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Influence of Low Load Truncation Level on Crack Growth for Al 2324-T39 and Al 7050-T7451

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Abstract

Tests with middle-crack tension (M(T)) specimens made of Al 2324-T39 and Al 7050-T7451 are conducted to investigate the influence of low load truncation level on fatigue crack growth. The six different truncated spectra are obtained by removing the small cycles of which amplitudes are less than the specified percentages of the maximum amplitude in the basic flight-by-flight loading spectrum and the remainder of the spectrum is untouched. The tests indicate that the mean level of fatigue crack growth life (FCGL) increases as the load truncation level is enhanced. Considering both the time saving and the influence on FCGL, there is an applicable choice (i.e. spectrum S2 or spectrum S3 in this investigation) for full scale fatigue test. The scatter of FCGL becomes much larger than that under the basic spectrum when the load truncation level is increased to a specified high level, mainly due to the occurrence of crack slanting and branching under the high level truncated loading spectra.

Keywords: fatigue crack growth; aluminum alloys; low load truncation; flight-by-flight spectrum

1. Introduction

The fatigue crack growth (FCG) analysis under the repeated load expected in service is the basis of damage tolerance evaluation. This evaluation ensures that should serious fatigue, corrosion, or accidental damage occur within the design service goal of the airplane, the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected[1]. However, the analysis must be supported by test evidence. The airplane structures suffer lots of gust loads including a large number of low amplitude loads. For full scale fatigue test (FSFT) loading spectrum, these low loads, which are considered to be non-damaging, tend to cause an unacceptable waste of time and cost. It is an economic and common practice to eliminate these low loads in each flight cycle, which will result in significant saving of testing time without changing the FCG characteristics. Nevertheless, the loss of small loading cycles might shift the balance between crack initiation and crack growth[2], and the delay of the FCG occurring after an overloading cycle is strongly sensitive to subsequent underloading cycle[3]. A great number of investigations have been emphasized on the influence of load sequence on FCG[4-11]. However, the amplitude level, below which the loads should be truncated, is affected by the property of structural material, the characteristic of loading spectrum, etc[12-16]. The truncated spectrum used in the FSFT must be substantiated by the FCG tests of specimens to show its validity.

The aim of this study is to investigate the influence of the load level to be truncated on fatigue crack growth life (FCGL), via the tests of standard specimens for two typical kinds of aluminum alloys which are widely used in civil airplane structures. The test results will be able to provide a reasonable support for establishing the FSFT truncated spectrum without unneglectable influence on FCGL.

2. Tests

The materials studied are alloys Al 2324-T39 and Al 7050-T7451. The mechanical properties of these alloys are given in Table 1. Middle-crack tension (M(T)) specimens are used in the tests. The dimensions of the specimens are shown in Table 2, where L-S represents that the tension load is applied in the longitudinal direction and the crack propagates along the short transverse direction, and L-T represents that the

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tension load is also applied in longitudinal direction and the crack propagates along the transverse direction.

Table 1 Mechanical properties of the alloys MPa

Alloy	Tensile strength	Yield strength	Shear strength	Elastic modules
Al 7050-T7451	510	441	289.0	71 000
Al 2324-T39	489	393	275.8	71 000

Table 2 Dimensions of M(T) specimens mm

Alloy	Length	Width	Thickness	Half length of linear cut	Orienta-tion
Al 7050-T7451	350	98.5	6.0	4	L-S
Al 2324-T39	350	98.5	4.5	4	L-T

The basic loading spectrum S0 is a 5×10 flight-by-flight spectrum which consists of five different flight types and a block is composed of 4 200 flights. The five flight types are arranged randomly within the block. Flight type 1 is the most severe loading condition and occurs only once during 4 200 flights, while flight type 5 is the least severe and occurs 2 958 times in 4 200 flights.

The spectrum S0 is then filtered by removing small cycles to study the effects of spectral truncation on the FCGL. The first truncated spectrum, marked with spectrum S1, is obtained by removing the cycles of which amplitude is less than 9.82% of the maximum amplitude in spectrum S0, while the taxiing loads during each flight are retained. About 26.56% loading cycles are eliminated compared with spectrum S0. The other four truncated spectra, i.e. spectra S2, S3, S4, and S5 can be gained in the same way. Table 3 gives the details of the spectra with different truncation levels and the percentage of eliminated cycles in each block. Fig.1 illustrates the segments of the flight-by-flight loading spectrum, including flight type 1 and flight type 5 with different truncation levels, where σ is the stress in the loading spectrum, σ_{max} the maximum value of σ, and N the load cycle.

Table 3 Comparisons of spectra

Parameter	Spectrum					
	S0	S1	S2	S3	S4	S5
Truncation level/%	0	9.82	11.72	13.98	17.11	21.36
Percentage of eliminated cycles/%	0	26.56	46.87	62.95	73.35	78.58

All the tests are conducted with MTS880 fatigue test system, and an observation system consisting of digital microscope, servo motor, and raster ruler is used to register the position of crack tip.

All the specimens are fatigue precracked under constant amplitude load of $R = 0.06$ and σ_{max}= 90 MPa and result in an initial crack of about 5.5 mm from the symmetry axis of the specimen, and then the FCG tests are conducted under spectral loads. The test frequency is 8 Hz. Under each loading spectrum, there are 5 specimens for Al 7050-T7451 and 6 specimens for Al 2324-T39, respectively.

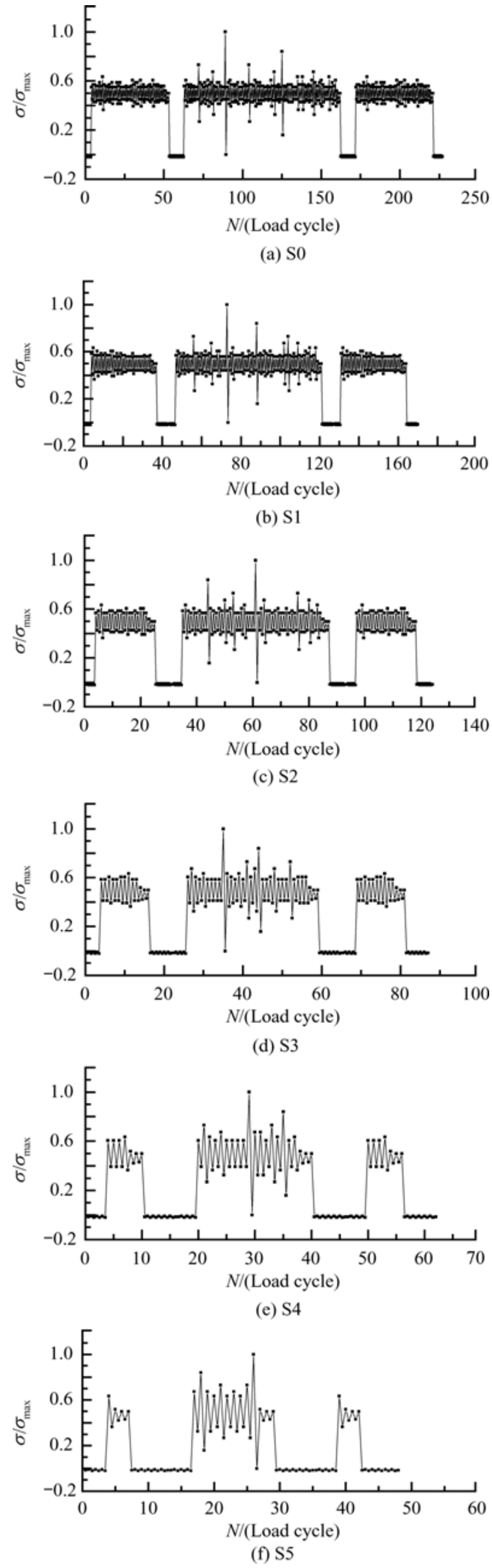


Fig.1 Segments of flight-by-flight loading spectrum with different truncation levels.

3. Results and Discussion

In order to investigate the influence of load truncation level on the FCGL for a specified initial crack length a_0 to a reference crack length a_{ref} (a_0 and a_{ref} are given in Table 4), the FCGL should be expressed with the number of flights other than the number of load cycles, because the numbers of load cycles contained in each flight under different load truncation levels are different. The original data registered in the tests are crack lengths and the corresponding load cycles, i.e. (a, N) data. The loading cycles corresponding to a_0 and a_{ref}, marked with N_0 and N_{ref} respectively, can be gained through the local polynomial fitting of original (a, N) data. Then N_0 and N_{ref} can be transformed to $(N_0)_f$ and $(N_{ref})_f$, which are the FCGL expressed with flights, since the relationship between the loading cycles and the number of flights can be easily obtained according to the loading spectrum. Then, the FCGL expressed with flights and marked with N_f is obtained by

$$N_f = (N_{ref})_f - (N_0)_f \tag{1}$$

Table 4 Initial and reference crack lengths investgated mm

Alloy	a_0	a_{ref}		
		Case 1	Case 2	Case 3
Al 7050-T7451	5.5	12.0	17.0	22.0
Al 2324-T39	5.5	11.5	16.5	21.6

3.1. Influence of load truncation level on mean value of FCGL

The mean values of FCGL from a_0 to different a_{ref} are given in Table 5 and Table 6. All of the values of FCGL have been normalized by the FCGL value corresponding to S0 for better understanding the influence. Fig.2 shows the changing trend of the influence of load truncation on the two kinds of aluminum alloys.

Table 5 Normalized FCGL corresponding to different a_{ref} for Al 7050-T7451

Spectrum	N/N_0		
	a_{ref}=12.0 mm	a_{ref}=17.0 mm	a_{ref}=22.0 mm
S0	1	1	1
S1	1.08	1.09	1.08
S2	1.25	1.27	1.26
S3	1.38	1.42	1.45
S4	1.70	1.73	1.79
S5	2.02	2.09	2.14

Table 6 Normalized FCGL corresponding to different a_{ref} for Al 2324-T39

Spectrum	N/N_0		
	a_{ref}=11.5 mm	a_{ref}=16.5 mm	a_{ref}=21.5 mm
S0	1	1	1
S1	1.09	1.11	1.10
S2	1.32	1.32	1.32
S3	1.46	1.48	1.51
S4	2.23	2.74	3.01
S5	3.33	4.33	4.82

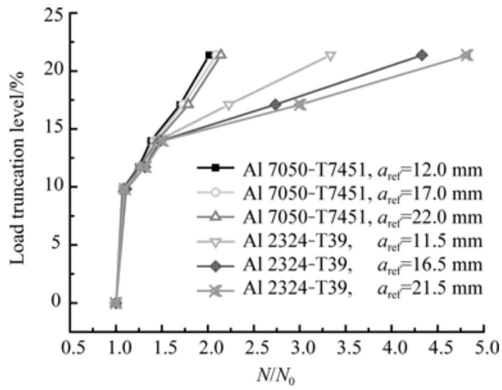


Fig.2 FCGL vs load truncation level for Al 7050-T7451 and Al 2324-T39.

The test results indicate that ① the FCGL for both kinds of aluminum alloys increase with the load truncation level being elevated, ② the influence of load truncation level on FCGL for Al 2324-T39 is greater than that for Al 7050-T7451, ③ the influences of S4 and S5 on FCGL are much more severe than that of S1, S2, and S3, especially for Al 2324-T39.

If the aforementioned six kinds of loading spectra are used in fatigue test of aircraft components, the test duration can be predicted based on the results of this article. Assuming that test duration corresponding to S0 is 1, then the test duration with respect to another spectrum can be obtained via multiplying the loading cycles retained in it and its influence factor on FCGL. Table 7 shows the predicted values for Al 2324-T39. The FCGL influence factor used here is that of a_{ref} = 21.5 mm, which is the maximum of the presented test results (see Table 6). It can be easily seen that S2 or S3 is an applicable choice which will save lots of test duration and their influences on FCGL are not very significant.

Table 7 Test duration prediction under six kinds of loading spectra for Al 2324-T39

Predicted value	Spectrum					
	S0	S1	S2	S3	S4	S5
Cycles left/%	100	73.44	53.13	37.05	26.65	21.42
FCGL influence factor	1.00	1.10	1.32	1.51	3.01	4.82
Time cost/%	100	80	70	56	80	103

3.2. Influence of load truncation level on scatter of FCGL

It is observed that the influence of load truncation level on both the mean value and the scatter of FCGL for Al 2324-T39 is much more severe than that for Al 7050-T7451. Therefore, the following discussions are based on the test results of Al 2324-T39.

Considering that FCGL follows the log-normal distribution[17], that is, $X = \lg N$ follows the normal distribution $N(\mu,\sigma)$. Fig.3 gives the probability density functions of X corresponding to a_{ref} = 21.5 mm. It indicates that the scatter of the logarithm of FCGL corresponding to S5 is the maximum, while that corresponding to S1 is the minimum. The F-test method is adopted to judge if there are significant differences in the scatter of FCGL under the six kinds of loading spectra.

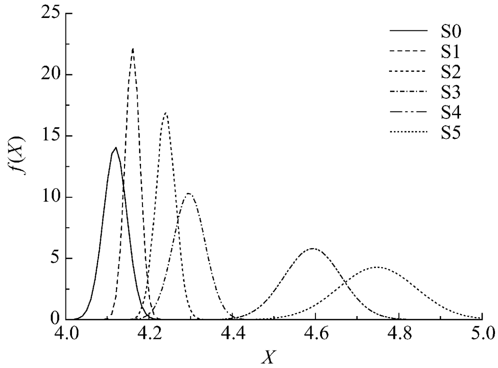


Fig.3 Probability density functions of X for Al 2324-T39 (a_{ref} = 21.5 mm).

The null hypothesis is that the standard deviation of the logarithm of FCGL for the ith spectrum does not differ from that for the jth spectrum, that is, $\sigma_i = \sigma_j$ and the alternative hypothesis is $\sigma_j > \sigma_i$. Then the F-statistic is

$$F = s_j^2 / s_i^2 \tag{2}$$

where s_i^2 and s_j^2 are the sample variances corresponding to the ith spectrum and the jth spectrum respectively. For the convenience of analysis, $F \geq 1$ is set, i.e. $s_j \geq s_i$.

The F-statistic has the F distribution with five degrees of freedom for both numerator and denominator. $F > F_\alpha$ is the critical region for the F-test with the significance level of α. Let $\alpha = 5\%$, then, the upper bound of confidence limits is $F_\alpha(5,5) = 5.05$. If $F > F_\alpha$, the alternative hypothesis of $\sigma_j > \sigma_i$ is accepted.

The calculated values of F are given in Table 8.

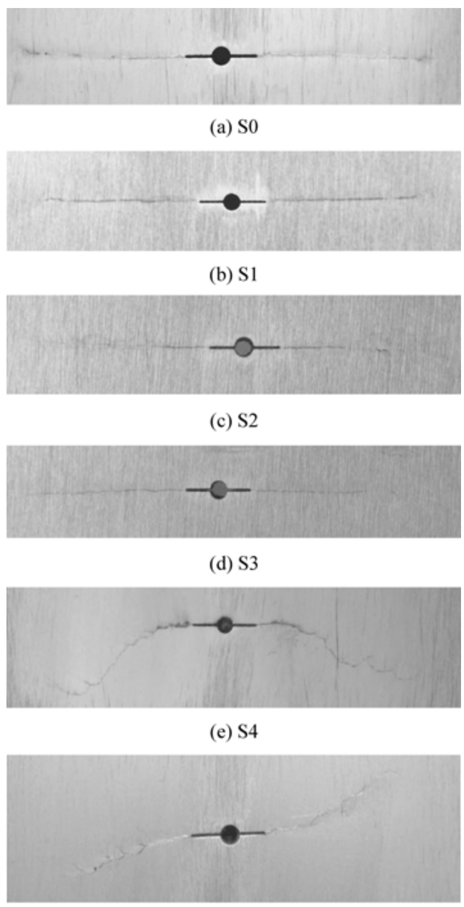
Table 8 *F* values

Spectrum	S0	S1	S2	S3	S4	S5
S0	1					
S1	2.500 0	1				
S2	1.450 2	1.723 6	1			
S3	1.850 8	4.626 1	2.684 0	1		
S4	5.893 1	14.73 0	8.546 3	3.184 1	1	
S5	10.84 5	27.10 9	15.72 8	5.860 2	1.840 4	1

It can be accepted reasonably that the standard deviations of the logarithm of FCGL under spectra S0, S1, S2, and S3 do not differ from each other. The variance of the logarithm of FCGL under spectrum S4 is larger than those under spectra S0, S1, and S2. However the difference between those under spectra S4 and S3 is not significant. The variance of the logarithm of FCGL under spectrum S5 is larger than those under spectra S0, S1, S2, and S3, while there is no significant difference between the variance of spectra S4 and S5. It should be mentioned that the above conclusions of the statistical test is based on the hypothesis of $\alpha = 5\%$.

3.3. Influence of load truncation level on crack morphology

It has been mentioned in Section 3.2 that the scatter of FCGL becomes much more significant under spectra S4 and S5, it is mainly resulted from the remarkable crack slanting and branching observed in the crack growth test under spectra S4 and S5. Spectrum S5, containing the least small cycles, tends to make the cracks at both the left and right sides be slanting or branching significantly for all the six specimens tested. However, for the six specimens numbered 10, 12, 13, 17, 32, and 33 under spectrum S4, remarkable branched cracks are observed at both sides of No. 12,13,17, and 32 specimens, while for the No.10 and No. 33 specimens, the branched cracks are seen only at one side of these specimens. Under spectrum S3, the cracks show slightly branching but one of these cracks grows rapidly to turn into a dominant crack. The cracks under spectra S0, S1, and S2 are straight and perpendicular to the applied tension strength. The representative crack morphologies under different spectra are shown in Fig.4.



(a) S0

(b) S1

(c) S2

(d) S3

(e) S4

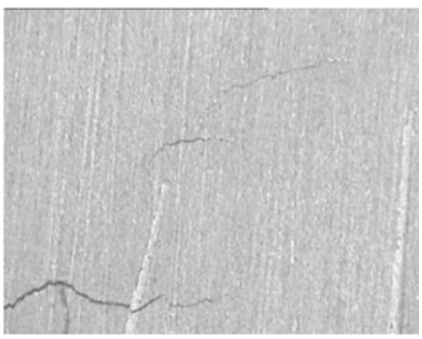
(f) S5

Fig.4 Crack morphologies under different loading spectra.

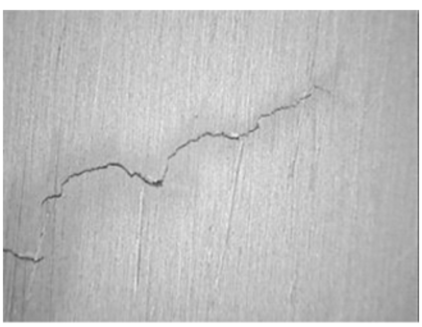
The crack growth rate dropped significantly after the crack branching appeared, which led to the increase of FCGL and the larger scatter in crack growth life.

Generally, the crack slanting or branching can not be observed immediately after the high load is applied. Branching mostly occurrs first at the middle part of the crack face along the direction of thickness and then is observed at the surface of the specimen. The inner branching always induces one or two small secondary cracks at the surface. Both the previously dominant crack and the secondary cracks will keep growing for several load cycles and then the cracks will link up with each other. Fig.5 illustrates the process of secondary cracks appearing and cracks linking up observed in No.37 specimen under spectrum S5.

(a) Appearance of a secondarycrack
(173 283 load cycles)



(b) Appearance of another secondary crack
(185 804 load cycles)



(c) Linking up of cracks (377 452 load cycles)

Fig.5 Appearance of secondary cracks and linking up of cracks.

The significant crack slanting or branching phenomenon can only be observed in the specimens subjected to spectra S4 and S5, which must be due to the elimination of small cycles with higher amplitude level when spectrum S0 is turned into spectra S4 and S5. Virtually, all of the eliminated cycles for spectrum S3 have amplitude less than 11.8 MPa, while the eliminated cycles for spectrum S4 have amplitude below 14.4 MPa, and the remainder of the spectrum is untouched. Interestingly, there are significant differences between the results produced by spectrum S3 and those produced by spectrum S4. The mechanism of the crack slanting or branching being created under tension stress is still not clear. Further work is under way to examine the effect of small cycle removal in other spectra for trying and casting more light on this issue.

4. Conclusions

(1) For the flight-by-flight spectrum investigated, spectrum S2, which has a load truncation level of 11.72%, will save about 30% test duration and the maximum influence factor on FCGL is 1.32, spectrum S3 with load truncation level of 13.98% induces 44% saving of test duration and the FCGL influence factor is no more than 1.51. Spectrum S2 or spectrum S3 is an applicable choice for the FSFT of both Al 7050-T7451 and Al 2324-T39.

(2) The scatter of FCGL becomes much larger when the load truncation level is increased to a high level, which is mainly due to the change of crack morphology.

(3) The crack slanting and branching appear when the elimination of small cycles is raised to a higher level, and the secondary cracks are observed during crack propagation.

References

[1] Federal Aviation Administration, Advisory Circular. Damage tolerance and fatigue evaluation of structure. Federal Air Regulations 25, AC No.25.271-1C, 1998.

[2] Underhill P R, DuQuesnay D L. The effect of dynamic loading on fatigue scatter factor for Al 7050. International Journal of Fatigue 2008; 30(4): 614-622.

[3] Bacila A, Decoopman X, Mesmacque G, et al. Study of underload effects on the delay induced by an overload in fatigue crack propagation. International Journal of Fatigue 2007; 29(9-11): 1781-1787.

[4] Schijve J. Effect of load sequences on crack propagation under random and program loading. Engineering Fracture Mechanics 1973; 5(2): 269-280.

[5] Suresh S. Fatigue of materials. Cambridge: Cambridge University Press, 1991.

[6] Huang X P, Zhang J B, Cui W C, et al. Fatigue crack growth with overload under spectrum loading. Theoretical and Applied Fracture Mechanics 2005; 44(2): 105-115.

[7] Zitounis V, Irving P E. Fatigue crack acceleration effects during tensile underloads in 7010 and 8090 aluminium alloys. International Journal of Fatigue 2007; 29(1):108-118.

[8] Hamam R, Pommier S, Bumbieler F. Variable amplitude fatigue crack growth, experimental results and

modeling. International Journal of Fatigue 2007; 29 (9-11): 1634-1646.

[9] Herler P, Klatschke H. Generation and use of standardised load spectra and load-time histories. International Journal of Fatigue 2005; 27(8): 974-990.

[10] Ray A, Patankar R. Fatigue crack growth under variable-amplitude loading: Part I—model formulation in state-space setting, Part II—code development and model validation. Applied Mathematical Modeling 2001; 25(11): 979-1013.

[11] Kim J H, Lee S B, Hong S G. Fatigue crack growth behavior of 7050-T7451 attachment lugs under flight spectrum variation. Theoretical and Applied Fracture Mechanics 2003; 40(2): 135-144.

[12] Everett R A, Jr. The effect of load sequencing on the fatigue life of 2024-T3 aluminum alloy. International Journal of Fatigue 1997; 19(93): 289-293.

[13] Zhuang W, Barter S, Molent L, et al. Flight-by-flight fatigue crack growth life assessment. International Journal of Fatigue 2007; 29(9-11): 1647-1657.

[14] Underhilla P R, DuQuesnay D L. Effect of small cycles and load spectrum truncation on the fatigue life scatter in 7050 Al alloy. International Journal of Fatigue 2009; 31(3); 538-543.

[15] Yan J H, Zheng X L, Zhao K. Experimental investigation on the small-load-omitting criterion. International Journal of Fatigue 2001; 23(5): 403-415.

[16] Schubbe J J. Evaluation of fatigue life and crack growth rates in 7050-T7451 aluminum plate for T-L and L-S oriented failure under truncated spectra loading. Engineering Failure Analysis 2009; 16(1); 340-349.

[17] Gao Z T. Statistics in fatigue. Beijing: National Defence Industry Press, 1986. [in Chinese]

Biography:

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