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Applying Fatigue Research to Engineering Design

REFERENCE Smith, I. F. C., **Applying Fatigue Research to Engineering Design,** *The Behaviour of Short Fatigue Cracks*, EGF Pub. 1 (Edited by K. J. Miller and E. R. de los Rios) 1986, Mechanical Engineering Publications, London, pp. 15–26.

ABSTRACT This paper reviews some crack initiation and short crack propagation models, and examines their impact on engineering design methods. Many industries are not able to use some proposals due to a lack of relevant information and inspection difficulties. Further work is needed in many areas. When fatigue research is planned and carried out, recognition of practical applications is important for the development of rational design guidelines.

Introduction

Considerable differences exist between a scientific investigation and an engineering design. Frequently, a scientific investigation is motivated by a need to explain observed behaviour. Usually, the investigation concentrates on a comparison of theoretical models with average experimental data. After an iterative process of adjustments to the model(s) and further testing, the investigation concludes whether or not the theory agrees with the experimental data. In this way, a greater understanding of fatigue behaviour is achieved.

An engineering design is motivated by a demand for a structure or a component, and design models are based upon upper or lower bounds of test data. The designer begins with simple models using approximate methods. If the component is fatigue sensitive, a more sophisticated assessment is performed and testing may be carried out. The goal of most engineering designs is to achieve a high probability of survival at low cost. Figure 1 is a schematic showing the base-line differences between a scientific investigation and an engineering design.

Considering such differences, it is understandable that a model which performs well during a scientific investigation may not necessarily improve an engineering design. For example, a fatigue assessment of a surface scratch of average depth on a given component may require a sophisticated short crack analysis. However, a deeper scratch which can be assessed satisfactorily using a simpler model may determine the fatigue life.

The significance of recent fatigue research has been discussed previously for specific design philosophies **(1)(2)**. Generally, it is assumed that specialists are available to perform the fatigue assessment. However, many fatigue

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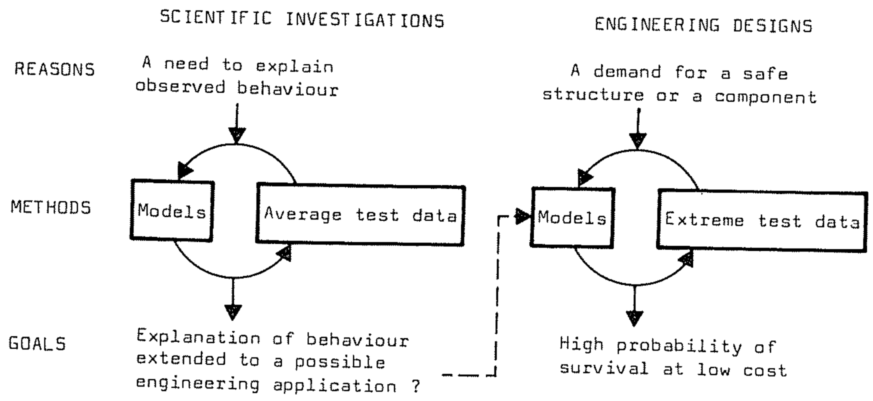

Fig 1 **Typical base-line characteristics of scientific investigations and engineering designs**

sensitive components and structures are not assessed by design specialists. For example, cranes, ships, engine components, farm machinery, pressure vessels, bridges, marine structures, and automotive parts may be assessed by an engineer who has only a rudimentary knowledge of fatigue, Fig. 2. Such designers invariably rely on design guidelines in order to carry out the fatigue assessment. Many of these documents recommend the use of empirical relationships which bear little resemblance to the theoretical models currently examined in scientific investigations.

Over the past thirty years, much fundamental work has increased our understanding of the mechanisms which determine the fatigue life of engineering materials and structures. Advances have been reported within three research areas: fatigue crack nucleation, short crack growth, and long crack propagation. The next thirty years should be a period where these advances are consolidated into guidelines for general use by design engineers. However, a useful synthesis of these three fields, followed by the drafting of design guidelines for a range of design problems, will be difficult to achieve.

This paper reviews some models proposed for crack initiation and short crack behaviour and investigates their applicability to engineering problems. The conditions necessary for new design guidelines are discussed and opportunities for further work are identified.

Terminology

Fatigue terminology varies widely among scientists and engineers. Certain definitions are assumed in this paper; in order to avoid confusion, a short list of terms is given below.

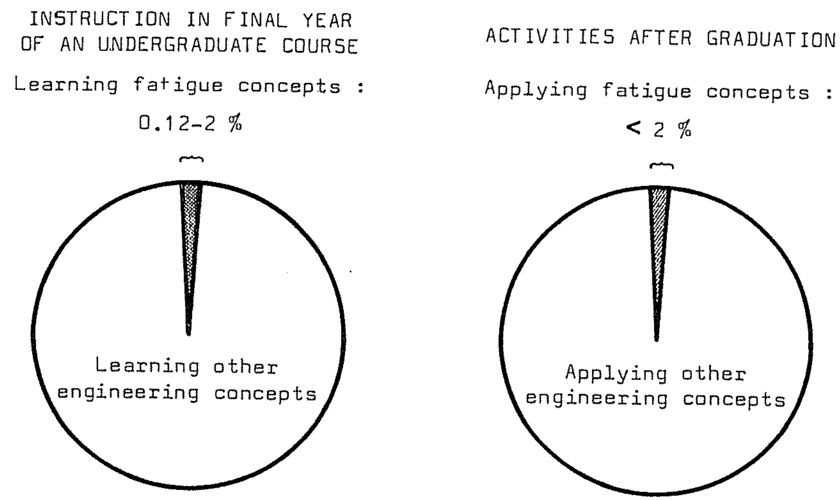

Fig 2 **A designer's exposure to fatigue concepts**

Crack: a sharp discontinuity which grows in size upon application of fatigue loading. This loading must exceed a critical level determined by stresses, environment, material properties, and geometrical parameters.

Crack initiation: the fatigue life resulting from a strain-controlled fatigue test of a smooth unnotched specimen.

Crack nucleation: the fatigue life expended in the formation of a crack.

Designer: an engineer whose exposure to fatigue concepts may be described by Fig. 2. Such engineers use design guidelines for fatigue assessments.

Design guidelines: standards, recommendations, directives, handbooks, notes, specifications, requirements, commentaries, and codes published by international, national, industrial, private, and professional organizations. Drafting committees are made up of fabricators, consultants, contractors, suppliers, inspection experts, and design specialists.

Design specialist: an engineer or scientist with research experience. A specialist should be competent to evaluate and use models proposed in the scientific literature and to provide technical input during the drafting of design guidelines.

Long crack propagation (LCP): fatigue crack growth which is similar to the behaviour described by linear elastic fracture mechanics (LEFM). Near-threshold crack growth, measured using standard LCP specimens, and crack growth in the elastic region of the material affected by a notch is included in this definition.

Short crack propagation (SCP): fatigue crack growth which cannot be described by LEFM.

Fatigue research

Early fatigue research concentrated on empirical correlations based on component testing. Over 100 years ago, the use of laboratory specimen testing began to replace full scale tests, thus introducing the similarity (similitude) problem and the subsequent need for representative models. Early models such as the stress range–fatigue life relationship, the Goodman diagram, the fatigue reduction factor and Miner's rule were developed. These relationships still enable satisfactory fatigue assessments in many situations. Nevertheless, fatigue failures still occur and economic pressures for efficient designs remain strong. In addition, new challenges such as energy conservation and increased litigation risks have further encouraged modern fatigue research.

For many years, crack nucleation and LCP remained separate and distinct disciplines with specific applications for particular structures, components, and materials. During the past decade, SCP studies have provided opportunities to unify the two disciplines. To date, the relative roles of crack nucleation, SCP, and LCP are not clear for a range of components. However, many studies have provided proposals and some models are reviewed below.

Crack initiation

Many models have been proposed for crack nucleation and early crack growth. Each approach has its own set of definitions and corresponding applications. The strain-controlled fatigue life of a smooth unnotched specimen, crack initiation, is the basis of many engineering models. The model described herein was chosen due to the large amount of design-oriented research which supports its application.

The principal parameter, strain range, was originally studied by Bauschinger around 1880. In the 1950s, it was revived independently by Manson and Coffin for use in low-cycle fatigue. This parameter is divided into plastic and elastic strain components in a formula which includes fatigue life. These two components contribute to 'damage' which accumulates until failure occurs. When plasticity is negligible, this formula simplifies to the relationship proposed by Basquin in 1910. The Manson–Coffin formula, sometimes known as the low-cycle fatigue equation, has formed the foundation for many subsequent studies and became the subject of an ASTM standard in 1977.

Researchers in this area have studied cyclic stress–strain behaviour, notch analysis, temperature effects, mean stress, variable amplitude modelling, and computer simulation using a wide range of materials. Important contributions include the determination of the cyclic stress–strain curve, cumulative damage rules, approximations of the cyclic strain at a stress concentration, and the development of sophisticated testing systems. References (**3**) and (**4**) are detailed reviews. The development of a formula which determines the fatigue strength reduction factor for rough surfaces is a recent advance (**5**).

Limitations of crack initiation models include difficulties associated with the definition of 'damage', high-cycle fatigue, surface roughness, corrosion, and multiaxial effects (**3**). Also, the percentage of crack initiation spent in SCP is not included in most test data. Proposals for the crack length of a so-called initiated crack vary from zero to several millimetres. Such lengths depend upon the crack growth model which is used to calculate the remaining fatigue life.

Short crack propagation

SCP models were developed to give a more detailed description of the 'damage' modelled by the crack initiation approach. Short cracks may be microstructurally short due to material characteristics, or mechanically short due to crack tip conditions which are mechanically different from those characteristic of long cracks, e.g., plasticity, crack closure, etc. Often, these two types of SCP were not studied independently and much confusion exists in the literature. Nevertheless, microstructurally short cracks usually dominate when cracks are less than a few grain diameters long and when they are subject to stress ranges near the fatigue limit. On the other hand, mechanically short cracks can be several millimetres in length and they are most obvious when the cyclic stresses are much higher than the fatigue limit.

Frost (**6**) recognised the importance of microstructurally short cracks before 1960 in his study of non-propagating fatigue cracks. He defined a minimum crack length 'of the order of the grain size' where the propagating stress no longer varied with crack length, but converged on the fatigue limit. Kitagawa and Takahashi (**7**) attempted to obtain data missing from Frost's original study, thereby examining SCP in the absence of bulk plasticity. These studies aroused considerable interest in the behaviour of short cracks at stress ranges near the plain fatigue limit.

Amplified growth rates due to bulk plasticity were modelled in 1965 by Boettner *et al.* (**8**) who proposed a strain intensity factor which accounted for cracks growing in cyclic plastic strain fields. An approximate analysis showed that if the initial crack length is the same for all conditions, the integration of the growth law results in Coffin's law for crack initiation. This study is believed to be the first attempt to model short crack growth in terms of the product of crack length and an elastic–plastic loading parameter. Later, Pearson (**9**) explored the limitations of LEFM and demonstrated that linear elastic modelling underestimated the growth rates of short cracks.

Since these early studies, theoretical models have been proposed by many researchers. Table 1 contains a list of investigations grouped into three categories according to the type of model used and the principal parameters considered. The majority of the models in Categories 1 and 3 describe microstructurally short cracks, whereas Category 2 is concerned mainly with mechanically short cracks.

Table 1 Models for short crack propagation

Category	*Parameters*	*References*
① Modified elastic fracture mechanics	$\Delta K_{th}(a)$	(7)(10)
	$\sqrt{(D\rho)}$	(11)–(13)
	l_o	(14)–(17)
	ΔK_{eff}	(15)(18)
	$f(\Delta\sigma) + f(\Delta K)$	(19)
② Elastic–plastic growth models	CI*	(20)–(24)
	$\Delta K(\Delta\varepsilon)$	(8)(22)(25)(26)
	$\Delta K_{eff}(\Delta\varepsilon)$	(24)
	ΔJ	(26)–(29)
	$\gamma_p^2 a$	(30)
③ Microstructural fracture mechanics	$(d - a)^{1-\alpha} a_\alpha$	(31)
	$\Delta K^n \left\{1 - k(\Phi)\left(\frac{D - 2X}{D}\right)^m\right\}$	(32)
	$\frac{\tau(L - a)}{L}$	(33)
	$\tau\sqrt{(aR)}$	(34)
	$R\,\Delta\varepsilon_p^{1/c}$	(35)

* CI: Crack initiation model is used to represent the growth of short cracks to some crack length.

Most investigations are placed in either Categories 1 or 2. In Category 2 the first parameter, CI, refers to studies which employed the crack initiation model to represent short crack growth. Some proposals account for both microstructurally and mechanically short cracks using unified models. For example, Cameron and Smith **(22)** suggest that the crack initiation model, CI, can represent crack lengths smaller than the constant, l_0 **(14)**, and a strain based approach **(25)** is proposed for longer cracks. Others studies concentrated on only one type of SCP. A comprehensive study of the merits of these models is hindered by a lack of compatible data, although attempts have been made for some proposals **(13)(24)(26)(35)–(37)**.

The characteristics of the parameters employed differ from category to category. In Category 1, they are far field or global values and consequently, they can be determined simply. In order to give greater accuracy in non-elastic cases, Category 2 models require the knowledge of an elastic–plastic parameter. This demands a more detailed analysis than prescribed by the models in Category 1. Category 3 introduces parameters such as grain size, d, and grain orientation, Φ, in order to model cracks less than a few grain diameters in length. In a recent review, Miller **(38)** has proposed that crack nucleation occurs immediately, and thus the fatigue limit is defined by a crack growth threshold which is determined by microstructural parameters.

The impact of SCP models on fatigue design assessments

The fatigue strength calculation completes only part of a fatigue design. Figure 3 gives an example of the amount of design time spent evaluating the fatigue strength in relation to other factors. Uncertainty in loading data and material properties as well as the effect of the consequences of failure, the costs, quality assurance, and in-service monitoring must be taken into account. Note that in considering these factors, a designer employs less than 2 per cent of his total design time, see Fig. 2.

One design criterion is the verification of a certain probability that the effect of fatigue loading is less than the fatigue strength – at minimum cost. The consequences of failure usually determine the required probability of survival. Consideration of both this criterion and the characteristics of the factors in Fig. 3 may preclude a rational use of SCP models. For example, the loads may be so poorly defined that increased sophistication in the fatigue strength calculation changes neither the probability of survival nor the final cost of the component.

The occurrence of SCP

Another difficulty may arise upon identifying those cases when short crack behaviour should be expected. Many welded structures contain large discontinuities and suffer low service stresses, and thus it is easily determined that no short crack analysis is needed. Other cases are not as clear.

For example, the fatigue critical discontinuity is usually the deepest discontinuity in a notch and its depth may be more than five times the centre-line

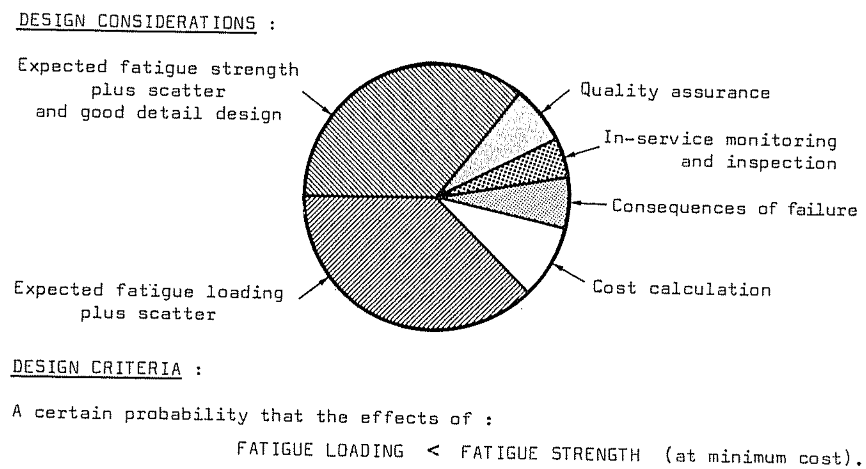

Fig 3 An example of the relative importance of various considerations in a fatigue design assessment

average value measured at the same location. Furthermore, this discontinuity may have a root radius of less than one micron (**39**). It is not known if there is a relationship between surface roughness and the deepest discontinuity for a range of materials and surface finishes.

Another case is related to the service conditions of the component. Machined components become worn, scratched, and corroded during service due to fretting, poor lubrication, misuse, scouring, corrosive attack, etc. A SCP model may not be applicable to the fatigue strength calculation if the component is exposed, accidentally or otherwise, to service conditions which introduce surface discontinuities.

Nevertheless, improvements in fabrication techniques, load analyses, stress measurement, quality assurance, and new design methods are increasing the number of situations where SCP models are useful design tools.

Design methods and SCP models

A damage tolerant design method (fail-safe, fitness for purpose, etc.) provides the greatest justification for the application of propagation models to life and remaining life calculations. Designs are improved by emphasising quality assurance and in-service inspection, Fig. 3. These methods use data taken from measurements on the actual component and, as a result, a more precise estimate of its behaviour under fatigue loading is possible. In addition to improving fatigue strength calculations, damage tolerant design methods enable great flexibility during quality evaluation and structural repair.

Unfortunately, advances in related fields, such as crack detection, do not coincide with the development of SCP models. Accounting for human error, present non-destructive inspection (NDI) technology is rarely able to detect discontinuities which behave as short fatigue cracks. Previous papers (**1**)(**2**)(**40**) have discussed the significance of NDI with respect to damage tolerance design.

SCP models may be useful when a design method *other* than damage tolerant design is employed. Accurate models are essential when the similitude of existing data is in doubt and prototype testing under service loading is not practicable. Also, SCP models may provide important design tools even if they are not directly used in the fatigue strength calculation. For example, SCP models can be useful for selecting materials, changing existing designs and approximating inspection intervals. In these cases, the initial crack size need not necessarily be detectable by NDI.

Guidelines for fatigue design assessments

The options available to a designer are limited by the sophistication of design guidelines. Some of these guidelines are based on the stress range–cycle life approach developed by Wöhler over 100 years ago, e.g., (**41**).

Simple LEFM calculations often result in very conservative life predictions; they can be more than an order of magnitude less than test results. This is especially true for high-cycle fatigue. Although LCP guidelines have existed for some years, e.g., (**42**), only a small amount of design information exists for near-threshold crack growth at stress concentrations.

One recent attempt to draft LCP guidelines resulted in a list of warnings against misuse (**43**). This document recognises that in many large steel structures, information concerning load levels, lack of fit, thermal stresses, differential settlement, and fabrication stresses is unavailable. Thus, it is recommended that all applied compressive loading is included in the analysis and that the intrinsic threshold stress intensity is used in calculations – unless the mean stress can be determined. Additional prudence is recommended for other factors such as plasticity, stress analysis, variable amplitude loading, and crack size.

Some studies have examined the importance of SCP by identifying those cases where SCP can be ignored, even though it occurs. For example, Taylor and Knott (**44**)(**45**) have suggested an inherent discontinuity equal to the deepest influence of microstructurally short crack effects. Cameron and Smith (**22**) have identified cases where LEFM calculations do not change the fatigue life by more than 50 per cent.

In general, greater sophistication can be hindered by cautious drafting committees which rely more upon the practical experience of their members than upon the conclusions of scientific investigations. Design specialists are often in a minority on drafting committees.

Before changes are made in any guideline, most committees wish to establish that:

- present engineering practice is unsafe, costly, or inappropriate;
- an easier way does not exist;
- the principles behind the change can be explained in simple terms;
- the change is acceptable to designers.

Short crack investigations which establish these points are rare. The absence of such information contributes to a lack of understanding between the scientist and the designer.

Further work

Despite concentrated research activity, little information is filtering down to the non-specialist. Further work is needed in many fields before design guidelines can be written. Without guidelines, many industries cannot profit from recent progress. A short list of possible research topics is given below.

LCP topics requiring further work include:

- crack growth laws and material constants in the near-threshold crack growth regime;

- a compendium of stress intensity factors for surface cracks in engineering notches, including various welded joints and bolted assemblies;
- experimental methods for the determination of the threshold stress intensity factor;
- crack retardation and acceleration due to variable amplitude loading;
- the intrinsic threshold stress intensity factor;
- the effect of residual stresses at notches;
- crack growth from notches for numerous stress ratios;
- crack growth at high and low temperatures;
- crack growth laws for corrosion enhanced fatigue crack growth, etc.

Considering the amount of research which is needed in the domain of LCP, it is understandable that much work on SCP remains to be completed. Some of the more practical areas include:

- surface finish and initial discontinuities;
- comparative studies of SCP models and the crack lengths at which they are relevant;
- identification of situations when LEFM cannot be used;
- elastic–plastic stress analysis for cracked geometries;
- short crack growth and variable amplitude loading;
- experimental data for a range of materials and environments;
- the influence of fabrication processes;
- identification of relevant microstructural units for a range of materials, etc.;
- statistical analysis.

In the future, the importance of crack propagation models will increase with technical developments and greater expertise in related fields such as:

- non-destructive inspection technology;
- fatigue loading, impact, and vibration;
- stress analysis;
- in-service monitoring;
- safety and reliability analysis, etc.

Conclusions

Although many new models are proposed for calculating fatigue strength, designers are rarely able to make use of them. Scatter in design parameters and service conditions may not justify increased sophistication. Damage tolerent design methods have improved the significance of SCP and LCP models but frequently, crack lengths cannot be detected reliably. Nevertheless, the significance of new models will increase with improved fabrication methods and advances in related fields. Research which considers the information necessary for drafting design guidelines will help many industries exploit the possibilities offered by modern fatigue research.

Acknowledgements

The paper was funded by the Swiss National Science Foundation. The author is grateful to Professor M. A. Hirt for helpful discussions and to the staff at ICOM for their help in the preparation of the document.

References

(1) WANHILL, R. J. H. (1981) Some case studies and the significance of fatigue thresholds, *First International Conference on Fatigue Thresholds*, Stockholm (EMAS, Warley, UK), pp. 953–965.
(2) SCHIJVE, J. (1984) The practical and theortical significance of short cracks. An evaluation, *Fatigue 84* (University of Birmingham, UK), pp. 751–771.
(3) MORROW, J. and SOCIE, D. F. (1981) The evolution of fatigue crack initiation life prediction methods. Materials, experimentation and design in fatigue, *Proceedings of Fatigue 81* (Westbury House, Guildford, UK), pp. 3–21.
(4) COFFIN, L. F. (1984) Low cycle fatigue – A thirty year perspective, *Fatigue 84* (University of Birmingham, UK), pp. 1213–1234.
(5) LAWRENCE, F. V., HO, N. J., and MAZUMDAR, P. K. (1980) Predicting the fatigue resistance of welds. Fracture Control Program, Report No 36, University of Illinois, USA.
(6) FROST, N. E. (1959) A relation between the critical alternating propagation stress and crack length for mild steel, *Proc. Instn mech. Engrs*, **173**, 811–827.
(7) KITAGAWA, H. and TAKAHASHI, S. (1976) Applicability of fracture mechanics to very small cracks or the cracks in the early stage, *Proceedings of the Second International Conference on the Mechanical Behaviour of Materials*, Boston, USA, pp. 627–631.
(8) BOETTNER, R. C., LAIRD, C., and McEVILY, A. J. (1965) Crack nucleation and growth in high strain-low cycle fatigue, *Trans. Met. Soc. AIME*, **233**, 379–385.
(9) PEARSON, S. (1975) Initiation and fatigue cracks in commercial aluminium alloys and the subsequent propagation of very short cracks, *Engng Fracture Mech.*, **7**, 235–247.
(10) ROMANIV, O. N., SIMINKOVICH, V. N., and TKACH, A. N. (1981) Near-threshold short fatigue crack growth, *First International Conference on Fatigue Thresholds*, Stockholm (EMAS, Warley, UK), pp. 799–807.
(11) SMITH, R. A. and MILLER, K. J. (1977) Fatigue cracks at notches. *Int. J. Mech. Sci.*, **19**, 11–22.
(12) CAMERON, A. D. and SMITH, R. A. (1981) Upper and lower bounds for the lengths of non-propagating cracks, *Int. J. Fatigue*, **3**, 9–15.
(13) HUSSEY, I. W., BYRNE, J., and DUGGAN, T. V. (1984) The influence of notch stress field on the fatigue crack growth threshold condition, *Fatigue 84* (University of Birmingham, UK), pp. 807–816.
(14) EL HADDAD, M. H., SMITH, K. N., and TOPPER, T. H. (1979) Fatigue crack propagation of short cracks, *J. Engng mater. Tech.*, **101**, 42–46.
(15) TANAKA, K. and NAKAI, Y. (1983) Propagation and non-propagation of short fatigue cracks at a sharp notch, *Fatigue Engng mater. Struct.*, **6**, 315–327.
(16) HARKEGARD, G. (1981) An effective stress intensity and determination of the notch fatigue limit, *First International Conference on Fatigue Thresholds*, Stockholm (EMAS, Warley, UK), pp. 867–879.
(17) DUGGAN, T. V. (1981) Influence of notch-geometry on fatigue threshold, *First International Conference on Fatigue Thresholds*, Stockholm (EMAS, Warley, UK), pp. 809–826.
(18) LIAW, P. K. and LOGSDON, W. A. (1985) Crack closure: an explanation for small fatigue crack growth behaviour, *Engng Fracture Mech.*, **22**, 115–121.
(19) SAXENA, A., WILSON, W. K., ROTH, L. D., and LIAW, P. K. (1985) The behaviour of small fatigue cracks at notches in corrosive environments, *Int. J. Fracture*, **28**, 69–82.
(20) SOCIE, D. F., MORROW, J., and CHEN, W. C. (1979) A procedure for estimating the total fatigue life of notched and cracked members, *Engng. Fracture Mech.*, **11**, 851–860.
(21) MAZUMDAR, P. K., CHEN, W. C., and LAWRENCE, F. V. (1981) An analytical study of the fatigue notch effect, *First International Conference on Fatigue Thresholds*, Stockholm (EMAS, Warley, UK), pp. 845–865.

(22) CAMERON, A. D. and SMITH, R. A. (1982) Fatigue life prediction for notched members, *Int. J. Pres. Ves. Piping*, **10**, 205–207.

(23) DOWLING, N.E. (1979) Fatigue at notches and the local strain and fracture mechanics approaches, *ASTM STP 677*, pp. 247–273.

(24) LEIS, B. N. (1985) Displacement controlled fatigue crack growth in inelastic notch fields: implications for short cracks, *Engng Fracture Mech.*, **22**, 279–293.

(25) EL HADDAD, M. H., SMITH, K. N., and TOPPER, T. H. (1979) A strain based intensity factor solution for short fatigue cracks initiating from notches, *ASTM STP 677*, pp. 274–289.

(26) STARKEY, M. S. and SKELTON, R. P. (1982) A comparison of the strain intensity and cyclic J approaches to crack growth, *Fatigue Engng mater. Struct.*, **5**, 329–341.

(27) DOWLING, N. E. (1977) Crack growth during low-cycle fatigue of smooth axial specimens, *ASTM STP 637*, pp. 97–121.

(28) EL HADDAD, M. H., DOWLING, N. E., TOPPER, T. H., and SMITH, K. N. (1980) J integral applications for short fatigue cracks at notches, *Int. J. Fracture*, **16**, 15–30.

(29) OBRTLIK, K. and POLAK, J. (1985) Fatigue growth of surface cracks in the elastic-plastic region, *Fatigue Fracture Engng Mater. Structures*, **8**, 23–31.

(30) IBRAHIM, M. F. E. and MILLER, K. J. (1980) Determination of fatigue crack initiation life, *Fatigue Engng Mater. Structures*, **2**, 351–360.

(31) HOBSON, P. D. (1982) The formulation of a crack growth equation for short cracks, *Fatigue Engng Mater. Structures*, **5**, 323–327.

(32) CHAN, K. S. and LANKFORD, J. (1983) A crack-tip strain model for the growth of small fatigue cracks, *Scripta Met.*, **17**, 529–532.

(33) DE LOS RIOS, E. R., TANG, Z., and MILLER, K. J. (1984) Short crack behaviour in a medium carbon steel, *Fatigue Engng Mater. Structures*, **7**, 97–108.

(34) DE LOS RIOS, E. R., MOHAMED, H. J., and MILLER, K. J. (1985) A micro-mechanics analysis for short fatigue crack growth, *Fatigue Fracture Engng Mater. Structures*, **8**, 49–63.

(35) REGER, M., SONIAK, F., and RÉMY, L. (1984) Propagation of short cracks in low cycle fatigue, *Fatigue 84* (University of Birmingham, UK), pp. 797–806.

(36) SURESH, S. and RITCHIE, R. O. (1984) Propagation of short fatigue cracks, *Int. Met. Rev*, **29**, 445–476.

(37) LANKFORD, J. (1985) The influence of microstructure on the growth of small fatigue cracks, *Fatigue Fracture Engng Mater. Structure*, **8**, 161–175.

(38) MILLER, K. J. (1984) Initiation and growth rates of short fatigue cracks, *Fundamentals of deformation and fracture* (Cambridge University Press, UK), pp. 477–500.

(39) SMITH, I. F. C. (1982) *Fatigue crack growth in a fillet welded joint*, Ph.D. thesis, Cambridge University.

(40) WANHILL, R. J. H. (1984) Engineering significance of fatigue thresholds and short fatigue cracks for structural design, *Fatigue 84* (University of Birmingham, UK), pp. 1671–1681.

(41) BS 5400: Part 10 (1980) *Steel, concrete and composite bridges, Code of practice for fatigue* (British Standards Institution, London).

(42) BSI PD 6493 (1980) *Guidance on some methods for the derivation of acceptance levels for defects in fusion welded joints* (British Standards Institution, London).

(43) Recommendations for the Fatigue Design of Steel Structures, European Convention for Constructional Steelwork (1985). Avenue Louise 326, Bte 52, B-1050 Brussels, Belgium.

(44) TAYLOR, D. and KNOTT, J. F. (1981) Fatigue crack propagation behaviour of short cracks; the effect of microstructure, *Fatigue Engng Mater. Structures*, **4**, 147–155.

(45) TAYLOR, D (1982) Euromech Colloquium on short fatigue cracks, *Fatigue Engng Mater. Structures*, **5**, 305–309.