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Improved measurement on probabilistic fatigue limits/strengths by test data from staircase test method

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ABSTRACT

Appropriate approach, local true and/or virtual *S–N* relations deduced maximum likelihood approach (GMLA), is proposed for improving measurement on probabilistic fatigue limits by test data from staircase test method. The test data are distinguished as three cases, i.e. fully paired failure–survival specimens, partial paired plus individual survival specimen(s), and partial paired plus individual failure. Innovative way for deducing fatigue strength data is found by constructing physically paired local *S-N* relations for all test failure or survival specimens. Non-liner exponent law is introduced physically for describing the local relations under addressing the concaved character of fatigue *S–N* curves. The deduced data are determined by addressing physically the fatigue life for defining the test method to assure the strength data distributed orthogonally projection to the life section. Statistical parameters for fatigue limits and key element, the exponent to decide shape of the local relations/curves, are finally solved mathematically from a statistics by a maximum likelihood function for the deduced data from entire test data. Therefore, fatigue limits/strengths relative physics and math have been addressed by the present approach. Two existent approaches, Dixon–Mood approach (DMA) and Zhang–Kececioglu approach (ZKA), are reviewed together with the present approach by checking their effects of treating the test data of railway EA4T axle steel and wheel rim material of CL65 wheel steel. Applications verify that the present approach can give minimum evaluation on standard deviation and appropriate evaluation on average value for fatigue limits. While DMA and ZKA show a bigger evaluation on standard deviation and bias evaluation on average value. Basic case is that their deduced strengths do not address the concaved character and the defined fatigue life. They are not gotten from reasonable locations of local relations so to give the bias evaluation of average value. And they not distributed orthogonally to the life section so to give the bigger evaluation of standard deviations.

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1. Introduction

To fascinate a comprehensive understanding on an appropriate approach for measuring fatigue limits/strengths by the test results from staircase test method, a global review is carried out below on fatigue strengths related achievements in physics and academics.

1.1. Concept of fatigue limits in physics

Fatigue limit is physically defined as fatigue strength of engineering material anti–fatigue damage, below which no fatigue failure occurs. This strength connects always to a special physical background. Four kinds of situations and one character are summarized below:

Material micro–structural barriers. A typical physical phenomenon was observed by a series of tests on carbon steel by Miller et al. [1–4]. The material had a banded ferrite–pearlite structure with a weaker phase of ferrites. Micro–structural barriers were graded into a scaled sequence as $d_1 < d_2 < d_3$. Using a test loading policy of increasing stress ranges as $\triangle\sigma_1 < \triangle\sigma_2 < \triangle\sigma_3 < \triangle\sigma_4 < \triangle\sigma_5$, separately, staircase fatigue limits were shown in Fig. 1 and corresponding crack growth rate curves were shown in Fig. 2. Combined with the test observations, following information was revealed as:

1. Fatigue cracks were initiated from the material weaker phase, ferrites, having orientations similar to maximum shear stress–strain plane under the smallest test stress range of

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Nomenclature

A	cumulative probability density parameter by DMA
B	cumulative offset parameter by DMA
C	confidence
CA	conventional approach
ds	increment of stress amplitude
DESFC	dominate effective short fatigue crack
DMA	dixon–Mood approach
ESFCs	effective short fatigue cracks
$F(\cdot)$	transition function of the likelihood function $L(\cdot)$
F_{BA}	normalized offset parameter by DMA
GMLM	general maximum likelihood method
$k(P,1-C,n_s)$	coefficient of one–sided tolerance limit of a normal distribution
k' $(P, 1-C, n_s)$	the equivalent coefficient of $k(P,1-C,n_s)$
l	number of specimens for fatigue limit tests
MLM	maximum likelihood method
n	number of specimens in the less frequent event at a stress amplitude level
n_S	sample size for statistical measuring fatigue limits
n_t	totoal number of specimens in fatigue limit tests
n_1	sample size for paired failure–survival specimens
n_2	sample size for virtual paired failure–survival specimens
N	fatigue life
N_L	fatigue life for defining staircase test method or measurement on statistical fatigue limits
N$(\cdot)$	normal distribution function
PDF	probabilistic density function
P	survival probability
r_{ad}	adjusted rank to F data for measuring fatigue limits by ZKA
r_{in}	inversing rank for measuring fatigue limits by ZKA
r_{pre-ad}	previous adjusted rank for measuring fatigue limits by ZKA
S	fatigue test stress
S_a, S_{aL}	fatigue stress amplitude, material fatigue limit
S_L	test stress amplitude of staircase test method
S_o	lowest stress amplitude corresponding to the less frequent event by DMA
SSUDA	small sample up–and–down test approach
$t_{1-C}(n_S-1)$	t–distribution function value with a degree–of–freedom of $n_S - 1$ at a significant level of $1 - C$
w	average exponent of local S–N relation around fatigue life for defining staircase test method
ZKA	Zhang–Kececioglu approach
Z_P	percentage of normal distribution function with P

Subscripts

av	average value
C	confidence
j	ordinal of fatigue limit tests
k	ordinal for Paired failure–survival specimens
P	survival probability
s	standard deviation

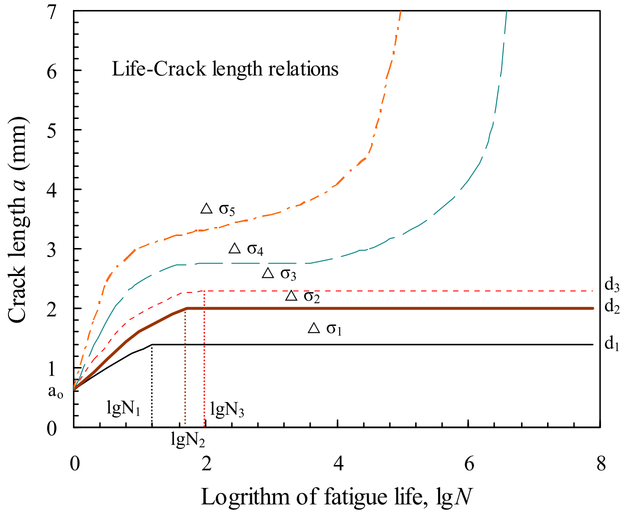

Fig. 1. Stair like test fatigue life–crack length relations under constant amplitude loading mode [1].

$\triangle\sigma_1$. Initiated cracks grew fast to meet granular bounds or inter–crossing points. The cracks might be arrested when $\triangle\sigma_1$ was below the resisting force from the scaled barrier d_1.

2. When test stress range rose to $\triangle\sigma_2$, fatigue cracks initiated much fast and grew quickly to the next granular bounds or inter–crossing points. After then, the cracks might grow slowly and continuously till a new orientation was constructed to break through the scaled barrier d_1. And then, they might grow fast again in an inner granular mode till meet a higher resisting

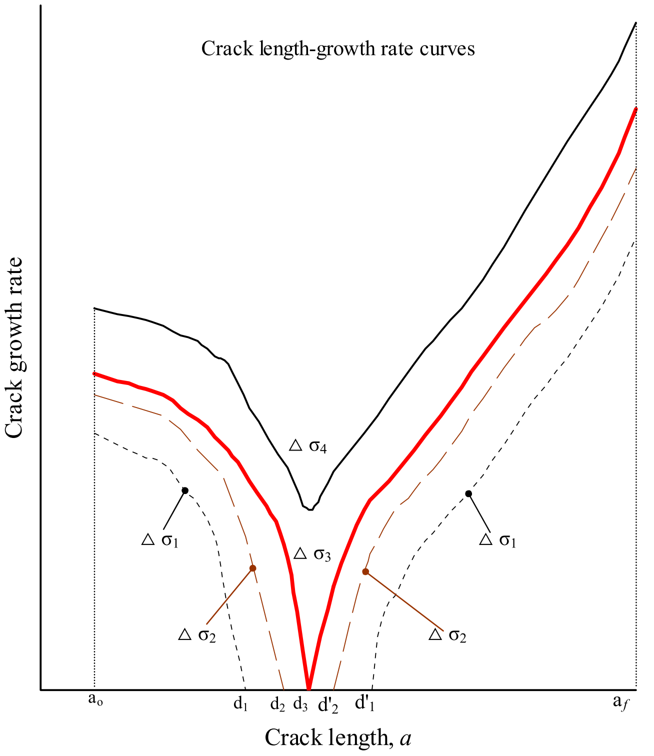

Fig. 2. Deduced crack growth rate curves for the carbon steel under constant stress amplitude mode [2–4].

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