THE CENTENARY OF IMPERIAL COLLEGE, LONDON

1907 - 2007

The Experimental Age of “Strength of Materials”

Recollections of Five Ages of Strength of Materials in the Mechanical Engineering Department,
Imperial College, London: Youth, Growth, Maturity, Decline and Renaissance.

by
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PREAMBLE

The subject known until recently as ‘The Strength of Materials’ was conceived at the turn of the C15-C16 by Leonardo da Vinci and brought to birth some 50 years later by Galileo. About 100 years later Robert Hooke stated that for small deformations, extension was proportional to load. During the next 100 years many well known scientists or mathematicians, working mainly in France and Germany, began the theoretical basis for the subject. The first known lever arm tensile testing machine was built by Musschenbroek in Holland, in 1729. During the Industrial Revolution, roughly 1750 to 1850, Britain took the lead in many aspects of practical engineering - smelting by coke as resources for charcoal became scarce, the first iron bridge at Coalbrookdale in 1777, hot blast furnaces to produce large quantities of wrought iron, rolling mills and a host of machines and artefacts from the great engineers of that period, culminating in the railways of the Stevensons and Brunels. Meanwhile, the first large testing machine, of 100t (c 1,00kN) capacity and some 100ft (c.33m) in length, was built in London in the early C19th when the Admiralty moved from using hemp anchor cables to wrought iron anchor chains. In the late 1850s the benefits of steel were exemplified by David Kirkaldy, working in Glasgow, and then by designing a 400t (c.4MN) capacity hydraulically powered testing machine which, in 1862, he set up in Southwark, London, to become the first materials commercial test-house. In the 1860s, Bessemer and Siemens brought in the mass production of steel thereby encouraging the use of steel rather than the wrought iron of the early industrial revolution.

In 1835, Sir William Fairburn wrote that the French and Germans were in advance of the British in theoretical knowledge, seemingly due to better educational facilities for ‘chemistry and mechanical science’. Albert, The Prince Consort, recognised this problem and after the Great Exhibition of 1851, and arranged that land in South Kensington was reserved for an engineering college with associated museums and libraries. The City and Guilds of London became the main instrument in setting up a response, though courses in engineering science were being set up at a number of Colleges in the industrial midlands and Scotland. In the mid-C19th Rankine, somewhat of a polymath at the University of Glasgow made the first ‘proper’ definition of stress (related to load) and strain (related to deformation) and wrote text books on mechanics that were still being reprinted in up-dated form in the early C20. At Cambridge, Professor J.A. Ewing wrote a book in 1899, ‘Strength of Materials’, which emphasised the engineering aspects of the theory of applied mechanics for beams, struts, shafts and so on, with one chapter on the experimental behaviour of metals (including some reference to micro-structure and alloying) and another devoted to testing.

So at the turn of the C19th to C20th the City and Guilds became one of the main colleges teaching engineering albeit some 50 years after the subject of Strength of Materials was recognised. Many college and university courses that followed taught ‘Materials’ allied to ‘Structures’, as witnessed by many text-books, or pairs by the same author, with titles such as ‘Materials and Structures’. The former might or might not include a gesture towards the micro-structure of iron and steel with the latter covering constructions in steel, concrete and perhaps timber. Imperial College followed a pattern n which ‘Strength of Materials’ was taught in the Mechanical Engineering Department (M.E.D.), ‘Structures’ in the Civil Engineering Department (both of course within the City & Guilds) and ‘Metallurgy’ in the Royal School of Mines.

The City & Guilds College had its foundations in the Finsbury Technical College, which became the City and Guilds Central Technical College and moved to Exhibition Road, South Kensington, around the turn of the C19th to C20th. In 1907 it became part of Imperial College, itself an integral part of the University of London until 2007. The ‘Guilds’ was housed in the Waterhouse Building, an imposing structure externally of red brick, some four or five stories high, fronting Exhibition Road with an entrance hall and main staircase of yellow terra-cotta tiles. The workshops and material laboratories were immediately behind the main entrance to the Guilds but one floor lower, to give rear entrances at the ground level there. They were housed in a single story of brick with pitched part-glass roof.

I joined the Department in late 1948. Remarks dating before that are based on hear-say from members of staff then serving, some from around 1910 or 1920, and from the relevant technical literature or earlier published histories of the College. From 1948 to the present day (2007), they are my own recollections, some no doubt clouded by the passage of time.

YOUTH, 1907 to 1955

The early years

Materials had always been a strong subject within the Department, with renowned teachers in the early C20th such as Professors W.C. Unwin and W.E. Dalby. Unwin is recorded as the first Dean of Engineering of the City and Guilds, in 1885, albeit the name of the College was then ’The City & Guilds Institute for Advanced Technology’. Dalby was Dean from 1906, thus serving when the amalgamation of the R.C.S and R.S.M. and C.& G. came about to form Imperial College.

Unwin’s book ‘The Testing of Materials of Construction’ was written around 1888 but a much enlarged Second Edition carries a Preface dated ‘Kensington, 1898’. The frontispiece is entitled ‘Engineering Laboratory at The Central Institution of the City and Guilds College’ and shows a large 50t (c.500kN) Buckton testing machine that remained in place in the M.E.D. until about 1955. The moving jockey weight could be supplemented with a hanger at the end of the lever arm, to allow a load of 100t to be reached. The Introduction to his book states ‘With that part of applied mechanics which deals with the determination of the simpler straining actions on the members of complex structures we have not in this treatise to deal’. The definitions of stress and strain and a derivation of the stresses induced by simple bending are given. The recognition that plastic flow occurs at constant volume is illustrated by the work of Tresca in 1878 but that is the limit of ‘applied mechanics’ in his book, two chapters out of sixteen. The terms ‘crystal structure’ or ’metallurgy ‘ are not indexed so how far beyond a very comprehensive treatment of testing of metals the undergraduate teaching went, and what other books were used in Structures and Mechanics is not known to me.

Dalby’s book was conceived in 1911 though not published until 1923 and contains even less ‘applied mechanics’. The terms ‘stress’ and ‘strain ‘ are not defined though of course they are used in the text, and neither ‘strain’ nor ‘bending’ are indexed. However, one chapter out of six is devoted to the ‘Inner structure of metals’ one to ‘Elastic and plastic states of metals’ and many chapters refer to various alloy steels and to other metals. The emphasis is very heavily experimental and again it is not clear what supporting lectures in stress analysis and applied mechanics in general might have been given to the undergraduate students.

This known emphasis on experimental work sets the tone for all that follows where the lecture courses per se receive no more than passing mentions.

Some of the first machines in the Waterhouse Building were either transferred from the fore-runner institution at Finsbury or acquired new c.1895 when Unwin became the first Dean. Several such machines were still in regular service in when I first saw them in 1948 and remained so for a number of years. The 50 ton (c 500 kN) capacity single lever arm ‘Buckton’ testing machine, shown Fig.1, has already been cited and there was a 10t (c.100kN) single lever Buckton machine with a mechanically operated single screw of long traverse that penetrated the floor. These were British machines of about 1880 or 1890 vintage, originally known after the name of their designer, Wicksteed, but later called

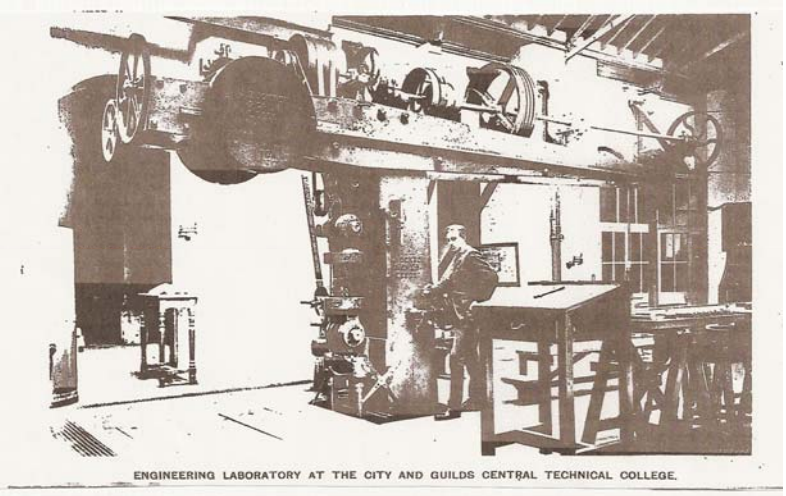
ENGINEERING LABORATORY AT THE CITY AND GUILDS CENTRAL TECHNICAL COLLEGE.

Fig. 1 The 50t Buckton Testing Machine
(from The Testing of Materials of Construction; W.C. Unwin; Longmans, Green & Co; 1899)

Buckton after the name of the manufacturer: they were no doubt built into the Waterhouse building since some of the operating parts were in pits below the floor. Both machines were suitable for tension, compression and bending tests and may well have been used for some of Unwin's own researches, notably his 'law' for the variation of extension along the length of a tension piece taken to fracture, for which the determination of 'Unwin constants' was still part of the undergraduate work in the 1950s. A 25ton (c 250kN) twin screw Riehlé machine of about 1900 vintage or a little earlier, Fig.2, is also a strong candidate for being equipment original to the Waterhouse building. It was of American construction and used a compound lever system to give a floor mounted machine of very compact layout, albeit not equipped for bending. The battery and wires for automatic balancing of the lever arm, shown in Fig. 2, were not there in 1948, although the terminals at the outer end of the arm were still fitted. All three machines were originally belt driven, the lineshafts still being in place in 1948 but only used for moving the crosshead to the required position. The actual tests by undergraduates were operated by hand.

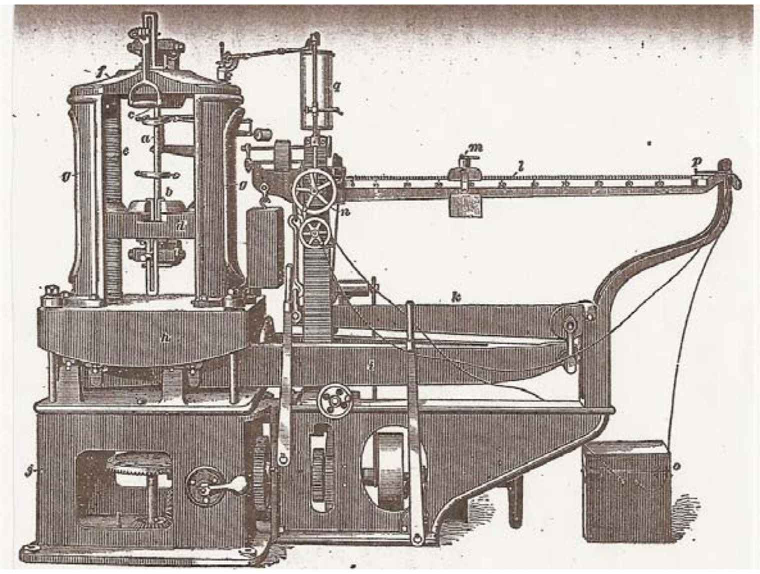

Fig. 2 The Riehlé machine.
This machine is now preserved in the Kirkaldy Testing Museum, London.
(from I.C.S. Reference Library : Testing of Materials,
International Correspondence Schools Ltd, 1906)

There were five machines of perhaps 1900-1920 vintage, none then very common in university testing labs; Charpy and Izod impact testing machines, a Haigh fatigue testing machine, a small bench mounted Haigh-Robertson fatigue machine, and a Dalby strut testing machine.

The Charpy, called 'shock-testing machine' in Dalby's book, Fig. 3(a), is now known as an 'impact testing machine'. It was of French design and manufacture; the Izod machine Fig.(3b) was British. Both were very early models. In both, a swinging pendulum fell onto a notched bar test piece of 10mm x10mm cross section, the former as a beam in simple supports of 40mm span, the latter as an up-standing cantilever. Each put the notch in tension; Charpy originally specified a 'keyhole' shaped notch whereas Izod used a V-notch, which is now commonly specified for both tests. The energy absorbed by bending the test piece, or fracturing it, as may be, is calculated from the known mass of the pendulum, its initial angle of swing and the recorded angle of rise after the impact. This gives an energy measure empirically related to the ductility or brittleness of the material being tested - usually steel with different compositions or heat treatments. The Charpy machine will shortly be donated to the Kirkaldy Testing Museum.

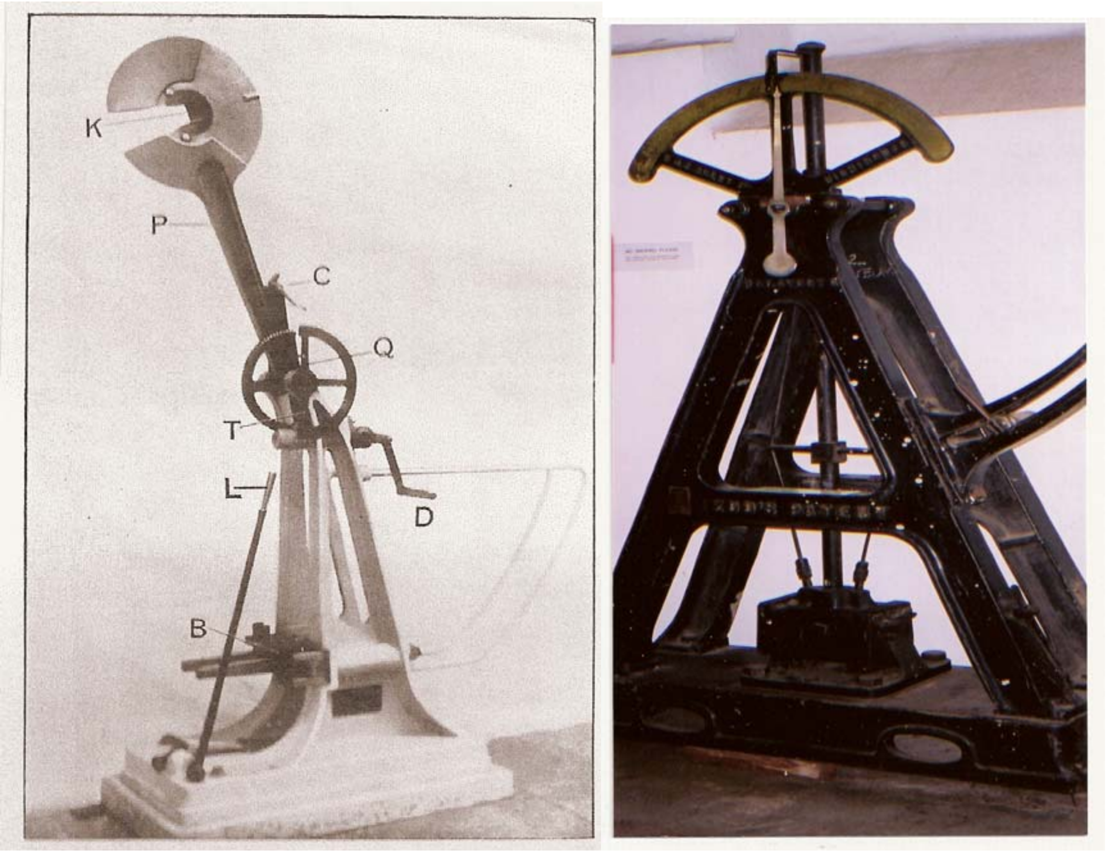

Fig. 3a Fig. 3b

Fig. 3 Impact testing machines c.1910 a) Charpy machine b) Izod machine.
The Charpy machine was moved in about 1970 to the new 'E-Block' and still survives.
((a) from Strength and Structure of Steel and Other Metals; W.E. Dalby, E.Arnold & Co 1923)

The Haigh was an unusual machine for fatigue tests under axial loading, in some respects ahead of its time. It stood about 6ft (c.2m) high, ran at about 3,000 cycles per minute, with, as I recall, ±3t (c 30kN) capacity. It was driven by electro-magnets from its own small generating set. The moving parts were carried on leaf springs which could be adjusted to give a mean load to the cycle. The M.E.D. machine was the third of its kind ever built, inspired, I believe, by the need to test metal cables, being made by (or at least supplied and serviced by) Bruntons, a Scottish cable manufacturer. The Haigh-Robertson machine was for testing individual strands of wire in rotating bending. One end of the sample was clamped in the chuck of a small electric motor, the motor pivoting on a vertical axis to allow the axis of rotation of the test wire to self-adjust to whatever angle was required. The other end of the wire was held in some form of spherical grip with the whole wire compressed until it took the curvature of a buckled strut. When rotated by the motor, alternating bending stresses of a magnitude dependent on the lateral deflection of the crippled strut, were applied to the wire. I do not know how many of either of these machines existed in the 1950s - or indeed had ever been made. They were the only copies I ever came across. In the 1950s the Haigh machine was used by 2nd year undergraduates for the alternating fatigue of steel pieces of about 0.4in (c.10mm) in diameter. To my recollection, the Haigh-Robertson machine was only demonstrated occasionally for its novelty.

In his book (cited for Fig.3) Dalby describes a micro-photographic apparatus of his own design, constructed in the City & Guilds c.1910, but the writer never saw the instrument. He also devised a mirror and photographic load-deflection recording apparatus. Mirrors fitted to rotate under load, showed the load on one axis and the deflection on the other. The instrument attached to a tensile test piece, is shown Fig.4 but the writer only saw its remains, not then in working order, on a strut machine which may or may not have been an application by Dalby since it is not mentioned

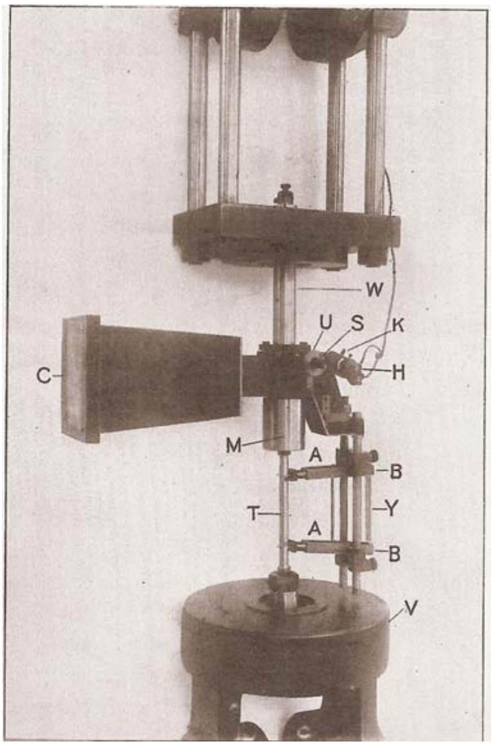

Fig. 4 The Dalby recorder fitted to a testing machine
(from Dalby's book cited Fig.3)

in his book. The uses of the optical recorder just mentioned were for static testing but the instrument had very low inertia and had been used by Dalby for recording dynamic tests, long before the now ubiquitous cathode ray oscilloscope came into use for that purpose.

In 1913, the Goldsmith's Extension to the Waterhouse Building was erected. This was an L-shaped stone faced building of four or five stories extending north along the Exhibition Road frontage and then west along the Prince Consort Road frontage. The main building housed Civil Engineering and the R.S.M. Within the corner of the L was a single storey glass roofed laboratory with basement, used

Fig. 5 One of the M.E.D. 5t Buckton machines in the Science Museum Reserve Collection, Wroughton, Wilts, 2007 .

by the M.E.D. to extend both its materials and engine testing facilities. For materials, it housed four machines; two 5t (c.50kN) Buckton single lever hand operated tensile testing machines (one is now in the Science Museum Reserve Collection at Wroughton, Fig.5.) a large horizontal 100t (c.1,000kN) Buckton lever arm machine and a spring 'scragging' machine. This last, for testing the 'shaking down' and subsequent stiffness of leaf springs (no-doubt originally used for railway springs) was no longer used when I knew it, and was scrapped in the early 1950s. At the same time, the two small Buckton machines were transferred to the Waterhouse laboratory for convenience in teaching.

The hydraulically operated horizontal 100t (c.1 MN) Buckton was powered by high pressure water from the London Hydraulic Mains Co, supplemented by an hydraulic accumulator all clearly installed when the Goldsmith's extension had been built. In the re-arrangements just mentioned, it remained in the Goldsmiths but for some years before I knew the machine it had not been used because the hydraulic accumulator system no longer worked. In about 1960, a research student of mine brought the machine back into service by fitting it with a small motorised hydraulic pump and 'tying down' the end of the weighing lever using a thin strip carrying strain gauges connected to a recently acquired X-time chart recorder. In this 'one -man' form the student operated the machine and conducted his reseaches quite easily. In Fig. 6, the machine is called called a 'Wicksteed' after its designer but the M.E.D model was clearly named 'Buckton' by its maker so the M.E.. machine was probably of a slightly Also the main handwheel was at the front and the hydraulic accumulator in a pit to the right.

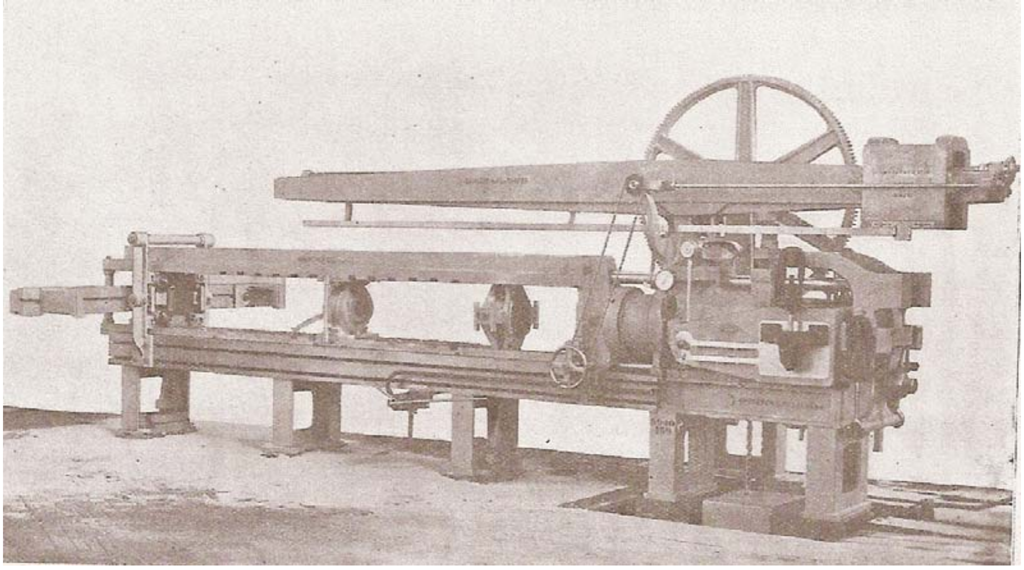

Fig. 6 Wicksteed's horizontal 100t Buckton testing machine
(from J. A. Ewing's book The Strength of Materials, 1914, Cambridge University Press)

Three more machines, all in the Waterhouse lab when I first knew them, were of about 1930 vintage, or perhaps a little earlier. Two were a hand operated Avery torsion testing machine fitted with a lever systen responsive to twisting in either direction Fig.7 (a). and a Vickers hardness testing machine, an early model donated by the makers, Fig.7(b). In such a machine, a small square-based pyramid of diamond is pressed into the surface of the test block under a known load for a short duration, and the resulting size of indentation then measured by microscope to assess the hardness of the test metal. The third was another single lever arm 10t (c.100kN) Buckton machine, this one of twin screw design suitable for routine tension, bending or compression testing, but of only modest stroke with no projection into the floor.

Associated instrumentation to allow meaningful measurements in the elastic or small displacement regimes of tests were, in this period, rather basic. Dalby's optical recorder (of which he had made a version specifically for elastic deformations) was no longer in evidence. There was a pair of mechanical extensometers working on a defined test-piece gauge length of 8in (c 200mm)). The

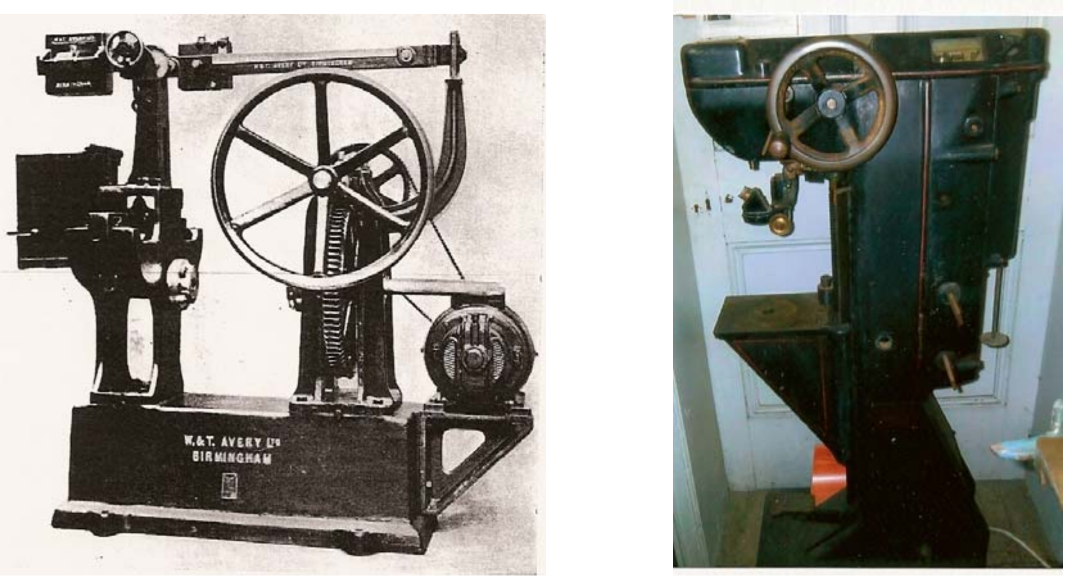

Fig.7 Two machines of c.1930.
(a) Avery's reversing torsion machine The Guilds machine was not fitted with an electric motor; it was hand operated
(b) The Vickers hardness testing machine, now in the Kirkaldy Testing Museum with parts of the microscope lost. It carries a plaque reading 'Presented by the makers,Vickers Armstrong'.
(Fig. 7a from Mechanical Testing, Vol. 1, Batson & Hyde, Chapman & Hall)

design by Ewing, Fig.8a, was one of the first and came into use at around the turn of the C19th to C20th. It was of substantial steel and brass construction, weighed 2 or 3lb (c.1 - 1.5Kg) and was clamped onto the piece by substantial thumb screws. It had a 2:1 mechanical magnification coupled with a microscope eye-piece with hairline and was read by using an in-built micrometer fixed to one end of the instrument's frame, to focus on the hairline.

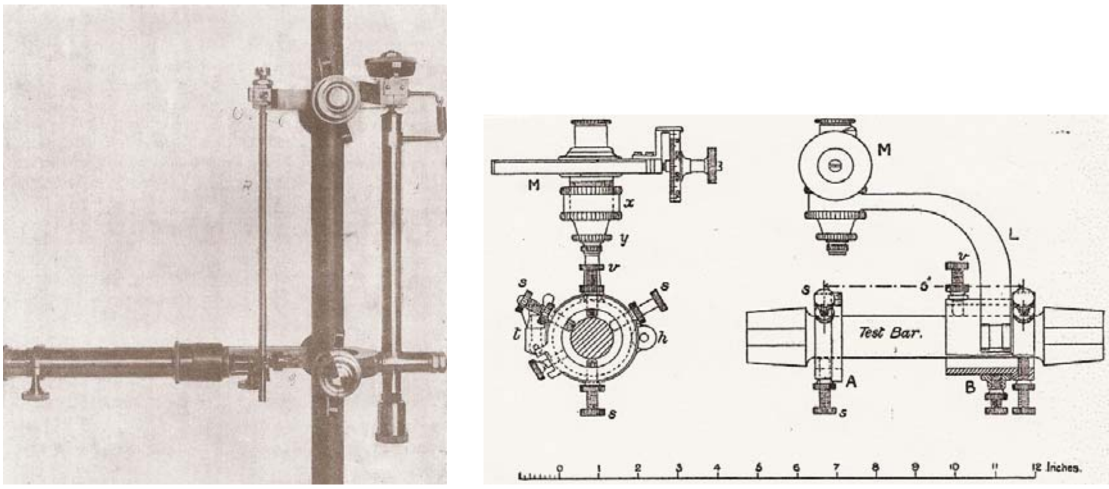

Fig. 8a Fig. 8b

Fig. 8 Two early instruments used for testing materials
(a) Ewing's extesometer invented in 1895. The type shown,was probably of about 1910-20.
(b) Unwin's torsion micrometer is of about 1900. Both were used up to about the mid-1970s and are now in the Kirkaldy Testing Museum, Southwark Strret, London,
(Fig. 8a from Ewing's book cited Fig.6; Fig. 8b from Unwin's book cited Fig.1).

Another such instrument was an Unwin torsion meter, Fig.8b. This consisted of two rings 6in (c.150mm) apart to be clamped around a cylindrical torsion piece. One ring carried an arm with a micrometer eyepiece and the other a datum mark. The circumferential movement of one end relative to the other was thus measurable. On both of these instruments, adjusting the micrometer for every reading required a hand operation, inevitably rather clumsy on first acquaintance. Each was an expert's instrument rather than for use by students, most of whom had little experimental experience! In view of the date referred to in Ewing, 1895, and of Unwin's book, 1899, both instruments must surely have been brought to the Guilds from such as the Central Institution already mentioned. The only other instrumentation for testing was a Lamb's extensometer of about 1920 vintage with 6in (c.150mm) gauge length, Fig.9. This consisted of two pairs of plates each with 'knife' edges, one pair clamped on each side of the test piece. The plates of each pair were separated by roller 'pins' carrying mirrors that were arranged such that the whole was viewed by telescope and vertical scale, to give an optical lever-arm of one or two yards (c.1 or 2m) and thus a quite high magnification. Also, it did not require touching by hand during a test. It was used by 2nd year the Civils' students to measure the modulus of granite in compression.

Autographic recording of complete load-extension diagrams was very basic. On the Riehlé, two small double pulley blocks, giving four-fold magnification of the extension, could be clamped by thumb screws to a test gauge length, with a cord leading to a paper covered rotating drum, to give a rotation of the drum equal to the magnified extension. Vertical motion of a spring-loaded pencil was driven by a bevel-gear from the lever weighing system, giving a motion proportional to load, providing the lever was kept in balance throughout a test. As already noted the machine had been equipped with an automatic load balancing system which might have given a good load-extension diagram although obtaining adequate but not excessive clamping of the pulley blocks against the friction load of the string and pulleys was not easy. Balancing the weighing lever by hand during the rapid rise in load for elastic extension, the rather oscillating pattern of load at 'yield point' and the final reduction of load as necking occurred just before fracture, needed care also so that reliable records were not always obtained .

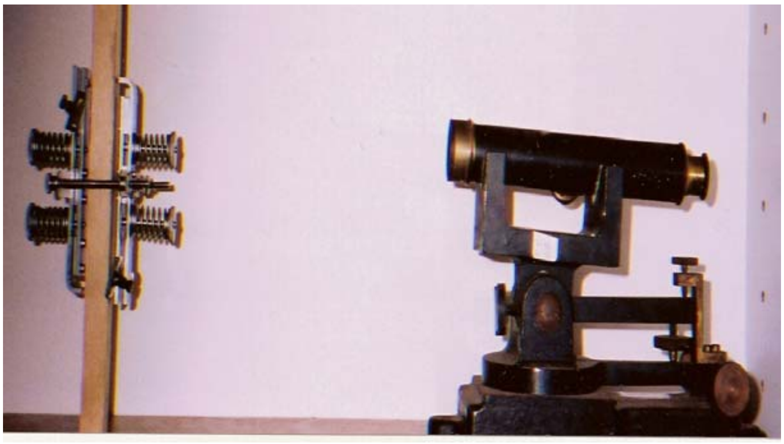

Fig.9 Lamb's optical extensometer c.1930. The reading scale is a few feet (c.a metre or so) off the picture to the left
This instrument is also in the Kirkaldy Testing Museum

Post World War 11: the gradual start of growth

The post WWII period started with a Head of Department, Professor (later Sir) Owen Saunders, a thermo-dynamacist, appointed in 1946, and a collection of old equipment, some already in service for about 50 years. This was still useful for demonstrating principles but quite unsuited for the needs of research. But when I joined in 1948, most of the academic staff, about 12 in number, were teachers of several subjects rather than researchers. Indeed, one of these told me that in the 1920s and 1930s only the professorial head of department could conduct research, the general lecturing staff being forbidden to do so. Of the 12 or so staff teaching in the late 1940s, three could perhaps be assigned primarily to Materials, Dr Howard and Mr Chalk (later Senior Tutor), both of whom had been in M.E.D. since about 1920 and Dr Heywood. All three certainly took laboratory work in both material properties and engine testing, much of the experimental equipment for both being side by side. Design was taught by Wilfred (Wilf) Collins aided by an elderly colleague, Mr Beale, who taught Engineering Drawing when communication to a workshop for making anything was entirely by 'blueprint' of a complete design. The leading lecturer in Theory of Machines was Dr Dyson; in Fluids, Dr Lewitt; in

Thermodynamics, Dr James. Two others, probably appointed in the late 1940s, were Dr Glaister in Internal Combustion Engines and Mr Treharne in Machines and Manufacturing the last three all joining in various lab classes. At least one member of staff from the Mathematics Departments of the R.C.S., Professor Bickley, blind before I first met him, was on more or less permanent assignment to M.E.D. He proved to be a most helpful 'reference point' to newcomers such as me, who sometimes required mathematical techniques beyond their conventional engineering training.

With the appointment of Hugh Ford as Reader in Applied Mechanics in 1948, the first moves to a revival in that subject came about. A post in Vibrations was established, Peter Grootenhuis being appointed in 1948. In Strength of Materials several machines existed but facilities needed bringing up to date so that some research could start.

Hugh Ford obtained a Denison 50t (c.500kN) capacity hydraulically operated 'universal' machine (i.e. one capable of several test functions, tension, compression, bending 'punching' shear and so on). It was a quite compact unit that had been developed in the 1940s to meet the demands for rapid and simple testing for war-time production. It was powered by a small motor pump unit and measured the load by multiple levers that terminated in a spring device, making the machine self-indicating and thus easily operated by one person. It was located in the Waterhouse lab and became the mainstay of a bourgeoning research activity in material properties and stress analysis for several years. By 1950-53, several younger staff with specific research interests had been appointed in Materials, though Sir Owen always insisting that teaching was part of the duties of all staff. Frank Ellis worked in plasticity, I in general properties and stress analysis, and two or three years later, Peter Benham in fatigue and a little later, Allen Shelton in plasticity. All were at first working for their Ph.D degrees, together with three or four research students. In the foregoing and following, research students are mentioned by name only if they later became members of the staff of the Materials Section.

The first Materials researches conducted on the Denison were the study of the plane strain compression test, soon followed by my own stress analysis work. That called for the use of electrical resistance strain gauges for the first time in the Department (though the Civils had beaten us by a couple of years or so). I arranged the purchase of a 50 channel Savage & Parsons unit suitable for static loading for my tests on thin-walled corrugated pipes (or bellows), a research project related to the first installations of gas turbine power in naval ships. The equipment and the Denison machine, Fig.10, continued in service for many years. I later wrote a book introducing plate and shell theory at the undergraduate teaching level.

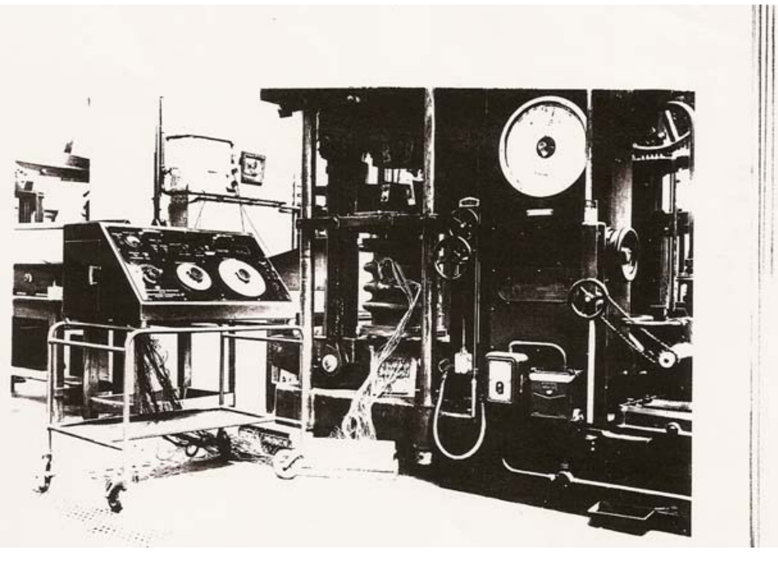

Fig.10 The first 50ton Denison machine acquired by the M.E.D in 1947 or'48.
In the foreground is a Savage & Parsons multi-channel strain gauge bridge wired up to a corrugated expansion bellows as tested by the author in about 1950. (from his Ph.D.thesis)

An unusual addition to the facilities was a 6in two-high cold-rolling mill. This was located within the Waterhouse lab but screened off for safety purpose by a blue painted partition, thus creating the so-called ‘Blue Room’. It was used initially by Frank Ellis for strip rolling research, a topic closely connected to Hugh Ford’s own earlier work, followed by another project on the effects of lubrication in strip rolling. A bench mounted Hounsfield miniature testing machine, of up to 2t (c 20kN) capacity, Fig. 11 was acquired particularly for use with the thin strip products of the rolling mill.

Fig. 11a

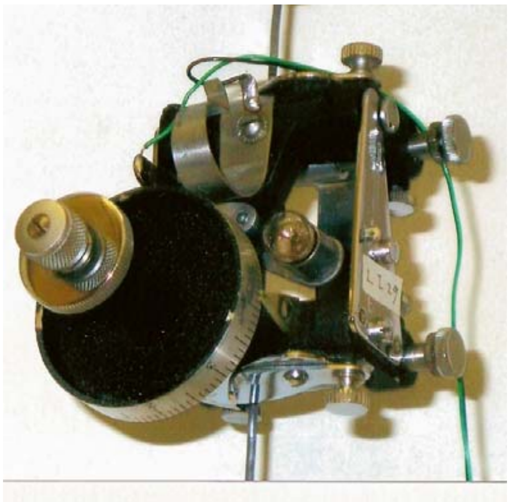

Fig. 11b

Fig.11 a) The bench mounted Hounsfield testing machine of early 1950 vintage
b) a 2in Hounsfield extensometer, here mounted on a thin rod
This machine and extensometer are now in the Kirkaldy Testing Museum.

A study of plastic expansion of boiler tubes into header plates was made by John Alexander, who on completing the work, left but returned a few years later, in due course becoming Professor of Engineering Plasticity. This experimental work was followed up by L.E. (Dick) Culver, who in due course succeeded Mr Chalk as Senior Tutor. Thick-walled pipe-bends under internal pressure were studied by Alan Swanson, using strain gauges. He later returned to the Department and became a Professor, still later becoming Pro-Rector.

In the late 1950s, an American, Professor Prager, gave a series of lectures on ‘slip-line field theory’; a method he had developed to find the patterns of deformation in plasticity problems, which in turn allowed limit or collapse loads to be found (or at least bounded). John Alexander adopted these methods enthusiastically, as mentioned later.

Other types of machines and equipment soon followed, in part to extend the range of equipment for teaching purposes, particularly for the then new idea of ‘special tasks’ for final year undergraduates and a trickle of M.Sc students. A Vickers projection microscope was installed in the Waterhouse lab

for studies on powders by Dr Heywood, which instrument also allowed demonstration of any micro-detail to be shown rapidly to a group of students.
I do not recall what conventional lab course was run for the 3rd year undergraduates at this time although I do remember an experiment using an aluminium 4% copper alloy, Duralumin, which when tested on the dead weight 10t Buckton machine, broke with no perceptible neck. A 2in (c.50mm) Lindley dial gauge extensometer was acquired, adequate for testing this sort of material, with a modulus only about one third that of steel, and was used in this test up to about the proof stress level and then removed well before fracture. A small photo-elastic bench, installed in the basement of the Goldsmiths lab was initially used by a research student to study local buckling of T-headed strips, but I think came into use for 3rd year students in about 1950.

At the time, M.Sc. degrees took two academic years and were done by research alone, though later a new course of one calendar year duration, partly taught and partly project work, was introduced by the University. New machines initially for use by M.Sc. students included two small Denison single lever creep machines of 1t (c.10kN) capacity and associated furnaces The topic was an entirely new departure that recognised the great importance of creep testing with the coming of gas turbines, the blades of which ran at very high temperatures under severe loading. Another fresh machine, by no means ‘new,’ was a drop-weight tensile impact machine, donated after serving its purpose by (as I recall) British Petroleum Research Division and used by an M.Sc student.
For one of the first special ask projects for 3rd year students, the Charpy impact machine was reinstalled. Its history was as follows. The machine was of 1916 vintage and had been consigned to the scrap heap some time before 1948, but not actually disposed of. The reason for this relegation was said to be that the machine gave such widely discrepant results that it was useless. This was attributed to torsional oscillations induced in the shaft of the swinging hammer, caused by the chance irregular action of the release catch that held the pendulum in its initial ‘up’ position. The pendulum consisted of an I-section shaft terminating in a relatively large circular head that contained an insert carrying the striking edge that impacted the test piece. ‘Slapping’ this head by hand, did indeed cause a visible torsional oscillation of the whole pendulum.
The reinstatement of the machine occurred at a time in the early 1950s when the problem of ‘brittle fracture’ of wartime ‘Liberty Ships’ was still unresolved. The then Admiralty, later to become the Navy Department, had set up an Advisory Committee on Structural Steel (A.A.C.S.S., later N.D.A.C S.S.) bringing together a wide range of expertise from several university and national labs, including N.P.L. a ‘civil’ part of U.K.A.E.A., the Welding Institute (now TWI) and some steel producers. This Committee was chaired by Hugh Ford and I became a university member. Early post WWII studies starting in U.S.A. had noted an empirical relation between such brittle fracture events and a low V-notch Charpy impact number. Low ambient temperature was also thought to be, in part, a detrimental feature for this type of fracture. The Charpy machine was therefore reinstalled. For the first tests conducted by a 3rd year special task student, the temperature was varied by about ± 20° C. The results were a quite smooth but very steep ogival shaped curve of impact value versus temperature, from low energy brittle fracture at about 0° C to high energy ductile fracture at about +20° C, Fig.12. The curve shows the energy absorbed in a notched-bend impact test as a function of temperature and the photographs, the appearance of typical ductile and brittle fractures.
The material that had been used in the ‘useless’ undergraduate tests and now for the special task, was a ‘bright’ mild steel supplied as the required 10mm bar and notched with an Izod type V-notch in the Departmental workshops. By chance, this material had a quite sharp brittle-to-ductile transition temperature range just at room temperature, so that the ‘useless’ results simply showed the inherent variation within the steep part of the temperature transition curve. With a few more tests under his belt there was one very satisfied special task student and a useful fracture research tool! The striker of this Charpy machine was later instrumented with strain gauges (I believe the second such instrumentation in Britain) and still exists. Later, the drop weight machine was greatly modified to allow bend tests up to about 2in (c 50mm) square to be conducted and the striker then instrumented. The main useful purpose of both impact machines was superseded in the late 1980s by high strain rate servo-hydraulic testing machines.

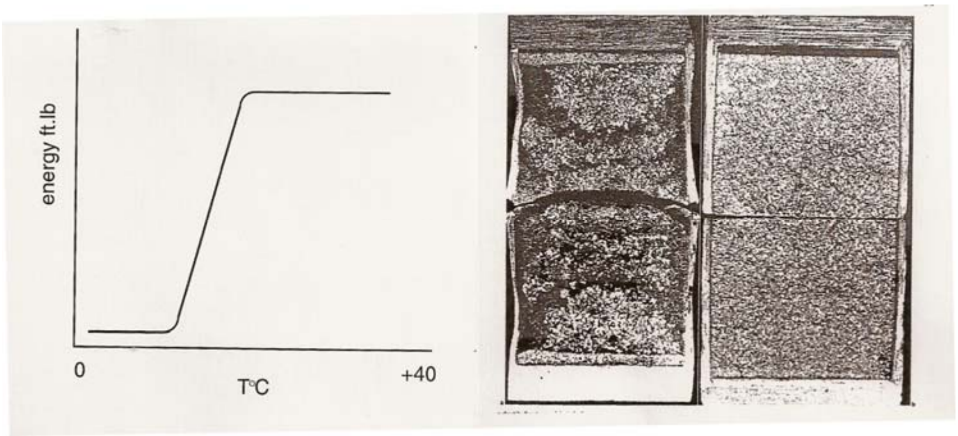

Fig. 12a Fig. 12b

Fig. 12 a) A rather schematic brittle to ductile transition curve, as I recall it in the above tests.
b) The appearance of typical ductile (left) and brittle (right) fractures in mild steel

In the mid 1950s a metrology lab was set up in the basement of what later became the Medical Centre just off Princes Gate Gardens. This lab was seen as the precursor of a Production Engineering group under Dr. (later Professor) John Alexander, to complement Hugh Ford's and John Alexander's prime interest in the plasticity of metal forming.

The Waterhouse laboratories and workshops were under the direction of a Departmental Superintendent, Reginald (Reg) Dubbins assisted by a general factotum, Tom Morley. Senior technicians were in day to day charge of each group of labs and the workshops, Mr Hallard in the main shop and Cyril King in a shop devoted to use by research students. The Materials lab was in the hands of Ernest (Ernie) Cox, who had the unusual distinction of having been born in the Guilds, when his father had been chief porter with a flat 'up in the attics' of the Waterhouse building.
Thus ended the early post-war years.

GROWTH; FROM c.1955 -1970:

The background to this era

When I joined in 1948, the rather limited research activities in Applied Mechanics were divided into two Groups, Materials and Vibrations, (later called Dynamics). For Materials, to which group I had been assigned, the main interests were in experimental stress analysis (before the advent of computers) and plasticity and metal working, work which grew out of Hugh Ford's own research interests. Some where around the start of this period, two new Sections were set up in the Department, Nuclear Power and Industrial Engineering, the latter soon to get renamed Management Engineering. The name of the Professor who set up the Nuclear Power Section escapes me - he left after a few years and was succeeded by Peter Grant (later Professor). Industrial Engineering was set up by Sam Eilon (also later a Professor).
A major event for the College occurred a few years after the end of WWII when the Government of the day announced that Imperial College was to be largely rebuilt and expanded to be the primary university science and engineering institution in Britain and indeed the Empire (or Commonwealth as it had become). This event was a few years before the Robbins Report on Higher Education, in 1963, which lead to the establishment of several new universities and upgrading of practically all others types of higher education We were given a more or less open brief to design a new building and a blank cheque to re-equip laboratories as we saw fit. The project was to take twelve years, and as far as I can recall, the cost of the building approached £20m with individual labs costing from £20k to £150k according to size and complexity. These were huge sums at the time and the later 'Robbins' expansion was much more tightly controlled and costed. Over the several stages of this rebuilding programme all teaching activities, here specifically the materials labs, had to be kept functioning.
Sir Owen took overall 'strategic' control of the planning for the rebuilding and expansion of research. Naturally, planning started along the then existing two specialisms, Thermo-dynamics and Applied Mechanics, and a working party was set up to map just an outline of what was involved. Much smaller re-equipment programmes had been or were being made at, I think, Nottingham and a little later at Queen's Belfast but it was realised that there was no guidance from others on such a large expansion

programme. Sir Hugh took 'tactical' control of all technical matters, delegated to him by Sir Owen in the role of Director of Laboratories, with all day to day contact with the architects, Norman & Dawbarn, in the hands of the Assistant Director in the Department, Russell Hoyle (later Professor at Durham). Most members of staff were given one or more labs to plan and equip in detail within this framework.

The new Departmental building was known throughout its construction period as 'E-block'. It was divided into what was first planned as four consecutive parts, E1, E2, E3, and E4 respectively (Fig.14) each of three years duration starting in about 1955 and so due for completion in 1967.The start of the new era, just before 1955, I think, was the erection of a steel framed three floor building within the then rather under-used Bessemer lab of the R.S.M.. This become a 'Transit Camp' to which the Departmental workshops and materials testing facilities were moved to allow the demolition of the corresponding Waterhouse facilities and thus pave the way for erection of the first stage of the new building, E1, behind the still used front part of the Waterhouse building.

The 'Transit Camp' and its equipment, c 1955-1961

In the 'Transit Camp', the Departmental machine shops were on the ground floor, the tool room, sheet metal and carpentry facilities on part of the first floor, with some new equipment for research on the remainder of that floor and the main Materials teaching lab on the second floor. A colleague, Peter Benham (later Professor of Aeronautical Engineering at Queen's, Belfast) and I were put in charge of this island outpost of the departmental empire.

To install the new and transferred equipment a 5t (c 50kN) capacity electric hoist was installed above the second floor, with trap doors to the ground floor. Needless to say, the hoist was not ready for use when the move into the Transit Camp had to be made and for reasons now forgotten, it was removed early in the dismantlement of the Transit Camp some four or so years later when the new E1 building became available. Apart from occasional use in the interim, it was strain gauged and used with suitable high speed recorders to familiarise final year students with such then quite modern techniques and to allow them to measure the stresses caused by both steady and shock ('snatch') loading events. It thus served a useful if not intended purpose during its few years of life.

The Materials teaching machines in the Transit Camp were nearly all those from the Waterhouse lab, Denison, Riehlé, the two 10ton and two 5ton Bucktons, the Charpy and Izod impact, Denison creep and Vickers hardness machines. Just before the move to the Transit Camp, the drive on the Riehlé machine was converted to a reversing two speed electric motor. The large 50ton (c.500kN) Buckton had to be scrapped so a second 50ton (c. 500kN) Denison machine was added, little changed from the 1947 model, for use partly for research work and partly for teaching. The Haigh fatigue machine was sent back to its makers, Bruntons of Leith, Scotland, for complete overhaul. Two Avery Wöhler type rotating cantilever bending fatigue machines were purchased together with a number of other bench type items for first year classes, many duplicated to accommodate parallel working by the then growing numbers of students.

There were two main new research machines. A 100ton (c.1MN) Avery vertical 'universal' testing machine, Fig.13, operated by hydraulics and measuring the load from the hydraulic pressure in a small auxiliary cylinder with very close control over the ram friction losses. It was used extensively for studies in brittle fracture. When pieces fractured in a brittle manner at near the maximum capacity of the machine the whole building shook, so it became the practice to warn the workshop staff below to put on 'hard hats' to protect them from what turned out to be an occasional flake of paint off the ceiling! Peter Grootenhuis took the opportunity to study the transmission of shock loads in such a steel framed concrete-floored building by mounting one of the 50t (c.500kN0 Denisons on the second floor on a cradle that could either rest directly on the floor or be suspended by heavy coil springs during fracture tests. The half-ton (c.5kN) jockey weight of one of the 10t (c.100kN) Avery machines was also used to cause shock loads directly into the structure. I believe he found good insight into some of the problems and responses for such loadings.

Fig.13 The 100t (c 1MN) Avery testing machine for the Transit Camp in 1955,
here pictured in the Heavy Testing Lab on level 1 of E3, in 2007
(photo courtesy Hugh MacGillivray)

The second new research machine was a horizontal Schenk low frequency resonant spring fatigue machine of about ± 5ton capacity to be used for one of the early studies into low-cycle fatigue, a topic consistent with the Section's main interest in plasticity. Low-cycle fatigue was brought into sharp focus by the failure of the de Havilland 'Comet' jet aircraft in the mid-1950s and became Peter Benham's speciality. A Denison 300t (c.3MN) hand operated hydraulic press was bought, I think at this stage, for some of John Alexander's work in plasticity. The existing drop weight impact machine was also moved to this lab. Another new facility was a 'Talysurf' instrument for measuring surface finish and roundness of bearings, matters not familiar to most undergraduates of the time (or perhaps even now?). This was strictly an instrument for the Metrology lab but was housed in the Transit Camp as a convenience and was used in the extended 3rd year lab classes of the spring and summer terms. It was placed in a small divided off 'clean' space together with another item, perhaps the Vickers projection microscope, I am not now sure.

At or just after this time, Ronald (Ron) Wells became Departmental Superintendent with the Materials labs still in the hands of Ernie Cox, with a new technician, Sid Smart, to assist.

Expansion and E-block, the new M.E.D. building

General organisation

A brief account is needed of the extensive labs that were to be set up, here only for Materials, but in reality for corresponding Thermo-fluids and other work, such as the new Section of Nuclear Power, in the forthcoming new and much larger building. At the time of this expansion, a 'Common Course' was provided by the Mechanical Department for all the Guilds first year students - Aeronautical, Civil, Electrical and, for some work, Chemical Engineers, in addition to our own Mechanical students. This meant that by the end of the expansion, some 800 different students would be using the Mechanical building for at least a few hours each week, so that several lab classes had to coincide, quite apart from the needs of the post graduate M.Sc. and research students.

Table 1 shows estimates used for planning. Somewhat similar numbers were in fact achieved. For most undergraduate lab classes the students were split into two cohorts. Teaching on that scale needed several separate facilities teach with most experiments duplicated or triplicated if even a remote connection were to be kept, time-wise, with any related lecture topics. The most convenient arrangement was for each year to have its own laboratory and appropriate equipment. All these labs were to be on the fifth floor, the 'lowest' level available for such an agglomeration of facilities. A 3rd year and P.G. lab was to be located in E2, a second year teaching lab was planned for the E3 stage and a first year lab in the E4 stage, the last opening in about 1967. To span the gap between the Transit Camp and the first teaching lab in E2, a temporary general Materials lab had to be set up in E1, roughly on the scale of the 2nd floor lab facilities in the Transit Camp, for all teaching and some research

Table 1. Estimates of undergraduate and post-graduate student numbers to be accommodated, for the purpose of planning of laboratory facilities in E Block. (a half of each cohort to be accommodated within Applied Mechanics at any one time)

Common 1st year course: (Materials and Thermo-dynamics)

Mechanical	Civil	Electrical	Aeronautics	Chemical Engineering
120	100	100	80	100

2nd Year courses:

Mechanical (Materials and Thermodynamics)	Civil (Materials for a few weeks only)
110	90

3rd year course
Mechanical: (roughly a half each in Applied Mechanics & Thermo-fluids)
100 :

Post-graduate students in M.E.D. (roughly a half of each in Materials)

M.Sc. courses	Ph.D students
Applied Mechanics 35	Applied Mechanics 30.

The E1 stage of the building, built from c.1955-1959, comprised the core of basement, lift shafts and adjacent areas, with a basement and eight floors above ground level and two rearward spurs and the stub of two forward spurs, each of five stories and an ‘in-fill’ of basement plus two floors between the two rear centre spurs. The main entrance from Exhibition Road to the Department, and temporarily to most of the College site, was at level 2 of the E1 building, passing, for the time being, through the Waterhouse entrance hall. The next stage of the re-building programme was more demolition, notably of the Goldsmith’s lab, to allow E2 to be built. This consisted of the northward extension of the spine to full height, a five storey spur rearward and also forward to Exhibition Road and a small basement area, the last three all at the north end. Then came the demolition of the remainder of the old Waterhouse building to allow E3, the southward extension of the full height spine with a rear spur of five stories and, as originally planned, a forward spur. Finally E4 was to follow as the new main entrance and the completion of two forward spurs, one each at the junctions of E1 with E2 and E3.
In the event, rising costs forced a redesign of E3 and E4 and due to falling behind building schedule for E1 and E2, the E3 and E4 stages were combined. In E3 and E4 the forward spurs were deleted and a three storey block with a light well was built at the south end, to ‘fill in’ between the main spine and the road frontage. The main spine of E3 suffered only reduced detailed specifications and the spine together with the three storey block was still known as E3 (though marked E3 east on Fig.14, for clarity). The designation E4 was assigned to a the seven storey ‘tower’ block, which was to form the new main entrance from Exhibition Road to both the Department and the College. Inside the departmental front entrance as finally built, was a quite large entrance hall, two stories in height, leading to the lifts and to a large lecture theatre in the re-planned E3 stage, able to seat more than 200 persons.

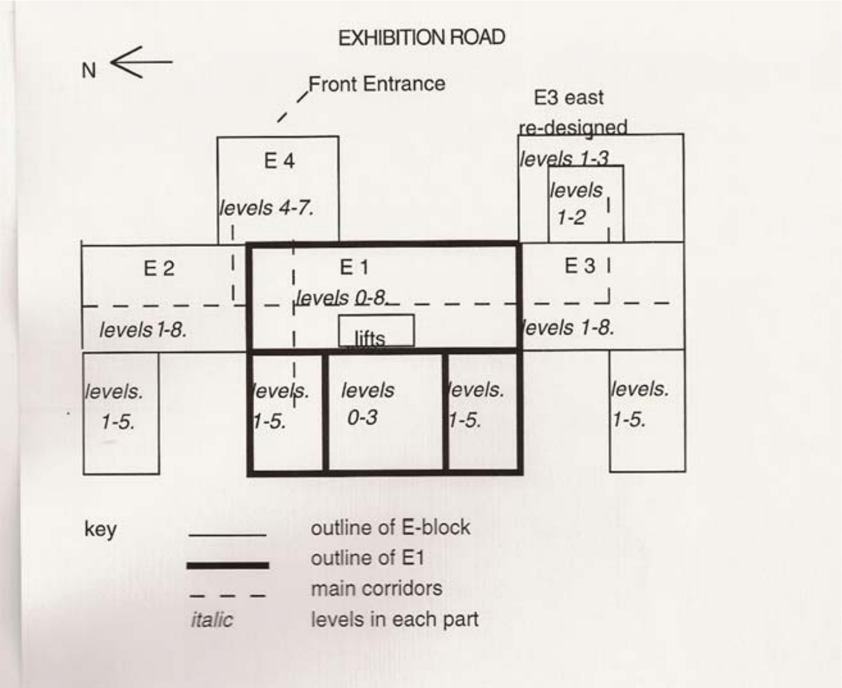

Fig.14 Schematic of the new Mechanical Engineering building, E-block, as built from 1955 -1967 in four stages, E1 to E4

With that re-design, the whole project was completed in the 12 year period and, I believe, more or less to cost.

The Materials labs and equipment in the first, E1, stage of the re-building, c 1955-1959.

As already noted, the E1 stage was located in the middle of what would emerge as the whole E-block building.

Two permanent Materials research labs were set up in the front of the basement, level 0, one for Fatigue (under Peter Benham, who left a few years later) and one for Creep (under George Webster, initially on behalf of John Alexander). On level 1, a large temporary lab for Materials was installed in what was planned to be (and later became) the Technician's Common Room. Most of the teaching machines from the Transit Camp were squeezed into that area for about three years. Level 5 was devoted to Applied Mechanics in all stages of E-block. Level 5 of E1 housed three Materials labs, some temporary, and a Section office. There were no more Materials labs until E2, E3 and E4 were built

Levels 6 and 7 of E1 housed general teaching rooms and staff offices, whilst at level 8, building services took up all available space.

The Fatigue lab on level 0 contained a 20 or 30t (c200 or 300kN) low frequency vertical Lösenhausen fatigue machine, mounted on air bags in a sub-basement, to avoid transmitting vibrations into adjacent labs. An Amsler 'Vibrophore', a high speed but rather noisy machine of about 5 or 10t (c.50 or 100kN) capacity was enclosed in a noise proof cubicle. The horizontal Schenk resonant spring machine already used in the Transit Camp was installed here, together with two or three smaller Schenk torsional machines, the re-furbished Haigh fatigue machine and a batch of 'home-made' four point rotational bending machines.

The Creep lab in the basement was a temperature controlled area, with its floor isolated from the main structure to avoid incoming vibration. It was equipped with a batch of four or five 5t (c.50kN) lever arm dead weight loaded Denison creep machines, all with quite elaborate furnaces and controls. There were also three or four 1t (c.10kN) small Denison dead weight loaded machines, similar to those used in the Waterhouse lab in the mid-1950s. High temperature extensometers were available and also an inert atmosphere chamber.

A tension-torsion machine designed by Shelton for studies in plasticity and made in the Department was housed for some time in the Creep lab as a matter of convenience early in the re-building work.

As just said, a temporary home for the teaching lab was provided on level 1 of E1, close to the site of the original (but by then demolished) Waterhouse lab. As noted, the first permanent Materials teaching lab was not scheduled to be in place until the E2 stages of the building, some two or three years later. The temporary space was intended to be ready for a move in the summer vacation of (I think) 1960 so that classes could start there in the new session. In fact the building work was more than three months late and the move was finally made to a very tight schedule over the Christmas vacation. The academic and technician staff from the Transit Camp worked hand in hand with the removal contractors over the whole vacation though I think working on Christmas Day was excepted!

This lab housed, in rather cramped conditions, most of the machines from the Transit Camp except the 100t Avery, which, I now suppose, must have stayed in the Transit Camp or have been stored pending its final home in E3. This space had to serve the teaching classes in materials for all students from the 1st, 2nd and 3rd years and I recall that two of my own research students working there in periods where the undergraduate work did not call for the machines they needed.
On level 5, a short lived lab situated in the northern rearward facing spur, was for Analogue Testing, under Russell Hoyle, the Assistant Director in M.E.D. The main machine was a resistance network analogue to allow him to model transient thermal stress on staring up a steam turbine. Other small analogues could illustrate the behaviour of some plates in bending and bars in torsion. With the coming of digital computing, all this equipment was soon discarded. A small space at the north end of E1 was used temporarily for research in plasticity and housed the second Denison 50ton (c. 500kN) machine and the 300t (c 3MN) press from the Transit Camp. In the original plan, this lab would have extended into the then planned forward facing spur in E4. An Applied Mechanics Section office was opened at the corresponding area at the south end of E1. What was to become another permanent Materials lab was set up for ‘Non-metallics’, in an area that had no natural lighting, across the corridor to the rear of the Section office. This was a last minute change following a suggestion to Hugh Ford by Peter Benham and the writer, who had both just attended a conference on that topic. Some small capacity machines, one at least a Zwick suitable for testing of natural polymers (wood, rubber, paper) were installed in this lab together with one or two small machines that I do not recall. A non-metallics study was later made by Jim Lewis, a member of the Dynamics staff who carried out some work in connection with the rescue of books following the severe flood in Venice, but that was not in this lab and I think the Zwick machine was moved to a small space on level 2 or 3. The Non-metallics lab proved to be the start of what was to become a strong group in ‘Polymer Engineering’, later still including ‘Composites’ and ‘Adhesives’. When its true nature as a Polymer lab became apparent, just a few years after E1 opened, a then freshly appointed member of staff, Gordon

Fig. 15 A 10.000kN (c 10t) Instron as installed in the Poylymer lab and later in lab 581.

Williams, took control and installed one or two electro-mechanical Instron machine with inbuilt chart recorder, Fig 15, the first of the new generation of testing machines, and also a low capacity bench mounted Hounsfield impact machine.

An engine of change in the early 1960s

The first of several external engines of change, apparent by the early-1960s, was the growing importance of computing across the whole of engineering. The advent of computing on a significant scale affected the research activity in all Sections, but at this stage, had little effect on the already planned layout of the building and uses of space.

In Materials, a first move into computerised stress analysis was seen by some as somewhat of a 'cuckoo in the nest'. It was made by one of my students, Pedro Marcal - I found myself 'too long in the tooth' and too heavily engaged with departmental teaching and administration to do more than encourage him and all later generations of my research students to adopt computer methods. At first, the facilities were a Pegasus (I think) computer for the whole University, at Senate House, with punch card input from machines in the Department and output on reams of paper brought by motor-bike courier from Senate House. This was soon improved to a main-frame I.B.M. for the College, housed in the Electrical Department. Pedro Marcal was outstandingly successful in establishing the first (two-dimensional and axi-symmetric) elasto-plastic program in Britain, albeit two leading lights were then saying that plasticity was not amenable to computing! He also pointed out that an earlier American plasticity program could not be shown to converge correctly whereas his own method of 'partial stiffnesses' did. His first program was restricted to 'plates and shells', but Marcal soon adapted his incremental plasticity routines to the finite element method

The second, E2, stage of re-building c.1961-'64

The laboratories and class arrangements

The next and first real major event to offer an extension of facilities for the teaching of Materials lab work, was the completion of the E2 stage of the building, built some three years later than E1, adjoining it to the north. It had had a spine of eight stories, a small basement area, one forward facing spur of five stories and a smaller rearward one contiguous to the R.S.M., both at the north end.

At the north end of level 1, there was a large double height entrance with craneage over and a goods lift of 5t (50kN) or more capacity to all the upper floors whereby equipment to the labs on the upper floors could be raised from the road level or, as foreseen but in the event little used, re-located from one floor to another. This entrance led directly to the main workshop which extended in part to level 2. The workshop also gave access to a basement lab, not connected to the E1 basement, which at first housed a van der Graaf accelerator for the Nuclear Power Section. On level 3, at the north end, there was a woodworking shop and a machine shop for use by post-graduate students.

On level 5 of E2, a Vibration lab and a Tribology lab were set up, the former an extension of the adjacent E1 facility, was under Dr (later Professor) Peter Grootenhuis, the latter, in the forward facing spur at the north end, was under Dr (later Professor) Alistair Cameron.

Also on level 5, a large, partly two storey, Materials lab, Room 581, was set up under my supervision for 3rd year undergraduates and post-graduate course students. A raised floor was built at the south end to allow as then unforeseen requirements for some floor-penetrating fitments. At the north end, the lab extended to level 6. This was a 'show-piece' lab in that it was the first new undergraduate lab in the re-building programme

Levels 6, 7 and 8 housed various teaching rooms and staff offices, including a Drawing Office with two staff to serve the needs of the M.E.D staff, some years before CAD came into being.

The undergraduate course was then of three years duration with, I think, 60 or rather more students per year. The 3rd year classes in both Sections, Materials and Thermo-Fluids, consisted of lectures and a one-day-a-week lab course compulsory for the 10 week Autumn term, in which facilities for all experiments had to be duplicated. Thereafter, students selected lectures to suit their own interests, including a number additional to the two subjects just mentioned, and those thought likely to gain high honours were given 'special tasks', if they so wished, usually of an experimental nature For the remainder of the students, a one day a week lab course was arranged for the spring and summer terms with each experiment lasting three or even four weeks, so that a relatively 'in depth' investigation could be made during each experiment.

In 1969 Hugh Ford became Head of Department and assumed the Chair of Mechanical Engineering. At the same time John Alexander became Professor of Applied Mechanics. The oversight of the teaching of Design was by now clearly within Applied Mechanics though staff from any other Section could be called on to help teach it. From the late 1950s, Richard (Dick) Ogorkiewitz had been the day to day organiser. His interests were in uses of early composites (and in Military History) but I do not think he assumed responsibility for the Non-metallics lab. With the growing size of classes, separate organisers for the Design work were required for the 2nd and 3rd years, and Cyril Laming, whose background was in the pressure vessel industry, joined John Alexander's group.

It was a chance of the timing of the expansion that, when planned, conventional machines of the 1940s and '50s were all that were available but by the time the labs were built (particularly those for the E3 and E4 stages), a new generation of electrically driven screw and servo-hydraulic machines were coming to the fore, each with electronic instrumentation.
On the main floor of Rm 581, a new 50t (c.500kN) Denison machine was installed, somewhat updated from the two earlier models. This third version was fitted with electrical contacts on the weighing dial that allowed the machine to be cycled automatically between two limits of load in either the tensile or compressive regime, though not passing through zero. That feature had been developed by a research student within the Department working in the Transit Camp, and became a normal fitment of this later generation of the machine. A small Denison machine of 15,000lb (c 70kN) capacity, driven mechanically by motor or by hand, Fig.16was installed together with a new motorised Avery torsion machine.

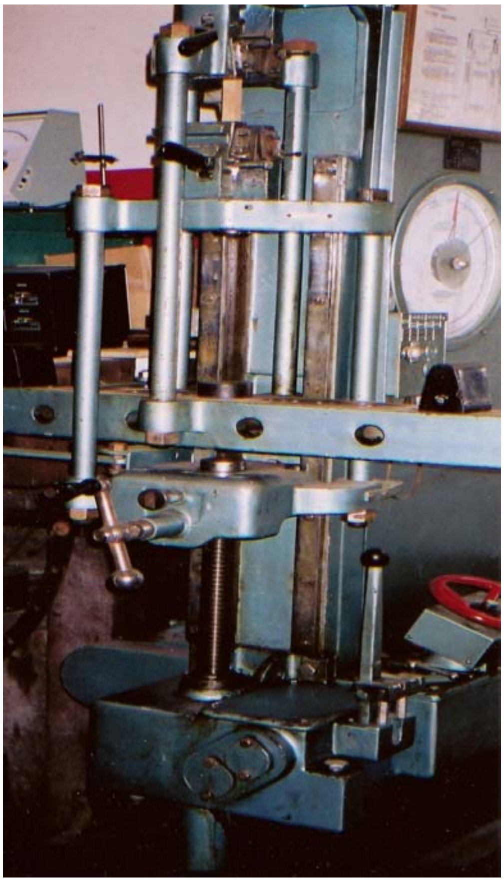

Fig.16 The 7.5t Denison machine, now in the Kirkaldy Testing Museum

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Though not calling for any penetration of the floor, two Avery machines were installed at the raised south end. The first was a 50t (c.500kN) capacity testing machine hydraulically operated, with the load measured from a small carefully honed cylinder subjected to the operating pressure. It introduced variety in machine weighing systems and other mechanical details whilst able to serve the same tensile and compressive functions (though not bending) as the Denison. Both machines had four load ranges so that good accuracy could be obtained over a wide range of loads below the rated capacity. The second Avery was a servo-hydraulic machine, a 'one-off' seen as the fore-runner of a new generation of machines. In fact it suffered many teething difficulties and other makes of machine, notably American, became the leaders in the next generation of equipment. It was intended for work on low-

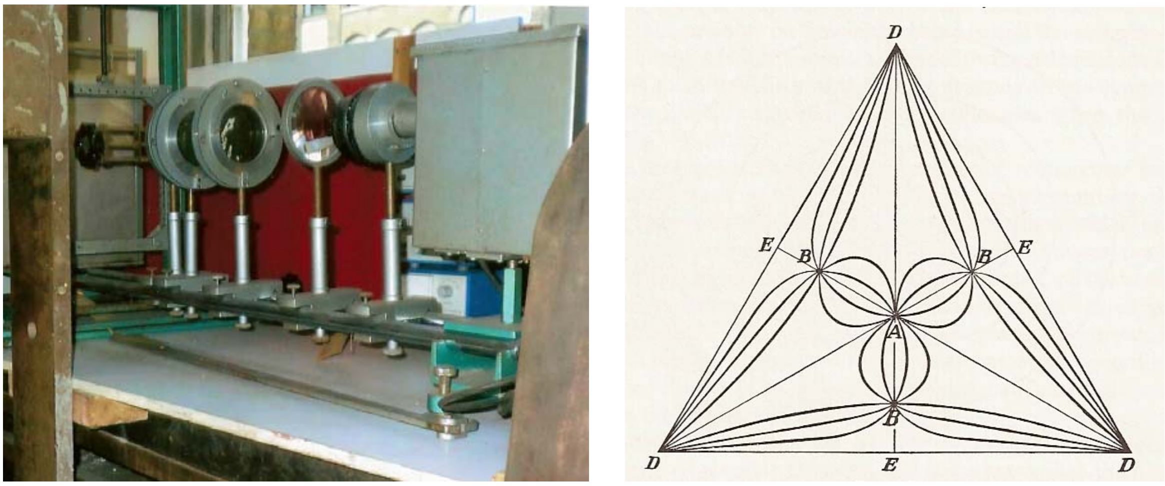
cycle fatigue with an in-built electronic recording system, but hardly ever performed as might be wished. A third item on this raised floor was a 1t (c. 10kN) electric hoist carried on a small gantry, which gantry was strain-gauged to allow dynamic loadings to be recorded, since the use of the large electric hoist in the Transit Camp had proven to be very popular with the students.
Several smaller machines or rigs were placed on the main floor. There were one or perhaps two bench mounted fatigue machines of the so-called N.P.L. type, made by Avery. Pieces could be tested in pure bending or torsion, or any mixed mode in between, to show the effect of stress system on conventional S-N. endurance curves. As already mentioned, the original Charpy impact was in this lab though earmarked for research use. It was during this period that the striker was strain gauged so that loads on the striker nose at impact could be recorded. A new Lösenhausen Charpy machine was installed, together with an Izod machine (whether the original from Waterhouse days or a new one, I do not recall). They were used to obtain transition curves of energy v temperature to give students an introduction to brittle-ductile transition behaviour (at a time just before Fracture Mechanics was established as other than a research tool). At the north end of this lab a third Denison creep machines was added to the existing two from the Waterhouse lab and new furnace control panels made up. The machines were used mainly for testing an aluminium alloy for which the basics of creep behaviour could be obtained during the one day a week over 3 or 4 weeks testing time of the extended lab course. Some smaller equipment including a strain gauge calibration rig, the original and a second Hounsfield Tensometer and several heat-treatment furnaces to allow study of quenched, normalised and tempered conditions, these last at the north end of level 5 where there was also a room for technician use and for storing delicate equipment. The lab was floored over at the north end to give a level 6 area on which there were two or three metallurgical polishing benches and associated microscopes. There were also three photo-elastic benches in darkened cubicles.

For the compulsory lab course in the Autumn term there were some dozen or more topics covering Applied Mechanics and Thermo-Fluids, roughly half in each. Of those in Applied Mechanics three, or perhaps four, were in Materials, with another in Vibrations. For the extended course, there was a list of some thirty topics, roughly half in Applied Mechanics with some ten or a dozen in Materials and several in Vibrations and Lubrication, some in the adjacent the eponymous labs. Students were at liberty to choose which topics they wished, subject to a reasonable balance between the two Sections and the availability of equipment, some of which served more than one topic. Most of these extended experiments had some element of uncertainty or choice as to which aspect was studied, again within the restrictions of the overall logistics. The post-graduate students worked under similar arrangements of compulsory and then optional extended experiments, but in number of cases they took a ‘special task’, usually an off-shoot of some ongoing research and housed in that specialist lab.
The experiments followed some aspects of the lectures in Materials and Elasticity given by Hugh Ford together with more explicit ‘material properties’ studies. His lectures included pressure and thermal stress in thick walled cylinders, criteria of yielding in three dimensions with some follow up reference to true stress - true strain curves, Soderburg’s design method for fatigue under complex stresses and an introduction to stress functions as the method by which, in more detail than time permitted, stress concentration solutions could be obtained. Hugh Ford later wrote a book on elasticity theory though not intended for undergraduate classes.
The 50t Denison machine was used for so-called Cooke and Larke compression tests, a seemingly Heath-Robinson method whereby true stress-strain curves could be found with surprising accuracy. Four small pieces of a malleable metal, each of different lengths but common diameter, were compressed by incremental loading with the compression measured at each point. The resulting four sets of data were plotted against the initial diameter to length ratio and then extrapolated to ‘infinite’ length, where the otherwise very marked effect of end friction could be neglected.
The strain gauge calibration rig, the small capacity Denison and the torsion machine were used for a strain gauge test to illustrate how to set about experimental stress analysis in the field. The calibration rig then (and still) in use was the smaller of the two rigs in Fig.16, which had been designed by the writer for the first use of strain gauges in the Department in about 1950 and was taken over for teaching use in about 1957. Time did not permit students to stick their own gauges but the calibration relevant to the batch being used was found from the four-point bending calibration rig, where the applied strain is a function only of the geometry of bending, independent of modulus. In the second test, gauges aligned axially on both sides of the piece and gauges also fitted transversely, gave tensile data independent of possible bending effects or vice-versa, and allowed an estimate to be made of

Poisson's ratio. Principal strains were found in the third, torsion, test from gauges fixed at 45° to the axis. The last two tests also allowed a second determination of Poisson's Ratio, as a bonus, since the tension and torsion pieces had been cut from the same steel bar.

Fig.17 Two strain gauge calibration rigs, now, in 2007, on the raised floor of Rm 581.In the foreground is the original 1950 rig and in the background a later addition of about 1980.
(photo courtesy of Hugh MacGillivray).

The photo-elasticity benches on level 6 were used to introduce the subject, calibrate the material used for stress-optical sensitivity and then to measure the stress concentration factor around a hole in a plate under tension. The photo-elastic effect, whereby alternate bands (black and white or coloured, according to the light source used) called 'fringes', map out the distribution of stress in models made of suitable 'bi-refringent plastics' when light is passed through the loaded model. This effect was first noticed in 1814 by J. C. Maxwell but did not come into practical engineering use until the early C20th. It must be recalled that, up to the 1960s, strain gauges and photo-elastic models were the only feasible means of assessing stresses in service, since the relevant computing techniques did not then exist.



Fig

Fig. 18a

Fig. 18b

Fig. 18 Photo-elastic stress analysis
a) Photo-elastic bench similar to that in Rm 581;
b) A stress pattern in a triangular plate taken from Maxwell's biography by Campbell and Garnett

A fourth experiment was, I think, in this course though possibly in the extended course of the spring and summer terms. It may be there were two versions, one covered in much more detail with micro-examinations and hardness tests as well as the simple tests mentioned here. Suitably machined samples of a 0.5% carbon steel were provided for heat treatments by quenching tempering and normalising, followed by tensile testing on the miniature Hounsfield machines and by Charpy impact tests, for which latter the pieces had to be notched after heat treatment to show the great superiority of the quenched and tempered steel. This notching was done during the lunch break, seeming to imply a one-day compulsory experiment.

For the students in the spring and summer terms not doing a special task, there was a list of some thirty experiments extending over three or four days each, roughly half in Applied Mechanics of which some ten or a dozen were in Materials. The theme of true stress - true strain curves was extended by tensile testing including measurements of the 'necking' part of the test as suggested by Bridgeman, on the 50t Avery machine. A hollow torsion piece was also used because of the difficulties of analysing the elastic-plastic stress system in a solid bar, albeit the hollow piece was useful over only a limited range due to torsional buckling of its thin wall. Both tests used procedures that brought out the difficulties rather than giving useful results!

Tensile testing of small samples of a range of alloy steels and aluminiums were offered, supplemented by micro-examination and some discussion of their special suitability for use at other than ambient temperatures.

Creep was now introduced to the undergraduate students by tests on an aluminium alloy (I believe that used for Concorde, RR52 was it? I am not now sure) tested at about 150°C to give some insight into primary, secondary and tertiary creep, as possible within a three or four week duration of testing.

Fig. 19 A 1t (c.10kN) capacity Denison creep machine, here shown in 2007 awaiting renovation in the Kirkaldy Testing Museum

Fatigue tests gave S-N curves (in the days before fracture mechanics), to allow some limited study of both Miner's Law for cumulative damage and, on the N.P.L. machines, fatigue under complex stress systems. Several pieces of industrial plant that had failed in a brittle manner were available, with students selecting what tests to conduct to 'sort out' the problem (with some guidance if their suggestions promised to go beyond the workshop facilities and time available for any one group!).

So all the new equipment was put to good use for a number of years until a change to all final year students taking a special task reduced the usage in the spring and summer terms to those materials based special tasks for both final year and post-graduate students that did not require use of machines in a specialist lab.

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The final, E3 & E4, stages of the re-building

Some organisational changes

The E3 and E4 stages of the building were completed in autumn 1967, about three years after E2. As already mentioned these two stages had been telescoped together and altered in layout from the original plans, for reasons of both economy in cost and to regain most to the lost time of construction. The final layout was as shown in Fig.14. The exterior finish to the frontage of the revised E3 block was much inferior to that of the main block. The so-called E4 'Tower Block' was on stilts for levels 2 and 3, above the main site entrance, mid-way along the whole building. This tower was connected to the main spine by corridors from level 4 upwards, but at only 7 levels, did not tower over the main block.

In 1967, Russell Hoyle, who had done so much day-to-day work on the whole project, moved to Durham as Professor of Engineering. I was appointed as Assistant Director in the Mechanical Engineering Department about six or nine months before the due completion date of E-block. I still retained academic responsibility for three labs in E3, a large lab with big testing machines on level 1 called (for want of a better name) 'Heavy Testing' and two adjacent areas on level 5, one called 'Elasticity' and one called 'Experimental Stress Analysis' in the rear facing spur at the south end of E3. For the equipment in the labs about to be described, other than those three, I had little direct knowledge beyond that of general interest, so that some of my recollections are now very sketchy.

Laboratories in the E3 & E4 stages of re-building

There were no basements in E3 and E4 but level 1 in the revised E3 stage contained only laboratories. Towards the rear, these were mainly Thermo-Fluids and related labs, with an Engine test lab on the front of the spine. At a later stage one of the rear labs was given over to Polymer Processing and now, in 2007, the Engine lab has also been given over to Materials, but more of that later. For Materials, the original layout of level 1 of E3 contained the so-called Heavy Testing and Applied Mechanics Contracts labs in or to the east of the spine, near its south end. A Metrology lab and a Polymer Engineering lab with no natural lighting were also to the east of the spine, whilst a Plasticity and Metal Working lab and a Nuclear Power lab fronted onto Exhibition Road, semi-basement with respect to the public pavement level.

Levels 2, 3 and 4 of E3 contained mainly drawing offices and staff offices. On level 5 of E3 there were the second year Materials Undergraduate lab with a balcony area on level 6, an Elasticity lab, a post-graduate Experimental Stress Analysis lab and a Photo-elasticity lab.

On levels 4 and 5 of the E4 Tower block, there was a partly double height first year Materials lab over part of which Sir Hugh's office, now located on level 5 at the junction of E4 with E1, intruded whilst giving a view down to the level 4 lab activities.

The 3rd year Materials lab and the Non-metallics lab on level 5 of respectively E2 and E1 were not affected other by renaming the latter as 'Polymers'. It was supplemented by the Polymer Engineering lab just mentioned on level 1 of E3 and with some outposts of work later spreading to various other labs on both level 5 and level 1. The two machines from the small Plasticity lab on level 5 of E1were moved into the large Plasticity and Metal Working lab, just mentioned, on level 1 of E3.

Equipment in E3 &E4 for Materials undergraduate teaching.

The Second Year teaching course in Materials centred on principal stresses and criteria of yielding, both in two-dimensions, axi-symmetric thick walled cylinders under pressure and thin rotating discs. I am not now sure whether out-of-plane bending of such as L-sections was discussed in the lectures or only in the lab. At about this time a short treatment of polymers came into the course. Their non-linear behaviour required some explanation and Gordon Williams wrote a book on stress analysis of polymers to cover this need. The lab was at level 5 in the spine of E3, with a balcony space on level 6. The experiments were mainly for Materials, though some more general experiments in Applied Mechanics were also included. This lab was controlled by Alan Swanson (later Professor, Head of Department and then Pro- Rector) and is one in which I only served on one or two occasions, so I am not now certain of many details. The experiments lasted for three hours, so had to be relatively 'cut

and dried' though most were conducted by the students (in groups of four) rather than by demonstration and called for some understanding of the associated theory. Most were duplicated to accommodate class numbers.
As I recall there were at two or three conventional testing machines, including one, or perhaps two, new Avery hydraulic machines, well suited for tension testing. I am sure that either (or both) an aluminium alloy and a non-glassy polymer were tested as examples of other than the mild steel met in the 1st year lab. To allow determination of principal stresses in other than self evident cases, a beam, already strain gauged, was subjected to bending and appreciable shear on the newer of the 10t (c.100kN) Bucktons from the Waterhouse and Transit Camp periods and on a simple hand pumped hydraulic rig specifically made for bending tests.
Criteria of yielding was studied using quite simple machines in tension, torsion and (I think) some intermediate stress state. A small hand loaded bench rig was used for the un-symmetric bending work I believe the original Izod machine was also in this lab. There were several Avery Wöhler type fatigue machines to allow a whole class collection of results to illustrate not only the general shape of an S-N curve but also the inherent scatter in fatigue life. The non-materials experiments were probably in vibrations and some aspect of mechanics, such as buckling, where geometry rather than properties (other than modulus) dictated the behaviour.
In the E4 part of the building, completed in I think 1967, more or less coincident with the E3 stage, was the Materials lab for first year Materials teaching, a partly double height space on levels 4 and 5 in the Tower Block over the main entrance. The first year lectures in Strength of Materials centred on the elastic laws and tensile properties of (at that time) metals, specifically, steel, stresses in statically determinate systems, then simple bending and torsion. This lab contained the old Riehlé machine for demonstrating tensile behaviour and the two 5t (c.50kN) Bucktons from the Goldsmiths lab after their peregrinations via Waterhouse, Transit Camp and E1 'Technician's Common room'. These three machines were kept, though out of date, for the specific purpose of showing students how they worked, there being no covers to any operating parts. Since new students had little if any prior knowledge of Materials (and in successive years, a decreasing knowledge of what in the 1950s had been 6th form teaching of properties of matter and applied mathematics) suitable 'elementary' experiments had to be provided, several in triplicate. One was the well known 'school' rig for obtaining Young's modulus by loading a wire in tension. For students who had done such tests at school, I think the 5t Bucktons were used to allow determination of Young's modulus for a bar of steel by using one of the Ewing 'brass-bound' mechanical extensometers of Waterhouse days, already shown, Fig.8. At some later date, the lack of elementary knowledge of moments of inertia and second moments of area was attacked by setting up an experiment to find centres of gravity and moments of inertia of some simply shaped solid bodies.

To allow the relevant lectures to 'get ahead' of the lab work two simple experiments were set up that did not call on the as yet un-taught theoretical knowledge. The first was a hand-loaded rig to apply three-point bending, Fig.20, seemingly identical to rigs of the late C19th as shown by Ewing. It was then used for 'measuring elasticity' (presumably Young's modulus) but that did not suit the present purpose since that result called on the form of the relationship between load, beam dimensions and deflection and a numerical constant therein ,which would have defeated the object of performing an experiment with no prior knowledge of the relevant theory. The experiment as actually used took five or six beams (of about 3 to 4ft (c. 1 to 1.2m)) and of relatively small cross section. Students were asked to find the form of the laws governing simple bending, planning their own tests (a novelty for most) to obtain the proportionality of deflection to load and the form of the dependence on span, width, thickness and modulus. Numerical values of any constant of proportionality in these relationships were not required. A second test that proved very popular was to design and make a beam from a given sheet of cardboard to carry the maximum obtainable load in simple bending over a stated span. Students drew up a design to their satisfaction and cut pieces of card to suit. These were fabricated into a beam by a technician, using glue and fillets of string, to be tested by the students in the following week, also using, I think, the just mentioned bending rigs of Fig.20, since the loads

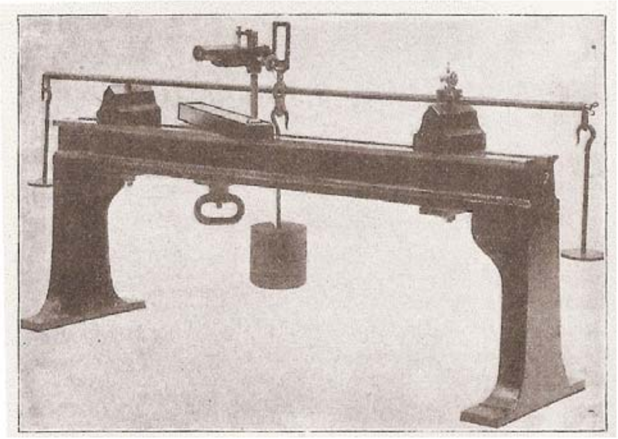

Fig.20 A bending rig in the 1st Year lab in E4. This picture is from Ewing's book first written in 1899 and is near identical to one of the rigs still in use in the 1960s (from Ewing, loc cit Fig.6)

required were too small to be measured with any accuracy on the 5t (c.50kN) Buckton machines. Most students tried to use the knowledge gained in the previous experiment on the laws of bending, only to find that nearly all their designs failed by either lateral or local buckling, a phenomenon quite new to most. As that knowledge seeped down from year to year, the highest failure loads obtained increased by nearly ten fold!

At some later date, perhaps the late 1970s when I was elsewhere, there was a 'revolt' against what was seen as old fashioned equipment. A Wheatstone bridge was used to demonstrate some feature I cannot now recall. This was a static unit with slide wire re-balancing to give an accurate null-point reading of change, generally as in Fig.21, but with the galvanometer in a separate mahogany box with brass terminals. The students objected to being asked to use such 'ancient' though easily explained equipment, demanding a 'self indicating' digital voltmeter to show the reading. As well as conceding that, a new testing machine of a type I do not recall but certainly enclosed so that its 'works' could not be seen, was purchased to 'modernise' the tension experiments on the Riehlé and the Bucktons, on which all the workings of the machine had been quite apparent.

Fig. 21 A Tinsley Wheatstone strain gauge bridge, here with built in galvonometer, bottom right Now in the Kirkaldy Testing Museum

Such is progress, though, it seems to me, not always accompanied by a better understanding of the basics of the experiment. The Riehlé , Fig.2, was given to the Kirkaldy Testing Museum where it is on display, still useable. One of the 5t Bucktons, Fig.5, was given the Science Museum where, in 2007 it remains in their reserve collection.

Equipment in E3 &E4 for Materials research

As already outlined, the Materials research labs in the E3 stage were many and diverse. Firstly, on level 5, the Polymer lab under Gordon Williams (later Professor and Head of Department) was equipped with a couple of new Instron electrically driven machines, Fig15, fitted with strain gauge load cells and chart recorders.

A Photo-elasticity lab, on the front of the spine, planned by Peter Benham (though he had moved to Queen's Belfast a year or two before the lab opened) contained, I think, two optical benches and an oven for three-dimensional 'stress freezing' technique.

Opposite, in the rear of the spine and in the rearward facing spur were the Elasticity and Experimental Stress Analysis and labs already mentioned. The so-called Elasticity lab was used for some six to eight years for a series of researches on curved pipes, the first with rather thick walled 'long radius bends' as used with steam turbines, the second (a follow-on from my own work on 'bends and bellows') with thin walled 'short radius bends' in bending, both with and without internal pressure, as used for naval gas turbines. The pipe bend studies called for a large testing frame with a number of hydraulic actuators and many dial and strain gauges. The second project, on pressurised thin-walled bends, was conducted by John Blomfield, a new-comer who later joined the staff and became the Section guru on computing.

This area was also used by Patrick Leevers who had undertaken some work on the effects of bi-axility on cracks in polymers, in which John Radon had joined in. That study received the unusual recognition of being mentioned in the novel 'Airframe' by the well known novelist, Michael Crichton! Patrick Leever's work was the start a long term (and still ongoing) study of the catastrophic failure of 'plastic' gas pipes by the running of a high speed crack, which in the field sometimes run for distances of hundreds of yards - indeed some metal gas pipes in Texas had sustained cracks that ran for several miles!

Fig. 22 A 2in Lindley dial gauge extensometer and a pair of 1in Huggenberger tensometers.

The Experimental Stress Analysis lab housed a large collection of strain measuring devices for purposes of research use or demonstration to the relevant post-graduate class, in the days before computational stress analysis was well established. There were small Huggenbuger and the 'minute' Johansson mechanical extensometers; Lindley dial gauge extensometers; a transverse Lamb optical extensometer to complement axial units in order to determine Poisson's ratio; a hand held auto-collimator for use with an American optical extensometer (the name of which now escapes me); a pneumatic strain measuring device and an acoustic vibrating wire gauge and circuitry - a few such gauges were installed in E1, which gauges could be 'tapped into' for post-graduate class demonstration and to allow long term readings to be taken by the Civil department of certain settlement strains in the structure. I do not know when such readings ceased. There were several resistance strain gauge measuring circuits - two Savage & Parsons 50 channel static strain gauge bridges (one from Waterhouse and Transit Camp days), two Tinsley static strain gauge bridges (one now in the Kirkaldy Testing Museum) and six channel switch box, dynamic strain gauge circuitry, some Philips 'carrier wave' circuits with high speed Kelvin Hughes pen recorders and some with drift corrected D.C. amplifiers and C.R.O display from Southern Instruments (all valve operated, in the days before chips and printed circuits); one or two inductive displacement 'pick-ups' and surely some instruments I do not now recall. A number of these strain gauge instruments were on more or less permanent loan to the already existing 3rd year/post-graduate lab in E2, including the Philips carrier wave bridge and a larger Kelvin & Hughes pen recorder for use on the electric hoist rig, as of Transit

Camp and E2 days, and the Savage & Parrons 50 channel bridges to the pipe-work tests in the adjoining Elasticity lab. It was one of the Tinsley Wheatstone bridges, but with a separate mahogany bound galvanometer, that was later rejected by the 1st year students as mentioned above.
A small mechanically operated Denison machine of 5000lb (c.25kN) capacity was also provided to help demonstrate some of the instruments that had no specific applications at the time.

The other new Materials research labs in E3 and E4 were all on level 1.

At the north end of E3 was a metrology lab housing the original equipment from the small pre-1955 lab then in Princes Gardens, the Talysurf machine from the Transit Camp and a number of other instruments, comparitors, gauge blocks and so on that I do not recall. This was a service lab under the general supervision of John Alexander but had a number of de-facto Heads from time to time. Next there was a Polymer Extrusion lab, under Gordon Williams, with specialist machines instrumented for recording the actual process of extrusion. This was an extension of interest from both metal working and from the polymer testing facilities on level 5 and was first used by Roger Fenner for his own researches. Roger later joined the staff and took over as computer guru when John Blomfield left.
On the Exhibition Road frontage was a Metal Working lab, associated with the long term Departmental interest in plasticity. It housed the many-times-moved 50ton (c.500kN) Denison machines, certainly the one brought down from its temporary home on level 5 in E1, and, I think, the first 50t (c.500kN) Denison from Waterhouse, Transit Camp and Technicians Common Room days and the small rolling mill of pre-1955 Waterhouse lab vintage. More importantly, there were one or two specialist machines for hydrostatic extrusion and forming, with associated high pressure pumps and instrumentation, of which I have no details. This lab was under the general supervision of John Alexander - who wrote a book on plasticity - but run for day-to-day work by Bela Lengyal for his own researches in hydrostatic extrusion of metals otherwise difficult to shape.

Towards the south end of E3 there was the so-called Heavy Testing lab, then under my supervision. As already mentioned, the timing of planning and ordering machines for the labs equipped for conventional testing was unfortunate. It started before the coming generations of electrically operated screw machines with built-in chart recorders, mechanically controlled servo-hydraulic machines and finally computer controlled machines were available. But by the time the E3 labs were built and being equipped, such machines were coming onto the world scene. In short, some of the facilities were rather outdated even before they were installed! The 100t (c.1000kN) horizontal Buckton from the Goldsmith’s Extension lab was stored with a view to installation in E3 mainly on account of its horizontal length and the first of the single lever arm 10t (c.100kN) Buckton machines from the Waterhouse labs and Transit Camp days was earmarked for use as a ‘dead-weight’ loading machine. I believe both were installed, certainly the latter was, but after only a very short period since as new machines were actually delivered and installed it was realised that they were both so outdated that further use was practically inconceivable. Both were offered to the Science Museum but on refusal, were scrapped. The Charpy and B.P. impact machines from the Waterhouse labs were retained, a colleague, John Radon, making much use of the former.
As a last minute change induced by the new era, an order for an Amsler machine, excellent for static use but with negligible even slow dynamic capability owing to inertia in the weighing system, was cancelled and an American 60t (c.600kN) mechanically driven Olsen was obtained, Fig. 23) This, though essentially for static work, had a low inertia torsion bar weighing system that gave good response to quite rapid changes in load. It became the mainstay of many fracture mechanics projects and is still in use in 2007 though beginning to show its age.
The vertical 100ton (c.1000kN) hydraulic Avery machine, seen in Fig.7, then only a few years old, was transferred from the Transit Camp (perhaps after a few years in store - I cannot now recall.) It was kept in regular use and in the late 1980s it was used for a series of final year special tasks on certain aircraft panels from the then de Havilland Aircraft Company.

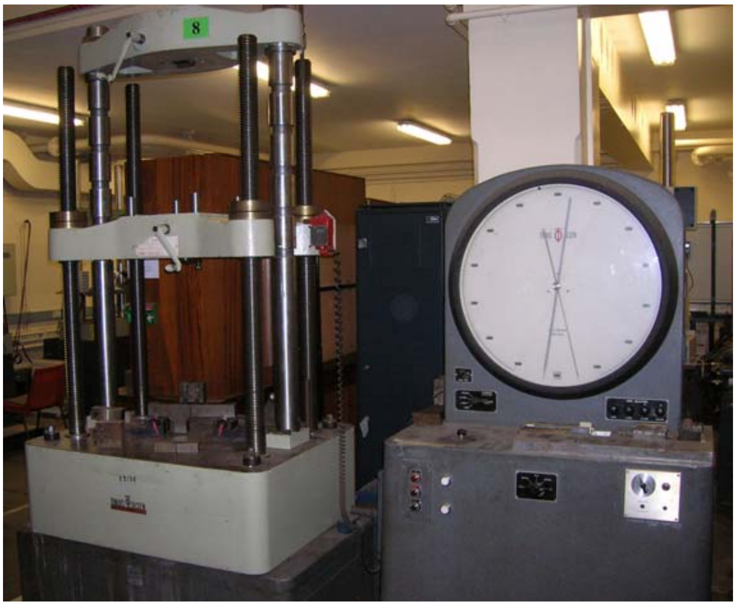

Fig.23 The 60t (c.600kN) Olsen testing machine.
(photo courtesy of Hugh MacGillivray)

On the opening of E3, a new 250ton (c.2500kN) capacity Avery was installed, the pit necessary for it to stand in being built into the foundations of E3. In the early 1980s Hugh MacGillvray took de-facto control of the lab and in about 2000 used this machine for tests on, as I recall, supports for large electrical insulators and then, in about 2005, for tests on a Dowty undercarriage leg for an Airbus aircraft. Other machines installed at the opening of E3 were a Dowty high frequency fatigue machine, one of the first of an excellent but not widely used servo-hydraulic machine of about 7 or 10t (70 or 100kN) capacity. This is likely to be up-dated and put into service again in 2007 for a particular range of test parameters for which is well suited. In the mid 1980s Hugh MacGillivray installed a large ring main hydraulic system with pumps and filters in the just mentioned pit under the 250t Avery, to serve a rapidly growing range of new servo-hydraulic machines. A large capacity system was chosen to allow the later installation of several more machines, without the demands on the system for one machine degrading operation of others. The machines installed from time to time were later used more for fatigue and creep testing of both metals and polymers than for static fracture testing. That service is still provided using the same ring main, today.

The final Materials, or strictly Applied Mechanics lab, in E3 was a so-called Contract lab at the south end of E3, where various short term contract testing was envisaged. In the event, this did not come about, mainly because of the administrative problem of juggling existing or employing extra technicians under the very ponderous College/U.G.C. system for such appointments. The area soon passed to the Nuclear Power section, where it was well used by their robotics group until indeed passing to Materials, I think in the 1990s.

Thus years of planning, demolishing, rebuilding, expanding and re-equipping came to fruition and lasted almost untouched for just a few halcyon years. This was a more or less euphoric state brought about from no longer having to move labs from pillar to post and being able to lecture with no loud background music of pneumatic drills, use of which, on any part of the structure, had for many years reverberated throughout the whole building.

In about 1970, academic staff numbers (including the Nuclear Power and Management Science Sections) totalled just over 80 whilst support staff (technicians including, I am sure, some research contract posts and all secretarial staff) peaked at 100 persons. Of these, there were in Materials, about 12 academic staff plus several research fellows or officers, all, except one, ‘metals’ oriented. The Materials teaching labs were in the hands of a Chief Technician, Eric Childs, aided by Sid Smart and one or two others on the departmental budget and perhaps six or so on contract engagements in several of the research labs.

MATURITY: from c.1967 to the early 1980s.

Engines of change in the Materials group in the 1970s

Quite soon after the completion of E-block in 1967, changes inevitably started to occur to what had seemed the goal of stability and rather more peaceful working conditions: ‘stability’ was going to be a ‘steady rate of change’! At the start of this period, the Materials Group had several main research strands, each with one or more specialist labs: Plasticity and Metal Working; Creep; Fatigue; Experimental Stress Analysis (based on strain gauges used on actual hardware and model tests by photo-elasticity but with an embryo of computer analysis); Polymers (later to include polymer-composites and adhesives) and the General Mechanical Properties of Metals -at first mainly empirical studies of brittle fracture but soon to embrace the new ideas of ‘fracture mechanics’. This topic soon spread to both metals and polymers, using the testing facilities in the 3rd Year and PG lab, the Polymer lab on level 5 and the Heavy Testing lab on level 1 By the 1970s there were several changes in the activities of the Materials group, first being computing and then the use of fracture mechanics for most studies in fracture.

The advent of computing in M.E.D. has already been touched on but in about 1970, its instigator, Pedro Marcal, went down the ‘brain drain’ to Brown University in Rhode Island, U.S.A., later to set up the MARC corporation and its associated programs. He was superseded as the sectional computer guru by John Blomfield. The Materials Stress Analysis group retained one of Marcal’s finite element programs that became known internationally as ‘MARK (or was it MARC?) minus 1’. Two generations of my research students used ‘MARK minus 1’ for plasticity studies in pressure vessels. The next generations then focused it on crack studies. A notable contribution to three dimensional problems was made by a research colleague, Bob Curr, based on a program called ‘WHAMSE, an elasto-plastic dynamic program, very quick in operation (most important before the coming of powerful individual ‘work stations’) but used isoparametric ‘solid brick’ elements known to be overstiff in bending, a problem that Bob Curr soon cured and then using the program regularly until about 2003. Computing applied to metal-working was slower off the start partly because the wide use of ‘slip-line field’ theory, already mentioned in the late Waterhouse days, satisfied many immediate needs and partly because algorithms had to be developed or imported that covered both large deformations and strains, to encompass the changes in shape during metal fabrication processes in general.

As numerical analysis came into the under-graduate course, computing facilities had to take over student ‘drawing office’ space and then, as its powers became ever more apparent, it reduced drastically the interest of many new research students in experimentation and thus the need for some of the labs and workshops set up in the 1960s and ’70s.

Fairly early in this period the College I.B.M machine in the Electrical Department was replaced by three or four modern machines controlled by a new college department, called, I think, Computing Science & Technology. A space had to be found for both the machines and the associated staff of this Computing Centre, which was to serve their own research interests and provide a service to all departments of the College. For reasons set out below, that space was found in the M.E.D. on level 4 of E3, with ‘temporary’ offices built on a convenient flat roof at the rear of E1.The occupation and the ‘temporary’ offices on the level 3 roof, remain to this day.

The change that determined that E-block was to be the home for the College Computer Centre was the demise of the ‘Common Course’. For as long as anyone could recall, all first year teaching and associated laboratory work in the core engineering subjects of Thermo-dynamics and Strength of Materials had been provided by M.E.D but that work was now largely taken back in-house by the various ‘home’ departments. One reason was a growing pressure from the specialist staff within each department that more time was needed for teaching their subjects. Another pressure, whispered rather than trumpeted, was the realisation that under the new financial regime of budgets based on (full time equivalent) student numbers, all departments other than M.E.D. would gain by taking to within their own departments as much as possible of their first year work. Most left just a rump of laboratory work requiring expensive equipment already available within M.E.D.

In around 1970 Management Science became a separate Department under Professor Sam Eilon, still housed mainly in E-block, mainly at the front of level 3 of E3 and in part of the E4 tower block. With the turning of what started as Industrial Engineering into Management Science, the original intention of setting up a group in production or manufacturing engineering within Applied Mechanics, vanished, albeit the Metrology lab remained in the Materials group

The growth of Fracture Mechanics in the 1960s and 1970s

In the 1950s and early 1960s, work on fracture of metals in M.E.D centred on a wide study of the effect of size, configuration, temperature and strain rate on the test results for fracture of notched (but not pre-cracked) pieces. As already mentioned, this work was started by the re-instatement of the Charpy machine of Fig 5, by tests in the Goldsmiths lab by a student of mine using the horizontal 100t (c. 1,000kN) Buckton machine of Fig.7. and in the Transit Camp where the then new 100t (c.1,000kN) Avery, was used for many tests on notched tensile pieces for the N.D.A.C.S.S. Such studies continued in the temporary facilities of the 'Technicians' Common Room' lab in E1 and then into the 3rd year and P.G. lab on level 5 of E2. The old Charpy machine from the Waterhouse lab was, in the mid-1960s, instrumented with resistance strain gauges on the flanks of the striker, to become, I think, the second such machine in the U.K (the Welding Institute beat us by a short head). This work was revolutionised by the coming of Fracture Mechanics, a topic that in due course spread to metals, polymers, composites and adhesives and still dominates the fatigue and creep aspects of such work.

The subject of Fracture Mechanics was started by A.A. Griffiths in England, who, in the 1920s, studied the fracture of glass using the interplay between the rates of change of elastic strain energy and surface energy, termed G. The concept was left dormant until George Irwin revitalised and extended the idea in U.S A in the 1960s. He used a charterising crack tip parameter called K, which he then related to Griffith's G, thus giving a duality that appealed to many workers and the discipline became known as 'linear elastic fracture mechanics', l.e.f.m.. Irwin's immense contribution to fracture problems was based on failures in rocket motor casings made of very high strength alloy steels which showed a critical value of either G or K at fracture, the so-called 'fracture toughness' of a material. Just a few years before the N.D.C.A.S.S .ceased its activities, it invited Irwin to give a few lectures in the M.E.D. at I.C. for the specific purpose of introducing the subject to a British audience, at a time when quick and easy travel to the U.S.A. was unknown In 1963, a Dutch student of mine tested sheets of rather brittle plastics containing a deliberate crack, and found a unique value of a critical fracture toughness and the corresponding half-power dependence of fracture load on size, as predicted by l.e.f.m. Encouraged by Hugh Ford, I took a leading role in bringing l.e.f.m. to wider attention in the U.K. A committee was set up to formulate what became a British Standard Specification, (B.S.S.) test method for l.e.f.m. in which work the Department did not have the financial and technical secretarial clout to do other than let me become a participating member. B.I.S.R.A., the then research arm of British Steel, took the leading role in bringing that work to completion.

In Britain there was concern over why l.e.f.m. seemed so readily applicable to rather brittle materials with very sharp notches or actual cracks, but not to the brittle, cleavage, fracture of lower strength structural steels as used in ships, nuclear power stations and presently, offshore oil and gas platforms, albeit test on the latter used notches of small root radius rather than actual cracks. Work in M.E.D. in 1967 showed a relevance of l.e.f.m. to the lower strength steels, using fatigues pre-cracked impact tests on the now instrumented old Charpy machine. This was followed by a demonstration of a validity for l.e.f.m. for conventional steel, using static notch tensile tests on two ship-plate steels with notches locally damaged by pre-compression, albeit at temperatures lower than normal service use of such steels.

The main objective of fracture studies of metal in the U.K. became the understanding of the role of plasticity in fractures of structural grades of steel and subsequently, to safe design and in-service procedures for these materials. The inclusion of elasto-plastic effects in fracture mechanics became known as elastic-plastic fracture mechanics, e.p.f.m. Alan Wells at The Welding Institute (now just TWI) made a major contribution by experimental studies based on the crack tip fracture criterion that he called 'crack (tip) opening displacement' C.O.D. (or C.T.O.D. in later American usage). In the late 1960s and early 1970s Jim Rice at Brown University, Rhode Island (where Marcal had developed his MARC suite of finite element programs) worked with colleagues to made a major theoretical contribution by introducing a term call the J-integral, J, as a possible fracture criterion in e.p.f.m. This proved a controversial but finally very useful concept, controversial because it was based on non-linear elasticity rather than incremental plasticity, thus not giving the e.p.f.m. equivalent of G, but finally useful since it did offer the e.p.f.m equivalent of Irwin's l.e.f.m crack tip characterising factor,

K. The lack of an e.p.f.m. duality corresponding to G and K did however make acceptance of J very slow in Britain, whilst American acceptance of C.T.O.D. (which could be theoretically related to J only by using very simplistic approximations) was equally slow. I gave an explanation of all this work in a co-authored book on post-yield fracture mechanics.
In the early 1970s, two students in the Section were, I believe the first to compute the behaviour of C.O.D. and of the J-integral for several configurations of test pieces, using the in-house 'MARC minus 1' two dimensional finite element program, which had a truly incremental plasticity formulation. Another first, by a third student making use of the same program, was to express the severity of a crack emanating from a region of stress concentration and in the wall of a thick cylinder under internal pressure in terms of J, both the important design cases. The growing interest of the metals industries in these new topics and methods of analysis was recognised by the Department and The Welding Institute setting up a series of joint 'post experience' courses aimed at those called upon to use these new ideas. Such courses went on for about 10 years. As fracture mechanics applied to polymers was adopted by industry a book covering this special topic was required and Gordon Williams wrote one. Also ,the University introduced a scheme whereby potential research students working in certain industrial research labs could do their experimental work in house and come to the College for some academic study and general overseeing of their work. The first M.E.D use of this scheme was by students from The Welding Institute, who wished to apply l.e.f.m. to the fatigue of butt welded joints. His tests showed that the fatigue crack growth rate (though not the fatigue life) was, in terms of l.e.f.m, .quite independent of the changes in micro-structure across the joint. I believe this was another first. The application of fracture mechanics to actual structures, immediately highlighted a different problem. Test pieces used sharp cracks of known size, but if a critical crack size was predicted for a particular structure by one of the design methods, how was the existence or not of such a crack to be established? This soon led to the development of several methods of so-called 'non-destructive testing' (N.D.T) or 'non-destructive examination' (N.D.E.). The Materials group was not involved in much work in this field, its continuing attempts to improve the understanding of the various concepts in e.p.f.m. being 'enough on its plate' during the hurly-burly of the re-building of the Department and subsequent events.

More changes but still progress in the late 1960s to mid-1970s

The discipline of Bio-mechanics had been set up by Hugh Ford as a new activity within the Applied Mechanics Section, not long after the E2 stage had been taken over. Alan Swanson, whose early career had been materials oriented, took up this work following a change in his interests to mechanics, by teeming up with a medical doctor, Dr Freeman, from, I believe, the Hammersmith Hospital. This growing activity was now housed in by conversion of the 2nd year Materials teaching lab in the middle of level 5 of E3. The teaching requirements for 2nd year lab classes in Material was taken up within the 3rd year/post-graduate lab, room 581 of E2. An Instron electro-mechanical machine, already shown Fig 25, was transferred to that lab for the testing of polymers experiment used by the 2nd year students.

Several changes continued to occur in fatigue. Following the departure of Peter Benham in the mid-1960s, David Burns was appointed. He started to include the recognition of fracture mechanics to fatigue crack growth rate as offering a major insight into what had hitherto been seen as just fatigue life. After a few years Burns left and John Rogan was then appointed, followed in about 1980 by Sean Crofton. Both carried out research work on fatigue in high pressure vessels, the latter bringing in some very noisy (and oily!) machines which were installed in what had been a small storage space adjacent to the Fatigue lab. Both had a main interest in the effect of micro-structure and composition on the design and fatigue life of their high-pressure vessels. Sean Crofton also brought into the erstwhile photo-elasticity lab on level 5 of E3, a scanning electron microscope, a not very common facility in a mechanical engineering department.

In the early 1970s an external engines of change of far-reaching consequences became apparent, the reduction in funding for both capital and recurrent expenditure as made available by central government funds via the U.G.C. The era in which the College, or at least some of its departments, had expanded with minimal financial constraints, was now over. Any new developments and later the use of space in existing developments, had to conform to norms introduced by the U.G.C so that the

physical use of certain labs was changed and any more new machines, financed from non-U.G.C. sources.
In 1973 I resigned as Assistant Director in the Department and reverted to normal academic duties. I have a poor recollection of the sequence of several consequential changes since some at least occurred whilst I was on secondment outside the Department in the mid to late 1970s.

Continued changes from the mid-1970s to the mid-1980s

In the year or two after reverting to normal duties, a quite extensive fracture mechanics programme funded by the then S.E.R.C., was set up on micro-macro aspects of fracture run jointly with Professor Peter Pratt in the Materials Science Department of R.S.M. This involved three or four research students and two or three post-doctoral research assistants between whom experimental studies of C.O.D. at both the mouth and at the advancing tip (C.T.O.D.) and of J-integral values were made, at both micro and macro scales. My main research student in this work was Steve Garwood. After working at TWI and Rolls-Royce, he has recently become a Visiting Professor to the Department.

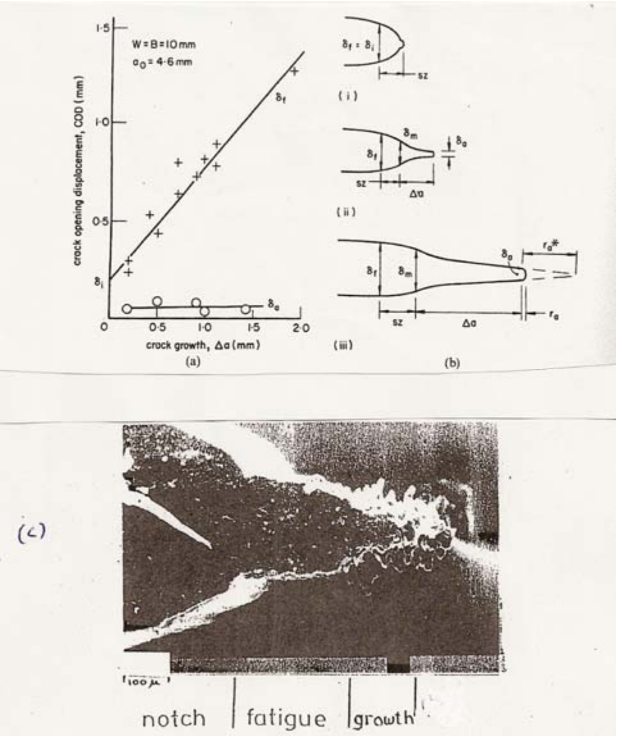

Fig.24 a) C.O.D. versus crack growth: upper line: at original tip, lower line: at advancing tip. b) A schematic of C.O.D. during growth : (top) at initiation; (middle) at first development of slow crack growth ; (bottom) with well developed growth. c) Advancing crack as infiltrated by silicon resin (Garwood, Pratt & Turner, Elasto-Plastic Fracture Mechanics I, Paper 11, CSNI Rep.I.1978)

Another development was in creep crack growth of metals at high temperatures. An l.e.f.m. approach had been tried tentatively elsewhere with little success but since secondary creep was well known to be linear with time but power-law dependent with stress, this was not surprising. The work, conducted in the Creep lab in collaboration with George Webster and a student of his, Kamran Nikbin (now a Royal Academy of Engineering Professor in the Section), soon paid off by showing that such growth could be well represented, if not actually explained, by a time dependent version of the J-integral which we denoted ‘J-dot’. Simultaneous similar work in U.S.A. adopted the symbol ‘C-star’ and that terminology gained general acceptance.

In.1976 I went on two and a half years’ sabbatical leave firstly to the National Physical Laboratory, N.P.L., and then to British Aerospace. At N.P.L. I had the good fortune to participate in the investigation into the complete failure and disintegration of the Great Clock of Westminster (usually referred to by the name of the bell, ‘Big Ben’). My contribution, outlined in the booklet ‘The failure of the quarter bells chiming mechanism of the Great Clock of Westminster', by N.B. Owen, C.E. Turner and P.E. Irving (pub. Inst Mech Engrs) was a novel fracture mechanics analysis of the fatigue life of the culprit tubular wrought iron shaft that caused the accident, showing that a crack in it had been growing ever since the clock had been built in the 1850s. In 1978 I went for a short period to British Aerospace, to help show the significance of small scale plasticity in the analysis of some of their fatigue and residual strength problems.

In the same period John Radon and colleagues worked on a wide range of l.e.f.m. fracture problems including slow crack growth and fracture by impact. Use of the 'double cantilever bend', D.C.B., test piece, which, suitably shaped, at a given load in the l.e.f.m. regime gave a value of K constant with crack length was introduced into the U.K. from U.S.A. A severity independent of crack length was a very useful characteristic for studying slow crack growth, notably in fatigue and later in environmental weakening of polymers. Brittle fracture by impact was studied experimentally by Radon and computationally by Dutch student of John Head, in the Nuclear Power Section, who modelled impact testing in a two-dimensional finite element program by including dynamic terms.

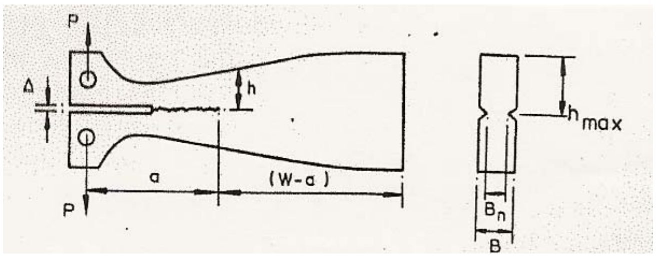

Fig.25 The side-grooved Double Cantilever Bend (DCB) test piece profiled to give K constant along its length. For simplicity a straight taper was often used with the useful regime restricted to the mid-length of such a piece.

In about 1977, whilst I was still on secondment to N.P.L., the Applied Mechanics Section was re-organised with the several disciplines referred to throughout this account as 'Groups', Strength of Materials, Dynamics, Tribology and Bio-mechanics, now becoming Sections of the Department. 'Materials' became 'The Strength of Materials Section', comprising the general mechanical properties of both metals and non-metals. Since I was then still on secondment, Gordon Williams took organisational control of all such work and when I returned, it did not seem worth separating out the metals component from what was a very amiable set-up. In 1978, Hugh Ford left the Department to become Pro-Rector and John Alexander also left to go to the University of Wales at Swansea. Because of the re-organisation just mentioned, a formal replacement as Professor of Applied Mechanics was not made.

Sometime in the mid or late 1970s - more precise dates escape me now - the undergraduate course was extended to four years, with an industrially based project taking up much of the extra time. I think it was in relation to this change that more Materials staff, Cyril Laming, Sean Crofton and Bela Lengyel, led the design courses in one year or another. A 3rd or 4th year lecture course on manufacturing technology was set up, given jointly by Sean Crofton and a part time member of staff, a metallurgist, Tim Baker (since deceased) who transferred from the R.S.M. to M.E.D. Tim had the very useful attribute of near instant appreciation of how any metal artefact had been made and the pros and cons of other possible methods and brought a wealth of consulting examples from across the world, all very helpful in getting a real engineering flavour to such a course.

Another external engine of change did not become apparent until the early or mid-1980s. In the late 1970s, a long delayed decision was reached to build a nuclear power station using a pressurised water reactor, a type not previously used in this country. The Metals group soon benefited since just after returning to the Department in 1979, the Central Electricity Generating Board, (C.E.G.B), and the Nuclear Installations Inspectorate, (N.I.I), asked me to join the so-called Marshall Committee then studying safety issues for the third generation of nuclear reactors proposed for the site at Sizewell. The N.I.I. set up an arrangement with the College whereby I was released half-time from normal duties to head a small task force consisting of myself, George Webster and Cyril Laming with Bob Curr as our computing guru, to advise N.I.I. on fracture aspects of the Committee's deliberations.

In the meantime, The Welding Institute had developed a so-called C.O.D. design curve aimed specifically at cracks in welded joints, small in relation to thickness. The C.E.G.B. had developed their own design method, known as R-6, aimed at cracks in pressure vessels and I offered values of J, estimated in two dimensions for small cracks, all seemingly very different in approach. Our task force was targeted at the R-6 procedure and at estimating J in relation to J toughness testing for both initiation of growth and limited amounts of slow stable crack growth. During the work for the Marshall Committee I had made a study of the R-6 and C.O.D. design curves and the J-based methodology strongly favoured in the U.S.A. Though my J-based design curve (or better J-assessment curve) was used only spasmodically by various research workers, it now enabled me to relate all three approaches. The seemingly wide differences in methodology were shown to be just an artefact of how the various parameters were presented and caused no inherent contradictions.

However by the mid 1980s, the de-nationalisation of some major industries was in full swing, often by splitting them into much smaller units unable to support the highly technical and costly research required for both safety and future technical progress of those industries. The dismantling of the Central Electricity Generating Board, (C.E.G.B.) was particularly relevant to materials research in the Department as it became clear that once the Sizewell 3 nuclear station was built, there might be no others - a situation still not resolved. The role of the style of the de-nationalisation of heavy industry, particularly the C.E.G.B. and parts of the U.K.A.E.A. now greatly reduced the metal fracture work in the department. By splitting the generation of electricity into several small companies, none had the resources (nor perhaps the wish) to continue the wide study of the effects of local plasticity and risk of fracture on in the design and operation of power plant. Indeed, there have been no major new plants calling for research studies to this day. This reflected on the un-willingness of the S.E.R.C to give support to a project, such as in fracture of metals, once it was no longer strongly called for by industry. The writing of ‘decline’ was on the wall for both the metals group and the Nuclear Power Section. The latter declined, with one member of its staff and his expertise in dispersion of particles by wind plumes, going to a new inter-departmental group on Environmental Studies and another set up a Robotics Laboratory into the so-called Contracts lab on level 1 of E3.

The one part of the metals fracture work that did not suffer from this change, and indeed gained a little, was that in creep. George Webster and colleagues concentrated strongly on crack growth by creep as the need to extend the life of existing boiler plant came very much to the fore, calling for a re-assessment of the original design and in service maintenance methods. Indeed throughout the 1990s and into the 2000s Webster and Nikbin held a number of Post-Experience courses in this work.

During this period the Polymer group had benefited from the trend in industry generally to use more plastics - for example ‘blown’ thin walled polyethylene bottles and extrusion of thick walled p.v.c. pipes for water and then gas. The accelerating trend towards study of polymers was overseen by Gordon Williams with Roger Fenner who had worked in polymer processing but was now moving strongly into computer modelling. Shortly after, Roger Fenner dropped much of his materials work and took charge of the Departmental work in CAD/CAM. The erstwhile van der Graaf lab in the basement of E2 was given over to Materials. The space was shared between the Heavy Testing lab, to house the impact machines and an appreciable amount of associated instrumentation, and by Polymer Engineering where Patrick Leevers installed a large testing rig for testing pressurised ‘plastic’ pipes. His work had progressed from the initial study of the effect of bi-axial stress, as recounted above, to modelling the behaviour in the laboratory on pipes of some 4 to 6in (c. 0 to 15cm) diameter and a few feet (a couple of metres) long. This requires the control by internal baffles of the depressurisation wave and the restriction of the ‘butterfly’ opening of the crack faces as a high speed crack propagates, Fig 35, to represent a steady state of growth that can be analysed.

All this work in polymers was soon supplemented by a move into polymer-based composites. An interdepartmental Composites Centre was set up in the Aeronautics Department in collaboration with the M.E.D polymer staff some, I think, in Chemical Engineering and in Materials Science (R.S.M.). A little later the polymer and composites work in M.E.D. spread to include adhesives, headed by Tony Kinloch. Fatigue and impact properties were of prime importance, many relevant tests being conducted in the Heavy Testing lab where a number of the servo hydraulic machines were updated and indeed new ones acquired. During this period, both stress analysis labs on level 5 of E3 were given over to the Polymer group to house a few small experiments and to provide rooms for research staff and students.

Fig. 26 'Plastic' pipe samples and test rig for Patrick Leevers' work.

DECLINE of Materials in the mid-1980s to the mid-1990s

Another change apparent from the mid-1980s was the decline of British research students. This was not just a local problem, but stemmed from a variety of causes including social and industrial change. Universities, although greatly increased in number since the 1960s and '70s, were recruiting few staff due to continued downward pressure on per capita grants. Many of the engineering industries were in decline and most of the large research facilities in which post-doctoral jobs might be found were closing down. However, the number of overseas research students grew, those still wishing to study fracture coming from Brazil, China, Holland, India, Iraq (though already domiciled in England), Nigeria, Northern Cyprus and Norway with just one from Britain in this period. Towards the end of this period the staff in the Materials group was little more than half of its size in its hey-day, and now had a very small interest in metals but a very strong expertise in polymers, adhesives and in the computational aspects of general mechanics of materials.

By the late 1980s only the one-time 3rd Year and post-graduate materials lab on level 5 remained for undergraduate work. Some of the original equipment was disposed of; the hand operated Avery torsion machine of the Waterhouse period and the 15,000lb (c. 75kN) Denison 'universal' machine found a home at the Kirkaldy Testing Museum. The electro-mechanical Instron machine hat had been acquired when the 2nd year classes were transferred to that lab, was replaced by a more modern version and at some time not now recalled the 50t (c.500KN) Denison and Avery machines and the small 1,500 lb (c. 7.5KN) Denison machine were all disposed of. One survivor was the strain gauge calibration rig of 1950 vintage together with a later model, already illustrated, Fig.21. The motorised Avery torsion machine bought in the 1960s had also been kept, it being, it was thought, the only such facility in the Guilds.

By the mid-1990s the modest floor space on level 6 originally used for micro-studies and photo-elasticity, was given up and a new floor built over the whole lab. Its use will be mentioned shortly.

On the research front most work on plasticity and metal forming had ceased. This was in part because, after about 40 years of study, the subject had reached maturity and also because as the staff interested left or retired, there were no plans for replacements in that field. Bela Lengyel continued some metal working research on hydrostatic forming until he retired a few years later. The erstwhile level 1 Plasticity lab on the Exhibition Road frontage of E3 was taken over by Dynamics. Fatigue studies in metals and the level 0 lab of E1 days came to an end for a combination of lack of funding and Sean

Crofton becoming Senior Tutor with no replacement junior staff appointed to work in fatigue. The level 0 fatigue lab is now about to have a second, quite different, life in the Materials group.

A couple of generations of work on the ductile tearing of metals was then supported by the Navy Department, with whom the long term contact from the days of the A.A.C.S.S. had never been lost. Two or three projects were undertaken on geometric effects on slow stable crack growth using the Olsen machine in the Heavy Testing Lab, two on a ship plate steel and, later, another on a titanium alloy. These revealed anomalies in the then conventional interpretation of size on so-called J-R curves of toughness versus crack growth which was not fully resolved when that type of work more or less shut down in both the U.K. and U.S.A. due to lack of funding. Some three dimensional computations of running cracks were made by Bob Curr using his modified version of the 'WHAMSE' program and, one of the few non-fracture experimental-cum-computational studies, was made in this period was on the development of stable cyclic hystersis loops from the well known Bauschinger effect, so that cyclic stress-strain curves for a material could be predicted from only one or two tests.
In the late 1980s an application of three-dimensional finite element studies of cracks in the T-joints of offshore oil or gas rigs was supported by S.E.R.C. A Norwegian student worked on that project with some collaboration from the research establishment Gas Board, at Newcastle. It lead to a better understanding of the role of small and large scale plasticity in such joints which in turn allowed the application of the R-6 design method, an application hitherto thought not possible because of its emphasis on pressure vessels. My last formal research student, Leda Braga, worked on geometric effects on slow stable crack growth in a titanium alloy of interest to the Navy Department and then joined the Sectional staff for a few years. She, and another of my late 1980 period students, went to 'the City' where familiarity with engineering concepts and computational ability were much valued.

Work in creep of metals thrived mainly, as mentioned above, on creep crack growth and problems on the extension of service life until George Webster retired in about 2003. However, Professor Nikbin continued some work with a research colleague, both computational and experimental. For the latter, British Energy supplied two machines capable of thermo-mechanical cycling (and the just mentioned colleague!) from one of their labs that was closing down. An outcome of this work will appear again later.
Early in this period, or perhaps just before it, when the post-graduate Nuclear Power work practically ceased, the use of the partly level 1 and partly semi-basement space fronting Exhibition Road, initially planned for Materials contract work and later taken over by Nuclear Power for their work on robotics, was finally handed over to the adjacent Heavy Testing facility. The instrumented impact machines were moved back from the E2 basement area to the semi- basement area in E3 and some new servo-hydraulic machines put into the extra level 1 space, leaving Pat Leever's 'plastic' pipe work in the E2 basement. Some of the early servo-hydraulic machines were updated, Fig. 27 and one or two new machines installed, used in part for tests required by industry or other external bodies. Several external calls were also made for use of the 250t (c.2,500kN) Avery machine, most of more modern machines being of smaller capacity in both load and dimensions. So the Heavy Testing Lab remained quite active under Hugh MacGillivray, with a combination of the remaining metals fracture studies, external work and many polymer, composite and adhesives studies.
The Scanning Electron Microscope installed by Shaun Crofton into part of the one-time photo-elastic lab in c.1970, was still in use.

Fig. 27 An updated Denison Mayes servo-hydraulic machine
(photo courtesy of Hugh MacGillivray)

In the early 1980s it had gradually been realised that both J, as a criterion for the onset of fracture, and the J-R-curve as a measure of resistance to stable crack growth in a ductile material, were not true material properties. This was due to variation of triaxiality of stress with configuration of test piece, a major effect well recognised in studies of plastic collapse but rather swept under the carpet in the early drive to get an understanding of elasto-plastic fracture adequate for immediate design use. By the late-1980s, just before I retired, this had lead theoreticians to propose a two parameter criterion for fracture, J with either T or Q, both measures of the degree of crack tip constraint. Such complexity greatly increased the need for lengthy computational studies, and a new member of staff, Noel O'Dowd, was appointed to computational work, including his own strong interest in modelling tri-axiality in J-related problems. However, this was the time when the main driving force for the fracture studies, nuclear power, was in decline in both the U.K and U.S.A. and in a few years' time he moved on to the University of Dublin.
On retiring in 1991, I became a Leverhulme Senior Research Fellow and worked for several years with an Austrian colleague, Otmar Kolednik, making studies on a rather novel interpretation of fracture toughness and stable crack growth. This mapped the behaviours from crack initiation to final unstable fracture, using a measure of total energy dissipation rate, D, explicitly NOT the conventional local crack face dissipation rate of G. Initiation of growth starting from a pre-existing sharp crack was followed by stable slow crack growth described by Crack Tip Opening Angle, C.T.O A., rather than the then popular J-R curve (of J versus crack growth) and finally the system-dependent energy rate, I, identical to that mentioned previously, for final ductile instability. Despite early promise to the contrary, this variation in crack tip constraint recognised in the term D for onset of growth also proved the Achilles heel of C.T.O.A. I finally stopped work on this approach and indeed all other active research work on computer modelling of slow stable crack growth with Bob Curr, in 2003 with, it must be said, no final 'Eureka!'.

Such were the many convoluted and interacting reasons for the wide decline in both undergraduate and research activities in Materials by the early 1990s, with a near demise of the studies of metals but with the Heavy Testing lab still thriving on the rump of that work, some creep of metals work and polymer testing. Polymers, Composites and Adhesives had however grow very significantly so that in about 1990 when staff in the Material Group numbered some eight or nine, only two concentrated on metals.

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AND NOW A RENAISSANCE?

During the 1990s the Department was re-organised into three Divisions. The Strength of Materials Section became the Mechanics of Materials Division, reflecting its spread over both metals and non-metals and the growing role of computing in studying the mechanics of deformation and fracture at both macro and micro scales; Dynamics, Tribology, Bio-Mechanics and one or two other groups including some work on vibration of cracked components, stress waves and ultrasonics, became the Applied Mechanics Division, whilst all the thermodynamic and fluid mechanics work became the Thermo-Fluids Division.

By about the turn of the C20th to the C21st a new pattern could be seen for the one time subject of 'Strength of Materials'. By 2007 just one undergraduate teaching lab remained, Room 581, now named Materials and Mechanics lab and without its one-time level 6 area. One of the original vibration rigs of E2 days, survives in updated form, Fig 28a. A servo-hydraulic machine of about 10t (c.100kN) capacity has recently been purchased and, in the summer of 2007, four or five bench mounted Instron machines, Fig. 28b, suggesting that any further contraction in undergraduate teaching lab space is not on the books for the moment

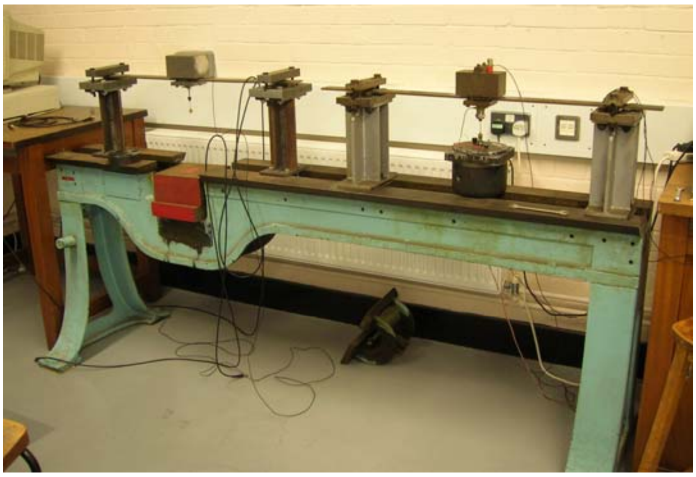

Fig. 28a

Fig. 28b

Fig. 28 Equipment now in the undergraduate Materials and Mechanics lab, Rm 581
a) A slightly up-dated vibration test rig in Rm 581, a survivor of the original lab as set up c.1962
b) One of a batch of new bench mounted Instron testing machines in lab 581
(Photos courtesy Hugh MacGillivray, 2007)

In research only the Polymer Engineering labs and the Heavy Testing Lab were still functioning quite strongly, as outlined above, with the level 5 the Polymer lab, 541, re-named Materials Testing Lab since adhesive joints have for some years been used for sheet metal components as well as polymeric composites. The lab has recently acquired two or three computer controlled Instron machines of about

10t (c.100kN) capacity for testing conventional laboratory-sized pieces of materials and adhesive joints. An example is shown Fig.29.

Fig. 29 A computer controlled Instron machine in the Materials Testing lab c. 1990

The south end of the one-time Photo-elastic lab on level5 of E3 has recently been converted to a Food Testing lab, with equipment for studying the mechanical characteristics and processing of soft solid foods and particulate composites, including paint, are now installed. This work is an offshoot of the Polymers group, and is being undertaken by a recent member of staff, Maria Charalambides.

In the more general mechanics of materials work with no specific allegiance to one class of materials, Professor Nikbin has recently suggested the setting up of an inter-departmental Structural Integrity Centre. The several departments with expertise in metals, polymer and composite components, micro and macro studies, as relevant to such industries as aerospace, automotives, chemical process and pressure vessels, electrical power and nuclear energy, can between them employ the whole gamut of tools from stress analysis, materials modelling, fracture mechanics and N.D.E. to assess structural integrity and extension to life plans.

A new experimental stress analysis technique which gives strain patterns that might at first sight be thought to be some form of photo-elasticity, is being used. It is in fact a computer based technique called Digital Image Correlation in which random points, or even small ‘splashes’ of paint, define a grid on the surface of an undeformed body which are monitored for movement whilst the body is deformed, with an accuracy that allows the determination of elastic stress patterns. Such a technique is a great advance on the use by Frank Ellis in the late 1950s of inscribed grids and optical microscope measurement by hand for plastic deformation during rolling, where even so the plastic strains derived were not of high accuracy. Fig 38 shows elastic stresses in the skin of a hollow composite wind turbine blade subjected to ‘four point’ bending. This study is being made by John Dear, in connection with the London Array of 200 wind turbines proposed for erection in the Thames estuary. It requires good computing facilities though within the capabilities of a modern work station and uses conventional lab space only for purposes of calibration. Indeed, much of the work of John Dear and colleagues on Endurance of Materials in Large Engineering Installations is based in industry, with currently six Visiting Industrialists from large well known energy and water supply firms, and although some of the students use various in house facilities, I am not aware of major new equipment bought expressly for their use.

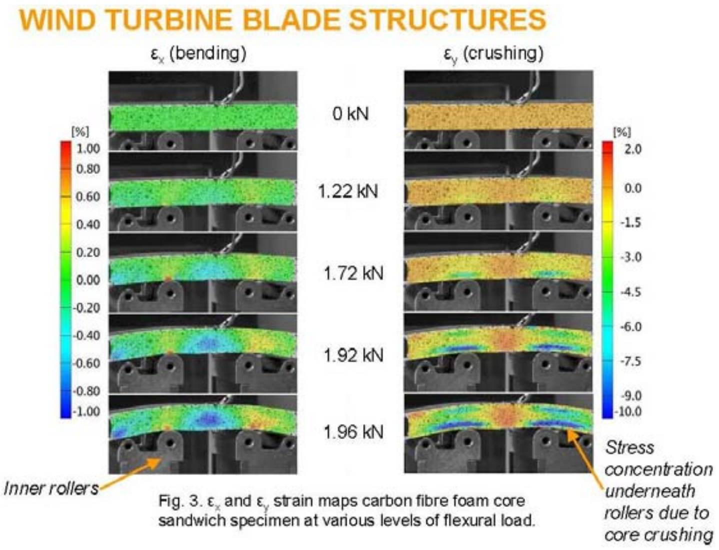

Fig. 30 Stresses in the skin of a composite blade for a wind turbine (Photo courtesy of John Dear)

Two recent appointment of new members of staff, David Balint, who has interests in micro-structural features of the fracture of metals and Ambrose Taylor, with interests in nano-composites strengthens still further the move away from metals and polymers to the Mechanics of Materials, in general.

In the 1990s and into the start of the C21st the Heavy Testing lab on level 1, now re-named the 'Fatigue and Impact Mechanics Lab' had been modernised with both a variety of servo-hydraulic machines and several rather exotic pieces of testing equipment mainly placed in the ex-nuclear power space fronting Exhibition Road. There are currently 14 servo-hydraulic machines many often used for creep, fatigue and environmental crack growth testing of polymers and adhesive joints. The first 'exotic' new machine was a two axis fatigue machine, a one-off British ESH model, Fig. 31. It was used at first for reversed bending fatigue testing of fibre-reinforced composite road springs, a long way removed form the old spring scragging machine of the Goldsmith's Lab era.! It is capable of applying torsion on the second axis, to simulate the type of loading found in members such as aircraft wing spars where the wing flexure is coupled with some twisting of the wing.

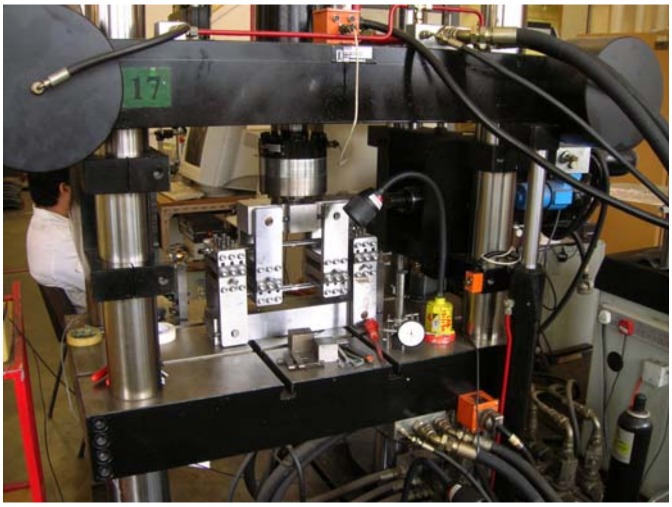

Fig.31 The ESH two axis hydraulic machine for fatigue testing (Photo by courtesy of Hugh MacGillivray)

The next to come was an Instron hydraulic impact machine capable of high strain rates, up to 25m/s, where a fairly short stroke operating system is driven by cylinders of pressurised nitrogen gas, Fig.32. I believe the high speed impact facility was used for tests on various types of material for body armour supplementing some tests made on a Hopkinson's bar rig, acquired I know not when or whence, but put back into service by Hugh MacGillivray.

Fig.32 The Instron high speed impact machine with compressed nitrogen used to pressurise the hydraulic system. (Photo by courtesy of Hugh MacGillivray)

A third machine of early C21st vintage is a strain rate controlled machine (also British made by ESH), Fig. 33 capable of a long stroke at high rates, up to 5m per second, but also able to be used at very low rates of strain. As I write, the slow speed facility is being used for experiments on cutting (machining) of certain 'plastics'. Both this and the ESH two-axis fatigue machine are being used to survey candidate materials for certain uses related to the recently proposed (though not yet agreed) new generation of nuclear reactors .Plans have already drawn up and work started to move the Fatigue and Impact Mechanics lab, as it is now called, to near the north end of level 1 of E3, to leave, with other changes, a fairly large area at the south end of level 1 between the spine and the Exhibition Road frontage to be demolished. That area will be replaced by one or more towers, almost entirely for office and computer space but with negligible, if any, laboratory space. Some of the rooms will be used by M.E.D. but some for other purposes, possibly involving a re-location of Aeronautics including the Inter-departmental Composites Centre. For this major alteration to 'E-block', the 100t Avery machine, Fig.17, will have to be disposed of. Most of the other machines will probably survive the move, including the 250t (2,500kN) Avery machine. A pit that originally held a large isolating block for an engine test cell when E3 was built, has now been altered so that the space can house the base of the 250t machine and new pumps for an enlarged ring main to serve all the servo-hydraulic machines.

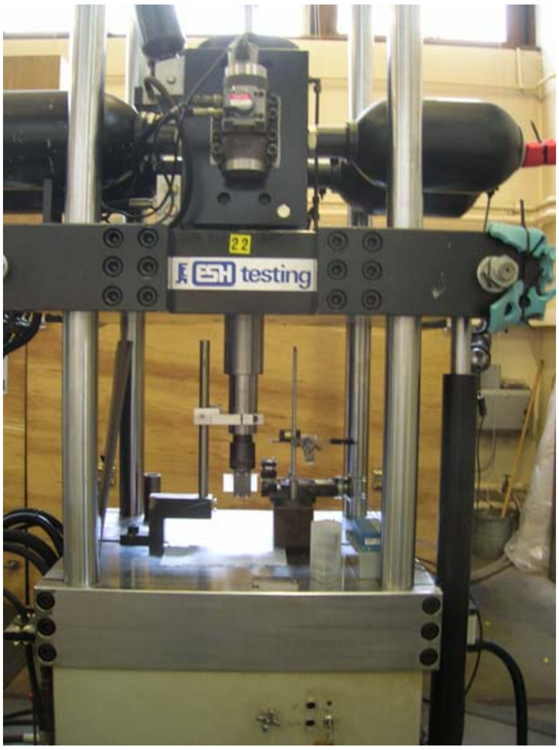

Fig.33 The high rate ESH impact machine.
(Photo by courtsey og Hugh MacGillivray)

This has involved cutting through a concrete foundation column, a piece of which is shown, Fig 40a, sitting on the floor by the 250t (c.22.5MN) Avery machine in the Fatigue and Impact Mechanics lab, waiting to be tested for its compressive strength. Many of the servo-hydraulic machines, including the early Dowty fatigue machine, re-furbished, and some new ones not yet obtained, will be housed on level 1 across the main corridor from the areas just mentioned, towards the back of the building, Fig 35b.

Pat Leevers 'plastic' pipes will be installed in the original fatigue lab in the level 0 basement of E1, just below the northern end of these building works, with 'serious' structural work for a new access route to allow any equipment for the basement to be lowered into place from level 1.

Fig. 34 Part of a reinforced concrete column cut from the E3 foundations, to be tested for its strength

The work mentioned earlier on vibration of cracked components and ultrasonics, started in about the 1980s by Peter Cawley (now Professor) grew rapidly to become the Non-Destructive Testing Group, now led by him within the Applied Mechanics Division. In the last three or four years this Group has become the lead body in a consortium of university interests forming the Research Centre for Non-Destructive Examination, sponsored by the Engineering & Physical Sciences Research Council. Two of its activities are ultrasonic testing of moving components, such as railway wheels, by use of a rubber wheel to ‘couple’ the ultrasonic waves to the component and guided waves that propagate along such as a rail, to give better detection of short transverse cracks. This work has an N.D.T. laboratory on the level 6 floor that was infilled above the original 3rd year Materials lab on level 5 of E2. Though clearly not in the Mechanics of Materials Division, the outcome of its work has a strong bearing on the safe life of many components and is thus surely in the spirit of the original ‘Strength of Materials’ activities of Unwin, Dalby and the many others since.

Fig 35a)

a) Another E3 lab, on the opposite side of the corridor, to be used for the majority of the servo-hydraulic machines, old and new.

Fig. 35b)

b) Peering into rather murky depths! A new staircase is being made from the new level 1 Fatigue and Impact lab, down to the old Fatigue lab, level 0, in which Pat Leevers pipe test rigs, updated from Fig. 26, will be re-housed.

Fig. 35 Extensive structural work on level 1 of E3, in preparation for moving the Fatigue and Impact lab in 2008. (Photos courtesy of Hugh MacGillivray)

In October 2007 Tony Kinloch became Head of Department, the fourth with a Materials background of the six since Sir Owen Saunders time in the 1940s to 1960s. I am told it has been agreed that a replacement professorial post will be established for Materials. Coupled with the changes just outlined, there seems good evidence that, far from contraction to vanishing point, Materials will be reinvigorated albeit with rather minimal undergraduate materials testing facilities but with extensive and modern facilities for both computer modelling and testing a variety of metal and non-metal materials under realistic types of loading, such as fatigue, impact, creep, thermal cycling and so on, for both in-house research and external projects.

All this investment is surely a sign of a significant revival in Materials testing in E-block for M.E.D. though whether that will last another fifty years remains to be seen.