

# Low Budget Fracture Mechanics Laboratory\*

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*Experiments are described that can be used to demonstrate various aspects of linear elastic fracture mechanics. These have been designed to run with minimal capital investment, specimen preparation and recurrent costs. Some of the experiments can be extended for use as topics for student projects.*

## AUTHOR QUESTIONNAIRE

1. This paper describes new training tools or laboratory experiments in fracture mechanics.
2. This is a senior course in materials offered by the University of Zambia: MM422 Physical Metallurgy II.
3. The course involves fourth-year students in a five-year undergraduate degree programme.
4. Methods for enhancing the teaching of fracture mechanics under conditions of restricted capital investment and running costs for laboratory work are a feature of this paper.
5. The material, as laboratory practicals, supplement the lectures on topics dealing with fracture mechanics such as stress intensity factor determination.
6. Several research publications and texts, such as *Fracture Mechanics* by J. Knott and P. Withey, are recommended supporting documentation.
7. The concepts have been fully tested and the students now appreciate the importance of using materials at conditions that do not promote fracture.
8. The paper shows that the basic concepts of fracture mechanics can be demonstrated by using simple equipment.

## INTRODUCTION

A SIGNIFICANT change in engineering design in the last forty years is the growing awareness of defect tolerance in structures as opposed to incorporating large factors of safety in design calculations. All metallic components will contain some defects and many will contain actual cracks. This does not necessarily prevent their use but it is desirable to know what size of defect can be tolerated in a structure and what the expected life

of a defect-containing structure will be. Additionally, cracks may form during the life of a structure. The most likely reasons for this are fatigue, corrosion fatigue and stress corrosion cracking. These problems, and those associated with life-extension arguments and/or the setting of inspection schedules, can be solved with the aid of linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM). Appropriate procedures have been developed but the test methods involved tend to be expensive to perform. The aim of this paper is to illustrate that the essentials of LEFM and EPFM can be demonstrated using simple, inexpensive experiments and equipment. The particular experiments described below were devised for a fourth-year laboratory class in the School of Mines, University of Zambia (UNZA), Lusaka using a Hounsfield tensometer and various rigs manufactured at UNZA. The specimens were in most cases of simple design to minimize workshop time and material procurement.

## BACKGROUND EDUCATIONAL CONSIDERATIONS

University engineering education in Zambia commenced in the late 1960s when the University of Zambia (UNZA) was established. Initially, the faculty of engineering housed Mechanical, Electrical and Civil Engineering Departments. Courses in metallurgy were introduced in 1973 and agricultural engineering and surveying in the 1980s. The initial metallurgy course at UNZA was biased towards extractive metallurgy with little coverage of physical metallurgy and materials science. Fracture mechanics and corrosion were not covered at all in any of the programmes. Materials science has been taught only as a small component of mechanical engineering and metallurgy courses.

Developments in Zambia connected with the changes in dominance of copper mining as the

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major industrial activity have generated a need for Zambian graduates with a more extensive training in materials science than was formerly the case. To satisfy this need, about eight years ago the Department of Metallurgy and Mineral Processing at UNZA began revising its undergraduate syllabuses to include courses in materials science. The teaching of fracture mechanics and of corrosion can benefit enormously by the introduction of suitable laboratory classes. Fracture mechanics is based on empirical rules, albeit supported by extensive mathematical analysis, and the involvement in laboratory experiments helps students to understand the empirical nature of the subject. Similarly, the effects of corrosion are vividly demonstrated in suitably designed laboratory experiments.

Unfortunately, running laboratory classes can be an expensive exercise and the capital and recurrent funds available in the School of Mines at UNZA are very limited. The aim of the present paper is to describe how quite sophisticated concepts can be demonstrated with experiments based on low budget capital investment and low running costs in the form of specimen manufacture, chemicals, etc.

The experiments described below are currently being performed by fourth-year students at UNZA taking the course MM422 Physical Metallurgy II. Prior to taking this course, students would have spent their first year in the School of Natural Sciences and the second and third years as metallurgy students. At third-year level, the students take their first course in physical metallurgy (MM321 Physical Metallurgy I). The laboratory experiments outlined in this manuscript complement the material covered in the lectures. The experiments are run by the students themselves with a little supervision from technical or lecturer staff, but well documented instruction sheets for each experiment are provided. Some supervision is essential because all laboratory experiments are potentially dangerous and adequate supervision is necessary to minimise any risk of injury and have someone present to deal with accidents if they occur. Nevertheless, the students are encouraged to do most of the work themselves and small groups, of not more than four students, co-operate in the performance of each practical exercise. Students benefit from performing the experiments because they are able to see, under laboratory conditions and within short time scales, phenomena such as creep and stress corrosion cracking which in real life are slow processes occurring over periods of years rather than days and which are often undetectable prior to final failure of a component.

However, a more important aspect of having laboratory experiments to complement the lectures on fracture mechanics is that students often find the concepts very difficult to absorb from lectures alone. For instance, Experiment 1 aims to factually demonstrate to students that a piece of material

containing a crack is more compliant than a similar shaped piece of material without a crack and that when both are stressed to the same stress level it is the cracked specimen that has the greater stored elastic strain energy. Additionally, the crack tip driving force can only be calculated theoretically for infinite or semi-infinite solids, but real components in structures are of finite dimensions. The corrections needed to allow the calculation of  $K$  in these are empirical and the student is taken through a procedure that will work for any specimen shape he desires to test. The calculations used to evaluate  $K$  are based on the concept of a totally elastic solid whereas metals plastically deform at relatively low loads. The high stress concentration at the tip of a crack causes localised plastic deformation to occur at the crack tip so the crack cannot maintain the very sharp tip geometry that would exist for a fully brittle solid. Nevertheless, the concept of a crack tip driving force,  $K$ , can still be applied and the form of the equations are similar to those derived for a totally elastic solid. Experiments 2 and 3 demonstrate that fracture mechanics equations still work in principle for relatively blunt cracks (i.e. cut with scissors) and the plastic zone at a crack tip can be seen to grow and can be measured as the load on the specimen increases. Experiment 4 again reveals visually to the student the development of a crack tip opening displacement and shows in principle how a measurement of this quantity can be used to predict the failure stress for cracked components that undergo large amounts of plastic deformation prior to fracture. Experiment 5 brings together fracture mechanics and stress corrosion cracking. The particular system used generates stress corrosion cracks that occur with a short initiation time at that grow at a rapid rate, so several experiments under different test conditions can be performed in the period of a normal laboratory class session. The experiment also demonstrates the importance of the plastic zone at the crack tip that was demonstrated in Experiment 3 and the need for active plastic deformation at the crack tip to generate stress corrosion cracking. In essence this means that localised creep is needed at the crack tip to make the pre-crack in the specimen start to grow. Experiment 6 demonstrates creep at an easily measured rate and shows that a loaded specimen initially creeps at a very fast rate but that with time the creep rate decays to very low rates of extension. Experiment 7 provides a link between the mathematics for stress concentrations for holes, notches and cracks.

## THEORETICAL CONSIDERATIONS

The elements of LEFM follow from Griffith's theory of fracture [1, 2]. Under constant stress loading, Griffith argued that, to cause unstable fracture, the external work done had to be equal or greater than the sum of the extra strain energy

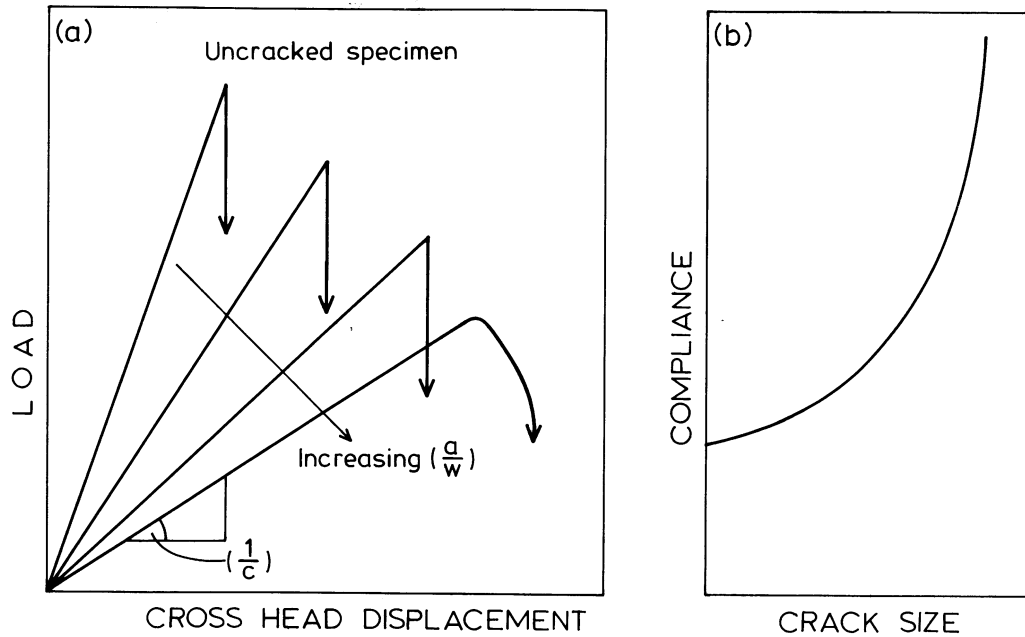


Fig. 1. Compliance curves for cracked specimens.

stored due to an extension of crack length 'da' and the work needed to generate the new surfaces, i.e.  $4\gamma da$ . The intrinsic surface energy used by Griffith was modified later by Orowan [3] and by Irwin [4] to include the total work done in creating the new surface. This effective surface energy,  $\gamma'$ , is a material property only if certain dimensional constraints are applied to the specimens used to measure it. LEFM and EPFM have evolved experimentally and provide guidelines for the effective assessment of the strengths of defect-containing components. These subjects are still evolving, as illustrated by the modifications that have been incorporated into the R6 fracture assessment procedure [5, 6].

Griffith's equation states that the fracture stress,  $\sigma_f$ , for a thin plate containing a '2a' long through crack is given by:

$$\sigma_f = \left( \frac{2E\gamma}{\pi a} \right)^{1/2}$$

where  $E$  is Young's Modulus and  $\gamma$  is the solid surface energy. This can be rearranged as:

$$\pi^{1/2} \sigma_f a^{1/2} = (2E\gamma)^{1/2}$$

The first step towards LEFM is to show that  $K = \pi^{1/2} \sigma_f a^{1/2} = (EG)^{1/2}$ , where  $G$  is the strain energy release rate. Subsequently, it is necessary to show that  $K$  is dependent upon the ratio defect length/specimen width, ( $a/W$ ), and the crack shape. These two correction factors arise from the calculation of the elastic stresses at crack tips in finite dimension specimens or structures. The  $K$  for unstable crack growth,  $K_Q$ , varies with material thickness. This is because yield in a ductile material occurs at a lower applied load under uniaxial stress than under

biaxial or triaxial tensile stresses. Localized deformation at the crack tip accompanies fracture in non-brittle materials and is the major component of the work of fracture. The larger plastic zone that forms under biaxial tension compared to triaxial tension increases the toughness of thin section material providing that the material thickness is not less than the crack tip plastic zone diameter.

The following experiments were used to demonstrate various aspects of fracture mechanics.

#### Experiment 1: Compliance and work of fracture

This experiment is to illustrate how the  $K$  for a finite sized cracked specimen can be evaluated. The students were provided with some specimens suitable for testing using the three-point bend jig for the Hounsfield tensometer. After measuring the width,  $W$ , and thickness,  $B$ , of the specimens a bend test was performed on an un-notched specimen. Perspex (PMMA) was used at UNZA but other materials could be used. Saw cuts were then made in other specimens to generate crack-like defects of various lengths. The  $a/W$  for each specimen was measured and the load versus displacement curve obtained up to the point of fracture. The experiments should generate a set of load versus displacement curves as shown in Fig. 1(a).

The slopes of the curves are measures of specimen compliance. The Hounsfield tensometer is a soft test frame and the slopes of the graphs contain a large contribution from the elasticity of the machine. This is unimportant with respect to the compliance calibration but may prevent the observance of stable crack growth with long crack lengths, which is best seen if the machine stiffness is large compared to that of the specimen. The curves yield compliance values,  $C$ , in units of  $m/N$ , for each crack length. Tangents to the curves

of  $C$  versus ' $a$ ' at various ' $a$ ' values, Fig. 1(b), give  $dC/da$  values and the  $K$  calibration can be obtained as follows. Let:

- $U_t$  = total elastic strain energy in the system.
- $U_m$  = stored strain energy in the machine.
- $U_s$  = stored strain energy for an un-cracked specimen.
- $U_c$  = extra strain energy due to presence of crack.

i.e.  $U_t = U_m + U_s + U_c$

$$\frac{dU_t}{da} = \frac{dU_c}{da} \tag{1}$$

Griffith showed that  $(dU_t/da)\Delta a$  is numerically equal to  $2\gamma'B\Delta a$ , where  $\gamma'$  = effective surface energy and  $B$  is specimen thickness. Also,  $U_t = Px/2$ , where  $P$  = load and  $x$  = cross head displacement. But  $C = x/P$ ; therefore  $U_t = CP^2/2$  and:

$$\begin{aligned} (dU_t/da)\Delta a &= (dU_c/da)\Delta a \\ &= (P^2/2)(dC/da)\Delta a = 2\gamma'B\Delta a. \end{aligned}$$

Also,  $K^2 = EG = 2E\gamma'$ . Therefore:

$$(P^2/2)(dC/da)\Delta a = K^2B\Delta a/E$$

i.e.  $K = \sqrt{((EP^2/2B)(dC/da))}$

Thus, substitution of a ' $P$ ' and an ' $a$ ' value will allow the calculation of  $K$  for the appropriate  $dC/da$ , which is a specific  $K$  for this specimen geometry.  $E$  for perspex is about 4.38 GPa.

However, the  $K$  for a three-point bend specimen with  $a/W$  close to zero is given by  $K_o = 6M\sqrt{(\pi a)}/(BW^2)$ , where  $M$  is the bending moment. Thus, for

any chosen  $a$ , or  $a/W$ , the ratio  $K/K_o$  can be evaluated and a graph of this ratio against  $a/W$  is called the  $K$  calibration for the specimen geometry under consideration.

It will be found that even very crude measurements on specimens with saw cut grooves yield a  $K$  calibration that is in reasonable agreement with data obtained by more exact procedures. Also, the students can use their measured fracture strengths and conventional LEFM equations to obtain  $K_c$  values that agree reasonable well with those calculated using  $dC/da$  and the Young's modulus for the material under test.

If the testing machine is hard enough to give stable crack growth when the crack lengths are long, the area under the load displacement curve can be used to estimate the **work of fracture**. The area under the graph that relates to the work of fracture, in appropriate units, divided by the area of new surface,  $2B(W-a)$ , gives an alternative estimate of  $\gamma'$ , and  $2E\gamma' = EG = K^2$ .

It is experimentally easier to use a simple cantilever beam, as an **alternative test procedure**, to load the pre-cracked specimens, as illustrated in Fig. 2. Although the displacements measured at the end of the lever contain large contributions from the elasticity of the test arrangement this is unimportant with respect to performing the  $K$  calibration, as was shown in equation (1).

*Experiment 2: Fracture in plane stress*

In linear elastic fracture mechanics the term 'plane stress' is used to indicate that deformation occurs easily through the thickness of the specimen. Plane stress fracture occurs in thin plate and is normally by shear at 45° to the applied tensile

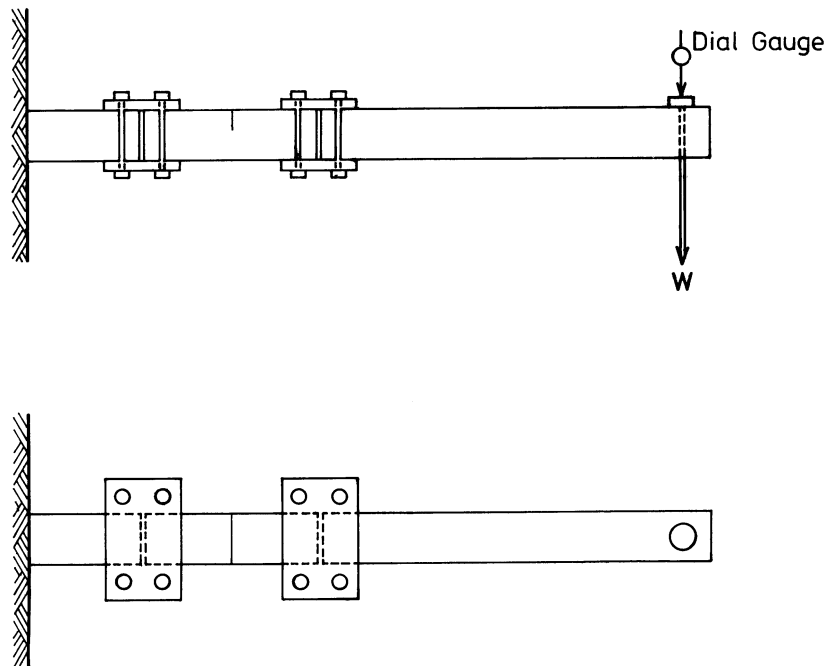


Fig. 2. Cantilever bend jig for compliance experiment.

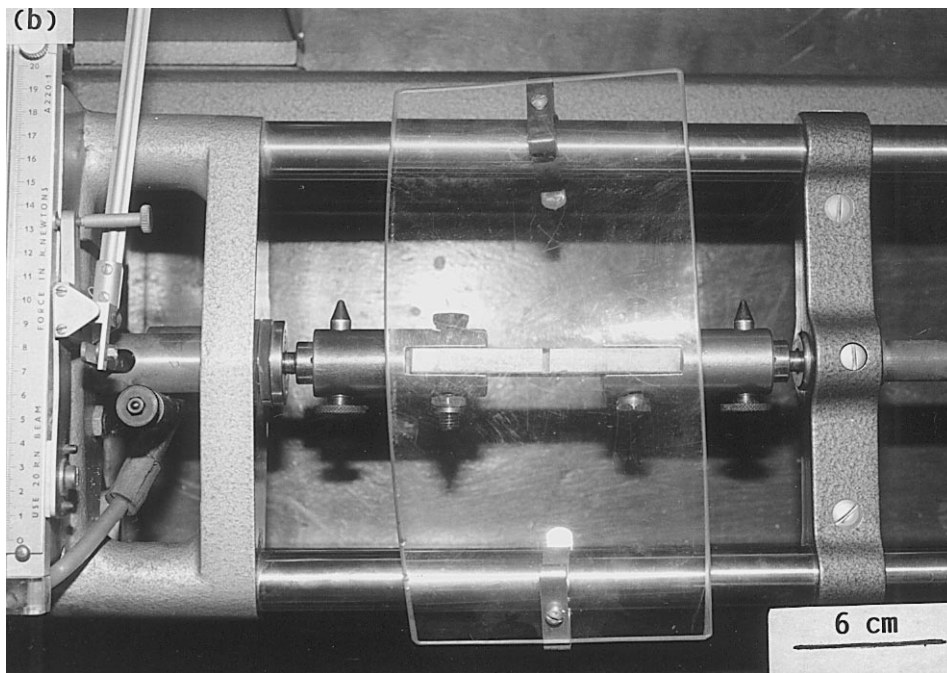
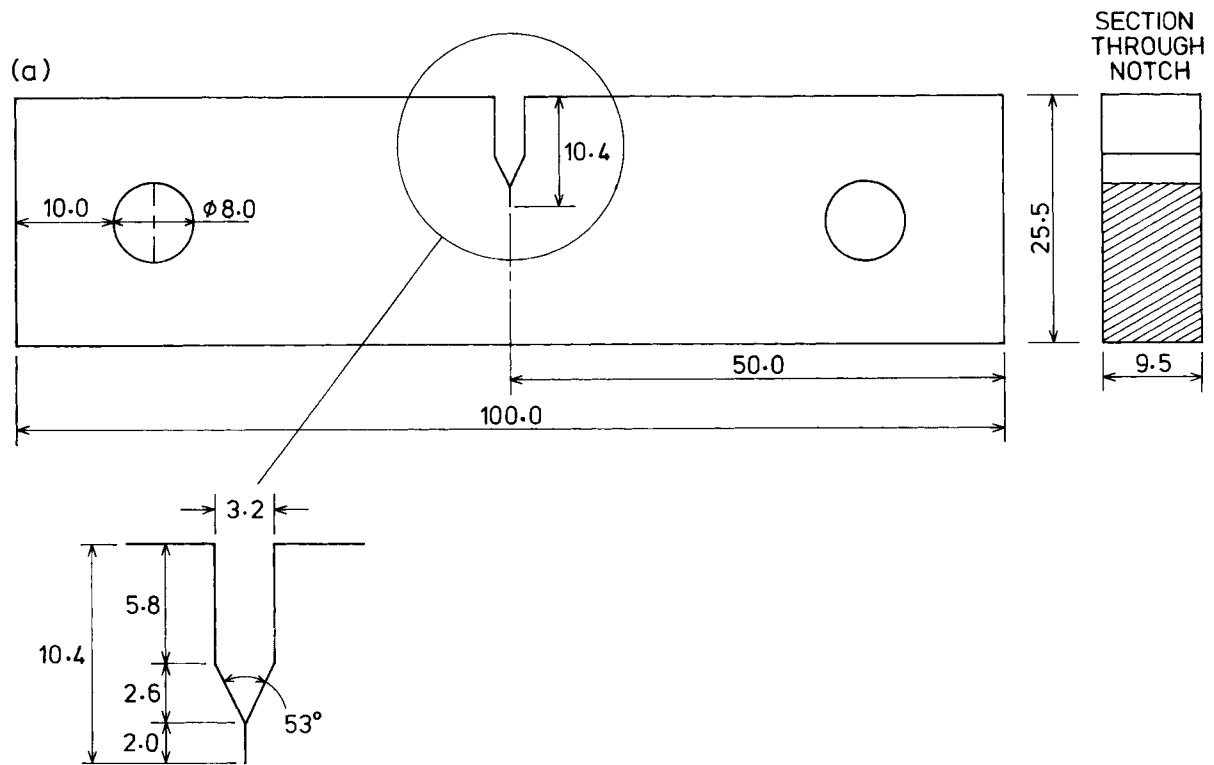


Fig. 3. (a) Notched tensile specimen of Al-7%Mg alloy; (b) Specimen mounted in Hounsfield tensometer.

stress. Under plane stress conditions the toughness increases with increasing thickness, but only to a maximum value that corresponds to the plastic zone size being similar in dimensions to the plate thickness. With thicker plate than this, the toughness decreases again until it achieves the  $K_{Ic}$  level. Despite the shear fracture that occurs in thin plates, cold worked steel sheet can be used to demonstrate the linear relationship between the

fracture strength and the reciprocal of the square root of the crack length multiplied by the compliance correction illustrated in Experiment 1.

Samples of cold worked steel shim, width,  $W$ , and thickness,  $B$ , were used that could be cut with a pair of scissors near mid-length to generate a crack of length ' $a$ '. It is preferable to ensure that all  $a/W$  values lie within the range  $0.2 < a/W < 0.6$ . Fracture strengths for various specimens were

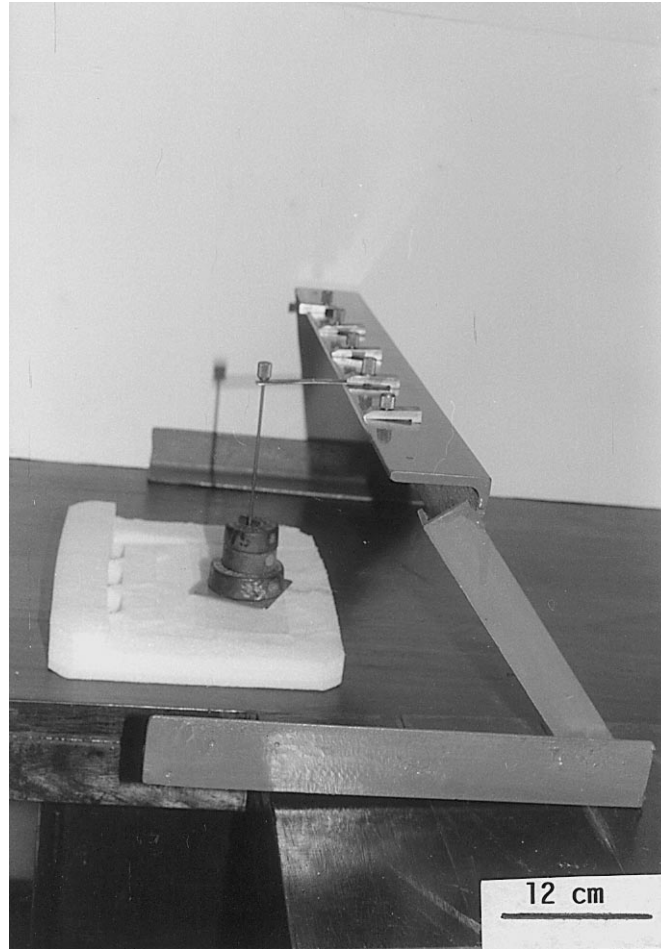


Fig. 4. Bend fixture for SCC tests.

measured and the  $K_c$  values calculated using the relevant fracture mechanics equation. For a single-edge-notched specimen,  $K$  can be calculated using the equation:

$$K_c = 5\sigma(\pi a)^{1/2} / (20 - 13(a/W) - 7(a/W)^2)^{1/2}$$

for a specimen with a large length-to-width ratio and assuming no specimen rotation, i.e. for a plate specimen loaded using serrated jaw grips [7].

#### *Experiment 3: Plastic zone at a crack tip under plane stress loading*

Annealed shim steel specimens cut with scissors to give a slit of length such that  $a/W \sim 0.5$  can be loaded to various levels to demonstrate the development of the plastic zone at the tip of the slit. The length of the plastic zone as a function of applied load can be shown to fit the theoretical estimate [8]:

$$r_y = \frac{\pi K^2}{16 \sigma_{yield}}$$

reasonably well. A value for  $\sigma_{yield}$  is required. The  $K$  can be calculated using the appropriate equation for the specimen geometry and loading arrangement [7].

#### *Experiment 4: Crack opening displacement*

It is impossible to measure a plain strain fracture toughness,  $K_{Ic}$ , for thin section materials of low yield strength and high toughness because the specimen thickness required for plain strain fracture is  $B > 2.5(K/\sigma_{yield})^2$ . Nevertheless, thin plates of tough materials can exhibit unstable crack growth so the toughness of such materials must be found. One possible approach is to assume that fracture occurs on the achievement of a critical strain at the crack tip. The plastic strain at a crack tip can be characterized by the crack tip opening displacement (CTOD). There are various ways for measuring this but the following experiment illustrates the principle in the very simple way that was used in the early days of LEFM experimentation [9].

If a thin sheet specimen of a tough metal, e.g. annealed aluminium, having two saw cut slits spaced about 20 mm apart and of equal depth is loaded in a tensile testing machine until fracture is just initiated at one of the slits, the necessary measurements can be made. A jig will be needed to cut the two equal length slits. From the load at which fracture just starts to propagate from the tip of one of the slits and the crack opening displacement measured at the other slit after the specimen is unloaded and removed from the tensile testing

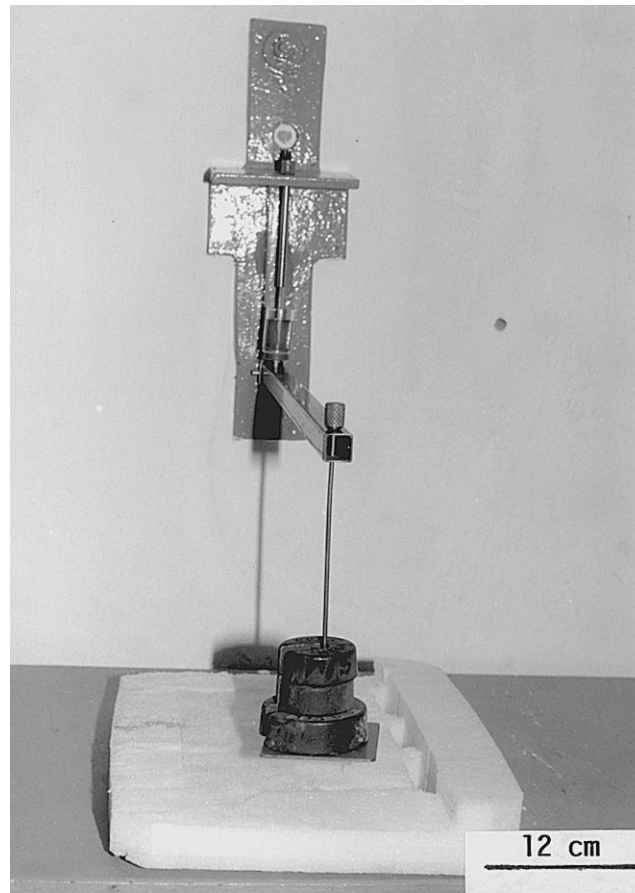


Fig. 5. Tensile fixture for SCC tests.

machine, it is possible to estimate the toughness. The work done at the crack tip to cause fracture is the product  $\sigma_{yield}\delta_i$ , where  $\sigma_{yield}$  is the yield strength of the material and  $\delta_i$  is the crack opening displacement for crack initiation. The strain energy release rate  $G$  can be equated to  $\sigma_{yield}\delta_i$  and  $G = K^2/E$ . More generally, it is assumed that  $G = m\sigma_{yield}\delta_i$  where  $m$  is an empirical constant that lies in the range 0.5 to 1.0<sup>6</sup>. The value of  $G$  obtained can be used to calculate a  $K_c$ , using the relationship  $K_c^2 = EG$ , that can be compared with the  $K$  calculated at the onset of fracture from the measured fracture load  $P$ , the crack length and the appropriate adjustment for finite specimen size. The experiment can be repeated with specimens of different thickness, for slits of different length and for cold worked material.

#### *Experiment 5: Stress corrosion of Al-7%Mg alloy*

Mg-7%Al alloy suffers stress corrosion cracking in potassium chromate/sodium chloride solutions. The cracking is quite severe and occurs rapidly in 20 g/L potassium chromate/20 g/L sodium chloride solution. The heat treatment is important and is best performed immediately before the experiments or only a few days before if some delay is inevitable between heat treatment and testing. The type of cracking depends upon the heat treatment of the alloy. One hour at 350°C followed by

furnace cooling causes mixed transgranular and intergranular cracking. One hour at 350°C with water quenching generates transgranular cracking whereas 1 h at 350°C + WQ + 24 h at 100°C generates intergranular cracking.

An LEFM-based stress corrosion experiment can be performed in a short time using notched tensile specimens as illustrated in Fig. 3(a). It is important that the tip of the notch is re-sharpened with a jeweler's saw blade after the heat treatment and that the specimen is degreased immediately before testing. A small retaining cell can be made around the notch region with adhesive tape. The specimen is then gripped in a Hounsfield tensometer and a few drops of the chromate/chloride solution introduced to the notch. N. B. It is wise to have a safety guard in place to protect eyes from splashes if the specimen breaks, Fig. 3(b). The specimen is loaded quickly to a maximum of 9 kN for the specimen size shown in Fig. 3(a). When cracking commences the specimen compliance increases and the load decreases. The latter can be allowed to reduce by about 10% of its original value, taking measurements of load versus time, then the specimen can be quickly unloaded and removed from the test machine. After washing away the test solution and breaking open the specimen by gripping it in a vice and hitting it with a hammer in a direction away from

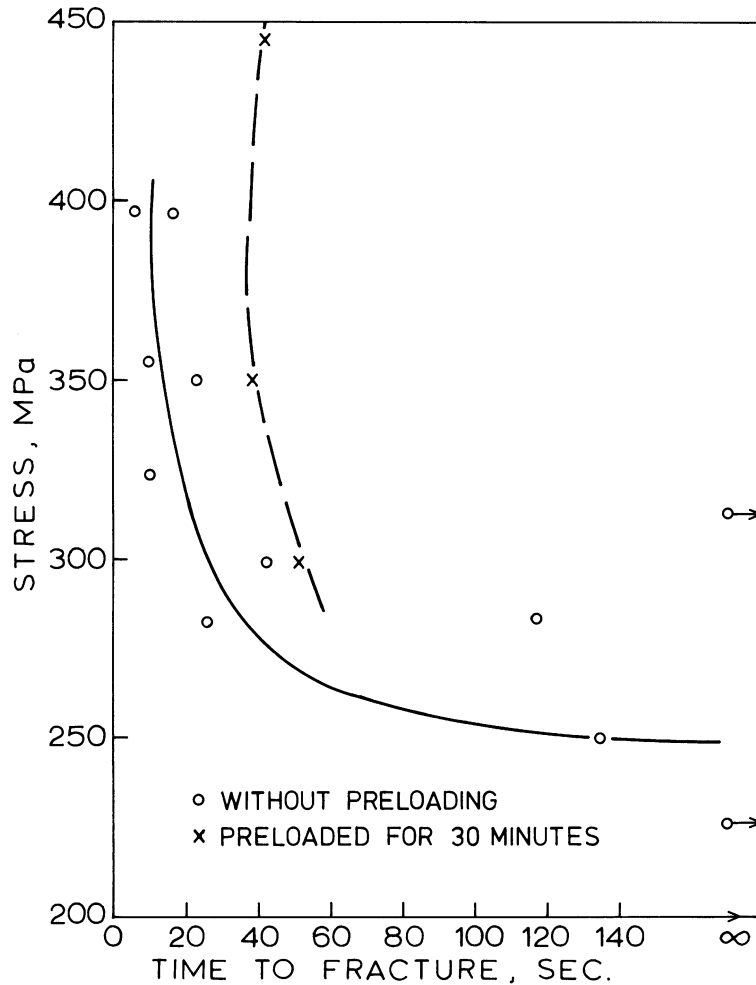


Fig. 6. Tensile test data for Mg-7%Al alloy in chromate/chloride solution.

the notch and away from oneself, the extent of stress corrosion cracking will be obvious on the fracture surface. Alternatively, load versus time measurements can be continued until the specimen fractures.

The  $K$  for this type of specimen can be calculated using the equation [10]:

$$K = P\sqrt{a}/BW\sqrt{(7.59 - 32.0(a/W) + 117.0(a/W)^2)} \quad (2)$$

or from the appropriate graphs in Rooke and Cartwright [11].

An average  $K$  for the test can be calculated from the initial and final  $K$  and an average crack growth from the amount of growth divided by the time from initiation to unloading or to fracture. If the loading system is hard enough, a reasonable estimate of crack length can also be made from the load reading alone via an appropriate use of the dimensionless compliance of the specimen.

A series of experiments using different starting loads for each specimen will generate data on average crack growth rate versus average  $K$ , initiation time

as a function of applied stress and a  $K_{Ic}$  if the specimen is allowed to break under load.

The main disadvantage of the above experiment is that the specimens are relatively costly to manufacture and a horizontal loading frame is required. An alternative solution cell could be devised for a vertical test frame. However, it is possible to demonstrate the principles of stress corrosion cracking with much simpler equipment, for instance simple bend (Fig. 4) or tensile (Fig. 5) fixtures. The equipment required is easily constructed and the specimens relatively inexpensive to manufacture. A suitable experiment is to investigate time to failure as a function of applied load. It is possible to compare the stress systems for tensile loading and for the notched bend arrangement and the fracture surfaces can be examined to assess the mode of cracking.

Figure 6 illustrates some typical tensile data for the Al-7%Mg alloy in chromate/chloride solution. Failure occurs within about ten minutes, or not at all, depending on the applied stress. It has already been indicated that the solution should be applied to the corrosion cell, or to the notch in the bend tests, prior to applying the load. This is important.



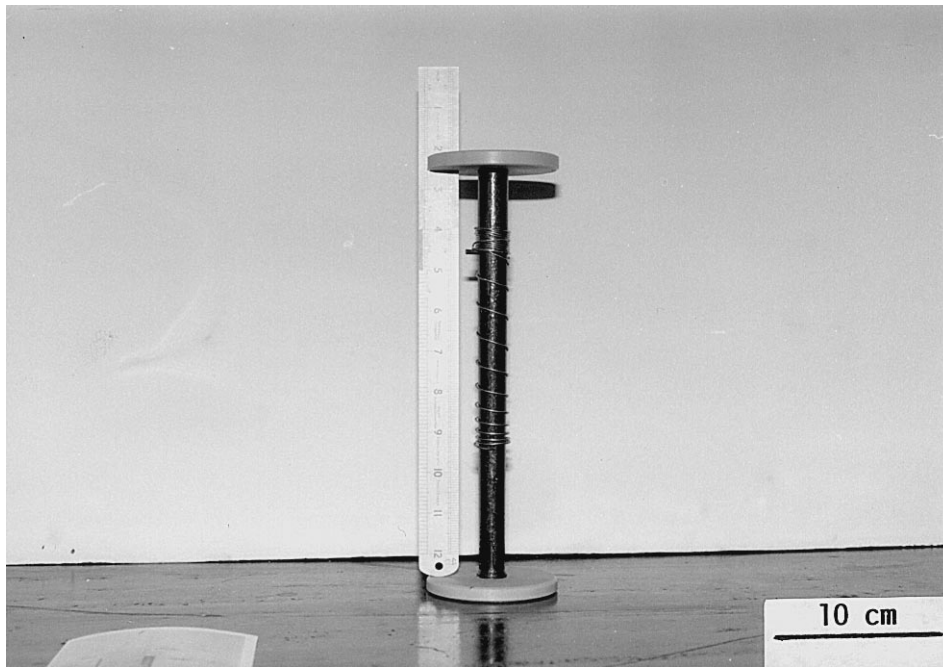


Fig. 7. Jig for creep of lead-tin solder.

If a load that will generate cracking in the absence of solution is applied and maintained for about 30 minutes, *prior* to application of the solution, a significant increase in the time to fracture should be seen relative to that obtained when the solution was present at application of the load. This is because stress corrosion results from the combined effects of plastic deformation at the crack tip and the presence of an appropriate environment. Preloading the specimen causes significant creep exhaustion at the crack tip prior to the introduction of the solution and the initiation time for stress corrosion cracking is increased.

#### *Experiment 6: Creep of a lead-tin alloy*

Macroscopic creep of metals occurs at temperatures = half the absolute melting point although micro-creep can occur at lower temperatures and can influence stress corrosion cracking as described above. A simple experiment to illustrate creep deformation of a lead-tin solder can be performed using the jig shown in Fig. 7. In the experiment used at UNZA, three coils of different lengths were positioned on the jig.

The topmost section of the lower (longest) coil was supported on the peg and a series of measurements of the segment positions were made over a period of about 20 minutes. A vertical line down the coils was drawn at the start of the experiment to mark their positions and this allowed the rotation of the coils to be measured in addition to their vertical displacements. After a suitable amount of creep had occurred, the experiment was repeated with the other, shorter, coils.

The uppermost sections of the coils extend more than the lower sections because the self weight below them is greater. It is possible to analyze

the coil position versus time data to deduce the dependence on stress of the creep rate. In its simplest form, the displacement of each coil with time generates a set of creep curves for which the applied load can be equated to the number of coils below the one that is being measured. A rigorous mathematical analysis of the creep in the spiral is more complex and will test the student's analytical ability.

#### *Experiment 7: Stress concentration at a notch*

In addition to the experiments on LEFM it is convenient to include a laboratory experiment to illustrate the stress concentration caused by notches and to demonstrate the differences involved in dealing with notches as opposed to cracks. The essential difference is that  $K$  values are calculated using the nominal applied stress, so  $K$  increases continuously as the crack length increases, whereas stress concentration factors often relate to the net section stress so the  $K_t$  values increase then decrease as the notch depth increases in a finite width specimen. The work of Inglis [12] showed that for an elliptical hole in a thin plate, the concentrated stress at the tip of the hole is given by:

$$\sigma_{\max} = \sigma_{\text{applied}} \left( 1 + 2\sqrt{\frac{a}{\rho}} \right)$$

where  $a$  = semi-major axis of the ellipse and  $\rho$  = root radius of the ellipse.

For a notch of depth  $a$  and root radius  $\rho$ , the maximum stress can be quite large if the material behaves elastically. Notched specimens made from a brittle material such as perspex can be tested and their measured fracture strengths compared with

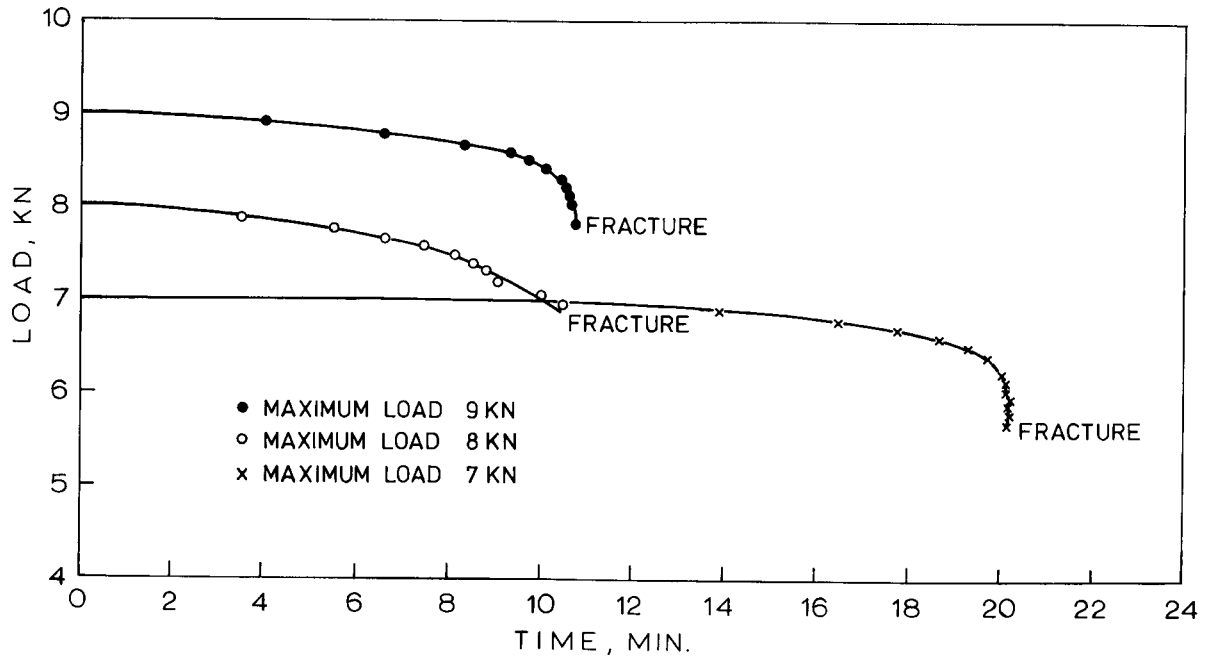


Fig. 8. Load versus time data for Mg-7%Al alloy in chromate/chloride solution.

those predicted by the Inglis equation and from other texts such as that due to Peterson [13]. The Inglis equation is based on the nominal applied stress whereas the Peterson  $K_t$  values are used with the net section stress.

**DISCUSSION**

The aim of the experiments was to illustrate various aspects of fracture mechanics using simple, inexpensive experiments requiring minimal equipment and involving little recurrent costs. This has been achieved and the experiments are capable of being developed to give a deeper understanding if required. An example of this is the stress corrosion test on tensile specimens of Mg-7%Al in a chromate-chloride solution for which a set of data are given in Fig. 8.

The reason for the load drop is the increase in specimen compliance with increasing crack length. If the machine was completely hard then the specimen displacement would be constant throughout the test and the crack length could be calculated from the known compliance of the specimen for any crack length. The  $K$  calibration equation for

this specimen is given in equation (2) and the student can obtain the compliance calibration curve by integrating the  $K$  calibration equation. The constant of integration is simply the compliance of an uncracked specimen, which can be calculated from the dimensions of the specimen and the Young's modulus of the material. The resulting curve is shown in Fig. 9. For any given load the new compliance of the specimen can be calculated by dividing the specimen displacement, assumed constant, by the load. The corresponding crack length can be read from the compliance curve for the specimen. As a Hounsfield tensometer is a soft machine, this calculation will generate a much smaller crack length than actually exists in the specimen because the machine imposes further displacements to the specimen as the latter cracks. It is possible to make the necessary corrections for machine stiffness and it is a useful exercise for the student to do this. Those data shown in Fig. 8 were obtained using a Hounsfield tensometer with 10 kN beam. The specimen compliance for a notch depth of 9.54 mm was  $9.1 \cdot 10^{-9}$  m/N and the machine compliance was  $5.9 \cdot 10^{-8}$  m/N. The additional specimen displacement that must be added for any specific load is the product of the load drop and the machine compliance. The new specimen compliance is the total displacement of the specimen divided by the applied load. Calculating this allows the instantaneous crack length to be evaluated. Clearly, once the crack length and load are known the instantaneous  $K$  can be calculated and crack growth rate versus  $K$  data can be generated with a reasonable degree of accuracy. Allowing for the machine compliance for the three sets of test data shown in Fig. 8

Table 1. Measured and calculated crack length data for the Mg-7%Al alloy tested in chromate/chloride solution.

Initial load kN	Measured final crack length	Calculated final crack length
9.0	15.11 mm	15.11 mm
8.0	15.14 mm	15.00 mm
7.0	16.125 mm	16.20 mm

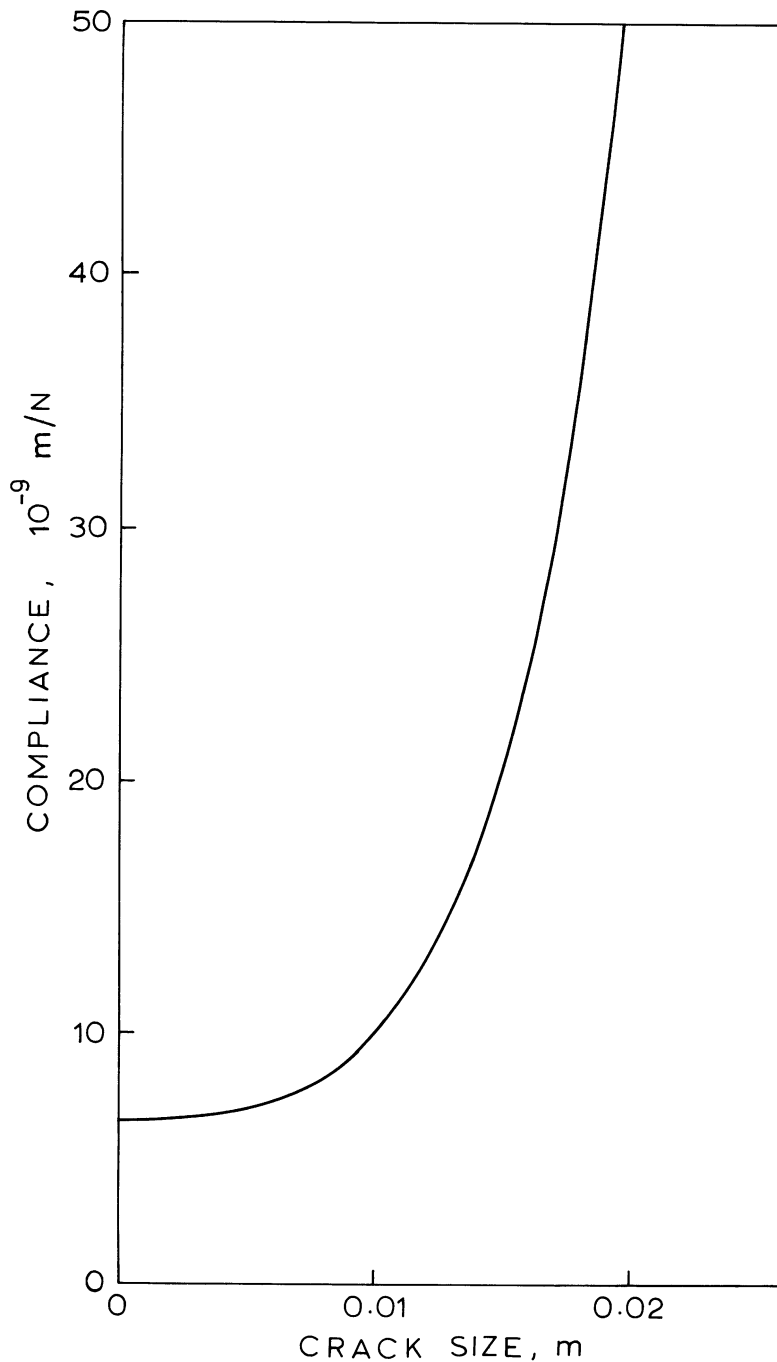


Fig. 9. Compliance curve for single edge-notched tensile specimen, Fig. 3(a).

gave the agreements between calculated and measured final crack lengths shown in Table I.

It is possible to develop the other experiments in a similar way to that described above for the stress corrosion cracking of Mg-7%Al alloy in chromate/chloride solution to help students achieve a deeper understanding of fracture than is at first apparent from the simple nature of the experiments. Indeed, some of the experiments could be expanded to fulfill the requirements for student projects, again following the low capital and low recurrent cost philosophy that was the basis for the development of these laboratory experiments.

## CONCLUSIONS

If severe restrictions on capital investment and the lack of available running costs for laboratory work exist, meaningful experiments can still be devised that demonstrate the principles and reinforce the teaching of linear elastic fracture mechanics.

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