PREDICTION OF CONSTANT-AMPLITUDE FATIGUE LIFE TO FAILURE UNDER PULSATING-TENSION ($R \geq 0$) BY USE OF THE LOCAL-STRAIN-APPROACH AND THE PROBLEM OF PROPER CHOICE OF K

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ABSTRACT

The aim of the investigation was to compare LSA life predictions with pulsating-tension tests to failure. It was shown that, in the case of pulsating-tension, the ratio N_i/N_f does not change considerably and therefore the relative LSA can be used for predicting S-N lines for $R \geq 0$. The accuracy of the prediction is associated with choice of the K value in Neuber's relation $K_\sigma \times K_\varepsilon = K^2$. The K values which give the best life predictions, were obtained close to those of the corresponding notch factors for pulsating-tension ($R = S_{min}/S_{max} = 0$). Because of the size and surface effects (which are not taken into account in LSA) and in view of the difficulty in knowing whether the considered specimen with a given K_T value has exactly the same cyclic parameters as those used in the LSA calculations, it is preferable to use a K-value proved to give a life prediction in agreement with a related pulsating-tension test.

KEYWORDS

Fatigue life prediction, Local strain approach, Crack initiation, Residual stress.

INTRODUCTION

The fatigue life of material coupons and structural elements is divided into two phases - the crack initiation phase and the crack propagation phase. The Local Strain Approach is conventionally applied for prediction of the life to crack initiation. This approach is based on the assumption that in notched and unnotched specimens with the same local strain history, cracking sets in at the same number of cycles to crack initiation.

However direct LSA predictions deviate considerably from the experimental crack initiation life, both for variable-amplitude and constant-amplitude loading. A scatter of N_{pred}/N_{exp} ratios between 0.1 to 10 was observed in many investigations and therefore some authors (Buch et al., 86) recommended the relative method for improving the accuracy of predictions. It was observed in many investigations by the author, that the ratio N_{pred}/N_{exp} has close values for related aircraft loading cases. Accordingly use of N_{pred}/N_{exp} obtained for one loading case as a correction factor for another related loading case, yielded in an improved predictive accuracy with the scatter limited to 0.5÷2.0. It was also shown, that in the case of typical aircraft loading distributions for the lower wing surface (which are predominantly of the tensile type), the relative method could be applied for more accurate prediction of the fatigue life to crack initiation, as well as of the life to failure, for cases where direct prediction resulted in large deviations from the actual life (Buch, 86-91). It should be noticed that the scatter of N_{pred}/N_{exp} is for direct predictions evidently larger than the scatter of N_i/N_f for different pulsating tension stress levels.

The aim of the reported investigation was to compare LSA predictions with pulsating-tension test results, with a view to better insight into application of direct and indirect prediction in the case of constant- amplitude tensile loading.

RESULTS FROM PREVIOUS INVESTIGATIONS

The LSA has many well-known weak points, which, combined, are a source of inaccuracy in direct predictions. LSA calculations do not make proper allowance for the loading sequence effect, since the used material memory rules are schematical and unreliable and as is well known, Miner's rule is not an exact one either. Another important weak point is the optional choice of the K-value in Neuber's relation $K_{\sigma}xK_{\varepsilon}=K^2$=const. Use of a specific value of K (e.g. K_T or K_F) may result in a good prediction for one loading case and in poor ones for others. The problem of poor allowance of the loading sequence effect and of the effect of Miner's rule inaccuracy exists, of course, only in the case of variable-amplitude loading. However, the effect of the chosen K-value on predictive accuracy exists also in the case of constant-amplitude loading.

It was observed in many investigations that in the case of pulsating tension loading ($R\geq0$), the crack propagation phase is short for massive parts and notched specimens. Table 1 presents Lowak's pulsating-tension test results for AlCuMg2 (2024-T3) sheet specimens of different sizes with a central hole (d/W=0.2, K_t=2.5) of different diameters (d=4,8 and 16 mm). As can be seen, the size has an effect on both the life to failure N_f and to crack initiation N_i, and also on the ratio N_i/N_f. However, the effect of the loading level on the ratio N_i/N_f of the specimens of the same size was not considerable.

Table 1: Life to Crack Initiation N_i and to Failure N_f for Geometrical Similar 2024-T3 Sheet Specimens with Central Hole of Different Size (d/w=0.2) Under Pulsating-Tension R=0, Lowak, 1981.

d	S_{max}=196 MPa		S_a=98 MPa	S_{max}=252 MPa		S_a=126 MPa
mm	N_i kc	N_f kc	N_i/N_f	N_i kc	N_f kc	N_i/N_f
4	41.0	56.8	0.722	11.7	17.4	0.672
8	42.8	53.4	0.801	12.8	16.7	0.766
16	42.6	50.6	0.842	13.8	16.5	0.836

Fig. 1 presents NASA pulsating-tension test results for 7075-T6 sheet specimens with central hole. It confirms the small difference between N_f and N_i in the considered case.

INVESTIGATED MATERIALS

The investigation covered various sheet materials: 2024-T3, 7075-T6, Ck45 (carbon steel SAE 1045) and 42CrMo4 (alloy steel SAE 4140). For these materials, the cyclic material data needed for LSA calculation (P_{SWT}, $S'_{0.2}$, n and E) are available from several sources (1,2,10), while S-N data for R=0 are to be found in handbooks and publications (11,13, 14). In view of (11-14) this diversity of sources, only data for chemically identical alloys with similar heat treatment and close properties (S'_u and S_y) were taken into account.

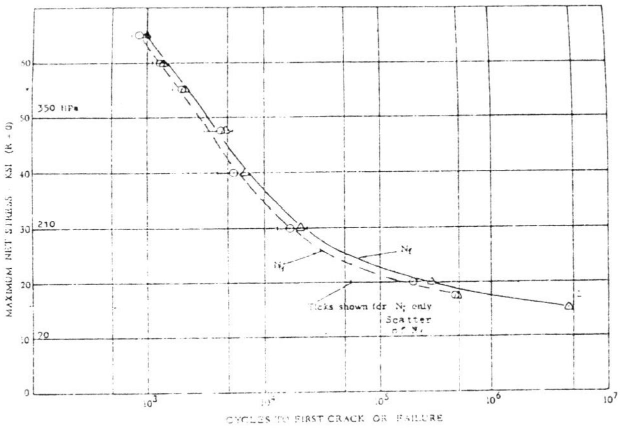

Fig. 1. Maximum stress versus cycles to first crack or failure for 7075-T6 sheet specimens with central hole (K_T=2.57) Smith, 1966.

The report, Buch, 91 lists the cyclic yield limit $S'_{0.2}$, the exponent n and the modulus of elasticity E of the considered materials and the damage parameter $P_{SWT}=(\sigma_{max}\varepsilon_a E)^{1/2}=f(N)$. The P_{SWT}-N line used in the LSA calculation was constructed in a piecewise-linear form (in the log-log scale) for $N=10^2$, $10^3 \ldots 10^7$ cycles with rectilinear prolongation for higher cycle numbers $N>10^7$.

RESULTS OF THE LSA CALCULATIONS OF S-N DATA IN PULSATING-TENSION

As was mentioned before, measurements show that in pulsating tension variations of N_i/N_f are small when $S_{max}=2S_a$ varies between the fatigue limit value for $N=10^6$ cycles and the yield limit of the material. Accordingly, when the ratios N_{pred}/N_i are close for two related loading cases, the ratios N_{pred}/N_f are also close.

Table 2 compares pulsating-tension test results from (the Military Handbook) for 2024-T3 and 7075-T6 notched sheet specimens (K_T=4, 2 and 1.5) with the authors' LSA calculation results. The calculations were performed for $K=K_T$ and for K values giving the best approximation of the fatigue life to failure. As can be seen, the life estimates obtained for $K=K_T$ deviated strongly from tests results, whereas for some chosen K values the calculated S-N data were close to the experimental. Steel specimens with K_T=3.6 were considered in Table 3. The life approximation was here also quite accurate (both for N_f and N_i), when some K-values evidently smaller

Table 2: LSA Life Predictions for 2024-T3 and 7075-T6 Sheet Specimens Under Pulsating-Tension (R=0).

Material K_T & R notch geometry	S_{max} MPa	$N_{exp}=N_f$* kilocycles	LSA predictions for dif. K kilocycles			Best K-value
<u>2024-T3</u>, $K_T=4$			K=4.0	K=3.0	K=2.8	2.8
R=0	280	2.27	0.14	0.97	1.56	
Sym. edge	238	4.56	0.43	2.91	4.53	
notch	140	60.26	12.10	40.44	54.90	
$K_T=2$			K=2.0	K=1.8	K=1.7	1.7
R=0	420	4.58	0.97	1.99	2.91	
central	350	8.94	3.31	6.43	9.00	
hole	280	27.53	12.10	18.70	23.73	
	210	120.70	40.44	64.78	84.62	
$K_T=1.5$			K=1.5	K=1.4	K=1.35	1.35
R=0						
Sym. edge	420	15.04	6.43	9.76	11.45	
notch	288	82.80	40.40	54.500	64.78	
<u>7075-T6</u> $K_T=4$			K=4	K=2.80	K=2.75	2.8
R=0	280	1.17	0.16	1.12	1.24	
Sym. edge	210	5.65	-	5.48	-	
notch	140	62.37	7.25	61.51	68.94	
$K_T=2$			K=2	K=1.75	K=1.70	1.7
R=0	420	3.33	0.78	1.59	1.87	
central	350	6.57	-	4.35	5.13	
hole	280	16.87	7.25	15.76	18.69	
$K_T=1.5$			K=1.5	K=1.35	K=1.30	1.35
R=0	420	7.62	3.72	6.75	8.40	
Sym. edge	350	20.22	-	19.53		
notch	280	76.36	39.94	77.47	98.62	

Experimental data were taken from the Military Handbook, 1975.

Table 3: LSA Predictions of S-N Data for Flat Steel Specimens ($K_T=3.6$) under Pulsating-Tension (R=0).

Material	S_{max} MPa	$N_{exp}=N_f$ cycles*	LSA predictions Number of cycles			$N_{exp}=N_i$ cycles
			K=3.6	K=2.4	K=2.2	
Steel	440	14000	3210	18300	29200	8000
Ck45=	340	50000	8680	71000	113000	45000
SAE1045	276	240000	25400	219000	347000	202000
			K=3.6	K=2.4	K=2.68	
Steel	740	3000	715	3550	2209	2000
42CrMo4	570	10000	1900	10700	6652	6300
SAE4140	440	50000	5730	59100	29074	41000

*Experimental data taken from Haibach et al., 1980.

than K_T were used for life estimation.

Table 4 summarizes fatigue data for the considered materials as well as the actual and predicted lives to failure for S_a=140 MPa in the case of Al-alloys, and for S_a=220 MPa in that of steel specimens.

For S_a=220 MPa the best LSA life predictions were obtained for K values closer to the notch factor K_F in pulsating-tension than in tension-compression with the single exception of CK45. In the case of Al-alloys, the best K-value was always closer to the notch factor K_F for R=0 than for R=-1. The notch factors for 2024-T3 and 7075-T6 were calculated using the two-parameter interpolation formula $K_F/K_T=f(r,A,h)$. The derivation of this formula is described in the book of the author (Buch, 88). In the case of steel CK45 the best K-value was larger than K_F for R=0 or R=-1, the exceptional result being probably due to the inaccuracy of the parameters used in LSA calculations, because they were taken from a different source than the fatigue test results.

Table 5 presents a comparison of pulsating-tension test results in the case S_m=30 Ksi=210 MPa=const ($S_a<S_m$) with LSA life prediction results, using K-values giving the best approximation of the life. As can be seen the K-values used in calculations were mostly close to the corresponding K_F-values for the previously considered specimens with K_T=1.5, 2 and 4 in the case R=0 (Table 4). They were, however, evidently higher than the corresponding K_F values for the considered case of S_m=210 MPa.

Table 6 presents a comparison of best LSA predictions with pulsating-tension tests performed on 2024-T3 specimens (off-center hole, K_T=2.6) for the loading cases $R=S_{min}/S_{max}$=0.25, 0.4 and 0.6. The best approximation of lives $N=10^6$ and $N=10^5$ cycles was obtained for K=1.8. However, in the case of low cycle fatigue life $N=10^4$, the K-value which resulted in best approximation, was 2.4 and not 1.8 for all three above stress ratios. This can be explained by the effect of unsymmetrical distribution of residual stresses generated in the case of small cycle number $N=10^4$ in the critical cross-section of specimens with a hole deplaced from the center line. For Al-specimens with central hole (Tables 2 and 4) the best K-value was identical for $N=10^4$, 10^5 and 10^6. The different behaviour of specimens with a central hole (K_T=2) and with an off-center one (K_T=2.6) in the case of small fatigue life $N=10^4$ is evident from the results presented in Tables 6 and 2.

DISCUSSION OF RESULTS

It should be noticed that the K-values which resulted in best life predictions were for 2024-T3 sheet specimens with K_T=1.5, 2 and 4 exactly the same for R=0 and for S_m=210 MPa (K=1.35, 1.7 and 2.8 corresponding to the SCF). For 7075-T6 the best K-values were the same in Table 2 (R=0) and Table 5 (S_m=210 MPa) for specimens with K_T=1.5 and 4 (K=1.35 and 2.8 correspondingly). Because of the effects of specimen size and surface quality which are not taken into account in direct LSA life predictions, and in view of the difficulty in knowing if the fatigue specimens have exactly the same cyclic properties as those used in LSA calculations (especially when handbook data are used) - it is preferable to use for LSA calculations K-values proved to give an accurate life prediction for some related pulsating-tension test performed on specimens with identical geometry and surface quality.

Table 4: Fatigue Properties of Investigated Materials (MPa).

Material and K_T	Fatigue limits for K_T=1		Notch factor		K used in LSA calcul.	N_{exp}	N_{pred}
	S_{pt}	S_{tc}	R=0	R=-1		kilocycles	
			Exp. values			S_a=220 MPa	
Ck45	500	320					
3.6			2.08	2.20	2.4	14	18
42CrMo4	750	510					
3.6			2.34	2.68	2.4	50	59
7075-T6	246	147	Calcul. values			S_a=140 MPa	
4			2.88	3.02	2.8	1.2	1.1
2			1.70	1.78	1.7	17	16
1.5			1.33	1.39	1.35	76	77
2024-T3	234	147					
4			2.88	3.02	2.8	2.2	1.6
2.5			2.14	2.24	2.1	10	9
2			1.70	1.78	1.7	28	24
1.5			1.33	1.39	1.35	83	65

The variation of N_i/N_f-ratio also has some effect on the predictive accuracy. However, the predictive accuracy, connected with the variation of the N_i/N_f-ratio with the stress level, is much smaller, than the inaccuracy connected with improper choice of the K-value. As can be seen from Table 3 the difference between N_i and N_f is for pulsating-tension much smaller than that between the two predicted fatigue live values when K=K_T and K=K_F are alternatively used in calculations.

In general, it may be concluded that the choice of a proper K-value is very important and should be supported by a related fatigue test result.

CONCLUSIONS

1. In the case of pulsating-tension (R≥0), the Local Strain Approach may also be used for prediction of life to total failure.
2. The K-value which gives the best agreement between life prediction and test is, in the general case of R≥0, mostly close to the value of the notch factor for R=0, for symmetrical specimens.
3. Residual stresses generated in non-symmetrical specimens have an effect on the best K-value in the LCF range $N \leq 10^4$.

Table 5: Comparison of Best LSA Predictions with Pulsating-Tension Test Results for Al-Alloy Specimens in the Case of S_m=210 MPa.

Notch Description	N_{exp} cycles*	2024-T3		7075-T6	
		S_{max} MPa	N_{pred}	S_{max} MPa	N_{pred}
			for K=1.7		for K=1.9
central hole d=76.2 mm	10^4	371	1.53×10^4	350	0.61×10^4
d/w=2/3	4×10^4	315	4.26×10^4	294	4.87×10^4
K_T=2.04	10^5	294	0.97×10^5	280	1.00×10^5
K_F=1.23 (2024)					
K_F=1.25 (7075)	10^6-10^7	273	1.24×10^6	266	0.43×10^6
			for K=1.35		for K=1.35
Edge notch	10^4	448	0.61×10^4	403	1.01×10^4
r=19.3 mm	4×10^4	357	3.96×10^4	350	4.12×10^4
K_T=1.5	10^5	329	0.81×10^5	322	1.16×10^5
K_F=1.16	10^6-10^7	290	2.75×10^6	280	1.46×10^6
K_F=1.22					
			for K=2.8		for K=2.8
Edge notch	10^4	287	1.92×10^4	280	1.32×10^4
K_T=4	4×10^4	266	5.09×10^4	259	4.94×10^4
K_F=1.4	10^5	259	0.76×10^5	252	0.86×10^5
K_F=1.5	10^6-10^7	235	0.79×10^6	235	4.71×10^6

*The experimental data were taken from Grover et al. 1960.

Table 6: Comparison of Best LSA Predictions with Pulsating-Tension Test Results for 2024-T3 Al-Alloy Specimens in the Case of R=const.

Notch Description and Mech. Properties	R= S_{min}/S_{max}	S_{max} MPa	N_{exp} cycles*	N_{pred} cycles
				for K=1.8
Off-center hole d=9.5 mm	0.25	187	10^6	1.57×10^6
w=38 mm	0.25	231	10^5	0.96×10^5
d/w=0.25	0.40	213	10^6	1.19×10^6
S_u=469 MPa	0.40	267	10^5	0.91×10^5
S_y=399 MPa	0.60	293	10^6	0.88×10^6
K_T=2.6	0.60	328	10^5	2.61×10^5
				for K=2.4
K_F=2.08 for R=0.25	0.25	289	10^4	1.24×10^4
K_F=1.77 for R=0.4	0.40	356	10^4	1.10×10^4
K_F=1.73 for R=0.6	0.60	441	10^4	1.65×10^4

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