Fracture research at Wits: an overview of activities, results, and directions

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Synopsis

The Fracture Research Group has been operating at the University of the Witwatersrand for some ten years and, in that period, has achieved a significant profile, both nationally and internationally, through its research publications, industrially-based technical reports, continuing short courses in engineering education, and conferences. This paper outlines the activities of the Group over the past few years, emphasizing the research thrusts and the results that have been obtained, as well as highlighting areas of current and future research interest. The capabilities of the Group in terms of equipment and expertise are also discussed briefly.

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Introduction

The Fracture Research Group at the University of the Witwatersrand in Johannesburg was established more than ten years ago by Geoff Garrett, then Professor of Physical and Fabrication Metallurgy. It initially had the status of a research programme but, after five years of successful operation, it was recognized as an official research group within the University. Professor Neil James has overseen the activities of the Group since 1987, and was appointed Director in 1989. During the period that the Group has been under the direction of the present incumbent, it has, within the constraints of personnel and funding, been successful in achieving a significant profile, both nationally and internationally, through its research publications, industrially-based technical reports dealing with failure analysis or cracking problems, continuing short courses in engineering education, and the organization of two major conferences.

Funding to the Group derives from the Foundation for Research Development, the University Research Council, and industry, the last component comprising about one-third of the total amount and representing support for particular research projects (around 13 in number in the review period).

The Group's activities since 1988 comprise the following:

- 18 publications in refereed journals accredited by the Department of National Education
- 1 chapter dealing with fatigue design in a guide to be published by the Aluminium Federation of South Africa
- 5 papers in 'popular' journals
- 8 publications in refereed conference proceedings
- 5 conference presentations
- award of 7 M.Sc.(Eng.) degrees and 1 Ph.D. degree
- organization of or participation in 14 short courses for industry
- organization of 2 major conferences, Fracture '89 and Fracture '94, the 3rd and 4th National Conferences on Fracture (selected papers from Fracture '89 were published as a special issue of the Pergamon journal *Forensic Engineering*, and selected papers from Fracture '94 are to be published as a special issue of Butterworth–Heinemann's *International Journal of Fatigue*, in both cases with Professor James as guest editor)
- 50 technical reports for industry dealing with failure analysis or cracking problems.

Papers published by the Director received the Ingham Award of the South African Institution of Mechanical Engineering in 1988, 1989, and 1994. This award is made for the best short technical paper published in their journal in a particular year. A measure of the Group's research profile is given by the fact that Professor James is on the Editorial Advisory Board of the *International Journal of Fatigue*, is consultant and comment writer for *Mechanical Technology*, and has reviewed research papers for *Materials Science and Engineering*, *Fatigue and Fracture of Engineering Materials and Structures*, and the *R&D Journal*.

Research thrusts within the Group over the past few years have fallen in the following areas:

- threshold of fatigue-crack growth and crack closure phenomena for long and small cracks
- crack growth from notches under fully compressive fatigue loading
- prediction of the fatigue strength and life of welded details, particularly cover plates on aluminium I-beams and reclaimed steel shafts
- variable-amplitude block loading of both small and long fatigue cracks
- residual stress measurements and their relationship to fatigue strength.

The work in a number of these areas has been collaborative and interdisciplinary, involving mechanical engineers and physicists. Materials that have been the subject of research in the programmes include steels, aluminium alloys, WC–Co hardmetals, alumina ceramic, and polyvinylchloride (PVC).

In addition, partly as a result of the technical consultancy work carried out for industry, the Group has a strong interest in the area of failure analysis and forensic engineering, i.e. in applying the principles of engineering analysis to determine the responsibility or culpability for failure or loss of function of engineering plant, structures, and components. The term *forensic engineering* is normally used when the investigations form part of a process of litigation. This interest has led to the publication of several papers dealing with failure analysis[1,2].

The purpose of the present paper is to briefly review and summarize the results of the research in the areas mentioned, and to point to future research directions that have been identified as being fundamentally interesting and relevant to the needs of industry. Firstly, however, the testing equipment available to the Group is described.

Testing equipment

The Group operates three general-purpose servohydraulic testing machines with closed-loop electronic control and with capacities of 50, 100, and 200 kN. The 50 and 200 kN loadframes were manufactured by ESH Testing Ltd, while the 100 kN machine was built by Instron Ltd. All three machines are on a ring-main hydraulic oil system driven by two self-contained Instron 80 l/min hydraulic power packs. Each loadframe can be powered up separately via individual hydraulic substations. The original electronic controller on the 50 kN machine was replaced late in 1991, and can be operated with computerized control and datalogging using a package developed in-house. Applied waveforms in this package are limited to simple block loading, because sequential sampling of waveform amplitude is used to provide feedback for the adjustment of errors. A Dartec modular 9500 digital control system has recently been installed on the 200 kN loadframe, which can be controlled via a 66 MHz 486 computer, and allows for the generation of complex random waveforms with up to 100 000 turning points. Software is installed that can perform tests on tensile strength, fracture toughness, and crack growth rate to the provisions of the relevant ASTM standards, while providing automated graphical and tabular output of the results. A 5 kN loadcell is also available for tests involving small loads, e.g. in double-torsion testing of ceramic materials.

Two Amsler electromagnetic resonant frequency-testing machines, with 20 and 100 kN capacities, are used for simple fatigue tests, e.g. the generation of stress–life (S–N) fatigue curves. There is a significant demand for such work both from industry and in research projects. The machines operate at around 150 Hz and can hence apply 10^7 load cycles in about 20 hours. Thus, in principle, data on the fatigue strength of non-ferrous alloys can be obtained at lives of 10^8 cycles. The 100 kN machine is fitted with a gearbox to adjust the mean load automatically and has a solid-state electronic controller.

Ancillary equipment operated by the Group includes a Charpy-impact testing machine (together with a miniature Charpy machine), tensile testing machines, furnaces that fit on the servohydraulic machines and allow tests to be performed at temperatures of up to about 1000°C, strain bridge amplifiers, microvolt meters, and a constant-current power supply for potential drop monitoring of crack length. The finite-element modelling capability is soon to be greatly enhanced by the acquisition of the ANSYS 5.0 package, which will be installed on personal computers.

Overview of research thrusts

Threshold and crack-closure phenomena

Almost all the research projects undertaken by the Group have involved threshold determinations and measurements of crack closure. The Group has obtained these data for several reasons: to use them as fundamental materials properties, to examine the use of closure data in interpreting threshold and growth-rate trends, to relate closure development distances in long and short fatigue cracks, and to investigate the resolution and accuracy of compliance-based closure measurements. Work has been carried out on both long and short cracks in steels and aluminium alloys.

Threshold data and crack-growth rates are often represented as fundamental material properties, particularly when the effects of closure are factored out through the use of an effective stress-intensity value ΔK_{eff}, defined as $K_{max} - K_{op}$ or K_{cl}, i.e. the difference between the maximum stress intensity in the fatigue cycle and the value at which the crack-tip region 'unwedges' or becomes subject to tensile stresses. (K_{op} relates to the opening half-cycle and K_{cl} to the unloading half-cycles—values that often differ by 10 to 15 per cent.) In a number of alloys, the use of ΔK_{eff} rationalizes the influence of mean stress, certain environmental interactions, and some aspects of short-crack behaviour. However, it has become clear that there are interpretation problems associated with closure measurements. These relate to the position in the crack wake where closure effects occur, i.e. near the tip or remote from the tip, correlating average bulk measurements (e.g. compliance data) with near-tip surface measurements (obtained with crack-tip strain gauges, optical techniques, etc.), resolution problems with bulk measurements, and the possibility of so-called 'strain intensification' occurring below K_{op} or K_{cl}.

Certain of these aspects have been addressed by the Group[3] in ongoing work started by the Director[4,5]. A paper by Garz and James[3] considers the curvature that may occur in the upper portion of a compliance trace for a 1040 plain carbon steel, and the possibility of strain intensification below the opening point for a 7017-T6 aluminium alloy. In the strain-intensification part of the work, two types of test were performed: in the first experiment, a load-shedding scheme was used to give a 'long' crack subject to an applied ΔK value of 6,3 MPa$\sqrt{m}$ with the stress ratio $R = 0,1$. K_{min} was then increased in steps to give stress ratios of 0,25, 0,33, and 0,5 whilst K_{max} was kept constant. The values of growth rate and K_{op} were monitored over 0,1 mm increments in crack length. The results of this test are given in Table I, and it is clear that, although K_{op} showed a slight decrease as K_{min} increased, the measured growth rate decreased steadily with a decrease in ΔK.

Table I

Variation in growth rate with increasing K_{min}

R	K_{op} MPa$\sqrt{m}$	ΔK_{eff} MPa$\sqrt{m}$	da/dN mm per cycle
0,1	5,6	1,4	$1,5 \times 10^{-5}$
0,25	5,6	1,4	$1,2 \times 10^{-5}$
0,33	5,2	1,8	$9,0 \times 10^{-6}$
0,5	5,2	1,8	$4,5 \times 10^{-6}$

The trends shown in Table I were confirmed by a second experiment in which a triangular steel wedge was inserted into the notch of the compact tension specimen. Its position was varied to give contact ratios of 0,4, 0,6, and 0,8 (contact could be detected from the compliance traces). The implication of the results from both experiments is that either strain intensification is occurring (because the crack-growth rate is a function of reversed slip, which may be sensitive to applied strain range), or asperity crushing on the fracture surfaces is influencing the results. Further work on these aspects is required to solve the problem of interpretation of compliance traces.

Another issue in the use of threshold data is the apparent dependence of the values on crack-generation techniques[4,6]. Reference 6 examines this question for small cracks generated under the following conditions:

(1) $R = 0,2$ with stresses $\geq$ the yield stress followed by annealing in vacuum
(2) $R = 0,2$ in hydrogen charging at low stresses followed by annealing in vacuum
(3) $R = -1$ with stresses $\ll$ yield followed by a change to $R = 0,2$ when a crack has been detected
(4) machining away the wake of a long crack to give through-thickness (2-*d*) short cracks.

The relevant data are shown in Figure 1, where semi-elliptic bend refers to method (1), H + F to method (2), semi-elliptic tension to method (3), and short through-thickness to method (4). The conclusion to be drawn from these observations is that neither through-thickness short cracks, nor those initiated at high stresses and subsequently annealed, would provide threshold values or near-threshold growth-rate data that could be applied confidently to life prediction for small, naturally occurring semi-elliptic cracks.

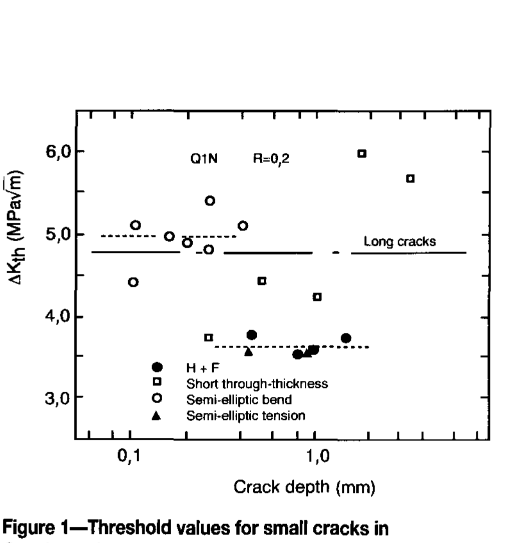

Figure 1—Threshold values for small cracks in Q1N (HY 80) steel generated under various conditions

Another interesting issue is the distance over which closure develops in long and small cracks, and whether it is the same for both types of crack. There is some evidence in the literature that short-crack effects end once a representative long-crack closure value has been obtained, and a simple analytical model was developed by Jira *et al.*[7] based on this hypothesis. Hence, if the closure development distance is common to all crack sizes, it may be possible to clarify some aspects of small-crack behaviour through the examination of long cracks, which are experimentally easier to handle because of their larger size. Reference 8 considers the relation between the closure development distance, a_{cd}, for long cracks and the extent of the short-crack regime, and compares the experimentally found long-crack, a_{cd}, values with the predicted curve for short-crack, a_{cd}, values obtained by Jira *et al.* Experiments were carried out on a 7017 aluminium alloy in the T6 and overaged conditions. The closure development distances for long cracks were around 0,2 mm and 0,35 to 0,4 mm respectively for the two conditions. When these values were plotted against the ratio of K_{op}/σ_y, where σ_y is the proof stress of the alloy, they fitted the predicted curve of Jira *et al.* Equally, short-crack behaviour appeared to end at crack lengths corresponding to these closure development distances. Thus, it was concluded that closure development distance appears to be a function only of material and loading variables, irrespective of crack size.

The measurement of closure values for small cracks and, thus, the determination of their closure development distances require different techniques from those used for long cracks. One system that has been applied successfully to cracks with a surface length as small as 50 µm uses a laser-based optical interference technique involving an interferometric strain-displacement gauge (ISDG). This was developed by Sharpe[9] and has been used in a study of the closure, growth rate, and crack-opening displacement behaviour of short cracks in fine-grained (FG—prior austenite grain size of 17 µm) and coarse-grained (CG—prior austenite grain size of 64 µm) A533B steel[10]. The main conclusions of this work were as follows.

- At $R = -1$ in both conditions of the steel, the onset of long-crack growth behaviour coincided with the development of a constant (long-crack) closure value, rather than a set number of prior austenite grains.
- At $R = 0{,}1$ in both conditions of the steel, the agreement between the crack sizes corresponding to the end of the short-crack regime and the attainment of a long-crack closure value was still better than that obtained by comparison with the grain size, although not as good as at $R = -1$.
- Comparison of calculated and measured crack opening displacements indicated that linear-elastic fracture mechanics (LEFM) provided a good estimate of crack-tip plastic-zone size in the FG condition, provided that plane stress conditions were assumed for small cracks. For the CG condition, however, the crack opening displacements were over-estimated by LEFM calculations, implying that the plastic-zone sizes were under-estimated. Hence, for small cracks, non-continuum plasticity may occur in situations where plastic-zone sizes calculated by LEFM are small compared with some dominant microstructural dimension.

Crack growth from notches under compression fatigue

It has been known for several decades that the application of fully compressive loading to a specimen containing a notch would result in the growth of fatigue cracks through the root region of the notch where tensile residual stresses exist. In metals, this region is a function of the reversed plastic-zone size whilst in brittle materials, like ceramics, it is related to the inelastic strain resulting from grain-boundary microcracking in the damage zone ahead of the notch. The occurrence and extent of cracking depend on mechanical factors like load range and stress ratio and on environmental influences (which may mean that the loading frequency becomes important).

Typically, the extent of such notch root cracks is less than or equal to 1 mm, and hence their presence in ductile materials is not too deleterious if the component experiences occasional tensile-stress excursions. In brittle materials, cracks of this size would have a significant effect on the tensile fracture stress. As the design philosophy for a number of ceramic components is based on the prime loading being compressive, it is clearly of some importance to characterize the growth of compression fatigue cracks and the effect of mechanical and environmental variables.

Of equal significance is the fact that compression fatigue offers controllable and simple precracking for the testing of the plane strain fracture toughness of brittle materials on specimens that conform to the requirements of existing standards (e.g. three-point bend with $0{,}45 \leq a/W \leq 0{,}55$). Also, if a sharp crack can be initiated at a notch, it then becomes possible to obtain fatigue-crack growth data for materials like WC–Co alloys, which is otherwise difficult.

Reference 11 reports the results of a study of β''-alumina ceramic, which investigated the effects of variables such as stress ratio with a constant minimum stress in the cycle, load range with a constant mean stress, frequency (1, 10, or 170 Hz), and a low vacuum of about 10^{-2} torr. The stress cycles are illustrated in Figure 2, and typical crack-growth data are given in Figure 3. It should be noted that these results represent the lengths of surface cracks averaged over both sides of the specimen from several tests at each stress ratio. An interesting observation relates to the fact that the extent of cracking passes through a maximum as the stress ratio changes from R = 2 to R = 10. This is due to an interplay between the following two factors:

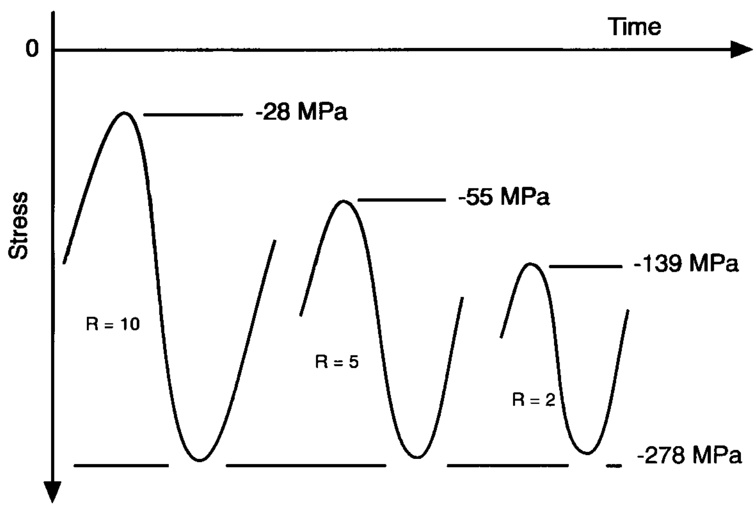

Figure 2—Stress cycles and stress ratios used in tests on the compression fatigue of β''-alumina ceramic

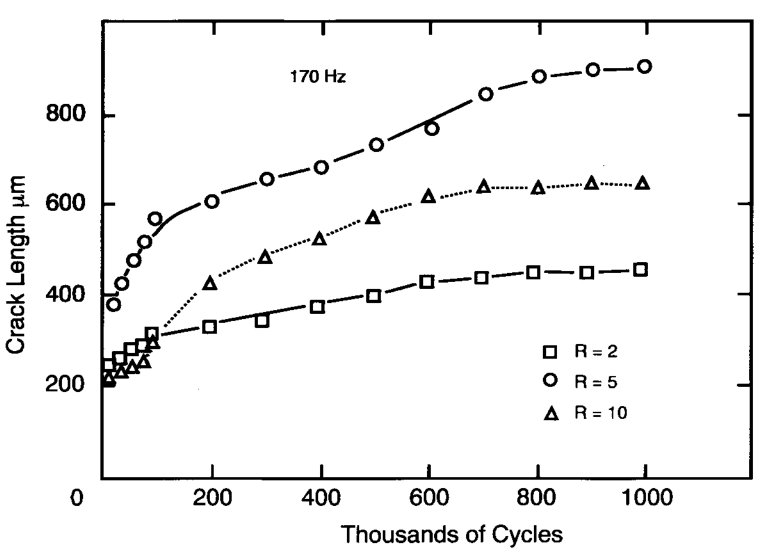

Figure 3—Crack growth in β''-alumina ceramic observed at R values of 2, 5, and 10

(1) the magnitude of the residual tensile stress developed, which increases as R increases, i.e. as $\sigma_{max} \rightarrow 0$ for a given value of σ_{min}

(2) the accumulation of debris between the crack faces as a result of intercrystalline microcracking.

Effect (2) can be shown by periodic ultrasonic cleaning of the specimen, which gives a doubling of the saturation crack length at R = 10. The effect can be seen where the crack intersects the surface as the breaking off of pieces of the material local to the crack plane.

In the experiments dealing with the effect of load range, it was found that an increase in the load range for a given value of mean stress gave a steadily increasing maximum crack length.

The fracture toughness of hardmetals is an important parameter. This is determined routinely in industry from simple tests such as the short-rod or fractometer test. It has, however, been suggested that the values obtained by this method may be influenced by artifacts of the specimen preparation process, at least for some materials[12]. Fracture toughnesses were determined for a WC–Co alloy containing 10 per cent cobalt by weight[13], according to the requirements of BS 5447, using compression–compression pre-cracking followed by tensile fatigue to extend the crack to an a/W of about 0,5. These K_{1C} values were compared with the results of short-rod toughness tests on the same grade of hardmetal. It was concluded from this work that the short-rod test may over-estimate the fracture toughness by some 7 per cent, and results obtained exhibited higher scatter than those from three-point bending tests to BS 5447. Another interesting observation was that, at crack arrest in compression fatigue (corresponding to $a/W \approx$ 0,3 to 0,35 in the specimens used), a zone of residual tension or damage existed ahead of the crack tip. Thus, when the toughness tests were performed without extending the crack in tension fatigue, low K_{1C} values were obtained from the three-point bending toughness tests.

Fatigue strength of weldments

Several research projects have been run over the past few years that focused on life prediction for weldments. One project examined the reclamation of steel shafts by welding[14], which is done either when there is wear or corrosion damage to the surface, or when a fatigue crack is detected in service. A considerable amount of work was done in this area between the late 1950s and mid 1970s, with the general conclusion that the fatigue strength was lower for built-up shafts owing to welding defects. Automated or semi-automatic processes gave better results than manual processes, and metal spraying was better than arc welding. Two factors prompted a

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re-assessment of the current situation regarding reclamation by arc welding: firstly, the improved control of welding processes and the ongoing development of welding consumables that have taken place over the past twenty years and, secondly, it is becoming more commonplace to reclaim cracked shafts of large diameter, in which a considerable depth of metal (≈ tens of millimetres) may have to be removed prior to the building-up of the shaft and machining back to the original size. Thus, in such cases, the weld layer may be much thicker than the typical sizes (1 to 3 mm) considered in the earlier studies.

The work was performed with normalized EN 8 steel (080M40 in BS 970 Part 1 1983), and most of the tests used small square-section specimens in 4-point bending under tension–tension loading. Specimens were manufactured by the deposition of over-matched weld metal circumferentially onto a bar of 100 mm diameter over a length of some 120 mm. Initially, 2 mm was machined off the surface of the bar, and then multipass submerged-arc welding was used to build up a weld layer either 3 mm or 10 mm in depth. In the case of the thinner layer, weld metal was machined off to just expose the interface between the weld metal and the heat-affected zone (HAZ) whilst the thicker layer was only skimmed to give a smooth surface. These two different preparation techniques were intended to represent the case where superficial wear or corrosion damage is repaired with a thin weld layer, and that where a deeper weld deposit is required to repair a cracked component. The centre of the bar was then machined out to leave a 'doughnut' from which square-section specimens around 10 x 10 x 80 mm could be cut.

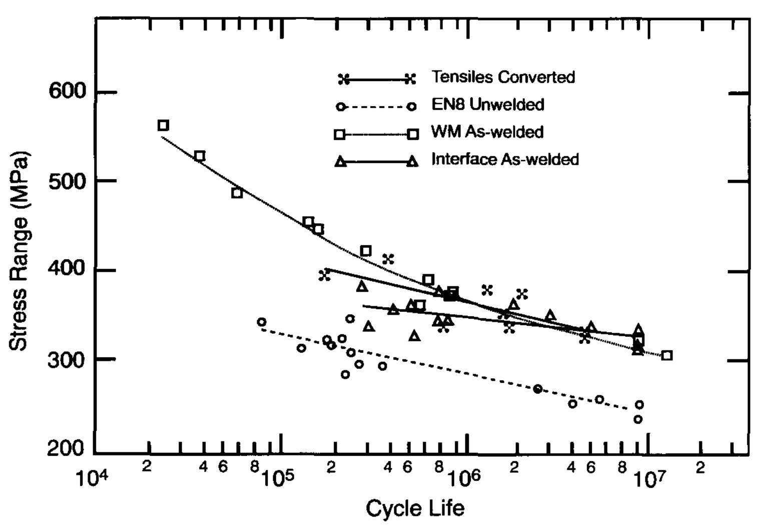

Figure 4—Fatigue strengths for all the as-welded geometries considered in the test programme dealing with the reclamation of shafts (WM = thick weld-metal layer, Interface = the weld metal–HAZ interface specimens, Tensiles Converted = the tension–compression specimens)

As the sequence in the manufacture of specimens destroyed the residual stress distribution, three steps were taken to assess the likely effects of residual stresses on the fatigue strength.

- The bend bars were tested at $R = 0{,}1$, rather than in reversed bend (which shafts are subjected to), since the main effect of residual stresses on fatigue-crack growth is to raise the mean stress level.
- Specimens were cut from built-up bars in both the as-welded condition, and after stress relief at 350 and 650°C.
- Specimens 25 mm in diameter were tested in tension–compression loading at $R = -1$, in both the as-welded condition and after stress relief at 350°C.

These tests also had the purpose of applying a uniform load throughout the whole cross-sectional area, thus enabling a complete assessment to be made of the influence of the weld layer in crack initiation. The main results of the test programme for all the as-welded geometries are shown in Figure 4. The tension–compression results were transformed through the use of Goodman's equation and other correction factors to allow a sensible comparison to be made between $R = -1$ tensile loading and $R = 0{,}1$ bend loading.

Two conclusions can be drawn from these results. Firstly, for lives of service interest (more than 10^6 cycles), the fatigue strength of all the welded specimens was higher than that of the unwelded EN 8 steel. Secondly, the fatigue strength of the interface specimens was generally lower than that of the weld-metal specimens. Also, scatter appeared to be more marked in the results from the interface and tensile specimens. This presumably reflects the influence of the more variable microstructure in these specimens and, for the tensile case, the presence of residual stresses.

A second, fairly extensive project dealt with 6261 aluminium alloy I-beams with welded cover plates[15]. The I-beams had a depth of 100 mm, a width of 75 mm, a length of 450 mm, and flange/web thicknesses of 4,2 mm. The cover plates were 3 mm thick and roughly 100 mm long by 40 mm wide, and five different geometries were considered (Figure 5). The specimens were tested in four-point bending at $R = 0{,}1$.

In the first phase of the work, the fatigue strengths of the various cover-plate terminations were compared. These results (Table II) show very similar trends to the fatigue strengths reported for steel cover plates[16].

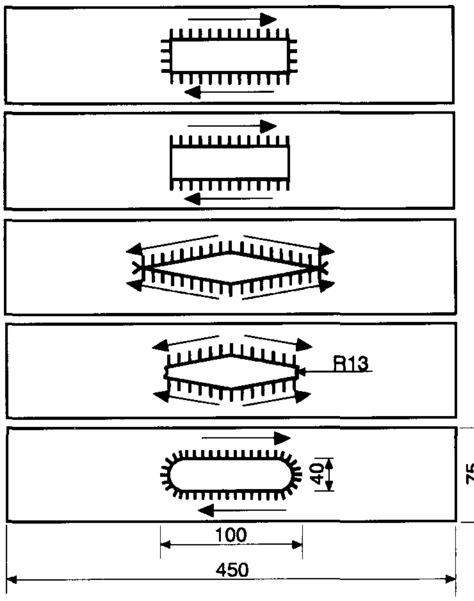

Figure 5—Details of the cover-plate geometries used in the work on the constant-amplitude loading of aluminium alloy I-beams (dimensions in millimetres). The welding directions are shown by the arrows. The welding was continuous for the fully welded oval and rectangular geometries

Table II

Fatigue strengths for cover plates of various geometries

Cover-plate geometry	End weld used	Fatigue strength, MPa 10^5 cycles	Fatigue strength, MPa 2×10^6 cycles
None		220	110
Rectangular	Yes	95	50
	No	120	43
Rhomboid	Yes	112	53
	No	114	48
Oval	Yes	100	50

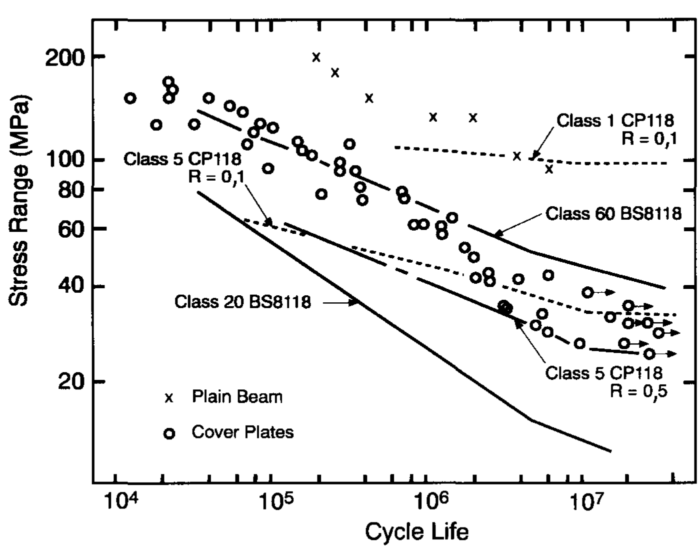

Figure 6—Comparison between experimental data from the constant-amplitude test programme on aluminium I-beams and the design curves from CP 118 and BS 8118

Clearly, there are significant increases in fatigue strength that could be gained from a careful choice of cover-plate end geometry (some 26 per cent at a life of 10^5 cycles and 23 per cent at 2×10^6 cycles). However, it should be noted that the ranking of the details changes from the shorter to the longer lives, and that the manufacturing cost may have to be taken into account.

The second aspect of this work was a comparison of the results of the I-beam test programme with the design curves given in BS 8118 Part 1 and CP 118. Figure 6 shows this comparison for plain extruded I-beams, as well as for those with welded cover plates. For both these cases, the CP 118 design curves corresponding to a stress ratio of 0,1 were conservative up to lives of around 2×10^6 cycles, but became unsafe at longer lives. It is generally accepted that the presence of residual stresses at a weld results in a high local stress ratio irrespective of that of the applied cycle. A more appropriate design curve may therefore be that corresponding to R = 0,5 in CP 118. This line is also shown in Figure 6 and certainly fits the experimental results better. Nonetheless, the safety margin in strength prediction at lives longer than 2×10^6 cycles is negligible for the details tested in this programme. In contrast, the design curves from BS 8118 corresponding to a 97,5 per cent probability of survival are conservative at all lives, and have slopes more compatible with those of the experimental results.

This work was extended to a consideration of variable-amplitude block loading, and this part of the work is discussed briefly in the next section.

It is clear that many questions remain to be answered concerning the life prediction of weldments. Welding research appears to offer a veritable 'panorama' of opportunity (as claimed, for example, by an item in the *Welding Journal* of the American Welding Society, vol. 72, no. 9, 1993, p. 73). A meeting of the US Department of Energy/EPRI Task Force prioritized a number of issues including the following:

(1) extension of fracture-mechanics concepts to deal with
  - heterogeneous microstructures
  - graduated microstructures
  - residual stress
(2) development of techniques for the mechanical testing of small standard specimens (i.e. how much of the crack front must sample the critical microstructure)
(3) crack initiation and growth in graduated microstructures (weak links, etc.)
(4) understanding of the effects of welding procedures and material chemistry on crack growth.

The Group intends to address these issues, where possible, over the next few years.

Variable-amplitude block loading

Several projects were initiated dealing with the topic of variable-amplitude block loading for both long and short cracks. Several of these are still ongoing, and only preliminary results can be mentioned. The aluminium I-beam project was continued using a cover plate of single geometry, i.e. rectangular with welded ends. The variables considered in this work included the following effects: change of fabricator, vibratory and thermal stress relief, ratio of load amplitudes in successive cyclic blocks (overload ratios from 25 to 150 per cent of the baseline loading), number of cycles in each block, and repeat distance between overload blocks (e.g. from 1 overload cycle every 10 baseline cycles to 1 in 50 000 and 10 in 20). In essence, constant-amplitude stress–life curves were developed for I-beams welded by the two fabricators, as well as for those from a single fabricator that had been vibratory or thermally stress relieved. The I-beams were then subjected to various simple two-step block-loading sequences until failure, and the life results were compared with the predictions of Miner's linear-damage summation rule. Some fundamental work involving measurements of crack closure and growth rate immediately post-overload was carried out on single-edge notched specimens.

The results from this programme have still to be analysed, but some interesting trends are apparent. For instance, I-beams welded by Fabricator 1 had a poor weld geometry and consistently gave lives under variable-amplitude loading that were lower than Miner's rule predicted, whereas I-beams welded by Fabricator 2 always gave lives under variable-amplitude loading much greater than the Miner's rule prediction. Yet, under constant-amplitude loading at lives longer than 10^5 cycles, I-beams welded by Fabricator 1 gave fatigue strengths higher than those obtained with I-beams welded by Fabricator 2, whose welds had a better profile but showed some cracking in the HAZ due to a higher heat input. Presumably, the effect of high-amplitude overload cycles is dominant under variable-amplitude loading, possibly because the plasticity induced by the stress concentration at the weldment swamps local plasticity effects at cracks in the HAZ.

Work was also carried out on crack initiation under simple block loading in 6261-T6 aluminium alloy. This was done in collaboration with Dr E.R. de los Rios while Professor James was on sabbatical leave at the University of Sheffield. It involved the linking of the experimental work with a dislocation-based model of early crack growth developed by Dr de los Rios. Two results of this work can be mentioned.

- Firstly, variable-amplitude loading appears to have its greatest effect on the initiation of a crack less than 20 μm in surface length, since Miner's rule works reasonably well for crack growth beyond this size.
- When overload ratios are small (about 8 per cent) and cracks have surface lengths of less than 100 μm, crack growth may be arrested during the overload block. This presumably reflects an interaction between crack-tip blunting effects and increased crack-tip stresses.

Another project dealing with variable-amplitude block loading in EN 8 steel has been continuing for the past year, and aims at linking very careful measurements of crack closure and growth rate subsequent to an overload with theoretical modelling of life prediction. Variable-amplitude and random loading are seen to be ongoing research areas in the immediate future since many life-prediction problems remain to be solved.

Measurements of residual stress

Residual stresses have a strong influence on fatigue lives in many situations, e.g. weldments, extrusions, and surface peening. The measurement of residual stresses is somewhat complex, while the interpretation of discrete results and their extrapolation to life prediction are still not fully understood. This is seen as an important area in which a greater research effort will be placed over the next few years.

A project has been initiated in collaboration with the Atomic Energy Corporation of South Africa, that is examining correlations between residual stress measurements obtained from strain-gauge rosettes, X-ray diffraction, and neutron diffraction for as-welded aluminium alloy I-beams and those stress-relieved by vibratory and thermal techniques. The aim is to relate the results to the stress–life results obtained in the programme mentioned previously.

The Group hopes to purchase an air-abrasive hole-drilling machine in 1995 for the purpose of making residual stress measurements using strain-gauge rosettes.

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Conclusions

In the first ten years of its operation, the Fracture Research Group at the University of the Witwatersrand has been fairly successful in increasing the capabilities of its equipment, training graduates in fracture and fatigue, and providing a contract research and technical consultancy service to industry. The costs of fracture to the South African and world economies remains high, at around 4 per cent of the gross domestic product, and it is clear that a significant effort will continue to be made worldwide in the development of fracture-mechanics and life-prediction methodologies.

Funding for fracture research in South Africa represents a much smaller percentage of the R&D spending than occurs in other developed economies. The Group hopes that this will change and that increased funding will allow for the development of a more comprehensive service to industry through the employment of post-doctoral research workers and the acquisition of advanced equipment. An indirect benefit would be a raising of the awareness of fracture problems among undergraduates, who often do not regard fracture as being in the mainstream of either metallurgical or mechanical engineering. ◆

Wits engineering is alive and well*

Professor Jan Reynders, Dean of the Engineering Faculty at the University of the Witwatersrand, says the disruptions on campus have not influenced the Faculty in any way, adding that admissions in 1995 rose by 18 per cent.

The degrees in electrical, chemical, and mining engineering, in particular, attracted higher numbers of students in 1995. There was also an increase in full-time post-graduate students and students entering extended curriculum programmes in engineering.

Professor Reynders attributes the improved enrolment to a significant improvement in business confidence, the awarding of more bursaries, the high standing of the university's engineering qualifications, and an increasing awareness among parents, students, and teachers that engineering is a wealth-creating career.

The faculty now has 464 first-year students, while a further 135 students have entered extended curriculum programmes. All the students, almost half of whom are black, have satisfied the faculty's demanding admission criteria. 'We are pleased to see greater numbers of top-quality students entering our nine degree courses, all of which are recognized internationally' says Professor Reynders.

The Engineering Faculty's extended curriculum programmes consist of the Pre-University Bursary Scheme (PBS), which allows educationally disadvantaged students to complete a bridging year prior to entering mainstream engineering, and the College of Science, which enables students to complete the first year of the engineering degree over a two-year period.

Professor Reynders states that the Department of Education and Training (DET) matriculants are encouraged to enter the Engineering Faculty via the extended curriculum programmes since a graduation rate of 64 per cent is being achieved by students who take this route. This is higher than the Faculty's overall graduation rate. However, DET students who meet the entrance requirements but do not enter the faculty via the extended curriculum system stand a 19 per cent chance of completing their degrees.

Professor Reynders points out that the Faculty of Engineering is committed to continued growth, and is currently seeking ways and means of providing the resources to make this possible. 'Our vision is in line with the University's mission to "foster its capacity in science and engineering and increase its output of graduates in these areas, especially from under-represented groups"', he says. ◆

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International Scientific Conference 1999

South Africa is to host the 15th Congress of the International Union for Quaternary Research (INQUA). The University of the Witwatersrand (Wits) academic, Professor Tim Partridge, has been appointed INQUA Vice President.

The conference is to be held in **Durban in 1999** with the prinicipal theme being ***'Africa, Cradle of Humankind in the Quaternary'***.

During the 14th Congress of the INQUA in Berlin, Germany it emerged that it is virtually beyond doubt that the earth's atmospheric temperature is rising due to human activity, according to Professor Partrigde of the Climatology Research Group at Wits.

He says that it is now a strong possibility that regions such as southern Africa will be hard hit by this changing situation.

For further information on the Berlin Congress and INQUA 99 please contact Professor Tim Partrigde on (011) 646-3324, cell phone 083-378-4073 or fax (011) 486-1689. ◆

School of Process & Materials Engineering*

The School of Process and Materials Engineering, offering three specialist degrees, has been launched in the Engineering Faculty at the University of the Witwatersrand. The new School, which follows worldwide trends in engineering education, was formed by the amalgamation of the Departments of Chemical Engineering and of Metallurgy & Materials Engineering. The degree courses offered have not changed, and students will still be able to graduate in chemical engineering, minerals processing, or physical metallurgy. The first two years of study are common to all three degrees, which gives students the important advantage of not having to make a final career choice before the third year of study.

'The decision to form the School was taken because of significant overlap in the teaching and research activities of the two former departments', says Professor Tony Bryson, Head of the School. 'By rationalizing, we are able to spread the teaching load so that lecturers can concentrate on their more specialized subjects. The School will also be able to expand its post-graduate activities, particularly the number and range of continuing engineering education courses offered to practising engineers.'

He points out that the School now has an academic staff complement of 20. While all three degrees offered are already recognized by relevant international institutions, he believes the students will benefit from better-quality teaching, research, and contact with industry in the new structure.

The School of Process and Materials Engineering currently has almost 250 under-graduate students and 78 full-time post-graduate students, and Professor Bryson says that one of its major aims is to realize its potential for substantial growth in both fields.

He adds that the establishment of several major centres of research within the School is expected to increase formal collaboration with industry. These include the materials research centre, the hydrometallurgy research unit, and a research group on the mathematical modelling of processes, all of which have access to a wide range of resources within and outside the university. 'The formation of the School should thus give industry access to a wider and more comprehensive range of expertise for contract research', he says.

Professor Bryson points out that traditional chemical engineering has made notable contributions to extractive metallurgy in South Africa. Metallurgy has also played a major role in developing processes that have enabled this country to beneficiate its mineral resources. 'Bringing the two together reflects the way in which Wits University is changing to keep in step with technological progress.' ◆

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Pyrometallurgy expertise for Wits Engineering*

Wits University's Branch of Extractive Metallurgy is gaining valuable expertise from the visit to South Africa of pyrometallurgy specialist Dr David Robertson of the University of Missouri-Rolla, Missouri.

Dr Robertson, who is professor of metallurgical engineering and director of the Centre for Pyrometallurgy at the University of Missouri-Rolla, is in South Africa for six months at the invitation of Mintek. His work at Mintek is involved mainly with a project on the recovery of zinc metal by fuming from slags and other waste materials.

During his sabbatical, he is liaising closely with Wits and other Gauteng universities. He has become particularly involved in a project in the Branch of Extractive Metallurgy in the School of Process and Materials Engineering at Wits to investigate processes for the production of low-carbon ferromanganese, low-carbon ferrochromium, and stainless steel.

The project is being undertaken under the leadership of Professor Hurman Eric, head of Extractive Metallurgy and deputy dean of the Engineering Faculty at Wits. It focuses mainly on fluid-flow and mixing phenomena such as the behaviour of gas jets in liquid metals during refining. Dr Robertson's contribution to the project has included his submission of a paper on the use of similarity criteria to ensure the relevance of the laboratory experiments to industrial practice.

Dr Robertson has also presented three seminars on the calculation of the kinetics of reactions between multiple phases, the submerged injection of gases, and the recovery of zinc and lead from waste materials. ◆

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