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FATIGUE CRACK PROPAGATION IN MUSTANG WINGS

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ABSTRACT

The rate of fatigue crack propagation has been studied in a large number of Mustang P51D mainplanes under repeated, programmed and random loading. It was found that for the particular type of failure considered (a crack initiating from a cutout in a sheet containing riveted stringers) the initial crack rate is constant and occupies a large part of the total life. From the repeated load tests crack propagation curves from 90 failures covering 21 different load levels were obtained. From these a relation between initial crack rate and load was obtained in the form of an Alternating Load—Mean Load diagram for crack rates. This diagram was used to predict the initial crack rate under complex loading by assuming a linear accumulation of crack increments. Reasonable agreement between predicted and experimental rates were obtained provided successive peaks and troughs in the random sequence were considered as forming cycles of continuously varying mean and alternating loads.

INTRODUCTION

Following the introduction of the "fail safe" philosophy in aircraft design, the problem of fatigue crack initiation and propagation has assumed vital importance. In this report the results of a study of fatigue crack propagation in Mustang wings are presented.

A large number of wings was tested under repeated loading[1] at various mean and alternating loads and it was found that for the particular type of failure considered (a crack initiated from a cutout in the skin at Sta. 80) the initial rate of propagation is constant and occupies a large part of the total life of the wing. The main object of this part of the investigation was to determine the effect of mean and alternating loads on the initial crack rate.

In addition to the repeated load tests a number of wings were tested under the following types of complex load sequence:—

(i) Programmed load sequence of three levels.

(ii) Random load sequence of 22 levels based on a symmetric (gust load) spectrum.

(iii) The same as in (ii) with a periodic downward load (representing the ground to air cycle) introduced.

(iv) Random load sequence of 21 levels based on an asymmetric (maneuver load) spectrum.

Crack propagation behavior was studied iu the above tests with a view to predicting crack rates under complex loading using repeated load data.

TEST METHODS

Two types of testing rig were used, namely, the Hydraulic Loading Rig and the Vibration Loading Rig. These are described in Ref. 2. Both rigs were used in the repeated load tests. The programmed load tests were conducted in the Vibration Loading Rig and the random load tests in the Hydraulic Loading Rig

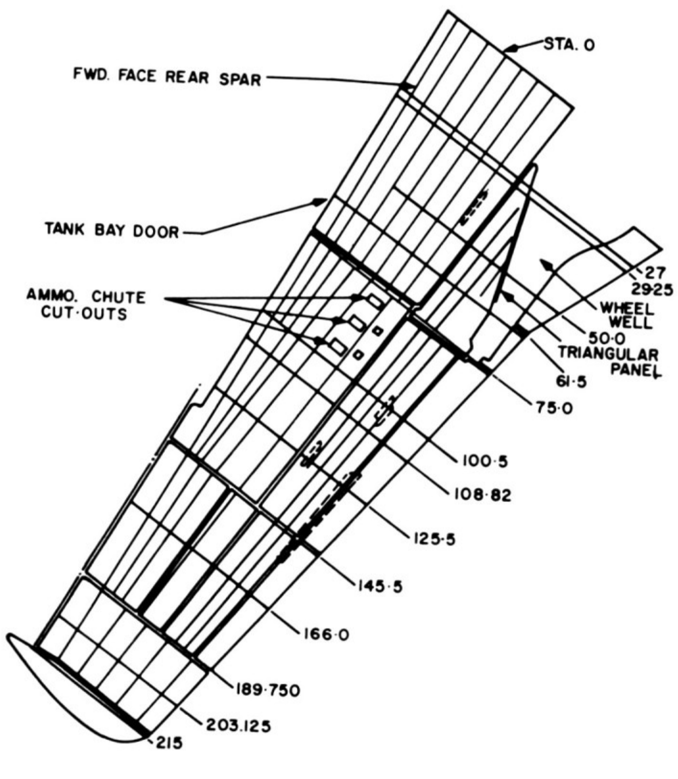

Fig. 1. P-51D wing stringer arrangement (lower surface).

DESCRIPTION OF TEST SPECIMENS

The Mustang wing is a redundant two-spar structure fabricated mainly from 2024 Alclad sheet and 2024 extruded sections. A view of the lower surface showing the spar and stringer layout is shown in Fig. 1 and a detailed description of the wing is given in Ref. 3. Since both port and starboard halves are structurally identical each half wing is regarded as one specimen.

SCOPE OF INVESTIGATION

This study is restricted to one type of failure (called Type I in Ref. 3), an example of which is shown in Fig. 2. This particular type of failure occurred most frequently in the repeated load tests over a wide range of test loads. In this region particularly, the structure is considered representative of the riveted skin and stringer type of construction. From the repeated load tests 90 satisfactory crack propagation curves were obtained, covering 21 different load ranges. These curves were compared with those obtained from the following load sequence tests:

(i) A programmed load sequence based on a gust load spectrum—one specimen.

Fig. 2. Fatigue failure at Station 80—Type I.

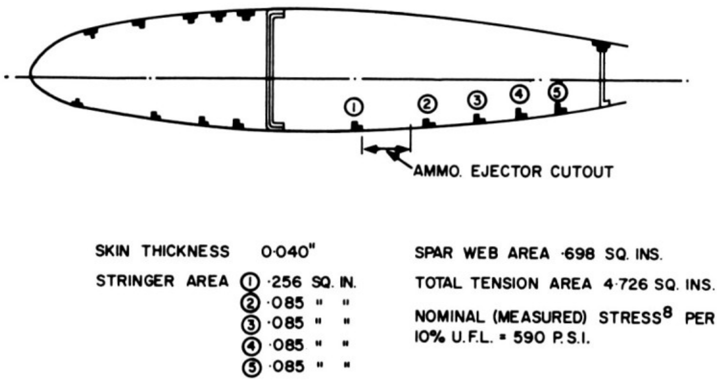

Fig. 3. Section properties of P-51D wing at Station 80 (Ref. 7).

(ii) A random load sequence based on a gust load spectrum—five specimens.

(iii) A random load sequence based on a gust load spectrum with periodic negative load—one specimen.

(iv) A random load sequence based on a maneuver load spectrum—four specimens.

The extent of each crack was measured in terms of the percentage of tension area failed. This follows the method used by Whaley, McGuigan, and Bryan in Ref. 4.

CRACK PROPAGATION UNDER REPEATED LOADING

DURATION OF CONSTANT CRACK PROPAGATION RATE

A list of typical specimens with moderate service life prior to testing and with cracks leading to ultimate failure is shown in Table I. It can be seen that the period of constant crack propagation rate occupies from 40 to 70 percent of the total life of the wing.

A typical crack-propagation curve is shown in Fig. 4. Similar behavior was observed on C46 Commando wings reported in Ref. 4.

CONSTRUCTION OF ALTERNATING LOAD-MEAN LOAD DIAGRAM FOR INITIAL CRACK PROPAGATION RATES

The initial crack propagation rates obtained are grouped according to load range in Table II. As the data holds for various alternating load and mean load combinations, an *A-M* diagram of crack rates can be drawn, although the limited test data available necessitates extrapolation of the curves in some areas of the diagram.

Curves of log crack rate vs. alternating load were drawn through the experimental points by eye for selected values of mean load. These curves were then

TABLE I. LIST OF TYPICAL SPECIMENS WITH CRACKS LEADING TO FAILURE

Spec. No.	Flying Hours	Load Range Mean % UFL	Load Range Alt. % UFL	Crack Rate % Tens. Area Failed per 10^6 Cycles	% Life at Const. Crack Rate
10	155:35	27.29	15.80	350	68
38	N/A	47.37	17.70	540	63
39	175:00	30.88	12.22	150	55
40	175:00	30.88	12.22	90.8	59
41	11:45	47.37	17.70	860	71
44	11:45	30.88	12.22	118	68
51	131:45	48.79	22.85	1730	61
53	110:25	48.79	22.85	2000	67
54	110:25	48.79	22.85	1875	66
61	116:50	49.12	9.73	120	61
84	114:00	6.00	10.52	18	44
89	14:00	6.00	10.52	16.7	40
105	N/A	16.28	24.28	212	70
108	125:50	16.28	24.28	700	77

used to draw the *A-M* diagram in Fig. 5 on which the means of the experimental points have been shown for comparison.

It bears a certain resemblance to the *A-M* diagram for fatigue lives of P51D mainplanes shown in Ref. 5.

DISTRIBUTION OF CRACK PROPAGATION RATES

Two probability distributions were fitted to the data at the load range 16.28 ± 24.28 percent U.F.L. These were a log normal distribution and a gamma distribution with a scale parameter. All parameters were determined from the data by

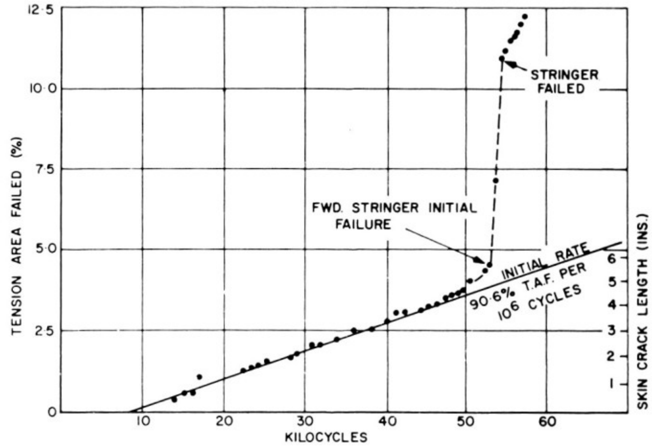

Fig. 4. Typical crack propagation curve under repeated loading. (Spec. No. 40. Load range, 30.88 ± 12.22% U.F.L.)

TABLE II. MEASURED INITIAL CRACK RATES IN REPEATED LOAD TESTS

Load Range % UFL			Rate		
Mean	Alt.	Spec. No.	% T.A.F. per 10^6 Cycles	Log Rate, y	Mean Log Rate, $\bar{y}$
16.00	7.71	161	2.35	0.37107	
		162	11.90	1.07555	0.999
		151	35.50	1.55023	
49.20	9.73	58	67	1.82607	
		56	93	1.96848	
		55	97	1.98677	1.984
		57	102	2.00860	
		62	110	2.04139	
		61	120	2.07918	
6.00	10.52	90	7.5	0.87506	
		89	16.7	1.22272	
		72	17.9	1.25285	1.268
		84	18.0	1.25527	
		88	25.5	1.40654	
		82	39.4	1.59550	
30.88	12.22	40	90.8	1.95809	
		43	92.2	1.96473	2.043
		44	118	2.07188	
		39	150	2.17609	
69.45	11.26	45	126	2.10037	
		50	215	2.33244	2.288
		46	270	2.43136	
24.63	13.14	31	142	2.15229	
		32	200	2.30103	2.161
		28	107	2.02938	
27.29	15.80	12	223	2.34830	
		9	350	2.54407	2.498
		10	350	2.54407	
		11	360	2.55630	
6.00	16.36	67	12.7	1.10380	1.751
		75	25	2.39794	
47.37	17.70	38	540	2.73239	
		37	825	2.91645	2.905
		41	860	2.93450	
		42	1100	3.04139	
32.77	21.33	13	838	2.92324	
		14	936	2.97128	2.996
		5	1240	3.09342	
48.79	22.85	51	1730	3.23805	
		54	1875	3.27300	3.302
		53	2000	3.30103	
		52	2490	3.39620	
16.00	23.04	171	120	2.07918	
		155	214	2.33041	2.270
		158	252	2.40140	
		157	186	2.26951	

TABLE II.—Continued

Load Range % UFL		Spec. No.	Rate % T.A.F. per 10^6 Cycles	Log Rate, y	Mean Log Rate, $\bar{y}$
Mean	Alt.				
16.28	24.28	141	290	2.46240	
		142	200	2.30103	
		105	212	2.32634	
		106	550	2.74036	
		107	442	2.64542	
		108	700	2.84510	
		133	394	2.59550	
		134	486	2.68664	
		147	155	2.19033	
		148	134	2.12710	
		153	115	2.06070	2.400
		154	280	2.44716	
		167	210	2.32222	
		168	227	2.35603	
		169	250	2.39794	
		170	174	2.24055	
		177	290	2.46240	
		178	300	2.47712	
		155	214	2.33041	
		157	186	2.26951	
		171	120	2.07918	
		178	280	2.44716	
8.05	26.40	117	96	1.98227	
		118	165	2.21748	2.093
		120	120	2.07918	
38.28	26.79	15	1375	3.13830	
		22	1500	3.17609	
		126	1480	3.17026	3.377
		125	4650	3.66745	
		16	5400	3.73239	
3.38	35.38	160	750	2.87506	
		159	945	2.97543	3.046
		131	1350	3.13033	
		132	1600	3.20412	
16.38	35.38	97	850	2.92942	
		95	1050	3.02119	
		101	1400	3.14613	3.244
		102	1675	3.22402	
		98	3250	3.51188	
		96	4200	3.62325	
48.70	37.28	25	11900	4.07555	4.062
		26	11200	4.04922	
32.45	40.33	66	6600	3.81954	4.004
		65	15400	4.18752	

the method of maximum likelihood. On the rather small sample of 22 points the log normal distribution was found to provide a better fit. This is shown in Fig. 6. The standard deviation for the logarithm of the crack rate was $S = 0.53$.

CRACK PROPAGATION UNDER COMPLEX LOADING

COMPARISON WITH REPEATED LOAD TESTS

Typical crack propagation curves obtained from the four complex loading sequences detailed in section 1 are shown in Figs. 7, 8, 9, and 10.

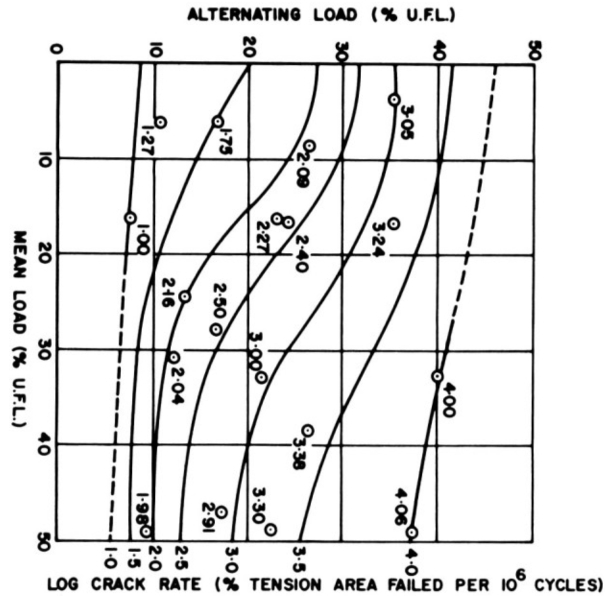

Fig. 5. *A-M* diagram for initial crack rates, P-51D mainplane Type I failures.

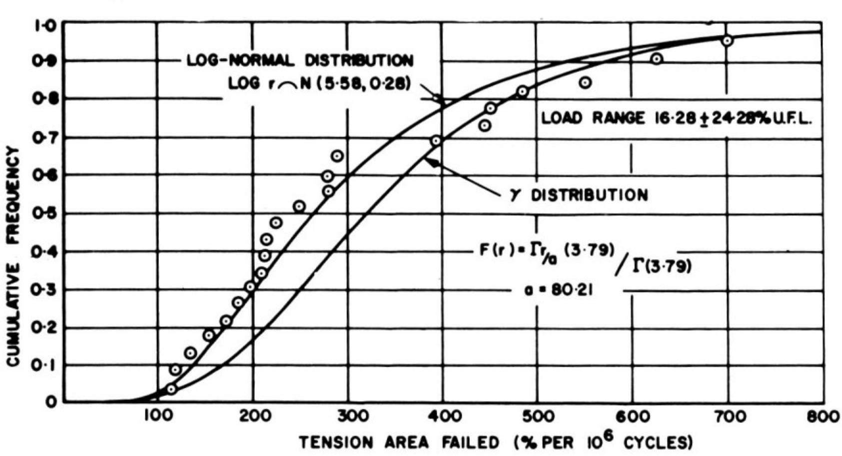

Fig. 6. Cumulative probability distribution of crack-propagation rate.

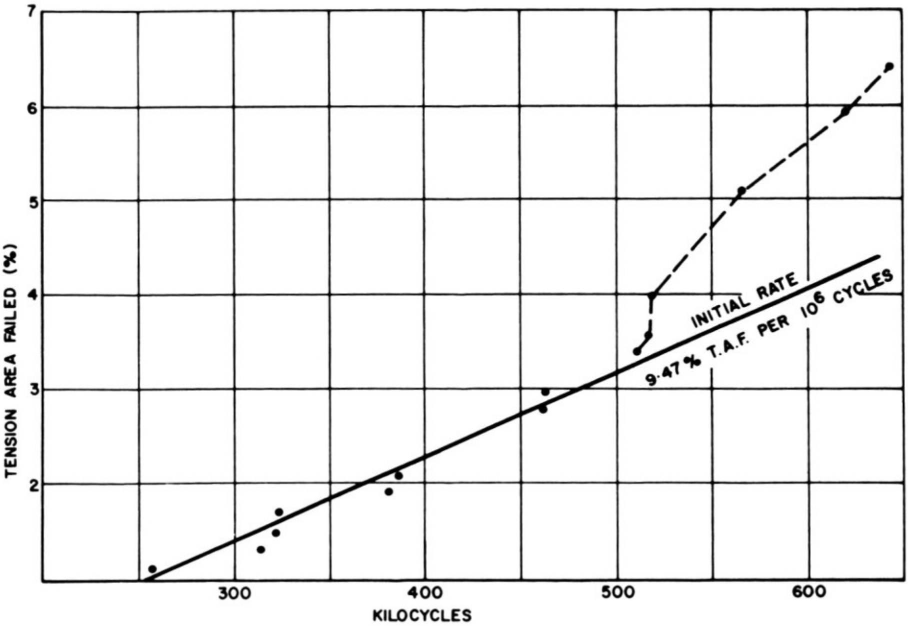

Fig. 7. Typical crack propagation curve under programmed loading, gust spectrum. (Spec. 3LL-4P.)

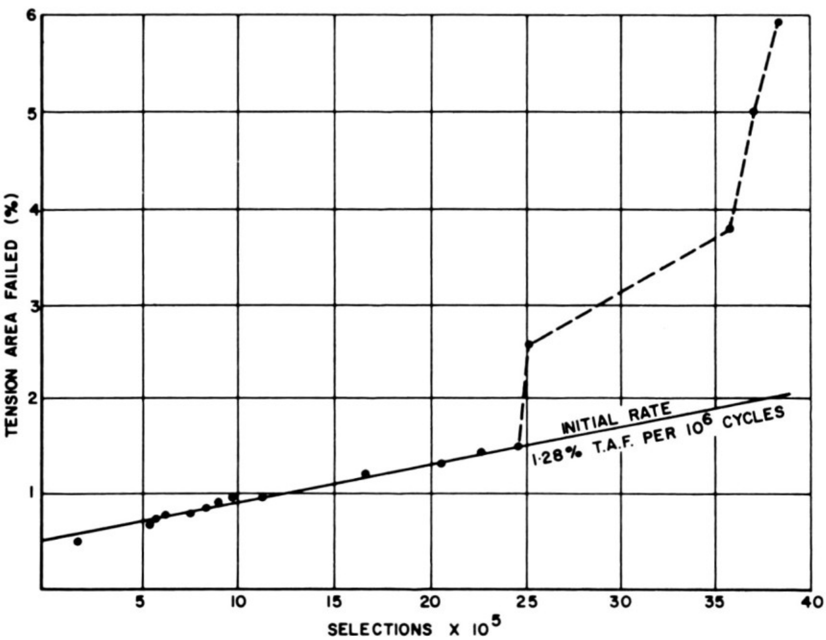

Fig. 8. Typical crack propagation curve under random loading. Gust spectrum. (Spec. RL-2P.)

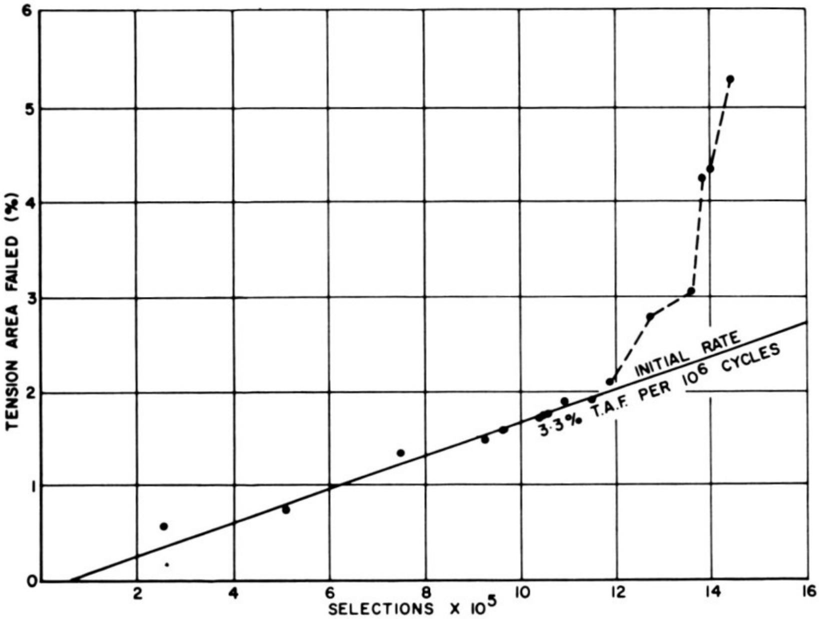

Fig. 9. Typical crack-propagation curve under random loading. Gust spectrum with a periodic downward load. (Spec. G.A.C.-6P.)

All these curves exhibit similar characteristics to those found under repeated loading. There is a constant rate of crack growth for a considerable part of the life, followed by a more rapid growth, leading to ultimate failure.

PREDICTION OF CRACK PROPAGATION RATES UNDER COMPLEX LOADING

In the case of random loading the problem arises of replacing the irregular sequence of loads by an equivalent series of load cycles. This has been discussed by Payne in Ref. 5 in relation to fatigue lives, and two hypotheses are considered here:—

H_1: The load changes determining crack propagation rate are obtained by combining equal maxima and minima about a constant mean load irrespective of position in the sequence.

H_2: The load changes determining crack propagation rate are the actual load changes in the sequence from each "peak" to the succeeding "trough," and vice versa.

The predicted rate for a particular sequence was obtained by assuming it to be a simple summation of the crack increments contributed by each cycle in the equivalent series. The actual rates and the predicted rates according to hypotheses H_1 and H_2 are compared in Table III for each type of complex load sequence.

It can be seen that H_2 gives a closer estimate of initial crack propagation rate than H_1.

TABLE III

Type of Load Sequence	Spec. No.	Initial Crack Rates (% tension area failed per 10^6 cycles)		
		Experimental	Predicted	
			H_1	H_2
Programmed Loading (gust spectrum)	3LL–4P	9.47	6.8	6.8
Random Loading (gust spectrum)	RL 2P	1.28	6.62	1.41
	RL 2S	1.18	5.82	1.46
	RL 3P	1.18	6.63	1.58
	RL 3S	2.24	4.9	1.58
	RL 5S	1.08	6.22	1.53
Random Loading (gust spectrum with periodic downward load)	GAC 6P	3.3	9.3	4.01
Random Loading (maneuver spectrum)	ML 1S	3.87	24.88	9.48
	ML 1P	3.75	24.88	9.48
	ML 2S	5.2	23.89	9.27
	ML 2P	3.75	23.89	9.27

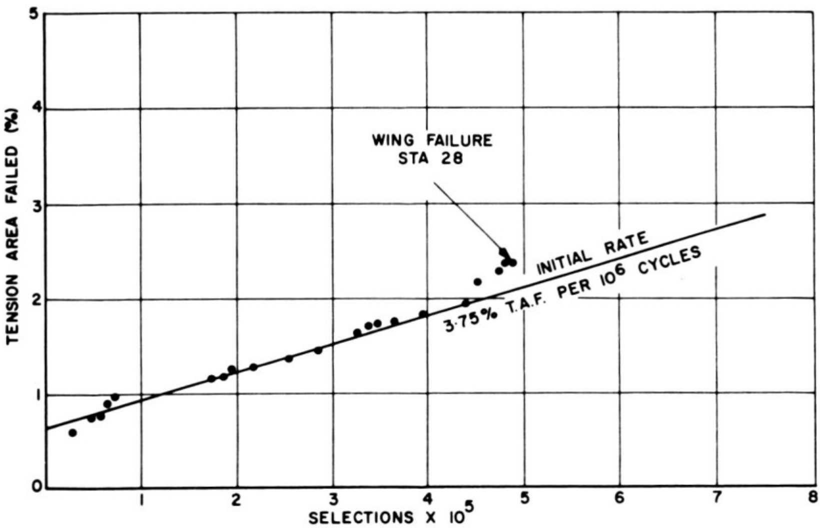

Fig. 10. Typical crack-propagation curve under random loading. Manoeuvre spectrum. (Spec. ML-2P.)

DISCUSSION

From both the Mustang tests and the C46 Commando tests it would appear that a substantially constant crack propagation rate for a large part of the life is typical in a 2024 structure of this type (i.e., riveted sheet-stringer construction). It may be that the nominal stress at the tip of the crack tends to remain constant as the crack progresses, the additional load being absorbed by adjoining stringers.

Weibull has discussed this in Ref. 6 where he states: "In a redundant structure it may happen that a crack, developing on one of the components, has the effect of diminishing the load in such a way that the stress amplitude is kept constant. . . ." If this is found to be substantially so (and it is proposed to explore this problem by the use of strain gages), then this would support Weibull's findings that the crack propagation rate is constant while the stress amplitude remains constant.[6]

CONCLUSIONS

From the foregoing it may be concluded that:—

1. In a redundant 2024 Al alloy wing of this type (light skin with riveted stringers) the initial rate of crack propagation under fatigue loading is constant and occupies from 40 to 70 percent of the total life.

2. Making due allowance for the inherent scatter the initial crack rate under spectrum loading can be predicted with reasonable accuracy from the crack rates under repeated loading by assuming a linear accumulation of crack damage.

3. Assuming a linear accumulation of crack damage under spectrum loading, the hypothesis H_2 has been found to provide the best agreement with experimental results.

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