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CRACK GROWTH UNDER SPECTRUM LOADING - A CRACK CLOSURE MODEL

by Wolf Elber

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ABSTRACT

A concept based on the crack-closure phenomenon has been developed to replace random-load spectra with constant-amplitude loading in both analysis tests. The maximum load and the crack-opening load in the constant-amplitude loading are chosen to be equal to those for the spectrum, so that both crack-growth mode and the crack length at failure are equivalent to those under the random-load spectra. The number of cycles of constant-amplitude loading is chosen so that the amount of crack growth is equal to that due to a given sequence or block of the random spectrum loading. The concept was tested experimentally after predicting the equivalent number of constant-amplitude cycles for six different random-load sequences. The agreement between predictions and test results was good.

KEY WORDS: Crack growth, fatigue, analysis, spectrum loading, crack closure.

INTRODUCTION

To insure the safety of aerospace structures, designers calculate the growth of possible cracks for the expected service loading conditions. The calculated crack growth is useful in determining inspection intervals, as well as in selecting materials and in establishing nominal operating stresses.

Currently available models of the crack-growth process require repetitive analyses, either cycle-by-cycle or block-by-block, of the service loading spectrum from the initial to the critical crack length. Analyses of the

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crack-growth process, such as those of Wheeler [1] and Willenborg et al. [2], are usually based on plastic zone sizes which change with crack length. Even when combined with fast calculation methods such as that by Brussat [3], these crack-growth analyses are cumbersome.

The equivalent constant-amplitude concept developed here is based on the crack-closure phenomenon [4] and on results of pilot tests that showed that the crack-opening load remained essentially constant while cracks grew under repeating random-load sequences containing several thousand load peaks. When the crack-opening load is essentially constant and known, the equivalent constant-amplitude concept replaces the random loads with constant-amplitude loads in crack-growth calculations.

The concept hinges on the determination of the crack-opening load. To obtain a design method based on this concept will require empirical or analytical methods of predicting the crack-opening load for a particular load spectrum. Newman [5] has developed a numerical analysis to calculate the crack-opening load; however, at the moment such an analysis is more complex than desired for design use. Also, empirical rules for determining the crack-opening loads for an arbitrary spectrum do not exist.

The search for an equivalent constant-amplitude test to replace the random-load test is not new. Barsom [6] showed that for some random-load distributions the rate of crack growth was generally equivalent to the rate of crack growth under a constant-amplitude test with the same minimum load and an amplitude representing the root-mean-square amplitude of the random test. However, Barsom's approach did not attempt to obtain equivalent failure crack lengths, or equivalent crack-growth modes.

In this report an equation of crack-growth equivalence was developed, and the validity of the concept was tested experimentally on six different random-load sequences. In the tests the crack-opening loads were measured in crack-growth tests run with both the random sequences and their predicted equivalent constant-amplitude sequences. To check the predicted number of equivalent constant-amplitude cycles, the number of random-loading sequences required to cause failure was compared to the number of equivalent constant-amplitude cycles required to cause failure.

LIST OF SYMBOLS

a	Crack length, m
C	Constant in crack-growth equation
$\frac{da}{dN}$	Crack growth rate, m/cycle
N_{eq}	Equivalent number of constant-amplitude cycles
n	Exponent in crack-growth equation
R	Stress ratio
S_i	Max stress in the ith cycle of a random sequence, Pa
$\tilde{S}_i$	Minimum stress in the ith cycle of a random sequence, Pa
$\hat{S}_i$	Effective minimum stress, Pa
S_{max}	Highest maximum stress in a random sequence, Pa
S_{min}	Minimum stress of the equivalent constant amplitude, Pa
S_B	Lowest minimum stress in a random spectrum, Pa
S_{op}	Crack-opening stress, Pa
U	Effective stress ratio
α	Crack-opening ratio
λ_i	Crack-growth parameter

δ_a Crack growth in a sequence of random loading, m

ϕ Crack-length correction function

ΔK_{eff} Effective stress intensity range, Pa - $m^{1/2}$

ANALYSIS

The Crack-Growth Law

The crack-growth law proposed by Elber [4], and experimentally verified under constant amplitude and some two-level variable amplitude loadings, states that the crack-growth rate is a power function of the effective stress intensity range only, that is,

$$\frac{da}{dN} = C(\Delta K_{eff})^n \tag{1}$$

where the effective stress intensity range, ΔK_{eff}, is measured relative to the load at which the crack fully opens.

The Equivalent Constant-Amplitude Concept

The equivalent constant-amplitude concept was developed to replace a repeating random-load sequence containing several thousand load excursions by a shorter constant-amplitude sequence. Random-load sequence, in this context, represents a fixed number of load excursions whose distribution is known. The constant-amplitude sequence which replaces this random-load sequence is selected so that the total crack growth, the crack-growth mode, and the critical crack length are equivalent for the two loading sequences. To achieve this, the maximum gross section stress for the equivalent constant-amplitude sequence was chosen to be the same as the largest maximum stress in the random sequence. Therefore, the crack length at failure under the constant-amplitude loading represents the shortest possible failure crack length under the random-load sequence. Also the minimum stress for the equivalent constant-amplitude sequence was chosen so that the crack-opening stress for that sequence is the same as the crack-opening stress in the random sequence. This produces equivalent maximum effective stress intensity ranges and hence the plastic zone envelopes are essentially equal for the two loading conditions. Also, this choice simplifies the equation of equivalence developed later. Last, the number of cycles in the equivalent constant-amplitude sequence was chosen so that the crack growth caused by those cycles is the same as the crack growth caused by the random-load sequence. This equivalent number of cycles, N_{eq}, was determined as follows.

If S_i is the maximum and $\tilde{S}_i$ is the minimum stress in the ith excursion of the random sequence, S_{op} is the crack-opening stress, $\hat{S}_i$ is the effective minimum stress, and a is the crack length, then from Equation (1) the growth increment due to the ith load excursion is

$$\delta_a = C(S_i - \hat{S}_i)^n \left(\sqrt{\pi a}\phi\right)^n \tag{2}$$

where

$$\hat{S}_i = \begin{Bmatrix} S_{op}, & \tilde{S}_i \leq S_{op} \\ & \\ \tilde{S}_i, & \tilde{S}_i > S_{op} \end{Bmatrix} \tag{3}$$

If S_{max} is the highest maximum stress in the random sequence, then this growth increment δ_a can also be expressed as a fraction λ_i of the growth caused by one cycle of the equivalent constant-amplitude loading

$$\delta_a = \lambda_i \, C(S_{max} - S_{op})^n \left(\sqrt{\pi a}\,\phi\right)^n \tag{4}$$

Equating Equations (2) and (4), yields the equation of equivalence

$$C(S_i - \hat{S}_i)^n \left(\sqrt{\pi a}\ \phi\right)^n = \lambda_i\ C(S_{max} - S_{op})^n \left(\sqrt{\pi a}\ \phi\right)^n \tag{5}$$

which, when solved for λ_i and then summed over all excursions in the random load sequence, simplifies to

$$N_{eq} = \sum \lambda_i = \sum \frac{(S_i - \hat{S}_i)^n}{(S_{max} - S_{op})^n} \tag{6}$$

With the crack-opening ratio, α, defined by

$$\alpha = \frac{S_{op} - S_B}{S_{max} - S_B} \tag{7}$$

S_{op} was expressed in terms of the highest maximum stress S_{max} and the lowest minimum stress S_B as

$$S_{op} = S_B + \alpha(S_{max} - S_B)$$

Then the final form of the equation of equivalence becomes

$$N_{eq} = \sum \frac{(S_i - \hat{S}_i)^n}{(1 - \alpha)^n\ (S_{max} - S_B)^n} \tag{8}$$

Equation (8) can be evaluated from the distribution of loads in the random sequence. The resulting relationship between N_{eq}, α, and n is a unique relationship for the particular spectrum. It is independent of configuration, environment, or material. When the concept is applied, and a particular value of N_{eq} is obtained, that value depends on the crack-opening stress and the materials' crack-growth exponent n. Differences in configuration and environment affect the crack-opening stress and, therefore, through α, will affect N_{eq}.

The relationship among N_{eq}, α, and n was obtained for the two spectrum shapes in this test series. The necessary steps are explained in the next section.

Spectrum Analysis

A pseudorandom noise generator was used to produce a continuous analog signal which is identically repeated after a given sequence length. Change in the shape of this spectrum were made using a variable nonlinear amplifier in the output stage of the noise generator. Two spectra were selected. The main stress parameters are defined in Figure 1. To calculate the equivalent number of cycles for these spectra from Equation (8), the distribution of stress excursions $(S_i - \tilde{S}_i)$ and the corresponding relative maxima $(S_i - S_B)$ was evaluated for the load spectrum. For simplicity of analysis and data presentation, the spectrum load excursions were sorted into a two-dimensional matrix of normalized stress excursions $(S_i - \tilde{S}_i)/(S_{max} - S_B)$ and normalized relative maxima $(S_i - S_B)/(S_{max} - S_B)$. The spectrum range $(S_{max} - S_B)$ was subdivided into approximately 20 intervals. The number of occurrences in each interval was then tabulated in the matrix.

The data from Spectra I and II are tabulated in Tables I and II, respectively. Using the values from these tables, Equation (8) was evaluated for each spectrum for a range of α, $(0 \leq \alpha \leq 1)$, and for a representative range of n, $(2.5 \leq n \leq 4)$. The resulting relationships between the equivalent number of cycles, N_{eq}, and the parameters n and α are plotted for Spectra I and II in Figures 2 and 3, respectively.

TESTING

Specimens and Material

Sheet specimens (100 mm wide, 3.29 mm thick) with 2.5 mm long central notches were tested. The test section configuration is shown in Figure 4. The specimens were made of 7075-T6 aluminum alloy, having a nominal tensile strength of 595 MPa, and a 0.2-percent offset yield strength of 540 MPa.

Testing Equipment

Both spectrum load tests and constant-amplitude tests were conducted in a 100-KN servo-hydraulic testing machine. The mean cyclic frequency for the spectrum load tests was 5 Hz. The cyclic frequency for the constant-amplitude load tests was 1 Hz. Load tracking accuracy at those frequencies was within 1 percent.

Crack-Closure Measurements

The crack closure and opening behavior of all specimens was continuously measured with a crack-opening displacement (COD)-gage [4]. The COD-gage output and the testing-machine load-cell output were analyzed to determine the stresses at which the cracks opened fully. The compliance method of Reference [4] was used for that analysis.

Spectrum Loading

Load Spectra I and II were applied as tensile loads to three specimens each at selected values of minimum stress level S_B, and spectrum range $S_{max} - S_B$. The matrix of test parameters is shown in Table III.

Constant-Amplitude Loading

The equivalent constant-amplitude stresses were determined analytically from the measured values of the stabilized average crack-opening stresses in each of the six spectrum tests. Because of lack of data for 7075-T6, the crack-closure behavior was taken from the published results for 2024-T3 [4], where

$$U = \frac{S_{max} - S_{op}}{S_{max} - S_{min}} = 0.5 + 0.4R \quad \text{for} \quad R > 0$$

from which S_{min}, the minimum constant-amplitude stress, was determined as

$$S_{min} = 1{\cdot}25\left\{\sqrt{1{\cdot}6\ S_{max}\ S_{op} - 0{\cdot}79\ S_{max}^2} - 0{\cdot}1\ S_{max}\right\} \qquad (9)$$

The resulting test matrix for the constant-amplitude tests is tabulated in Table IV, where specimen 7 is the constant-amplitude specimen corresponding to specimen 1, as indicated in the first column.

RESULTS AND DISCUSSION

Spectrum Load Tests

The equivalent constant-amplitude concept was based on the assumption that crack-opening stresses remain essentially constant during short (several thousand load peaks) random-load sequences. Figure 5 shows the relation between crack length and crack-opening stress for two typical specimens from the test series. Specimen 1 was tested under Spectrum I with a minimum stress of approximately zero. Specimen 6 was tested under Spectrum II with a minimum stress of one-third of the maximum. For both specimens, the crack-opening stresses were above the stabilized average just after initiation, and then stabilized to a constant value for the remainder of the test. This initiation effect has also been observed in surface crack growth in titanium alloy. The stabilized average crack-opening stresses and the number of sequences to failure are given in Table V.

Constant-Amplitude Tests

The stresses for the equivalent constant-amplitude tests were calculated from the measured crack-opening stresses and Equation (9). The cyclic stress ratios and crack-opening loads are tabulated in Table IV. The values of crack-opening ratio α are obtained from Equation (7). Values for the equivalent number of cycles, N_{eq}, were obtained from Figures 2 and 3 for these values of α, and the material's crack-growth exponent $n = 2 \cdot 7$ [7]. These values are tabulated in Table VI.

Results from the constant-amplitude tests consist of the stabilized average crack-opening stresses and the number of cycles to failure, N_{CA}. The values are given in Table VII. The measured crack-opening stresses were in good agreement with the opening stresses in Table VI, based on the 2024-T3 aluminum data. Failure crack lengths and failure modes of corresponding specimens were compared. Failure crack lengths were generally equivalent, except for the short-lived specimens 10 and 4. The change of crack-growth mode from normal to slant mode generally occurred at equal crack lengths. In all cases, the fracture surfaces from the spectrum tests showed more discoloration due to corrosion or fretting than the corresponding constant-amplitude specimens.

Comparison of Results

The number of constant-amplitude cycles to failure, N_{CA}, was divided by the equivalent number of cycles, N_{eq}, for each test and compared with the number of spectrum sequences to failure, N_S. The results are shown in Table VIII.

The ratio $N_{CA}/(N_{eq}\ N_S)$ ranges from 0 · 78 to 1 · 21, a range that is no greater than scatter that might be expected in fatigue crack-growth data. The results show no systematic differences between the test results and the predicted number of equivalent cycles, and that the crack-closure-based crack-growth law and the equation of crack-growth-equivalence gave valid predictions for these tests.

CONCLUDING REMARKS

To simplify crack-growth calculations, a concept has been developed for replacing relatively complex random-load tests and analyses with simpler constant-amplitude tests and analyses. An equation of crack-growth-equivalence resulting from derivations based on the crack-closure crack-growth law was obtained, and was used to determine a relationship between an equivalent number of cycles of constant-amplitude loading (producing the same amount of crack growth as a fixed sequence of the random-load spectrum) and the distribution of the random loads, the exponent in the crack-growth law, and the ratio of the crack-opening load to the maximum load. That relationship, which is independent of crack length and stress level, is unique for a given spectrum.

The concept was tested experimentally for six different spectrum loadings and the six corresponding equivalent constant-amplitude loadings. Good agreement was obtained between the experimental results and the predictions.

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$\frac{S_i - S_{min}}{S_{max} - S_{min}}$ \ $\frac{S_i - S_i}{S_{max} - S_{min}}$	0.00 - 0.05	0.05 - 0.11	0.11 - 0.16	0.16 - 0.21	0.21 - 0.26	0.26 - 0.32	0.32 - 0.37	0.37 - 0.42	0.42 - 0.47	0.47 - 0.53	0.53 - 0.58	0.58 - 0.63	0.63 - 0.68	0.68 - 0.74	0.74 - 0.79	0.79 - 0.84	0.84 - 0.89	0.89 - 0.95	0.95 - 1.00
0.00 - 0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.05 - 0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.11 - 0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.16 - 0.21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.21 - 0.26	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.26 - 0.32	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.32 - 0.37	3	0	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.37 - 0.42	26	11	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.42 - 0.47	84	76	39	28	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.47 - 0.53	120	163	151	99	52	11	0	0	0	0	0	0	0	0	0	0	0	0	0
0.53 - 0.58	92	147	182	186	115	69	10	0	0	0	0	0	0	0	0	0	0	0	0
0.58 - 0.63	24	69	98	131	177	119	47	3	0	0	0	0	0	0	0	0	0	0	0
0.63 - 0.68	4	14	41	52	60	35	67	19	4	0	0	0	0	0	0	0	0	0	0
0.68 - 0.74	0	3	6	8	15	25	27	22	9	1	0	0	0	0	0	0	0	0	0
0.74 - 0.79	0	0	0	0	0	4	4	4	3	0	0	0	0	0	0	0	0	0	0
0.79 - 0.84	0	0	0	0	0	1	4	0	1	4	0	0	0	0	0	0	0	0	0
0.84 - 0.89	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
0.89 - 0.95	0	0	0	0	0	1	0	0	0	2	2	0	0	0	0	0	0	0	0
0.95 - 1.00	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0

TABLE I--MAXIMA-EXCURSION MATRIX FOR SPECTRUM I

$\frac{S_i - S_{min}}{S_{max} - S_{min}}$ \ $\frac{S_1 - S_1}{S_{max} - S_{min}}$	0.00 - 0.05	0.05 - 0.09	0.09 - 0.14	0.14 - 0.18	0.18 - 0.23	0.23 - 0.27	0.27 - 0.32	0.32 - 0.36	0.36 - 0.41	0.41 - 0.45	0.45 - 0.50	0.50 - 0.55	0.55 - 0.59	0.59 - 0.64	0.64 - 0.68	0.68 - 0.73	0.73 - 0.77	0.77 - 0.82	0.82-- 0.86	0.86 - 0.91	0.91 - 0.95	0.95 - 1.00
0.00 - 0.05	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.05 - 0.09	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.09 - 0.14	15	5	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.14 - 0.18	58	50	22	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.18 - 0.23	158	168	126	68	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.23 - 0.27	150	228	242	201	99	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.27 - 0.32	44	105	158	197	167	74	2	[illegible]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.32 - 0.36	2	11	25	36	37	40	15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.36 - 0.41	0	4	2	18	19	26	[illegible]	7	2	0	0	0	0	0	0	0	0	0	0	0	0	0
0.41 - 0.45	0	0	1	4	12	18	32	19	5	1	0	0	0	0	0	0	0	0	0	0	0	0
0.45 - 0.50	0	0	0	0	4	4	13	13	12	4	0	0	0	0	0	0	0	0	0	0	0	0
0.50 - 0.55	0	0	0	0	0	1	1	3	1	7	3	1	0	0	0	0	0	0	0	0	0	0
0.55 - 0.59	0	0	0	0	0	0	2	0	4	4	4	1	0	0	0	0	0	0	0	0	0	0
0.59 -0.64	0	0	0	0	0	0	0	0	0	1	4	4	2	0	0	0	0	0	0	0	0	0
0.64 - 0.68	0	0	0	0	0	0	0	0	0	0	3	4	2	0	0	0	0	0	0	0	0	0
0.68 - 0.73	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	0	0	0	0	0	0	0
0.73 - 0.77	0	0	0	0	0	0	0	0	0	0	0	1	3	0	1	0	0	0	0	0	0	0
0.77 - 0.82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
0.82 - 0.86	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0
0.86 - 0.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
0.91 - 0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.95 - 1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE II--MAXIMA-EXCURSION MATRIX FOP SPECTRUM II

TABLE III—TEST MATRIX FOR SPECTRUM LOAD TESTS

Specimen number	Spectrum	S_{Bn}, Mpa	$S_{max} - S_B$, MPa	S_{max}, MPa
1	I	20	180	200
2	I	10	90	100
3	I	50	100	150
4	II	20	180	200
5	II	10	90	100
6	II	50	100	150

TABLE IV—TEST MATRIX FOR CONSTANT AMPLITUDE TESTS

Specimen number	S_{max}, MPa	S_{op},* MPa	R
7, 1	200	104	0.13
8, 2	100	53	0.18
9, 3	150	87	0.34
10, 4	200	102	0.07
11, 5	100	56	0.28
12, 6	150	89	0.37

*Measured values from spectrum tests.

TABLE V—CRACK-OPENING STRESSES AND NUMBER OF SEQUENCES TO FAILURE N_S FOR SPECTRUM TESTS

Specimen number	S_{op}, MPa	N_S
1	104	372
2	53	3400
3	87	930
4	102	26
5	56	640
6	89	68

TABLE VI—EQUIVALENT CONSTANT-AMPLITUDE PARAMETERS

Speciman number	S_{max}, MPa	Desired S_{op}, MPa	R	α	N_{eq}
1, 7	200	104	0.13	0.465	8.1
2, 8	100	53	0.18	0.48	7.8
3, 9	150	87	0.34	0.37	12.9
4, 10	200	102	0.07	0.45	126
5, 11	100	56	0.28	0.51	83
6, 12	150	89	0.37	0.39	191

TABLE VII—MEASURED RESULTS FROM CONSTANT-AMPLITUDE TESTS

Specimen number	Measured S_{op}, MPa	N_{CA}
7	105	3240
8	56	32200
9	84	13200
10	104	2800
11	53	41300
12	86	14300

TAFLE VIII—COMPARISON OF RESULTS

Specimen numbers	N_{CA}, cycles	N_{eq}, cycles/sequence	$\frac{N_{CA}}{N_{eq}}$	N_s sequences	$\frac{N_{CA}}{N_{eq} \times N_s}$
1, 7	3240	8.1	400	372	1.08
2, 8	32200	7.8	4100	3400	1.21
3, 9	13200	12.9	1020	930	1.10
4, 10	2800	126	22	26	0.85
5, 11	41300	83	500	640	0.78
6, 12	14300	191	75	68	1.10

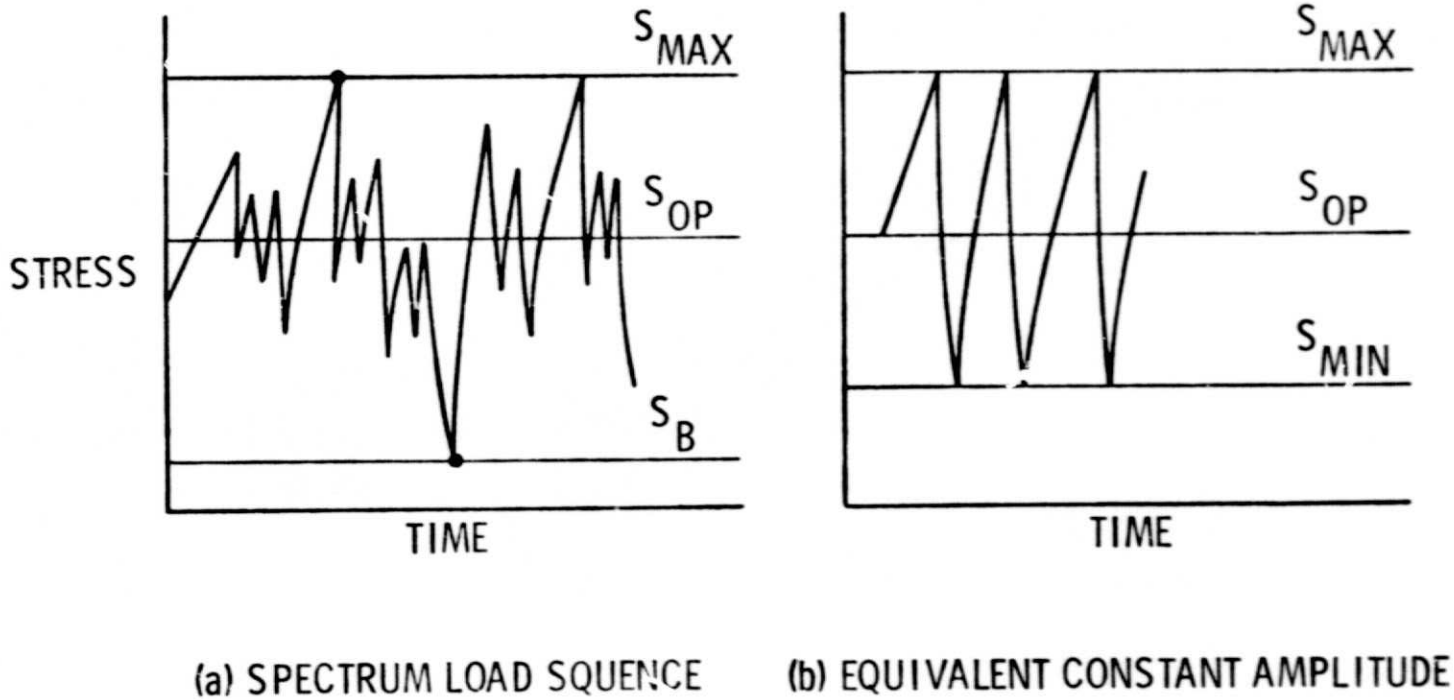

Figure 1. Definition of stress parameters.

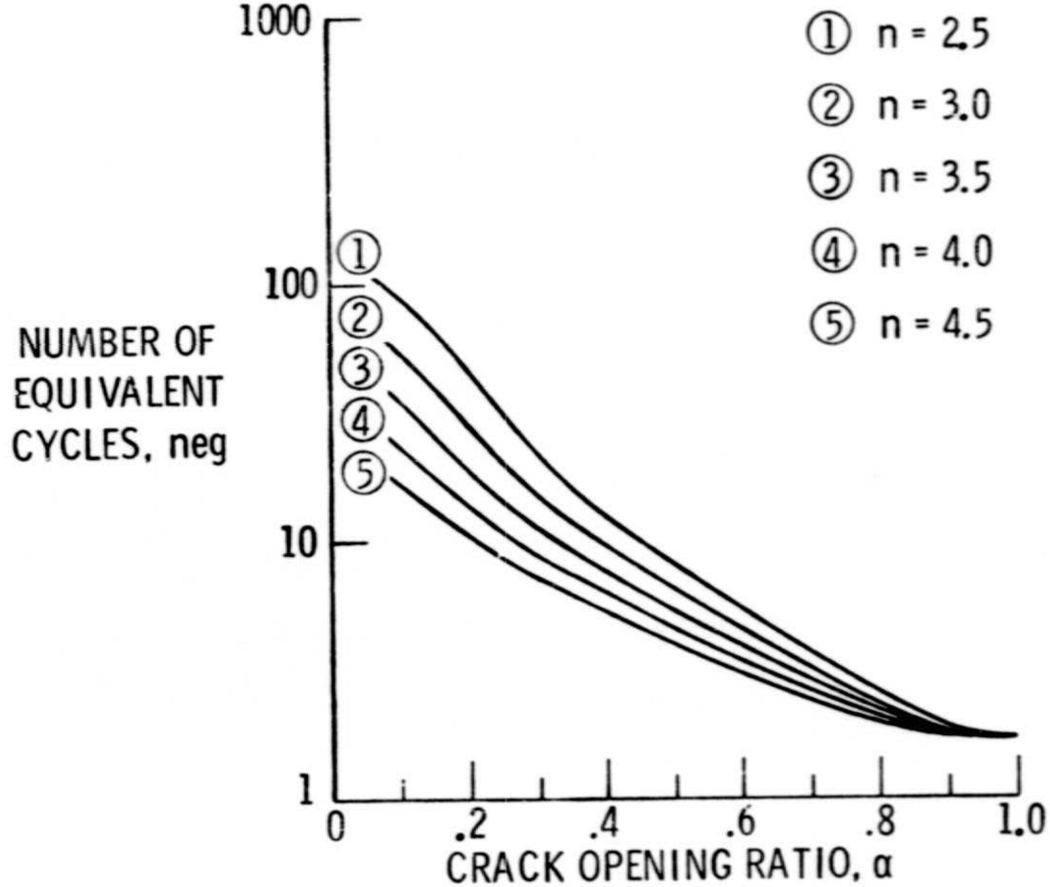

Figure 2. Equivalent cycles function for Spectrum I.

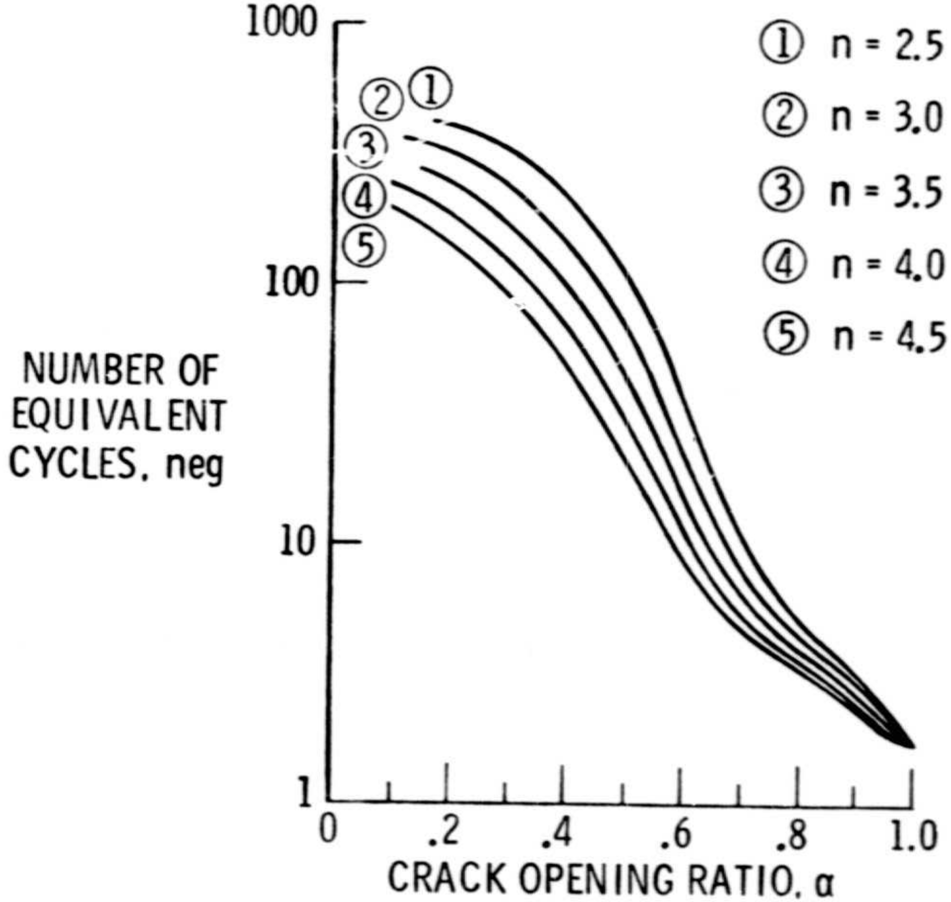

Figure 3. Equivalent cycles function for Spectrum II.

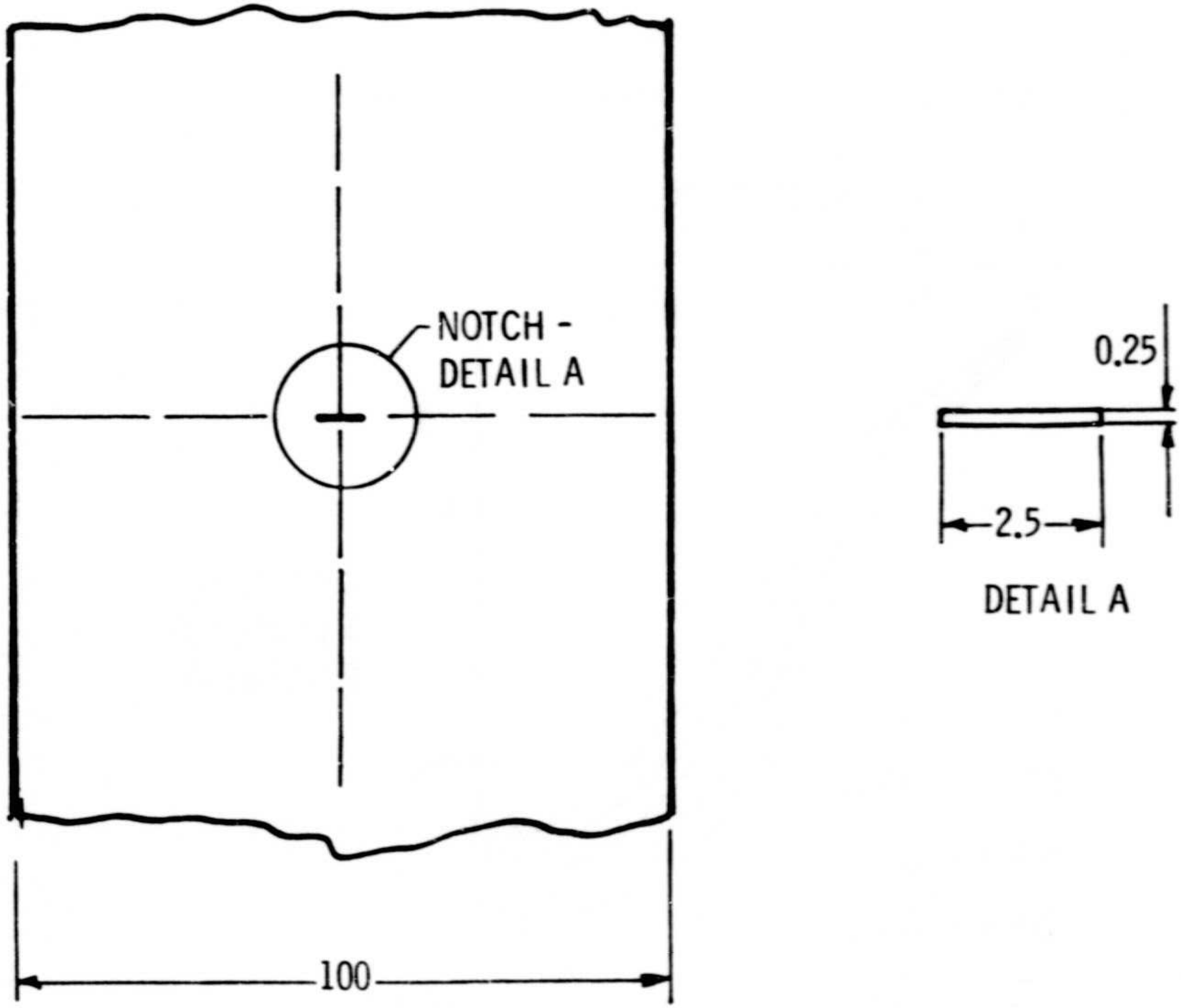

Figure 4. Specimen test section configuration.

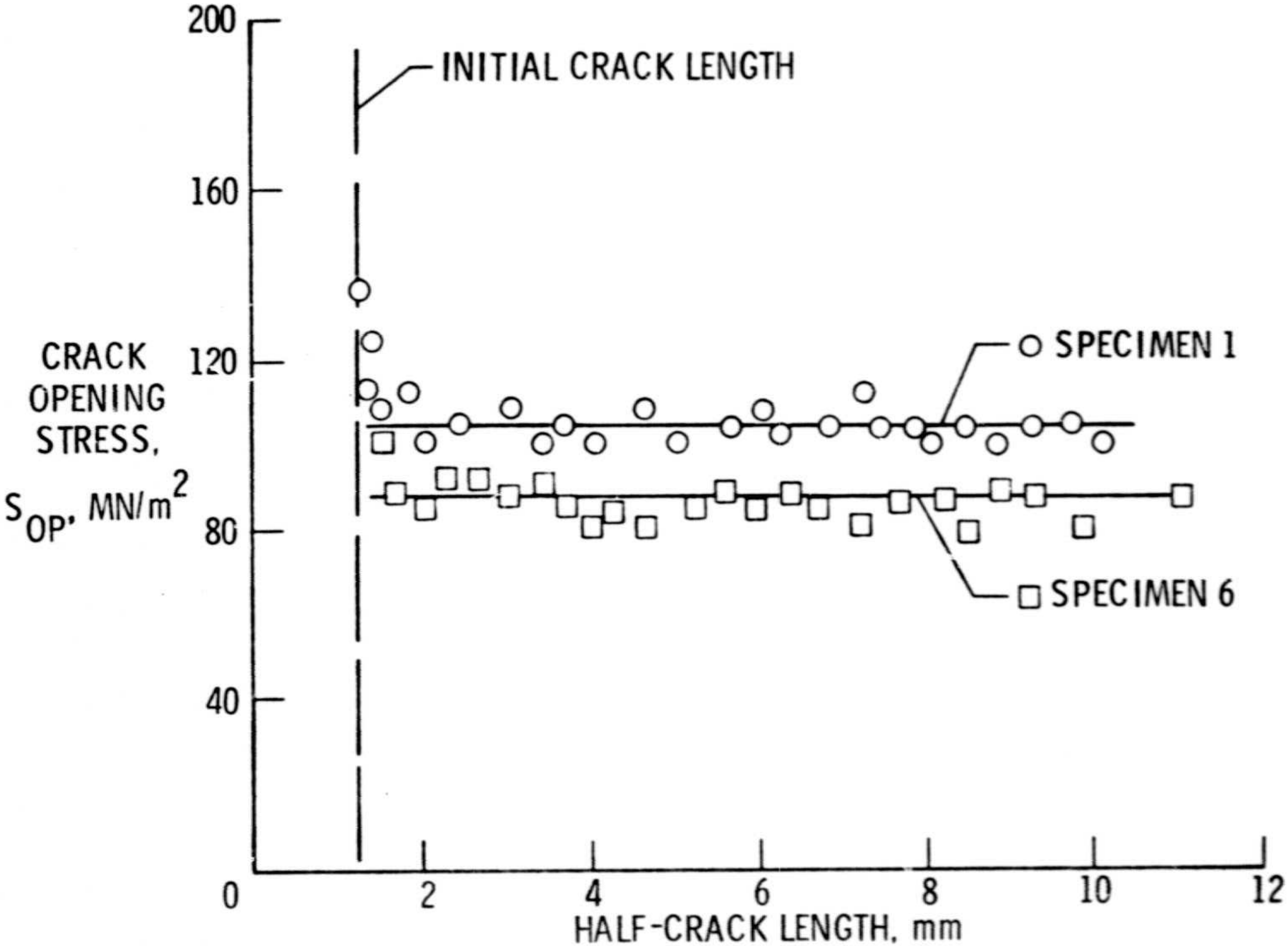

Figure 5. Crack-opening stress as a function of crack length for specimens 1 and 6.