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Combined action of crack closure and residual stress under periodic overloads: A fractographic analysis ☆

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ABSTRACT

The close relationship between sequence-sensitive near-tip residual stress and threshold stress intensity raises questions about load interaction models currently in use to estimate fatigue crack growth under variable amplitude loading. In an attempt to address them, experiments were performed on an Al–Cu alloy under specially designed load sequences with periodic overloads. Fractographic evidence from these tests confirms that fatigue crack closure, together with sequence sensitive variation in threshold stress intensity appear to explain all observed results. The fractographic data provide quantitative inputs for improved modeling of variable-amplitude fatigue, particularly at near-threshold crack growth rates. This study appears to suggest that conventional approaches based on the Wheeler and Willenborg residual stress models can provide reasonable estimates only by coincidence. They model the wrong parameter at lower fatigue crack growth rates and may simply not be valid at other growth rates.

1. Introduction

Engineering fatigue crack growth estimates are made using software built around one of three models of overload induced retardation. Of these the Wheeler model [1] and the Willenborg model [2] attribute retardation to residual compressive stress in the overload plastic zone, while Elber's plasticity induced crack closure model [3] relates it to increased crack opening stress intensity, K_{op}, due to the stretched wake caused by crack extension into the overload plastic zone. These two approaches essentially model entirely different and unrelated phenomena, yet, are both, claimed to be reasonably accurate in estimating spectrum load fatigue crack growth rates. More recently, an empirical relationship was established between ΔK_{th} and near-tip residual stress, σ^* [4]. The relationship reflects sensitivity of diffusion kinetics of active species and through it, atmospheric fatigue thresholds, to σ^* [5]. As σ^* is determined by hysteretic stress–strain response within the cyclic plastic zone, it must follow that ΔK_{th} is also cycle-sequence sensitive. Thus, ΔK_{th} is not a material constant. Its value for the next rising load half cycle will depend on the preceding peak-valley load excursion. In contrast, the Wheeler and Willenborg models consider the *monotonic* plastic zone response. σ^* reflects *cyclic* plastic zone response, that is ignored by models used in engineering practice.

The objective of this study was to assess the individual role of K_{op} and σ^* on near-threshold variable-amplitude fatigue. This is a fractographic study using specially designed load sequences with periodic overloads to serve both as sources of controlled K_{op} and σ^* as well as of direct fractographic evidence in the form of marker bands from which unambiguous conclusions may be drawn.

The next section describes the rationale behind the experiments. This is followed by details of the experimental procedure including the specially designed load sequences used in the tests. Fractographic data obtained from the tests are presented with a discussion of how they tie up with expected response from the different models in question.

1.1. Interpretation of the overload effect

Details of how exactly a particular crack growth model works may not be obvious from the table of computed results put out by the software that is built around it. However, one can draw important conclusions about the credibility of individual models from how each one handles the simple case of an overload cycle inserted into a constant amplitude load sequence.

Fig. 1 schematically describes the expected transient process following an overload cycle as interpreted by different models.

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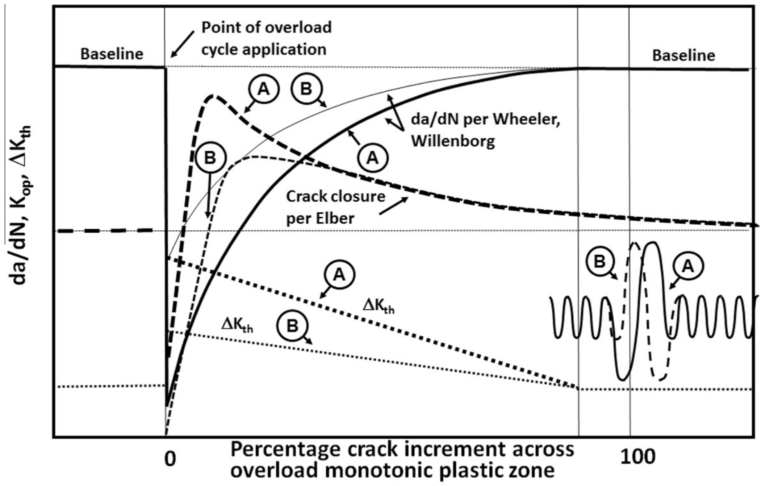

Fig. 1. Schematic interpretation of the overload effect. Overload cycle shown as inset with peak following valley (A) and valley following peak (B). Continuous lines show expected crack growth rate versus incremental crack extension for cases A and B according to Wheeler and Willenborg models [1,2]. Broken lines show transient response according to crack closure model [3]. Dotted lines show expected transient of ΔK_{th}.

The inset describes the two possible peak-valley combinations A and B. The magnitude of the overload cycle in both cases is identical, however the peak follows the valley in A, whilst the sequence is reversed in B. It is important to see how different models handle greater retardation seen in case of A.

Variation in response of the parameter being modeled is plotted in Fig. 1 against percentage fraction of the monotonic overload plastic zone traversed by the crack tip. The Wheeler model directly approximates crack growth rate retardation ratio as an exponential function of 'transient plastic zone ratio'. This is the ratio of the distance from the crack tip to the boundary of the plastic zone associated with the current load cycle, to that, associated with the tensile overload. This ratio will be initially very small, then exponentially tend towards unity as the boundary of the plastic zone due to the current load approaches the overload plastic zone boundary. The model attributes retardation to compressive residual stress within the *monotonic* plastic zone that is overload peak-valley sequence as well as overload stress ratio *independent*. Therefore, the Wheeler model *cannot in principle*, discriminate between overload cases A and B. Exponents for the Wheeler model need 'adjustment' to suit observed results as illustrated by the thick and thin continuous lines respectively in Fig. 1.

The Willenborg model proceeds on the premise that the transient plastic zone ratio causes proportional compressive residual stress inducing a downward shift in the effective stress variation seen by the crack tip. The effective maximum and minimum stress are truncated at zero. Until such an eventuality, the crack tip is deemed to see a reduced "effective" stress ratio. Beyond this point it also sees a truncated load range, much like a closed crack. In principle, unlike the Wheeler model, the Willenborg model does not require any empirical exponent because it operates directly on ΔK and R_{eff}. However, given the modifications introduced in later adaptations, the transient da/dN may be treated as similar to the one shown in Fig. 1 for the Wheeler model, with the possible exception of a change in slope associated with switch from truncated to full ΔK. Like the Wheeler model and for the same reason, the Willenborg model also does not discriminate between cases A and B.

As shown in Fig. 1, for both the Wheeler and Willenborg models, transient crack growth rate response terminates even before the crack tip crosses the boundary of the overload plastic zone. Plastic zone size computed for plane stress conditions being three times larger than for plane strain conditions, the simulated transition zone size is also adjustable in modeling by assigning different plastic constraint factors.

The discovery of fatigue crack closure by Elber opened the possibility of modeling overload effects from first principles [3]. Through direct measurements of near-tip compliance, Elber showed that the fatigue crack can remain partially closed even under fully tensile loading. Plasticity induced fatigue crack closure is the consequence of stretched wake coming in contact during the unloading half cycle. The stretch has two components. The main part is the monotonic plastic zone. Also, additional crack-tip stretch at the instant of crack extension by local fracture adds to wake contact. Obviously, crack closure will increase with increasing monotonic plastic zone size. Crack opening stress intensity, K_{op} is often expressed as a constant fraction of K_{max}. Thus, when a tensile overload is applied, K_{op} will tend towards a new, higher value associated with overload-K_{max}. This will demand some crack extension into the overload plastic zone, a necessity reflected in the phenomenon of delayed retardation [6].

Post-overload crack closure response is schematically described by the two broken lines shown in Fig. 1. Of note is the possible subdued decrease in K_{op} for case B, suggestive of reduced delay in crack propagation. Quite to the contrary, one may also argue, that if blunting indeed keeps the crack fully open, early wake contact upon unloading would in fact be promoted rather than avoided by the crack-tip re-sharpening action of case B. Note also, that the transient closure response for the two cases coincides beyond a certain point, underlining the possibility that initial difference if any, is attributable solely to the reduced initial K_{op} in B and given the fact that in both cases, monotonic plastic zone size profile is identical. Our study assumes similar closure levels in both cases for reasons that are forthcoming.

Finally, the closure transient response extends beyond the boundary of the overload plastic zone because of the need for the overload induced wake to move further away from the crack tip before closure returns to baseline levels. Experimental data confirm that post overload retarded growth and increased closure levels can extend beyond the overload monotonic plastic zone [6,7].

The crack closure phenomenon renders delayed retardation inevitable. However, in practice, one often encounters immediate retardation after a tensile overload [8]. This inconsistency unraveled with the discovery of the close relationship between σ^*, and closure free ΔK_{th} [4] as shown in Fig. 2. The procedure for

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