Investigation of Wake Contact Stresses Developed During Fatigue Crack Growth

EPSRC Grant Number GR/L42391

Professor M Neil James

Department of Mechanical & Marine Engineering
University of Plymouth
Drake Circus, Plymouth PL4 8AA
Email: mjames@plymouth.ac.uk

Professor Eann A Patterson

Department of Mechanical Engineering
University of Sheffield
Mappin Street, Sheffield S1 3JD
Email: e.a.patterson@sheffield.ac.uk

Background and Context of Research

This research grant has supported work jointly conducted by the Universities of Plymouth and Sheffield, that developed innovative experimental techniques to study the occurrence of fatigue crack closure and its influence upon the crack tip stress field (i.e. the crack tip shielding due to plasticity-induced closure). The work concentrated on studying fatigue cracks that were developed under constant load amplitude conditions in polycarbonate (PC) and aluminium compact tension specimens. Analysis of the specimens was attempted using all three of the principal photoelastic techniques, namely two-dimensional analysis in transmission, three-dimensional analysis using stress freezing and the surface analysis of opaque specimens through the use of coatings. The work has given new insight into the mechanisms of crack tip shielding by plasticity-induced closure.

This area is important to life prediction internationally, and is particularly valuable for aircraft, where closure models are routinely invoked. During the course of this project, the investigators learnt of US work into the use of transparent (PMMA and PC) specimens to examine crack closure, supported by the US Air force Structural Integrity Programme, which was presented in San Antonio in December 2000. It is believed that the work under Grant GR/L42391 is well ahead of the US work in certain critical aspects, but arrangements are being made to meet and discuss the respective research programmes.

Plasticity-induced fatigue crack closure has been the subject of extensive study, since its significance under tension-tension loading was first made clear by Elber (1970). Despite all this attention, and a number of modelling endeavours [Budiansky and Hutchinson (1978), Newman (1981)], controversy over fatigue crack closure and its measurement still exist [e.g. James (1997) and Donald (1999)]. Thus its use in life fatigue life prediction, although routine in certain industries, is not as well understood, or as easily generalised, as would be desired. This is particularly true for more complex cases, such as mixed mode loading, or variable amplitude loading.

A significant contributory factor to this uncertainty is the fact that experimental measurement of the occurrence of crack closure is generally obtained from indirect means. Typically, this is by compliance measurements or by endeavours to rationalise a set of fatigue crack growth rate data, which show the influence of a parameter believed to be influenced by closure (for example, stress ratio $R = K_{min}/K_{max}$). It would be very desirable to develop a technique which allowed a more direct assessment of closure, and which could explicitly link crack wake contact forces, and their occurrence, to the effective stress intensity factor. The effective stress intensity factor is usually defined as $\Delta K_{eff} = K_{max} - K_{op}$, where K_{op} defines the point in the opening half cycle where the effect of closure is overcome. In principle, one such technique is photoelasticity, which could provide a direct visualisation of the stress field in the presence of real fatigue cracks undergoing crack closure. In practice, photoelasticity has seldom been applied to visualisation of closure because of difficulties in developing fatigue cracks in photoelastic materials, in interpreting the effect of plasticity on fringe patterns, and because of the time involved in performing full-field stress analysis and determination of stress intensity factors. The work performed in this research demonstrates that these difficulties can be overcome to yield useful insight into closure, on a cycle-by-cycle basis for cracks in standard fracture mechanics specimens.

The use of polycarbonate in the work was dictated by the need to use a transparent or translucent material for the two and three-dimensional photoelastic work. The majority of such materials are too brittle for fatigue cracks to be developed in them, but polycarbonate exhibits sufficient ductility to allow fatigue crack growth [(James and Knott (1985)] and so is suitable for the photoelastic study of fatigue. Previous photoelastic crack analyses have been studies of sharp notches introduced into models that have generally been made from epoxy resins. While these analyses have produced useful information regarding the behaviour of cracked components, they have been unable to allow for any crack tip effects arising from the history of a crack. Historical effects manifest themselves as cyclic crack tip plastic zones, fatigue crack closure, and consequent crack tip shielding from the full applied ΔK value. This plastic enclave around the crack may have a significant influence over the stress field that exists in the material near the crack. In particular, the true stress intensity factor range during a fatigue cycle cannot be easily measured directly and so fatigue life prediction must, of necessity, invoke semi-empirical models and hence be conservative. Thus light weight design, using the full fatigue potential available with improved alloys, is difficult to achieve. It would clearly be desirable to extend the ability of photoelastic analysis to deal with real fatigue cracks.

In this work, it was found that the crack tip stress fields in polycarbonate compact tension (CT) specimens, and on the surface of aluminium CT specimens, could be obtained using photoelastic techniques. Qualitative analysis of the fringe patterns showed that fatigue crack closure was occurring in the specimens and having an influence on the crack tip stress field. It was possible to determine the extent of the closure from the fringe patterns and to deduce that the stress intensity factor range was being considerable reduced by the effects of the crack history. A complex mathematical model of the elastic stresses in the vicinity of a fatigue crack tip was developed to allow the stress intensity factor to be quantified. The model included crack closure forces, which were modelled as a uniform pressure on the crack flanks, and far-field loading of the crack tip. The model was suitable for mixed mode analysis, although this was not attempted during the course of this project. Thus it can cope with a uniform shear load applied to the crack flanks if friction between the crack flanks were to be an issue, as it might be the case under predominantly mode II loading conditions.

The model could be tailored to a given experimental fringe pattern by manipulating constants in the expressions for the far-field stresses and the pressure on the crack flanks. This optimisation was performed by a memetic algorithm, which will be described shortly, and was achieved for fringe patterns near a crack tip that were recorded at sequential loads through applied fatigue cycles. Stress intensity factors were evaluated from the tailored theoretical stress fields in the following way. The model was used to find values for the stress perpendicular to the crack axis, and for the shear stress between axes perpendicular and parallel to the crack at a number of points on a line extending from the crack tip and parallel to the crack. These values were then extrapolated back to the crack tip. By applying this procedure to photoelastic fringe patterns recorded at a number of points during a fatigue cycle, it was possible to obtain values for the stress intensity factor at loads through the cycle, including those at the minimum and maximum load. Plotting these stress intensity factors against time allowed the effective stress intensity factor range to be found. Deviations in the K-results from those predicted by standard K-calibrations for the CT geometry showed the opening and closing stress intensity factors. These could be compared with values deduced from the opening and closing loads obtained from plots showing changes in the specimen compliance with applied load. Good agreement between these results was obtained.

The work was supported by finite element analyses of plasticity-induced closure for a fatigue crack growing in a CT specimen, as a function of applied stress ratio. Various definitions of closure were used to define the effective driving force, i.e. onset of tensile stresses at the crack tip, and first node contact behind the crack tip. Numerical predictions of ΔK_{eff} were compared with the results from compliance measurements. A nonlinear regression technique was used to fit fatigue crack growth rate data to a two-parameter growth rate equation using FE model values of ΔK_{eff} and K_{max}. Coefficients of determination of this fit were higher for the first node contact assumption, than for the onset of tensile stress definition of closure. Values for ΔK_{eff} and closure contact force obtained from the photoelastic and FE models, were in good agreement. This supports the validity of the theoretical analysis and memetic algorithm optimisation.

Photoelastic coatings were applied to the surface of aluminium specimens in which fatigue cracks were then developed. The fringe patterns observed in these coatings showed that, although the crack growth mechanisms in aluminium and polycarbonate are microscopically different, the resultant stress fields in the bulk elastic material are comparable, supporting the fractographic and crack growth rate observations that both materials exhibited macroscopic ductile continuum mechanics growth. This finding is important in that it demonstrates that the computational techniques developed for use with fringe patterns recorded in transmission photoelasticity may be also applied to fringe patterns recorded in reflection, using coatings. A route is thereby opened for applying the results of this research to a much wider range of materials and components than would be the case if only polymeric materials had been considered.

Application was made in this work of a memetic algorithm to tailor the theoretical stress model to the recorded experimental fringe patterns. Memetic algorithms are a sub-class of evolutionary algorithms, which apply the principles of evolution and natural selection to mathematical optimisation. Genetic algorithms are the evolutionary algorithms that most closely mimic reproduction and natural selection as observed in natural species (other than those that reproduce asexually). Whilst genetic algorithms are capable of attaining the global optimisation of complicated problems that include multiple variables, and of doing so without reference to the actual problem being solved, they are slow and it is difficult to determine when optimisation of the problem has been achieved. Furthermore, genetic algorithms are not directed in any way and so may never find the true optimal combination of the variables. These difficulties in the application of a genetic algorithm are addressed in the memetic algorithm by combining a genetic algorithm with another local search technique. In the application of a memetic algorithm to tailoring of the theoretical stress model to that derived from experimental photoelastic fringe patterns, the downhill simplex method was used to perform the local search. This is convenient, because it requires no more information regarding the problem being solved than does the genetic algorithm. It was found that applying a memetic algorithm to this problem produced more consistent results more quickly than a genetic algorithm was able to individually.

It was assumed in developing the theoretical model of the stress field that the contact between the crack flanks took the form of a uniform pressure. This assumption was supported by examination of the plastic wake of cracks in polycarbonate specimens. A microscope that included a dark field reflection polariscope was used to study the strains in the plastic wake and the elastic material close to it. The observed strains showed that contact took place at discrete points along the crack length and could be attributed to both plastic deformation and asperities on the fracture surface. However, the theoretical model is linear elastic and it was also found that localised strains arising directly from the contacts were only evident in the plastic zone, and that the plastic zone exerted a uniform pressure on the elastic material that made up the bulk of the specimen. The microscopic work also clearly showed the development of the shear bands, the plastic zone ahead of the crack and of crazing within the plastic zone.

Some exploratory work was also conducted on the use of synchrotron strain analysis to measure the through-thickness strains, close to a crack in an aluminium specimen. Qualitative results were obtained that showed a strain variation on a line perpendicular to the crack and passing through the elastic and plastic material. Interpretation of these results to obtain strain values requires further work, together with an investigation into the ability of synchrotron strain analysis to determine strains in plastically deformed material. This is the subject of a planned proposal to the EPSRC.

Major Achievements

A number of aspects of this research have made original contributions to knowledge in the fields of fracture mechanics and experimental mechanics.

1. Full-field photoelasticity has been used to study fatigue crack closure in standard compact tension specimens, with identification of opening and closing points in the load cycle, effective stress intensity factors, and wake contact forces. This had not previously been achieved, although it had been shown that photoelasticity provided a highly visual and simple method of studying the stress fields close to sharp notches.
2. This work has been supported by FE modelling of these parameters, with good agreement being obtained between results from the two techniques.
3. Direct evidence of fatigue crack closure during real-time load cycling was obtained through observation of the photoelastic fringe patterns developing in the wake, and at the tip, of a fatigue crack.
4. The interaction between the crack wake contact and the crack tip stress field was clarified. Examination of crack wake contact force and effective stress intensity predictions (from both photoelastic and FE modelling) indicate that these two parameters are not simply related. Thus wake contact force is not a good indicator of the occurrence of crack tip shielding (defined as a reduction in the effective driving force for crack growth). This is interpreted as showing a need to reconsider crack tip shielding and crack tip extension in an holistic manner, as the net effect of a plastic enclave surrounding the crack (essentially producing a kind of 'back-stress' that may, in certain cases, be largely independent of wake contact force). This is a fundamental change in the way that plasticity-induced fatigue crack closure is considered. Furthermore, it is one which sheds light on the reasons why compliance-based closure measurements are reasonably effective in assessing crack closure, despite their acknowledged interpretative difficulties [James (1997)]. It is recognised that the relationship (or lack thereof) between wake contact force and effective stress intensity factor will be a strong function of material properties, such as elastic modulus.
5. Direct observations of the strains within the plastic zone surrounding a crack were made and a new understanding was gained regarding the manner in which crack wake contact exerts an influence over the stress field in the elastic material that makes up the bulk of a cracked component.

6. A mathematical model of the stresses near a crack tip was developed that includes both far-field stress effects and crack wake contact. This model is a closer approximation of the stress field actually existing in the vicinity of a crack tip than any previously fitted to photoelastic fringe patterns and is the first to include two load events simultaneously, that is both a crack tip load and wake contact force.
7. Fringe patterns were obtained from photoelastic coatings applied to the surface of aluminium specimens in which fatigue cracks were subsequently developed. Similar fringe patterns were observed to those seen in polycarbonate specimens. This confirms the validity of using polymers to study fatigue crack development and closure effects, at least under certain specific conditions, even though the majority of structures are metallic.
8. Software has been developed which automatically optimises fitting the theoretical analysis to the experimental fringe patterns, and calculates crack tip K values.

Research Impacts and Beneficiaries

The Universities of Plymouth and Sheffield benefit directly from the development of these innovative techniques in their laboratories. These are available for application to future industrially relevant research projects. They have also gained experience of the difficulties associated with the photoelastic characterisation of closure, and have developed more powerful automated analysis techniques than envisaged in the grant application. They are hence in a leading position internationally, to make rapid progress in future research dealing with more complex loading conditions, or metallic specimens. The insights gained into the mechanism of plasticity-induced crack closure, and into the applicability of compliance-based measurements in characterising it, materially impact on the directions of future research in their laboratories, and in DERA. This will lead to the potential for improved life prediction, with concomitant benefits for society, in terms of safety, better use of resources etc.

The publication of the results has also enhanced their international reputations as centres of research for experimental fatigue crack analysis. Both Universities have also individually benefited from their collaboration on this project through the cross-fertilisation of ideas and experimental techniques. There is little doubt that neither University could have over-achieved on the original aims of the grant working individually. Parts of the work has been presented at a number of conferences and seminars, or published/submitted to international journals. Web-sites have also been established that present some of the results and give a brief description of the work. These are accessible by any interested party, whether academic or industrial.

Through their regular meetings with the investigators, DERA Farnborough have had access to research output during the course of the project and have, in common with EPSRC, a detailed record of the results. BAE Systems took a close interest in the research during its progress and have been aware of the results obtained.

The research fellow employed on the grant, Dr. Mark Pacey, has benefited from the significant expansion of his knowledge and understanding of both experimental mechanics and fatigue crack growth. He has also gained valuable experience of project management and collaborative working, which has led to an immediate job offer (Cummins Engine Company).

Further Research and Dissemination Activities

The techniques developed for this project may be applied to a range of experimental fracture mechanics problems and the way is opened for a better understanding to be gained of stress ratio effects, of single cycle overload problems, of mixed-mode problems and of fatigue under variable amplitude loading. Application of more sophisticated mathematical stress field models that include elastic-plastic behaviour could further improve the results by making the model an ever-closer approximation of an actual cracked component. A second grant application is being submitted, which draws on the expertise of Oxford University in this respect, and continues the collaboration between DERA, Sheffield and Plymouth.

Some exploratory work was performed on the use of synchrotron strain analysis to measure fatigue crack closure through the thickness of an aluminium specimen. This work showed that there is potential for this kind of analysis to be used in this application and there is considerable scope for further work in this field. A direct beam-time application has been submitted to the SRS at Daresbury, in collaboration with the Materials Science Centre at the University of Manchester to further explore the potential of this technique, with a view to a full EPSRC grant application.

As noted earlier in this report, there is substantial USAF interest in this area and arrangements are being made to present the results of this work to personnel at the Air Force Materials Laboratory, Wright-Paterson AFB, and to academics at Purdue University during 2001.

References

Budiansky, B. and Hutchinson, J. W., 1978, Analysis of Closure in Fatigue Crack Growth, *Journal of Applied Mechanics*, **45**, 267-276

Donald, J. K., 1999 Introducing the Compliance Ratio Concept for Determining Effective Stress Intensity, *International Journal of Fatigue* **19 (S1),** S191-S195

Elber, W., 1970, Fatigue Crack Closure Under Cyclic Tension, *Engineering Fracture Mechanics,* **2** 37-45

James, M. N. and Knott, J. F., 1985, An Assessment of Crack Closure and the Extent of the Short Crack Regime in Q1N (HY 80) Steel, *Fatigue and Fracture of Engineering Materials & Structures,* **8 No. 2**, 177-191

James, M. N., 1997, Some Unresolved Issues with Fatigue Crack Closure – Measurement, Mechanism, and Interpretation Problems. *Advances in fracture research* Karihaloo BL, et al. editors. Proceedings of the Ninth International Conference on Fracture, Sydney, Australia, **5** Amsterdam: Pergamon Press, 2403-14

Newman, J. C., Jr., 1981, A Crack-closure Model for Predicting Fatigue Crack Growth under Aircraft Spectral Loading, in *Methods and Models for Predicting Fatigue Crack Growth under Random Loading, ASTM STP 748*, eds. Chang, J. B. and Hudson, C. M., American Society for Testing and Materials, 53-84