of my lecture, I think perhaps I should try to explain it, as I myself understand it. Rather than try to give a definition of design, I think it preferable to give a few examples from my own experience and try to draw attention to the different skills which are involved in formulating a problem in design.

Nevertheless, before doing that, I should like to indicate what is to my mind a central dilemma in design *education*. By and large, academics are best at finding clever solutions to problems. Therefore, they tend to concentrate on the analysis of one particularly elegant solution to any given design problem, rather than searching around to find a large number of possible solutions (often by a technique called ''brainstorming'') which can then be compared on some sensible basis and optimized. Optimization in this context often means finding the solution which involves the minimum cost over the whole of the lifetime of the artefact, either in respect of money or more realistically nowadays in respect of energy and/or material consumption.

One of the best 'educators' I know in the design field *never* produces any solutions *himself*. He spends his whole life in making his students formulate the problem in such a way that they are forced to seek a large number of solutions, often by making them work as a group, sometimes competitively, sometimes collaboratively. In that way his students produce a large number of good solutions which can then be compared with one another.

Unfortunately, I am not a good teacher of design myself—I, like most academics, tend to look for an elegant solution and then concentrate on developing it. During this development process it becomes evident that the designer must give a great deal of attention to the way in which his solution can be manufactured. The idea that a component or product has to be *designed for production* or *designed for manufacture* becomes apparent. It is that general theme which I want to develop this evening and I shall be inevitably discussing *solutions* rather than *methodology*, although I shall also be considering several manufacturing processes because they are so important in this context.

The first problem in 'design for manufacture' which I shall discuss involves safety in a nuclear reactor. In the second generation of natural uranium graphite-moderated reactors, the graphite core was made of bricks and tiles making up a large cylindrical block weighing about 2000 Tons and measuring about 16 m diameter x 8 m in height as shown diagrammatically in Fig. 1. Each graphite brick was about 20 cm square in cross section with a central hole of about 7½ cm dia. running down its length of 76 cm, forming the channel. These bricks were assembled in layers separated by 5 cm thick tiles which provided the end location of each layer. The tile layers were bound together with 'garters' which were to be



Graphite core
(APPROX. 2000 Te WEIGHT)

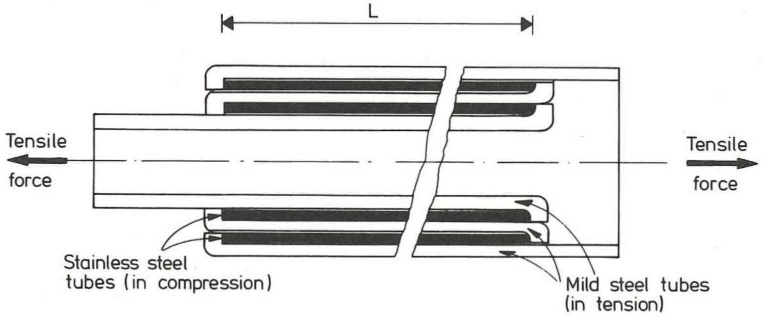
Exploded view of graphite brick and tile assembly

Fig. 1 Details of graphite core

tightened up rather like large elastic bands to hold the whole core together, through the medium of tile layers.

The overall design problem involved here can be simply stated. Bearing in mind that the temperature of the graphite can vary by as much as 400 C° how can the garters be designed so that the tension in them can be kept reasonably constant? Graphite has a very low temperature coefficient of expansion, **about 2×10^{-6} per °C as compared with about 12×10^{-6} per °C** for steel which is the obvious material to use for the garters which must have a high force in them to restrain the core against the various forces which can occur during the operation. Of course, an obvious solution would be to make the garters also of graphite but graphite has little or no tensile strength.

Metals with low temperature coefficients of expansion have been developed but they are very expensive and would have increased the cost of the reactor considerably. Eventually a design was developed which made use of the difference between the temperature coefficients of expansion of mild steel **(12×10^{-6}) and stainless steel (18×10^{-6}) by forming a spring** made up of alternate tubes of mild steel within stainless steel as indicated in Fig. 2. Using such a design it is possible to arrive at a spring element which can have virtually any desired effective temperature coefficient of expansion—I think that that is an elegant solution.



Total extension due to temperature change T will be $\Delta L = (3\alpha_{M.S.} - 2\alpha_{S.S.})\,LT = (3\times12 - 2\times18)\times10^{-6}\,LT = 0$

Fig. 2 Element of restraint garter

Even having arrived at what appears to be an economic solution, however, the problem is not over. How can the ends of the tubes be given the desired shape shown, having adequate strength, economically? Machining from the solid would be a very wasteful method although giving good strength, and welding on end pieces would not be a very desirable solution because of the need to control the welding process very carefully to give adequate strength. The best way of making such tubes would be by upsetting their ends by some form of metal deformation process such as rolling or swaging.

This simple example indicates many features which typify mechanical engineering design problems. First of all the need to create an economic solution which will be strong enough, safe and reliable. Then the need to devise a version of the solution which can be manufactured economically, a process often called "design for production".

Another example of "design for production" is to be found in the design of the graphite bricks and tiles themselves. The actual geometry and arrangement of the bricks and tiles in the graphite structure was fixed rather rigidly by the requirements of the nuclear parameters but there were still some problems in fixing them together. In the original Calder Hall reactor the brick and tile assembly was keyed together with keys and keyways machined out of the solid bricks and tiles as shown in Fig. 3. The keys and keyways were disposed along the centrelines of the channels as indicated and could easily be machined out by passing a profiled milling head cutter straight across the end of the brick. Obviously, for assembly there had to be clearances between the keys and keyways and these small gaps allowed sufficient leakage of the coolant gas (CO2) to cause a significant loss of power. In fact, it represented several millions of pounds lost revenue when spread over the life of the reactor. So how could the assembly be redesigned to avoid this loss? Keys and keyways were the preferred solution, for reasons which would take too long to describe here. This was another problem in "design for production" and it was solved by a production engineer eventually, by simply displacing the keys and keyways so that they did not cut through the fuel channel, as shown in Fig. 3—another elegant solution.

Another design problem in the nuclear reactor of some interest was that of finding a solution to the disastrous problem of accidentally dropping either a heavy fuel element or a control rod into the reactor. What was needed was a shock-absorber at the bottom end of each fuel or control rod channel to guard against this eventuality. The decision about what type of shock absorber to use presented a problem which could really only be decided by setting up a method of comparing different solutions. The problem resolves itself into that of providing a device which will give a fairly constant resistive force of known magnitude over a reasonably large distance to absorb the potential energy of these heavy components falling through perhaps 20 m or so. Several methods were considered such as the tensile stretching of a rod, the machining or broaching out of a suitable hole, the compression of gas in a closed chamber or the endwise buckling of a tube.

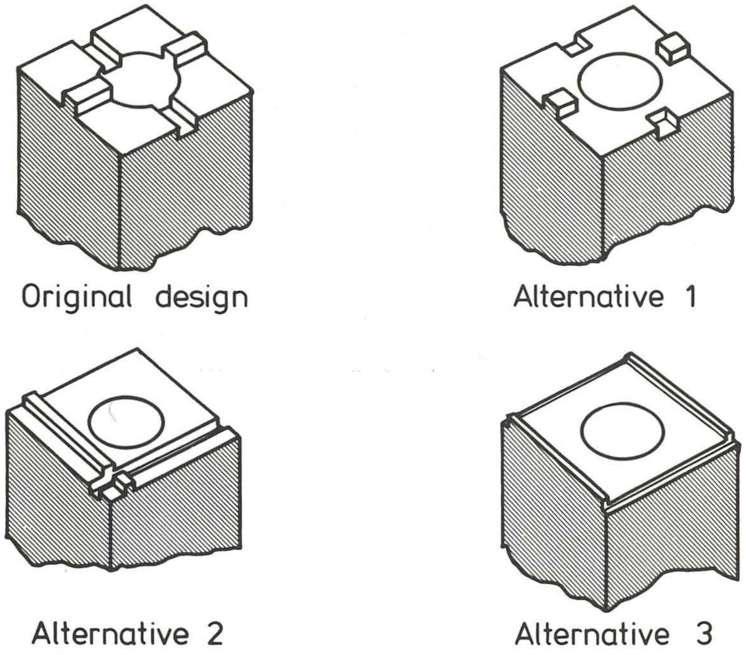


Fig. 3 Redesign of keys to prevent gas leakage

Considering this last method, the shape taken up by a buckled tube can be a very complex pattern of deformation as shown in Fig. 4 but, for the purpose of predicting its

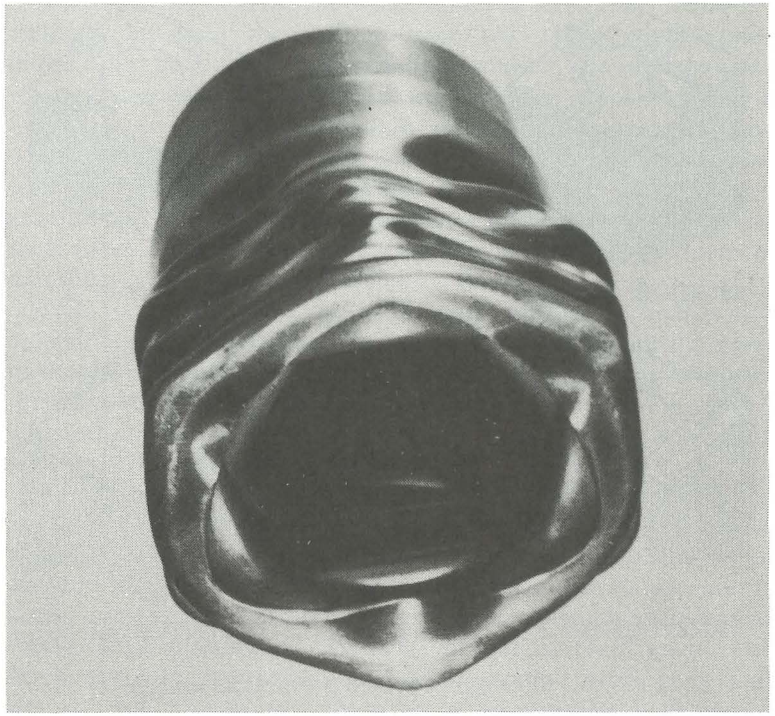


Fig. 4

behaviour the techniques of "limit analysis" can be used[3] and an "upper bound picture" assumed as shown in Fig. 5. These techniques tell us that if we choose a reasonably realistic deformation pattern and calculate the load required to enforce it we shall have a realistic upper bound to the collapse load (resistive force). The tube is assumed to buckle into a succession of conically shaped shells forming circumferential plastic hinges which are eventually flattened out as shown. The work done in stretching the conical shells and in bending the hinges can be equated to the work done by the external load, which can then be estimated. An experimental check of this theory is shown in Fig. 6 and the good agreement may be noted. This problem illustrates how stress analysis techniques are applied to help in the design process.

Another similar problem, to do with shock absorbers, has to

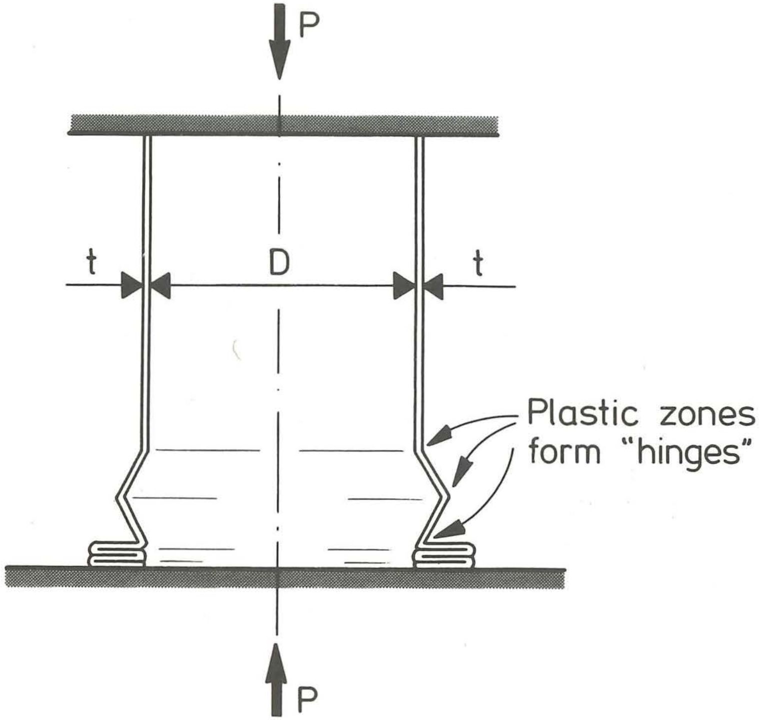


Fig. 5 Assumed collapse mode of end-loaded tube

do with mine shafts and pit cages. It may surprise you to learn that very few shock absorbers, apart from a thick rubber mat, are at present provided at the base of pit-shafts. Recently (at Markham Colliery) a number of miners were killed in a pit cage whose cable slipped, and attention is now at last being paid to developing suitable shock absorbing devices. It turns out that a distance of at least 7 metres is required to restrict the deceleration to 1 g, which the human frame can withstand safely and one solution proposed is to dissipate the energy by the successive bending and unbending of steel strips through a number of rollers, as indicated in Fig. 7. This is an attractive and reliable solution, and is being actively developed by a leading firm of mining engineers. As for the previous device, it is relatively easy to predict the forces generated by using a similar approach, which is very helpful in achieving a good

D (in.)	t (in.)	$t^{1.5}\sqrt{D}$ (in.^{2})	$\bar{P}$ (lb)
1·43	0·03	0·006216	2,600
1·43	0·04	0·009572	4,260
1·43	0·05	0·013375	6,650
2·12	0·03	0·007569	3,450
2·12	0·04	0·011652	4,990
2·12	0·05	0·016290	6,980
2·66	0·03	0·008481	3,700
2·66	0·04	0·013052	5,610
2·66	0·05	0·018250	7,480

Table 1

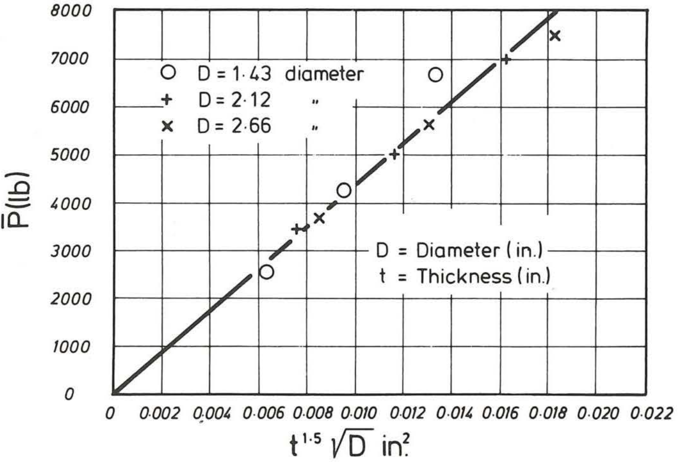


Fig. 6 Plot of mean collapse load P vs $t^{15}\sqrt{}$ D from tests on mild steel tubes of various diameters and thicknesses

design and allows the optimization of dimensions and material parameters.

It is interesting that, in all of these problems involving the creation of a solution to a problem, the most important aspect is that of the need to know the physical properties of the materials from which the final artefact is to be constructed or which have to be controlled by the device. This includes the whole spectrum of solids, liquids and gases, therefore. With modern computing power being capable of giving very accurate

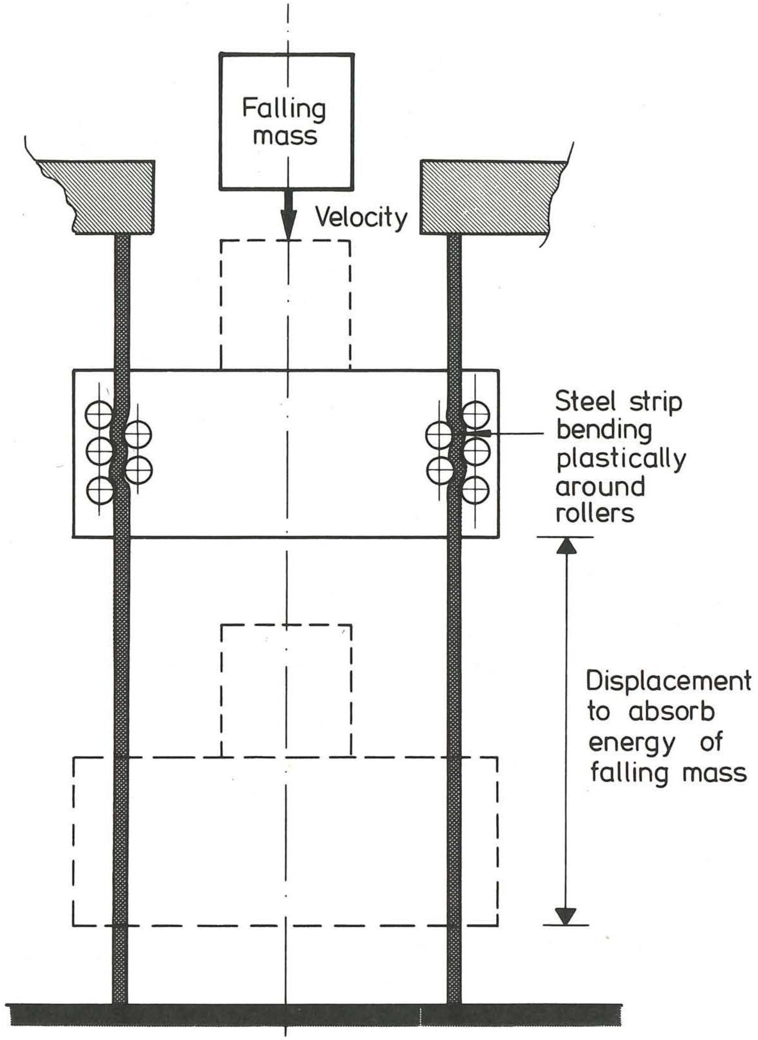


Fig. 7 Principle of energy-absorbing device for falling pit cage or lift

solutions to problems of stress analysis, heat transfer and fluid flow, for example (often using finite difference, finite element methods or similar numerical techniques) it is necessary to have more and more accurate basic data.

An important example of this is to be found in the effect of superimposing all-round hydrostatic compressive pressure on to materials. Following on the work of Professor Sir Hugh Ford, as I did, I spent a great proportion of the 21 years of my sojourn at Imperial College on research in that field. I suppose the most important effect of superimposing very high ambient pressures on to any material is to increase its apparent ductility. Metals as brittle as cast iron when subjected to tensile stresses can be made to stretch out like toffee when stretched under high enough all round superimposed pressures (of the order of 20,000 atmospheres). It is as if any cavities which would otherwise have formed are immediately healed up by the enormous all-round pressure. Of course, with even higher hydrostatic pressures the atomic structure of materials can be altered, as happens in the formation of diamond from carbon in the form of graphite in which the hexagonal crystallographic lattice structure of the graphite is squeezed into the tetragonal diamond lattice.

I have made a short film which illustrates the effect of superimposing a high hydrostatic pressure on the process of end-upsetting, in which a rod is pushed against a flat surface in order to form a flange on its end. The first part of the film shows the fractures which occur in the periphery of the flange when it is upset in the ambient atmosphere. The second part shows that no fractures occur when the flange is formed in an environment of high pressure fluid. The rod is made of plasticine and the apparatus is made of perspex so that we can see what is happening, firstly without any pressure, secondly with oil under pressure.

Thus, at Imperial College I studied the process of *extruding* materials under a superimposed all-round hydrostatic **pressure, following the work of Bridgman in the U.S.A.,** Vereschagin in Russia and Pugh at the National Engineering Laboratory in this country. We all studied various aspects of the effect of high pressure on materials, my own work being mainly devoted to hydrostatic extrusion in various forms. In hydrostatic extrusion the plunger or punch of the conventional extrusion press is effectively replaced by high pressure fluid which surrounds the billet and removes all friction between it and the container, as illustrated in Fig. 8. Fluid-to-fluid extrusion, illustrated in Fig. 9, is a version of hydrostatic extrusion which allows very brittle materials (for example green

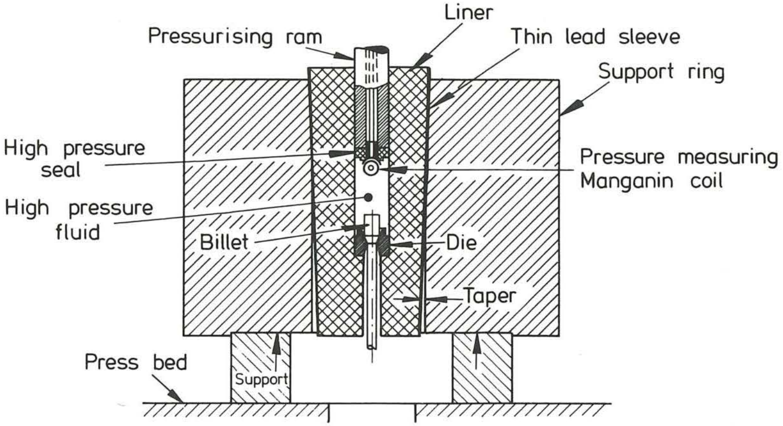


Fig. 8 Hydrostatic extrusion

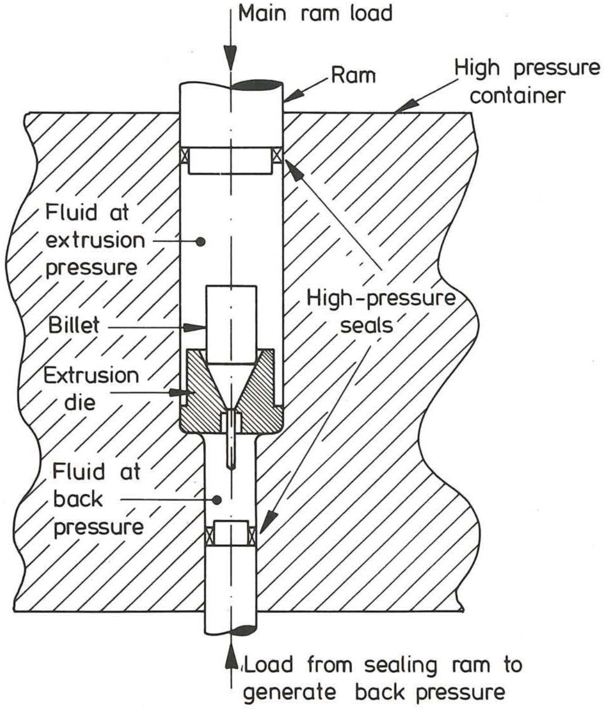


Fig. 9 Fluid-to-fluid extrusion

compacts) to be extruded without fracture. The enormous fluid pressures involve a volumetric compression of about 40% of the fluid itself.

Most extrusion presses, although allowing enormous reductions to be achieved in one passage through the extrusion die, are restricted in the size of billet they can accommodate (about ½ tonne maximum). In practice, large weights of long prismatic sections (such as railway lines, steel tubes, electric cables etc.) are often required. For example, coils of wire weighing up to 40 tons in one continuous length are needed for cable winding machines. Thus, it has always been difficult for extrusion to compete with fully continuous processes such as rolling or drawing, although it has many obvious advantages for such products. One of the main advantages of hydro-extrusion over conventional extrusion is that long lengths of billet can be pushed through the container due to the absence of friction. Thus hydro-extrusion seemed to me to offer, at last, the possibility of the continuous extrusion of metals. Dr. Lengyel and I developed, at Imperial College, a system which we called "semi-continuous hydrostatic extrusion" which would allow the hydrostatic extrusion of infinite lengths of billet, by introducing the idea of clamping an infinitely long billet where it entered the extrusion container and combining the processes of conventional and hydrostatic extrusion as illustrated in Fig. 10. The sequence of operation is simply to clamp, pressurize almost to the pressure of extrusion, extrude by pushing the die on to the billet, stop, release pressure, move billet and die back to the starting position and repeat the process.

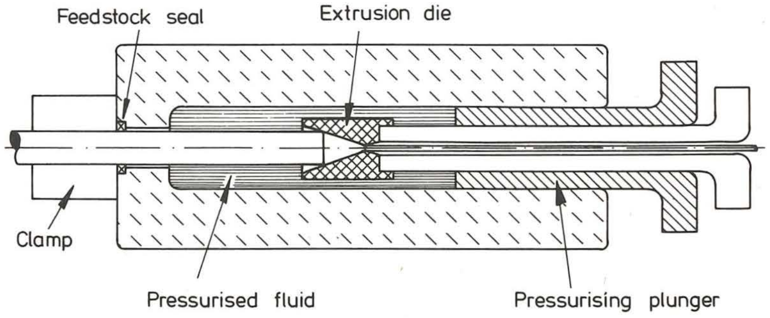


Fig. 10 Semi-continuous hydrostatic extrusion

We spent much time in developing this process, with generous support from the Science Research Council. It stimulated many other ideas for continuous extrusion, notably "Conform", a fully continuous form of conventional extrusion invented by the late Derek Green of the UKAEA, "Extrolling", invented by Professor B. Avitzur of Lehigh University in the U.S.A. and the Wire Extruder invented by Dr. W. Fuchs, Western Electric, also in the U.S.A. Conform is shown in Fig. 11. Extrolling in Fig. 12 and the Western Electric machine in Fig. 13. All these machines depend for their operation on our idea of clamping the material as it enters the machine, to carry it forward to the die. It is clamped by being forced into the groove of either one or two rollers which carry it into a *conventional* extrusion die in the first two machines, whilst the Western Electric machine has four tracks of clamps which meet and form a continuously moving container for *hydrostatic* extrusion. All these machines are under active development at the present time.

Western Electric gave me a short film showing the first prototype wire extruder which they developed. It is a silent film so I will try to describe the salient features as it proceeds.

Well, I must not digress from the theme of my lecture by being diverted into going over my past research activities. It is simply my intention to show you some typical solutions to difficult design problems which challenge all mechanical engineers at some time or other. Faced with the problem of designing a machine for the continuous extrusion of metal, you now see how many different solutions are possible and I have shown only a few of the more successful ones of those which have been put forward. Each of the designs I have shown has different problems, not the least being the task of providing containers and seals which can withstand internal pressures of the order of between 10,000 and 20,000 atmospheres.

Perhaps I should translate these pressures into stresses. A pressure of 15000 atmospheres, approximately 15 k bars, is about 1500 MPa or 1500 N/mm^2 or 1.5 GPa in the S.I. system of units which would be about 100 T/in^2 or 224,000 p.s.i. in the old Imperial system or about 150 kp/mm^2 (or kgf/mm^2) in the old C.G.S. system. When it is remembered that circumferential tensile stresses always greater in magnitude than the internal pressure are induced in the wall of the container of

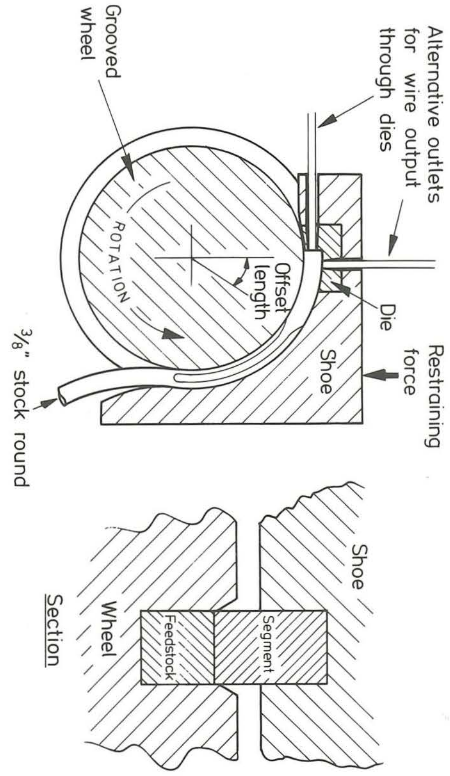


Fig. 11 "Conform"

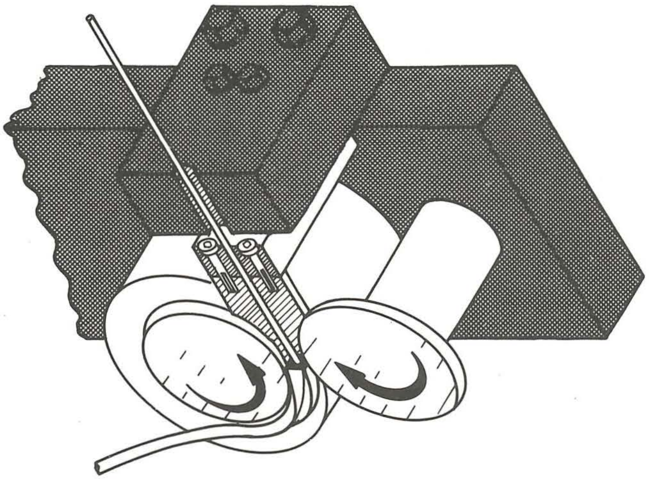
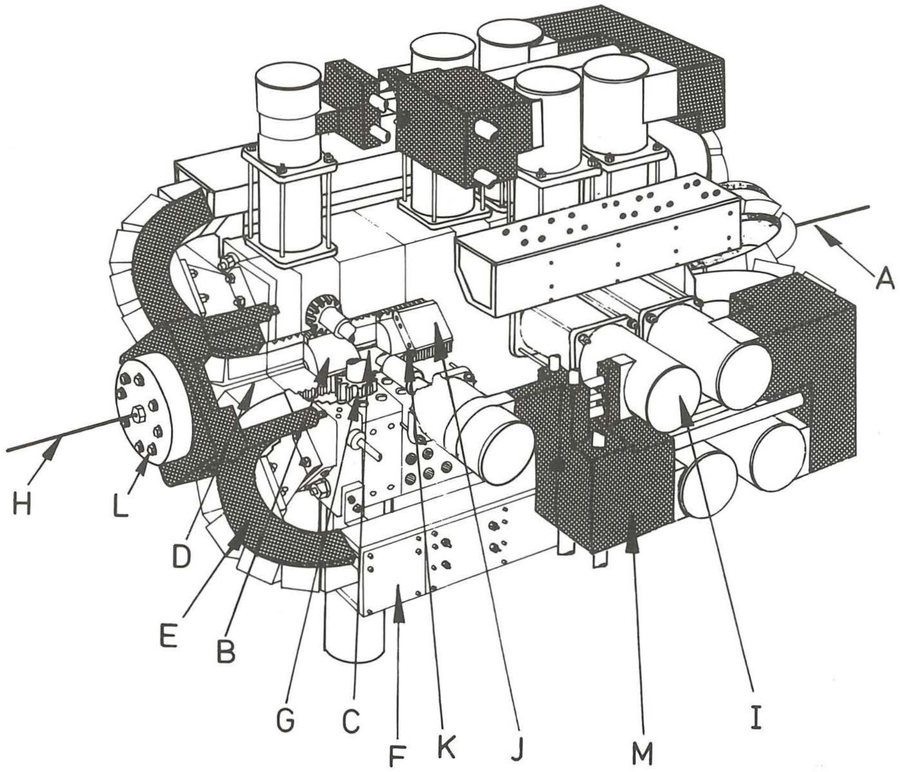


Fig. 12 "Extrolling"



A	Wire rod
B	Chamber segments
C	Extrusion die
D	Die stem
E	Track loop
F	Straight track
G	Pinion gear
H	Extruded wire
I	Hydraulic motor & gear reducer
J	Fluid pressure pad
K	Cooling water passage
L	Load cell
M	Hydraulic fluid manifold

Fig. 13 Western electric continuous wire extruder

such pressures the difficulty of designing such equipment becomes evident. Containers have to be constructed in such a way that residual circumferential compressive stresses can be introduced into their bores and techniques such as wire-winding, autofrettage, assembly by shrinkage or taper pressing have been developed. One central problem in design which has received much attention from academics during recent years is that of optimization of the solution and many mathematical techniques are available but not often applied in practice. The high-pressure thick-walled cylindrical vessel is one of the few cases which can be analysed in this way and several hydrostatic extrusion presses exist in the world today operating safely on a production basis.

I hope I am getting over to my audience the fact that the design problem is not simply that of finding a good draughtsman who is adept at thinking in three dimensions and making a good drawing. Of course, such abilities are invaluable and essential but the real work of design is in the creative function of finding an economic solution to the problem which satisfies many requirements, not the least important being function, safety and reliability. Several disasters have occurred because of the lack of attention to these requirements, as pointed out by Professor Davies[4] in his inaugural lecture here, so it must be extremely difficult to set up a systems approach or design methodology which really works. Otherwise we would not have had disasters like Ronan Point, the Ferrybridge Cooling Towers, the DC 10s, or the large empty Tower Blocks we now have (which are evidently non-functional), not to mention falling pit-cages, diving bells etc. We certainly need to improve our understanding of and methods for dealing with the design problem.

Of course, design problems can range over a large span of size. So far, I have discussed only relatively small problems forming part of a large system. Someone had to design the complete nuclear reactor, of course. An interesting problem of that type is the Channel Tunnel,[5] which has been a pipe-dream for more than a century now and surely must eventually come to fruition. One of my former colleagues at Imperial College, Emeritus Professor A. L. L. Baker, who is also a Visiting Professor in the Department of Civil Engineering here, has been working on this vast design problem for the last ten years

or so. He invited me to work with him on some of the mechanical engineering aspects of the problem and we have eventually evolved the overall scheme illustrated in my next Fig. 14 in collaboration with Sir Bruce White & Partners and Sir David Nicholson, who chairs our Steering Committee on the project.

Essentially the design is based on the *immersed* tunnel, which is made up of large concrete sections which can be floated into position over a trench which would be dug across the bed of the English Channel. Each section is dropped into the trench and sealed against its neighbour with special sealing membranes under the influence of the high ambient under-water pressure, the whole tunnel so formed being then covered over by sufficient rock-fill to provide safe cover against anchors or wrecks. The whole technique is well established by Dutch firms such as Royal Bos Kalis Westminster and Stevins and we are convinced of the feasibility of the whole project. We propose that there would be two three-lane motorways, each with a fourth hard shoulder and also a two-track railway. One main feature of the design is the conversion of two sand banks (at present hazards to shipping) in the middle of the English Channel into islands each of about 1½ miles in length to allow all motor vehicles to emerge into the air for a time. This would enable adequate ventilation of these long tunnels to be achieved (the longest being 10 miles, similar to the present Mont Blanc tunnel) as well as easing the monotony of driving through such long tunnels and providing service areas for the inevitable vehicle breakdowns. The rail track would remain underground for the whole crossing and would be electrified as for the proposed single track bored tunnel, without ventilation problems.

The great advantage of this design is that the overall length of the tunnel can be considerably shorter since it is not necessary to bore deep as with a bored tunnel. In this way a much more economical design can be produced and we are now working on the various aspects of the sub-systems which have to be evolved—what is called a pre-feasibility study. The main project will cost around £3 billion (£3000 million) and will provide employment for many people on both sides of the Channel. Fig. 15 shows an artist's impression of the dredger which Stevins is developing for this type of project. It is a

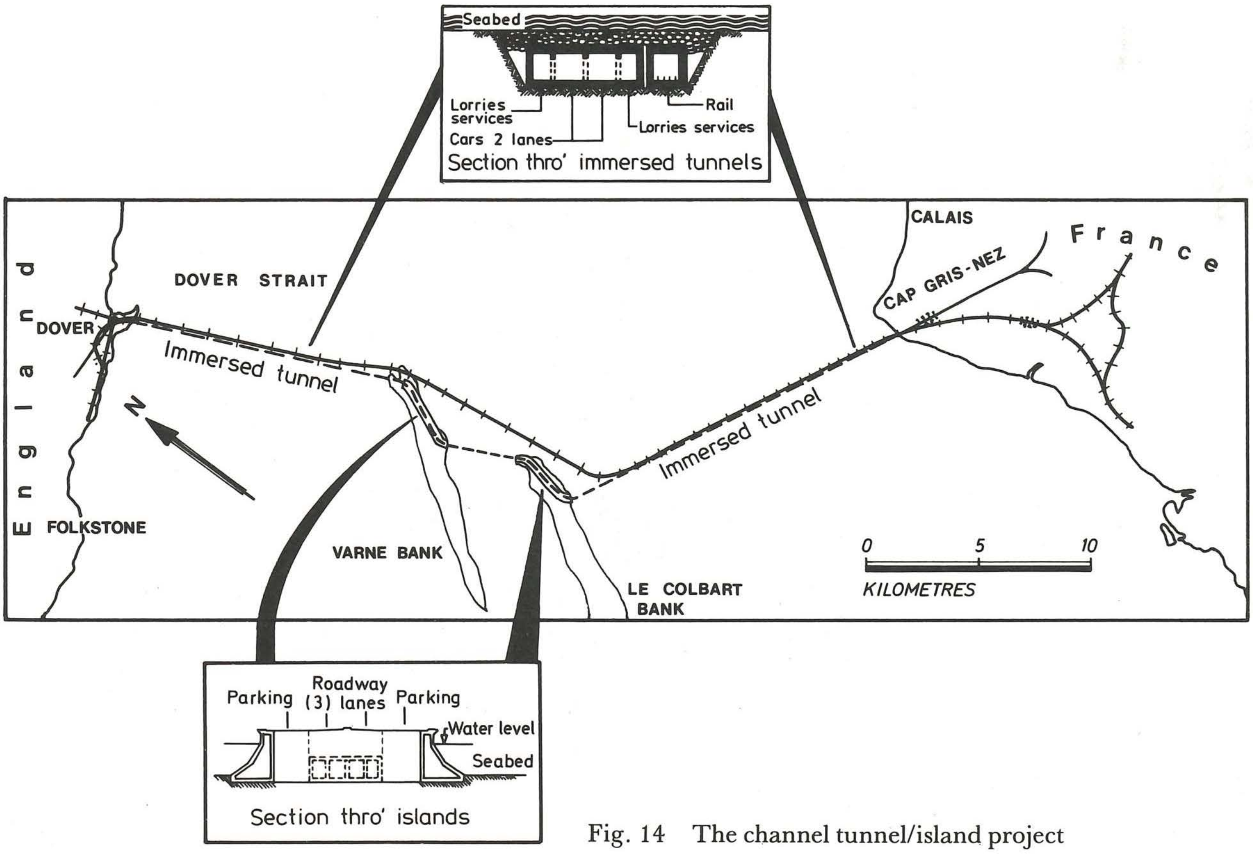


Fig. 14 The channel tunnel/island project

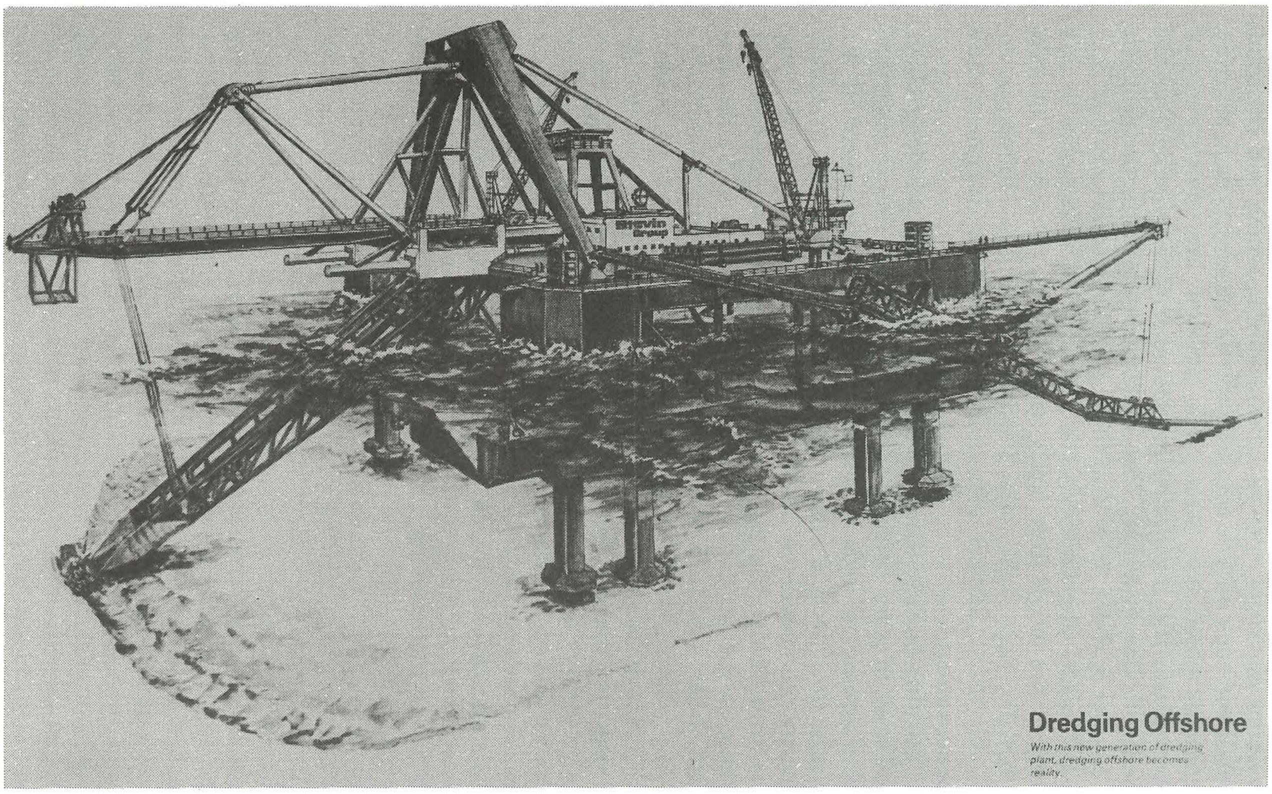
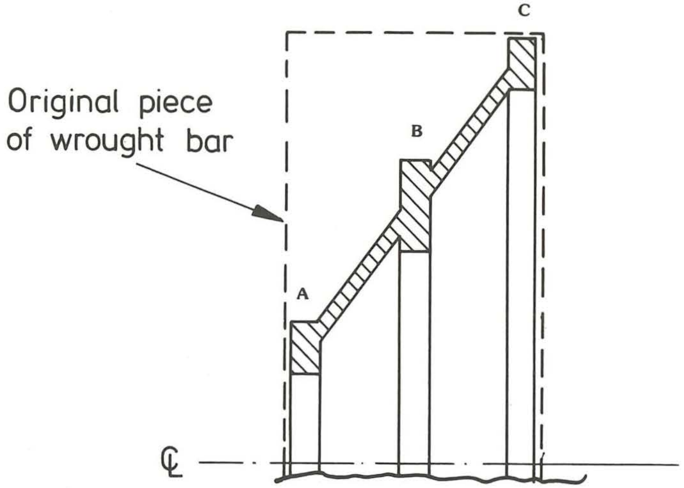


Fig. 15

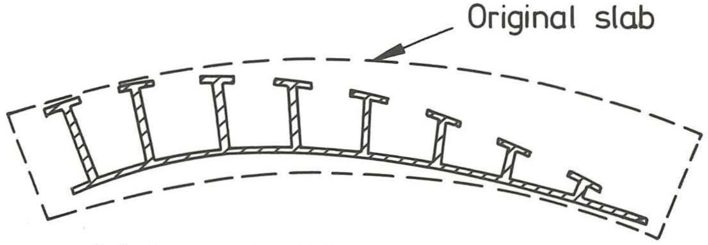
walking platform, costing around 50M£, which will cut solid chalk and suck out the resulting slurry, passing it back to cover elements which have been put in position. We envisage two of these platforms, one to dredge, the other to carry and lower the elements into position. The maximum depth of the English Channel is about 56 m and these platforms could work in that depth quite satisfactorily. The actual firms taking part in this project are Royal Bos Kalis Westminster (Dutch), Costains (British), Spie Batignolle (French) and Philip Holzmann A. G.(German). This is a very large challenge to designers of all persuasions!

Turning back to the small again, one design problem which has been of some interest to me over the past few years is that of designing in such a way that energy can be saved, in the production process itself. One of the main ways in which energy is wasted is in the massive cutting away of large amounts of metal by the machine tool, in order to give the final shape to the product. I believe that Sir Barnes Wallis once said, when asked what he thought of the Concorde aeroplane, "Marvellous, but I believe it was cut out of the solid, wasn't it?" Not quite true, of course, but indicative of the point I am trying to make. To avoid such massive cutting, good engineering design involves designing components so that they can be forged, rolled or extruded, either hot or cold, to their final shape. In some cases that is not possible, as shown diagrammatically in Fig. 16. It would be difficult to forge an object such as the gas turbine rotor indicated because of the difficulty of removing it from the die. At present such high-strength components have to be machined from the solid, with up to 97% of the expensive nickel alloy being converted into machine turnings or swarf. The swarf is admittedly recycled but this involves a large amount of energy. The reason for machining from the solid is not only one of complexity of shape but also because that is apparently the only way of achieving the high mechanical strength required, particularly against fatigue failure.

In an attempt to find another manufacturing route I have been trying to develop a process which I have called "deposition forming" which involves the building-up of such shapes by a simultaneous process of deposition and forming so as to produce the required complicated shape and high



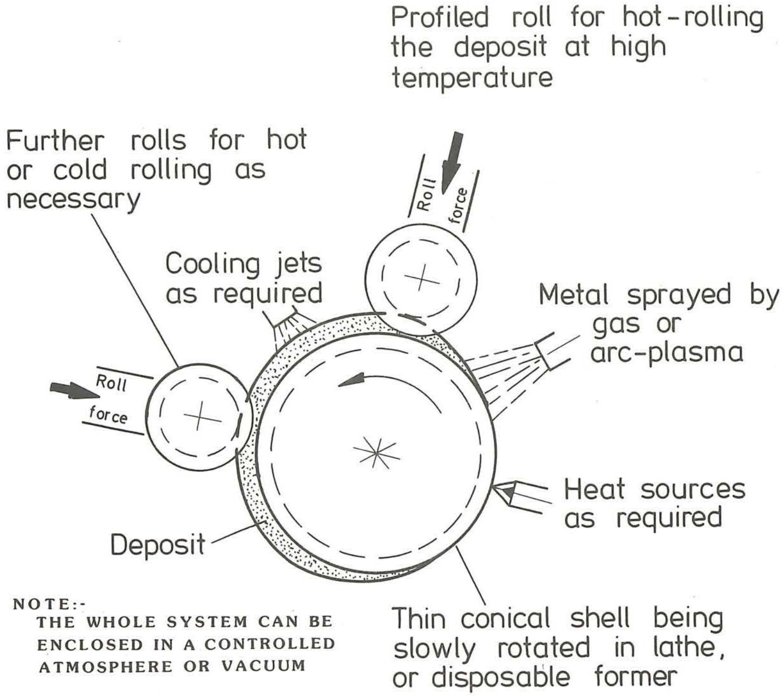
(a) Gas turbine component



(b) Integral stiffened aerofoil section

Fig. 16 Typical advanced engineering components which have to be cut out of the solid

strength (as a result of the forging process which confers high strength).[6] Initially I tried to apply the spray-forming techniques developed here by Professor Singer but found that it was not possible easily to achieve the necessary control of atmosphere required to avoid oxidation of the deposited metal. The system I used is shown diagrammatically in Fig. 17 and there are photographs of the equipment working in the next two (Nos. 18, 19). I am very grateful to Professor Singer for



NOTE:-
THE WHOLE SYSTEM CAN BE ENCLOSED IN A CONTROLLED ATMOSPHERE OR VACUUM

Fig. 17 Deposition forming

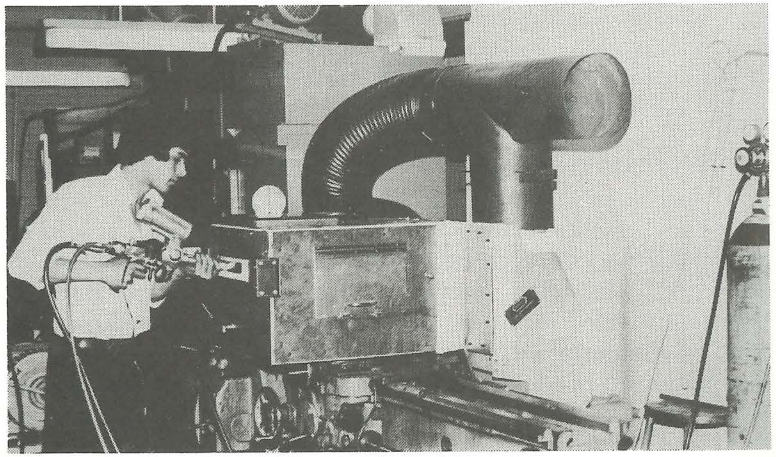


Fig. 18

the great help he gave me when he was a Visiting Professor at Imperial College. Eventually I decided to use MIG welding (metal-inert gas) which is a well-established welding technique in which the filler metal forms one electrode, the work piece the other and an annular inert gas shield is applied by the torch itself.[7] This has proved very successful. The next Figs. (Nos. 20, 21) show some of the discs built up by this weld deposition technique, with simultaneous hot rolling by a grooved roller.

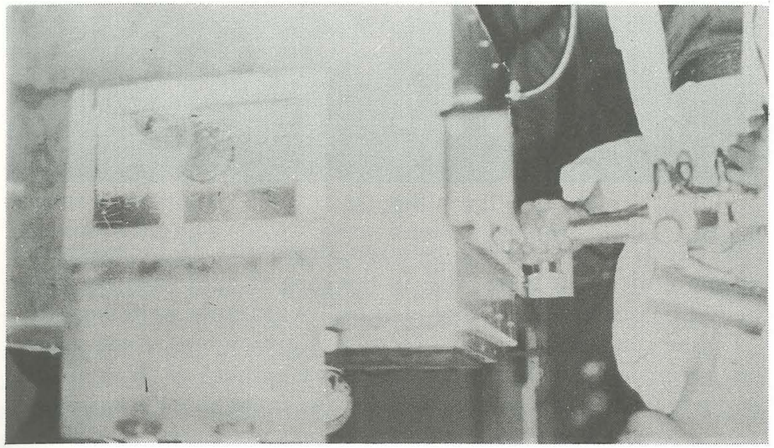


Fig. 19

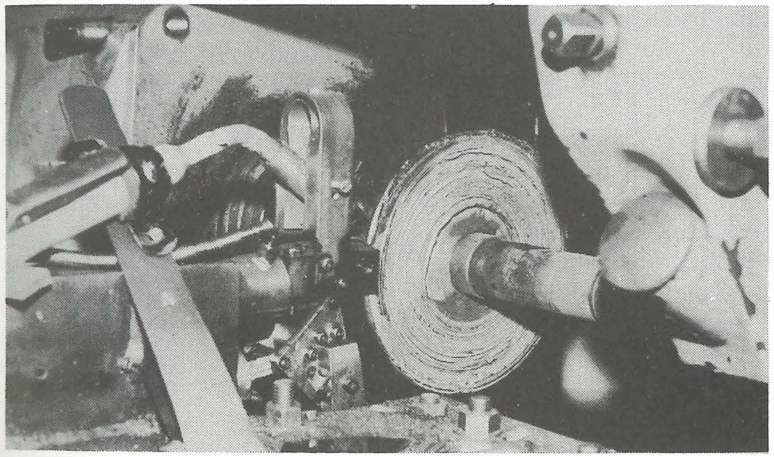


Fig. 20

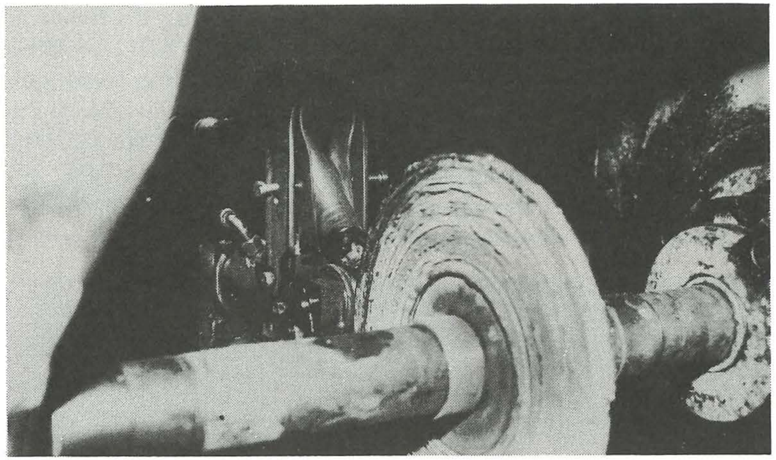


Fig. 21

The effect of the rolling is quite dramatic. It increases the fatigue limit by at least 30% in the case of mild steel and 15% for stainless steel, over what is found in a simple weld deposit.

I hope that my inaugural lecture is giving you some idea of the importance which I attach to the subject of design, particularly in relation to the need for the mechanical engineer to have a broad knowledge of the various materials available to him and manufacturing processes by which they can be shaped into useful products. Since starting here I have tried to establish a second honours undergraduate course in my department which will contain more emphasis on manufacturing technology than does the existing honours course and I have applied to begin a four year course of the type suggested by Sir Frederick Dainton, the then Chairman of the University Grants Committee, in 1977.* This 4-year Dainton course will again have much emphasis placed not only on management techniques (as suggested by Dainton) but on design and manufacturing technology. Personally, I believe that it is impossible to *teach* design (involving the creative types of activity I have described today) and that it can only be *introduced* to the undergraduate student by involving him in typical day-to-day problems in industry. To that end, we in my department are continually trying to establish both group and individual projects in industry for our final year undergraduate students jointly supervised by local industrialists and ourselves together. In the 4 year course, if it ever comes about, I hope that we shall be able to arrange for each student to spend half of his final year actually in industry studying a design problem of the type I have mentioned, to provide the subject matter for his individual project. Only in this way can the student be given a real understanding of the need to be able to *establish* and then choose between a multitude of possible solutions to any given problem and the need to endeavour to set up as many solutions as possible and to establish valid methods for comparing solutions.

Of course, many of my staff have already developed design projects of the type I have mentioned. For example, as in "Wales Today", seen recently on T.V., the design of a windmill by Mr. R. T. Griffiths to supply power and heating for remote buildings. This is a challenging problem involving Thermodynamics (e.g. heat losses through walls, overall power requirements), Fluid Mechanics (e.g. size of rotor to give necessary power, number, shape and twist of blades, performance characteristics), Materials (for blades, framework of supporting tower), Stress Analysis (strength of rotor, blades and tower), Mechanics (Gear box to match low-speed aerodynamically optimised rotor with high speed electrical generator), Electrical (characteristics required for generator—do we need A.C. or D.C. etc.), Automatic Control (feathering or braking in high winds, continuous pitch control of blades to optimise energy extraction for variable wind speeds), Energy Storage (batteries, reservoir, etc.).

Also, most of the research interests of my staff here have an impact on the design problem. Dr. Parker's studies of wake shedding and vortices have a wide application to problems as diverse as blowers in industrial systems, factory chimneys and lorry radiators and will undoubtedly indicate ways in which these artefacts can be designed to avoid noise which is damaging both to the environment and the structure itself. Also, possibly, how to stream-line motor cars! Mr. Clarke's studies of the adverse effects of vibration on the human frame will surely lead to better transportation systems. Most of the tribology work of the department will lead to designs which are better from the point of view of life and reliability of components. Mr. Watson's broad experience of the design func-

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*and more recently by Sir Montague Finniston in the "Finniston Report".

tion at all levels makes him an invaluable teacher of the subject. (I apologise to the rest of my staff who are also involved in projects of this type, for not mentioning them all, but time is pressing on).

As I have mentioned, my own research interest has always been in the application of the theory of plasticity to problems of forming materials and this is, I believe, a research area which, like tribology, is of great importance in the general field of mechanical engineering design. Recently I have been using the finite element method to solve problems in metal forming and have been very pleased to find that Professor Zienkiewicz here (who virtually invented the method) has also been studying metal working problems. Therefore I am not quite so worried about trespassing into his Civil Engineering domain with my interest in the Channel Tunnel and I hope that we can both, with Professor Singer, perhaps enhance even more the already high reputation that this University College has in the general fields of materials technology, manufacturing, civil and mechanical engineering. One of the ways I hope to do this is by bringing the annual International Machine Tool Design and Research Conference here to Swansea from time to time and we are at present busy organising the 21st which will be held here next September. It is very interesting to observe the change of emphasis in those conferences *away* from the wasteful massive cutting processes towards shaping components by plastic deformation.

To conclude my lecture, I should like to show in fact a few slides indicating the *power* of the finite element method for solving problems in the large strain plastic deformation of materials.[8] Historically, the finite element method was applied initially to the small strain elastic deformation of materials and structures. By replacing displacement with velocity and strain with strain rate and continually up-dating the co-ordinates of the deformed body we found it possible to use existing highly developed small strain finite element computer programs to follow the large strain deformation of a body. Fig. 22 shows, as a test of the method, the large strain frictionless compression of a solid cylindrical specimen. This is a deformation in which there is no 'redundant' distortion so that originally straight transverse and cylindrical planes remain straight. When high friction is present at the tool-workpiece interface, however, the

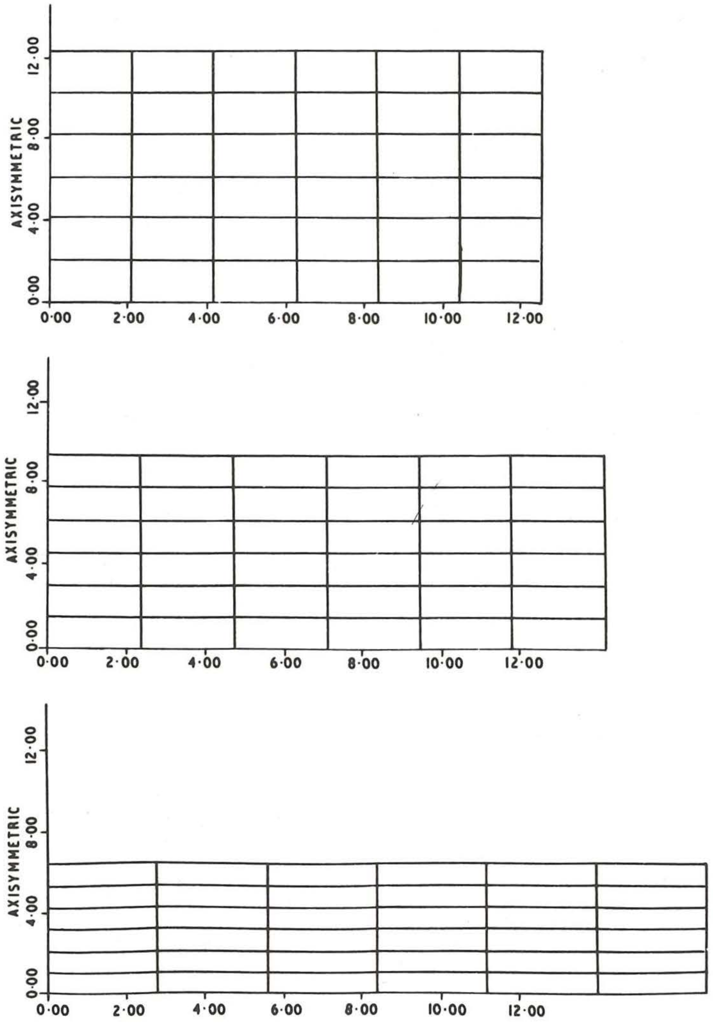

Fig. 22 Compression of a cylinder without friction, one quadrant shown. Initial dimensions 25 mm high, 25 mm dia.

distortion shown in the next Fig. 23 is predicted by the finite element method and there is no other method of determining realistically this detailed pattern of deformation. The method will work even up to compressions of over 80% as shown in

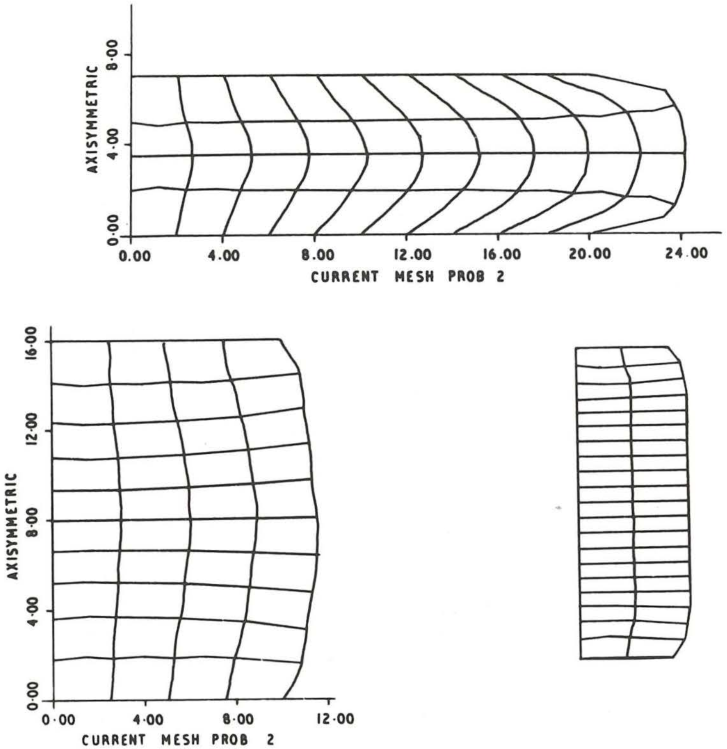

Fig. 23 Compression of cylinders of ratio $\frac{1}{4}$, 1 and 4 with sticking friction. Half of each specimen is shown

Fig. 24. The next two Figs. 25 and 26 show the behaviour of cylinders of different geometries—it can be seen how the cylindrical surface of the specimen gradually rolls over to come into contact with the surface of the tool, as observed in practice.

In order to predict frictional effects in compressions of this type, as often encountered in forging, the 'ring test' has recently been developed in which a ring (like a Polo mint) is compressed in the manner illustrated in Fig. 27. If friction is very high, as shown in that slide, the central hole of the ring becomes smaller as is predicted by the finite element solution shown. If friction is very low, the central hole becomes larger in diameter until the deformation is very large, as shown in Fig. 28. A comparison for the %age reduction in diameter ver-

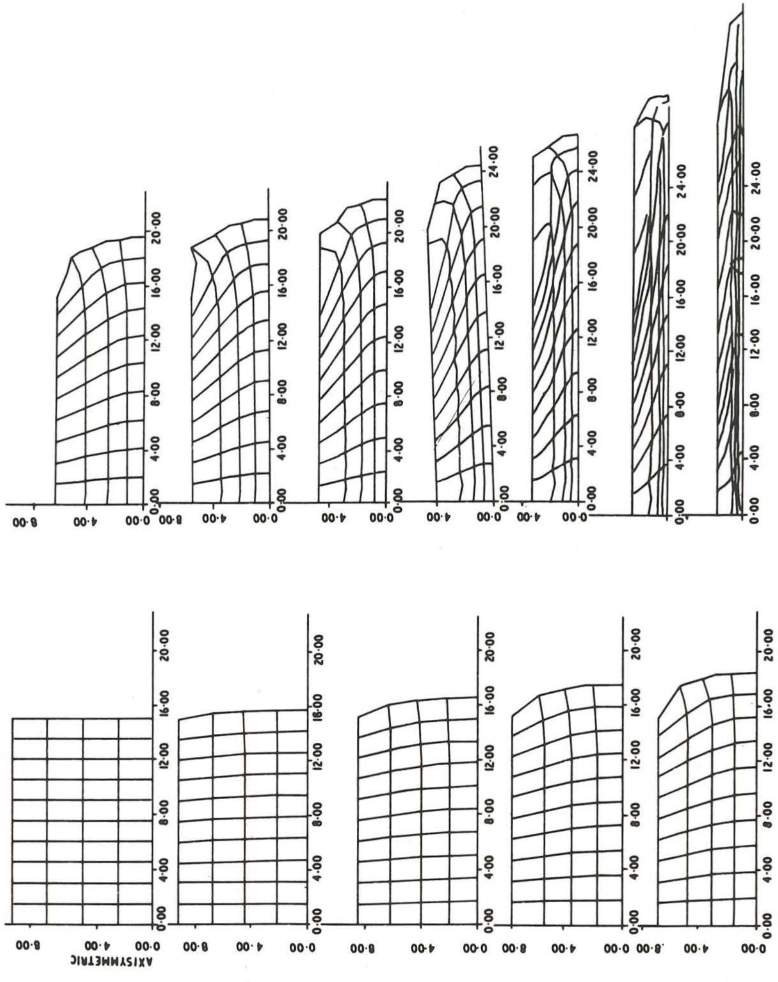

Fig. 24 Compression of a cylinder of starting height to diameter ratio 2/3 with sticking friction. Final compression shown is 82.5%

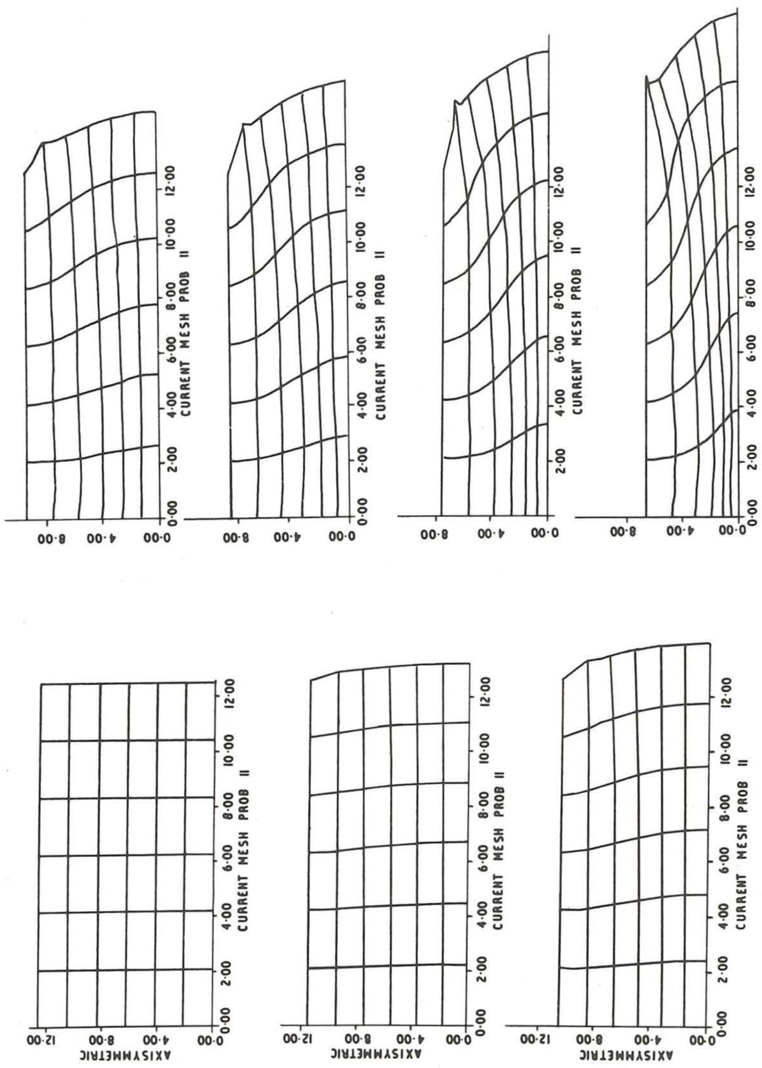

Fig. 25 Starting height to diameter ratio of 1; sticking friction. 54% compression shown in last figure

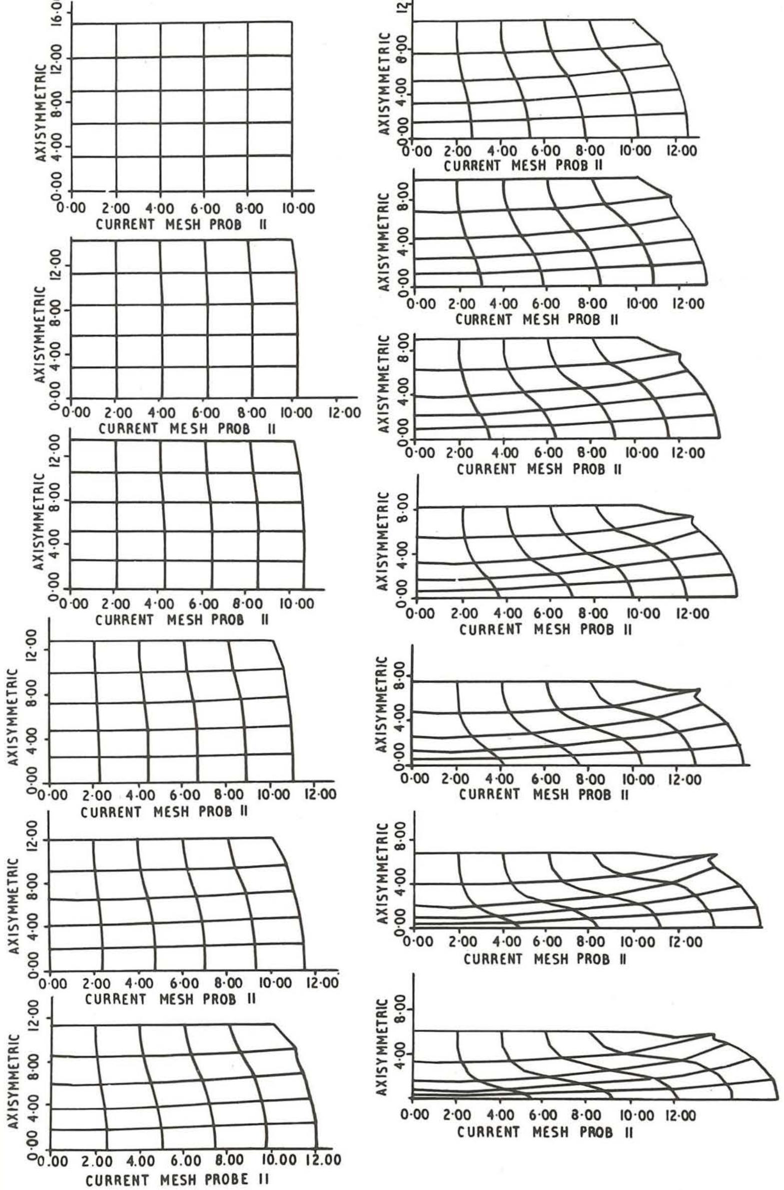

Fig. 26 Starting height to diameter ratio of 3/2; sticking friction. Final compression shown is 60%. One quadrant only is shown

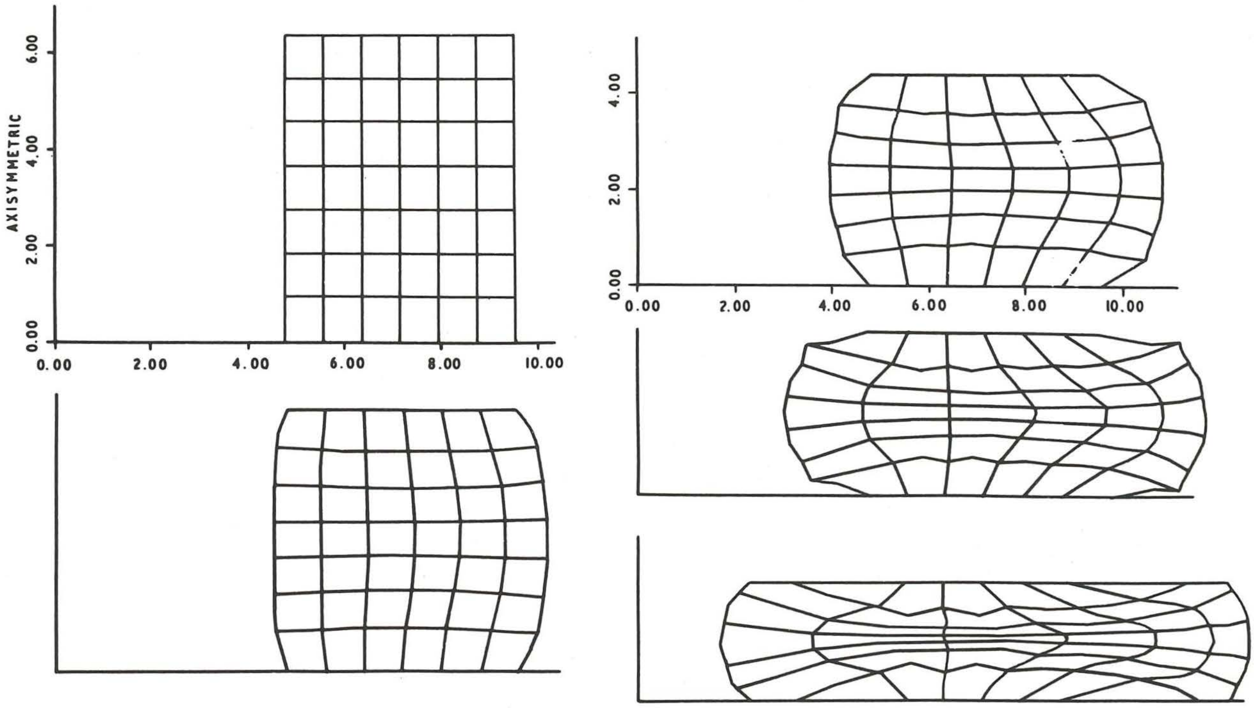

Fig. 27 Ring test with sticking friction, half a specimen is shown. Final compression is 38.8%

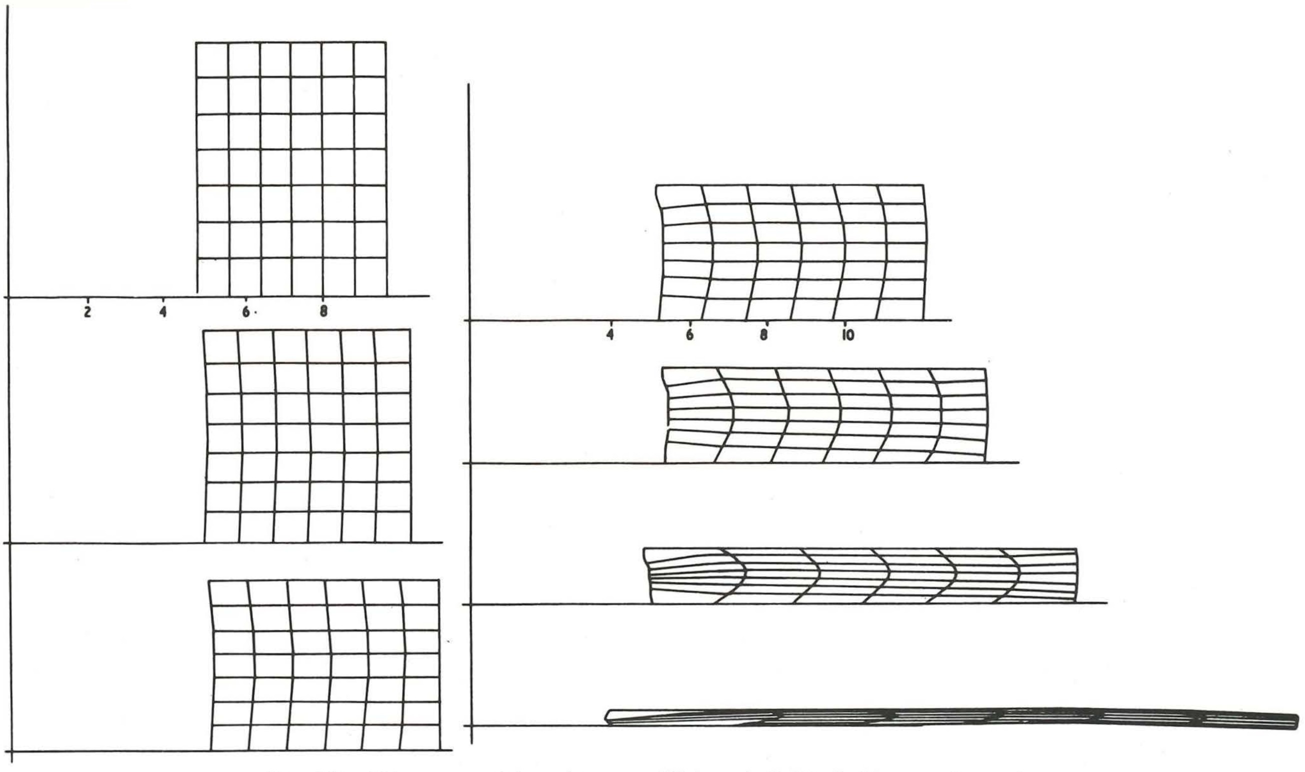

Fig. 28 Ring test with a shear coefficient is 0.06; half a specimen is shown. Final compression is 92%

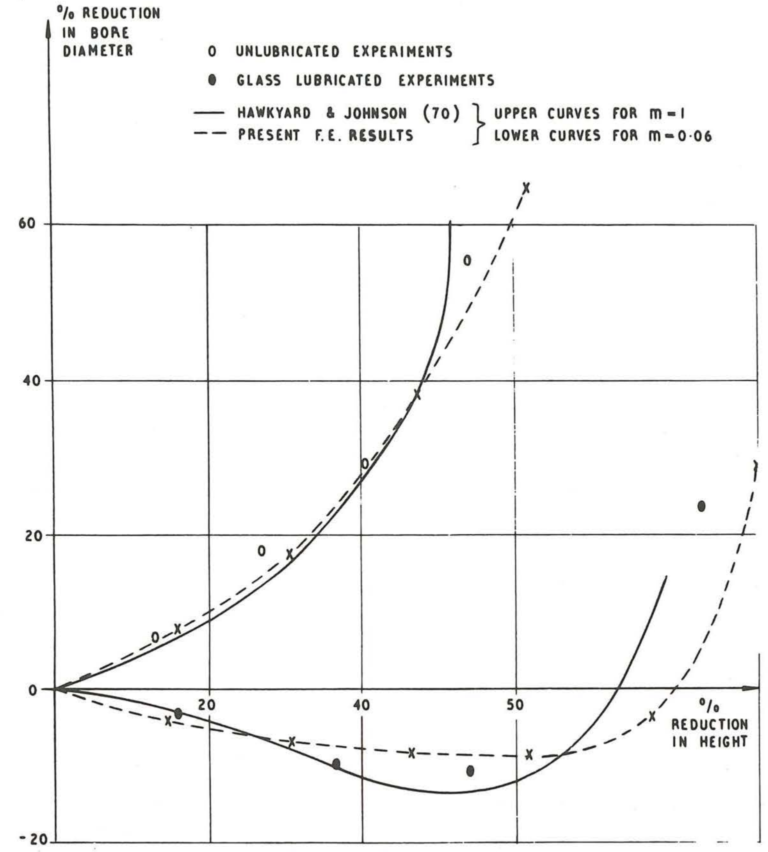

Fig. 29 Comparison of Hawkyard and Johnson[10] theoretical results, the present finite element predictions and some experiments for the ring tests

sus the % reduction in height between the predictions of the finite element analysis and experiment is shown in Fig. 29 and the good agreement can be observed. Fig. 30 shows the strain rate distribution determined from the theoretical solution and the stresses can also easily be calculated.

A difficult problem often encountered in the forging process is that of predicting the relative flow of material in different directions. For example, the next slides (Nos. 31 & 32) show the relative vertical and radial flow of material in deforming a

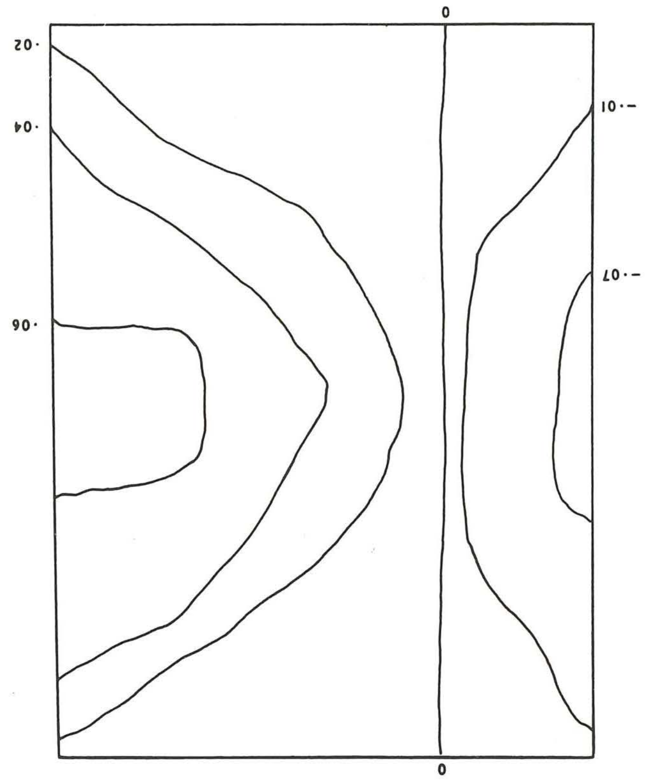

Fig. 30 Tangential strain rate distribution in the sticking friction ring test of Fig. 7.7 (first increment). Units are $\sec^{-1}$

solid cylinder of metal into a "top hat" shape. The last Fig. 33 shows a comparison between the predicted shape and that actually observed in some experiments which we carried out on the isothermal forming at 900°C of a titanium alloy. The good agreement can be observed.

Finally, I should mention that Dr. Price and I carried out that work at Imperial College and our work was made much easier through the generous co-operation of Professor Zienkiewicz and his colleagues here, who willingly gave us their computer programs to develop for our particular problems.

I hope my lecture has given some idea of the great challenge

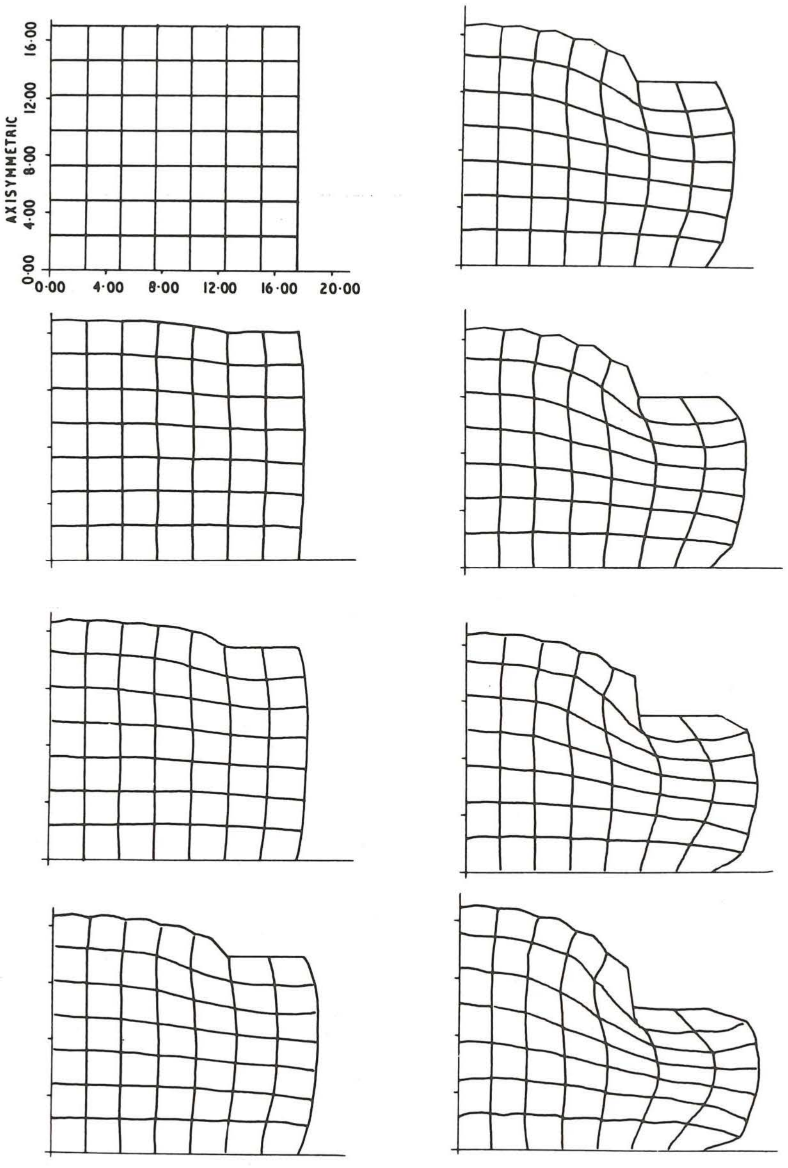

Fig. 31

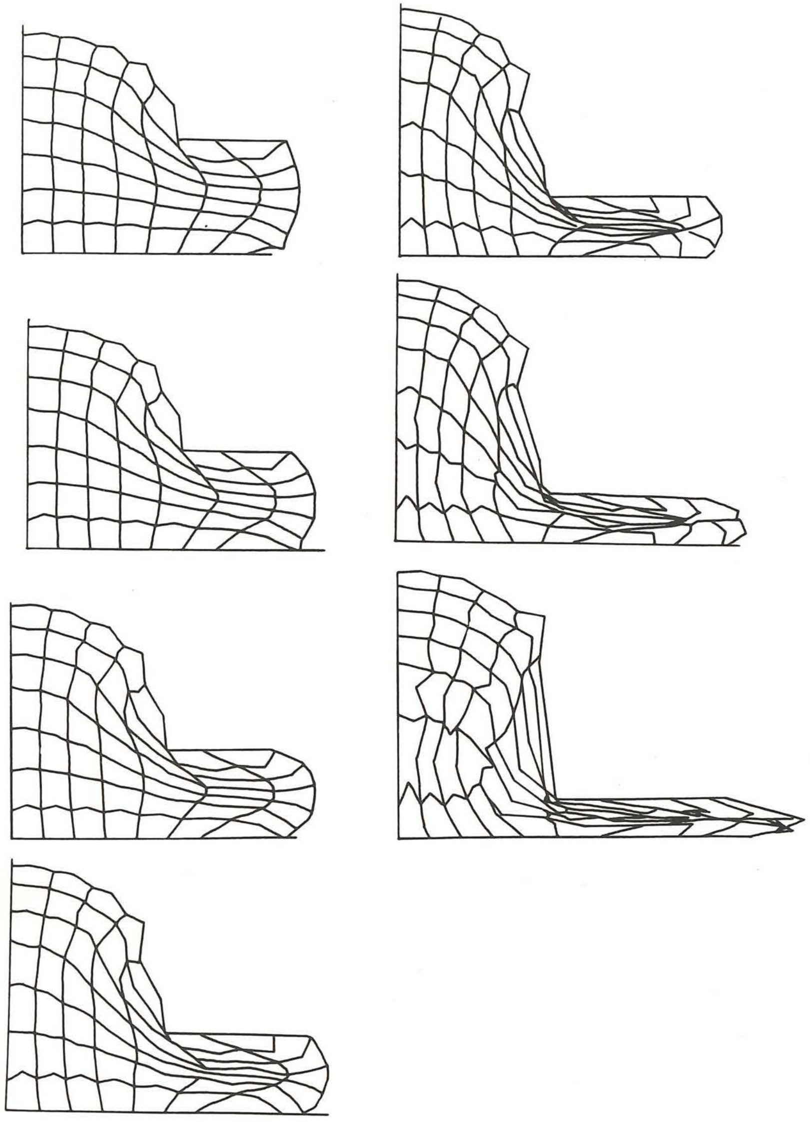

Fig. 32 Compression of 17.5 mm high, 17.5 mm dia. specimen with a profile die. The mesh is not reformed at any stage

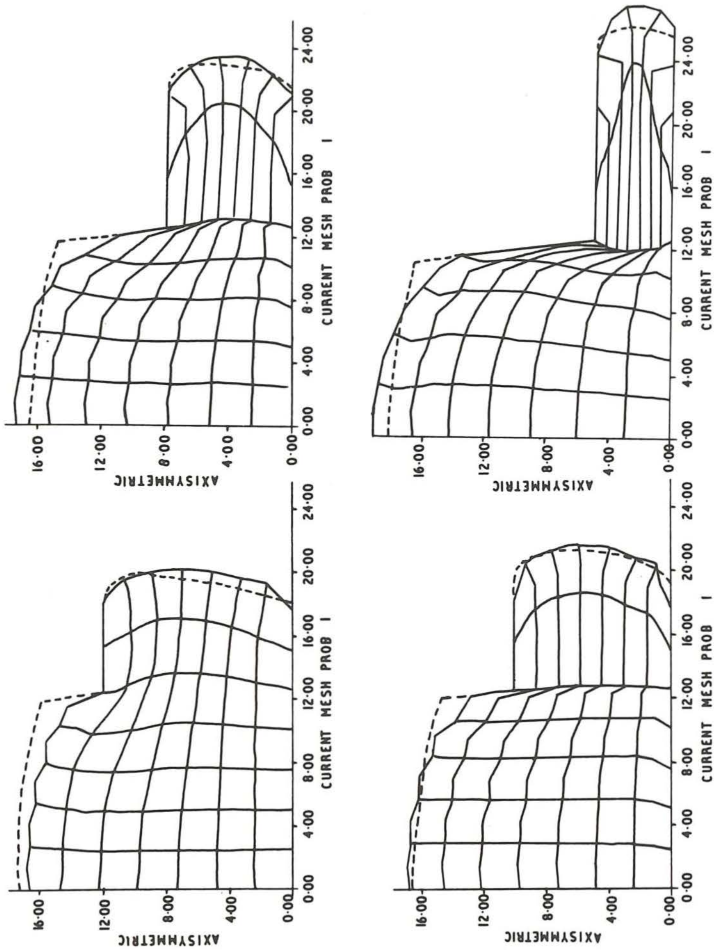

Fig. 33 Compression with a profile die (see Fig. 10). The mesh in this case is reformed at increments 7, 12. The dashed line gives some close experimental results for the outside profile of comparable specimens

which design presents to the mechanical engineer—it is great fun in practice but it implies also a heavy burden of responsibility. We have to design and produce safe, reliable and efficient devices *economically*, otherwise deaths may occur or firms go out of business.

May I conclude by thanking the Reprographics staff here who have helped me with illustrating this lecture, particularly Derek Gabriel who is up there behind the camera.

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