THE APPLICATION OF NEWMAN CRACK - CLOSURE MODEL TO PREDICTING FATIGUE CRACK GROWTH

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SUMMARY

Newman Crack - closure model and the relevant crack growth program were applied to the analysis of crack growth under constant amplitude and aircraft spectrum loading on a number of aluminum alloy materials. The analysis was performed for available test data of 2219-T851, 2024-T3, 2024-T351, 7075-T651, 2324-T39 and 7150-T651 aluminum materials.

The results showed that the constraint factor is a significant factor in the method. The determination of the constraint factor is discussed in this paper.

For constant amplitude loading, satisfactory crack growth lives could be predicted. For the above aluminum specimens, the ratio of predicted to experimental lives, Np/Nt, ranged from 0. 74 to 1. 36. The mean value of Np/Nt was 0. 97. For a specified complex spectrum loading, predicted crack growth lives are not in very good agreement with the test data. Further effort is needed to correctly simulate the transition between plane strain and plane stress conditions, existing near the crack tip.

INTRODUCTION

Crack growth analysis is one of the distinct elements of damage tolerance design for aircraft structure.

Prediction of crack growth under aircraft spectrum loading is very difficult because of retardation due to overloads, acceleration due to underloads which are followed by an overload and reduction of retardation caused by underloads following an overload.

There are a number of crack growth models. Table 1 gives the comparison of the typical models (ref. 1).

In these models, crack closure models are mathematically more complicated, they offer the potential to analytically predict many more characteristics than yield zone models and have received more and more attention. Newman's crack - closure model is one of the most recent works on this topics.

This paper summarizes the analytical results of crack growth under constant amplitude and aircraft spectrum loading on a number of aluminum alloy materials. Newman crack - closure model and the relevant crack growth program were applied to the analysis (ref. 2). The purpose of this analysis is to compare Newman's method with test and further to understand its application to aircraft structural damage tolerance design.

CRACK - CLOSURE MODEL

The crack - closure model developed by Newman was based on a modification to the Dugdale model describing the plastic-zone ahead of a crack. It is assumed that the crack could be fully or partially closed at positive minimum stresses due to residual plastic deformations left in the wake of an advancing crack. Upon reloading, the crack surfaces gradually separate until the crack is fully open at an applied stress equal to the " crack opening stress ". Figure 1 shows a schematic of the model.

The crack opening stresses (Sop) were calculated from the contact stress at minimun load. The contact stresses were calculated from displacement compatibility equations with constraints added.

A constraint factor α was introduced to account for the effect of the state of stress on the plastic-zone size. The material is assumed to yield in tension when the stress is $\alpha\,\sigma_0$ and in compression when the stress is $-\sigma_0$. The flow stress σ_0 is taken to be the average between the yield stress and the ultimate tensile strength. Ideal plane stress or plane strain conditions are simulated with $\alpha = 1$ or 3, respectively. In general, the constraint factor will lie between the ideal limits and may additionally vary with crack length.

Newman's crack growth rate equation is as follows:

$$\frac{da}{dN} = C_1\,\Delta K_{eff}^{C_2}\,\frac{1-\left(\frac{\Delta K_o}{\Delta K_{eff}}\right)^2}{1-\left(\frac{K_{max}}{C_5}\right)^2} \tag{1}$$

Where

$$\Delta K_o = C_3\left(1 - C_4\,\frac{S_{op}}{S_{max}}\right) \tag{2}$$

$$K_{max} = S_{max}\sqrt{\pi a}\,F \tag{3}$$

$$\Delta K_{eff} = (S_{max} - S_{op})\sqrt{\pi a}\,F \tag{4}$$

The coefficients C_1 to C_5 were determined from the best fit to constant amplitude experimental data. For 2219-T851 aluminum plate, the coefficients are (ref. 2):

$$\begin{aligned} C_1 &= 1.764 \times 10^{-10} \\ C_2 &= 3.18 \\ C_3 &= 2.97 \text{ Mpa m}^{1/2} \\ C_4 &= 0.8 \\ C_5 &= 77 \text{ Mpa m}^{1/2} \end{aligned} \tag{5}$$

TEST DATA

The analysis was performed for the available test data (ref. 3 and ref. 4). Crack growth tests were all for center cracked tension (CCT) specimens. For constant amplitude loading, the test data on 2219- T851 aluminum material are shown in Table 2 ; the test data on 2024- T3, 2024-T351, 7075-T651, 2324-T39 and 7150- T651 aluminum materials are shown in Table 3. For spectrum loading, the test data on 2024- T3 and 2024-T351 aluminum material are shown in Table 4.

CRACK GROWTH RATE DATA

To obtain the crack growth rate $\frac{da}{dN}$ against ΔK_{eff} relationship, the following methods can be used:

1) Newman's crack growth rate equation (see equation (1)), which was employed for 2219-T851 specimens in this paper.
2) Table look - up method, which was employed for all specimens except 2219-T851 in this paper.

The $\frac{da}{dN}$ versus K_{max} relationship was obtained from the test and further was transformed into $\frac{da}{dN}$ versus ΔK_{eff} using Newman's crack opening stress equation (ref. 5).

RESULTS AND DISCUSSION

The crack growth lives from the initial crack length to the final crack length were calculated with various constraint factors.

1) Results for constant amplitude loading

The effect of the constraint factor on the ratio of predicted to experimental lives for various materials is summarized in Figure 2.

Figure 2 shows that there is a value of α, which gives the best comparison with calculated results for a material of a given thickness and stress ratio.

For 2219-T851, Reference 2 pointed out that the equations (1) through (5) with $\alpha = 2.3$ would give a good correlation under constant amplitude loading. But in our analysis (see Table 2), it was found that at the intermediate stress level (S_{max} = 138 MPa), the crack front is in a state of stress transition. As a consequence $\alpha = 1.9$ is found to give a better correlation. At the higher or lower stress level, the prediction could not best fit the test data. It seems necessary to fit a new set of coefficients and constraint factor. The tendency is as follows: at the lower stress level (S_{max} = 55 MPa) - plane strain conditions should prevail and α should vary from 2.3 to 3.0 as stress ratio R decreases; at the higher stress level (S_{max} = 276 MPa) - plane stress conditions should exist and α should approach 1.0 at positive R.

The calculated lives are not very sensitive to α when using the table look - up method. For all other aluminum materials except 2219-T851, with R = 0.1 (S_{max} = 124.2, 82.8 MPa), $\alpha = 1.0$ ($t < 3.175$ mm) and 2.7 (6.35 mm $\leqslant t \leqslant$ 12.7 mm) give the best results respectively.

Comparison of experimental and predited crack growth lives obtained with the optimum α for all specimens is shown in Table 3. Figures 3 through 5 show the crack growth analysis curves and test curves for three aluminum materials.

The ratio of predicted to experimental crack growth lives, Np/Nt, ranged from 0.74 to 1.36 for all 29 constant amplitude data. The mean value of Np/Nt was 0.97.

2) Results for spectrum loading

The original crack growth program only allowed input loading with a specified periodic load sequence. It has been modified to be able to analyze typical transport spectra, which have a random sequence in a block included thousands of flights.

For this spectrum loading, predicted crack growth lives are not in very good agreement with the test data. Comparison of experimental and predicted crack growth lives for 2024 aluminum alloy under transport spectrum loading is shown in Table 4.

The predictions made under spectrum loading were more sensitive to the constraint factor. Therefore, it is very important to correctly simulate the stress state, either plane stress or plane strain, existing near the crack tip.

CONCLUSION

Newman crack - closure model was applied to the analysis of crack growth under simple and complex load histories for a number of aluminum materials.

The conclusions are drawn as follows:

The key to applying the Newman crack - closure model is to determine a proper constraint factor α. There is a value of α, which gives the best calculated result for a material of a given thickness and stress ratio. It means that correct judgement and adequate assumptions in the state of stress have an important effect on the accuracy of analysis.

For constant amplitude loading, in general, satisfactory crack growth lives could be predicted once the proper constraint factor α has been determined. The ratio of predicted to experimental crack growth lives, Np/Nt, ranged from 0.74 to 1.36 for 29 constant amplitude data. The mean value of Np/Nt was 0.97.

For spectrum loading, the analytical complications increase and the information on the transition between plane strain and plane stress is needed. The constraint factor α would be a variable and a function of the plastic zone to thickness ratio. At short crack lengths and low stress levels, plastic zone size is small compared to material thickness, plane strain conditions may prevail and α may be in the range between 2 and 3. As the crack grows longer, α will drop steadily until at some longer length where plastic zone size is more likely close to the thickness, plane stress conditions may prevail and hence α nears 1.

One thing which could be pointed out is that the material input data should cover the complete relevant range of ΔK and R values when using fatigue crack growth rate table as the input to the crack growth program.

Note that crack - closure model, which performs a cycle by cycle calculation, is time - consuming. It is hopeful to do some simplification for engineering practice.

The following are some recommendations for the program:

As the calculated crack opening stress was held constant in the program while the crack growth over the length ΔC^*, the crack growth accumulation procedure may be simplified.

An " equivalent " crack opening stress might be used as early as possible in order to reduce the computer time.

REFERENCES

1. Si, E.: A Comprehensive Review of Models of Crack Growth Analysis and Life Prediction Methods under Spectrum Loading. ACTA Aeronautica ET Astronautica Sinica Vol. 8, No. 2, 1987.
2. Newman, J. C., Jr.: A Crack - Closure Model for Predicting Fatigue Crack Growth under Aircraft Spectrum Loading. ASTM STP 748, 1981.
3. Chang, J. B. and Stolpestad, J. H.: Improved Methods for Predicting Spectrum Loading Effects - Phase I Report. AFFDL-TR-79-3036, Vol. II, March 1978.
4. Miller, M., Luthra, V. K. and Goranson, U. G.,: Fatigue Crack Growth Characterization of Jet Transport Structure. 14th Symposium of the International Committee on Aeronautical Fatigue (ICAF), Ottawa, Canada, June 1987.
5. Newman, J. C., Jr.: A Crack Opening Stress Equation for Fatigue Crack Growth. International Journal of Fracture, Vol. 24, 1984.

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Table 1. Comparison of Typical Crack Growth Models

TYPE	FEATURE PARAMETERS	CONTRIBUTORS
[1] Plastic Yield Zone Model	Effective Stress Intensity Range	Wheeler (1970) Willenborg (1971) Gallagher (1974) Chang (1981) Johnson (1981)
[2] Crack Closure Model	Crack Opening Stress	Elber (1969) Newman (Finite element 1974) (Contact stress 1981) Bell (AFFDL) (1974) Maarse (1977) Matsuoka (1976) De Koning (1980)
[3] Modified Model Based on One or Both of above Types	One or Both of [1] and [2]	Huang (1980) He (1980)

Table 2. Comparison of Experimental and Predicted Crack Growth Lives for 2219-T851 Aluminum Alloy

Smax MPa	R	a_i mm	a_f mm	Np/Nt α=1.0	α=1.9	α=2.3	α=2.7
55	-0.1	3.91	18.7			1.62	1.36
55	0.0	3.55	52.4			0.99	0.83
55	0.3	3.87	6.9			0.76	0.64
138	-0.3	4.13	45.7		1.11		
138	-0.1	3.85	43.0		0.99		
138	0.01	3.87	50.0		0.99	0.83	
138	0.01	4.00	42.0		1.04		
138	0.01	6.67	38.3		0.95		
138	0.2	4.57	48.0		1.22		
138	0.3	4.06	43.6		0.80		
138	0.7	3.94	12.1	1.12	0.87		
276	-0.1	3.94	21.4			1.15	1.09
276	0.01	3.83	14.9	0.75	0.75	0.72	
276	0.3	3.94	12.9	0.74	0.60	0.58	
276	0.7	3.94	23.5	0.86			

Note: R - Stress Ratio (Smin/Smax)
a_i - Half Length of initial crack
a_f - Half Length of final crack
Np - Number of cycles predicted from analysis
Nt - Number of cycles from test

Table 3. Comparison of Experimental and Predicted Crack Growth Lives for Various Aluminum Materials under Constant Amplitude Loading

Material	Temper	Smax (MPa)	R	t (mm)	a_i (mm)	a_f (mm)	Np/Nt	α
2024	T3	124.2	0.1	3.175	7.214	57.302	0.92	1.0
	T3	124.2	0.1	1.600	8.687	59.715	0.96	1.0
	T351	124.2	0.1	3.175	10.008	57.302	0.97	1.0
	T351	124.2	0.1	6.350	8.992	56.667	0.93	2.7
	T351	124.2	0.1	12.70	8.484	58.522	0.98	2.7
7075	T651	82.8	0.1	3.175	7.366	60.452	0.97	1.0
	T651	82.8	0.1	6.350	6.655	58.293	0.99	2.7
	T651	82.8	0.1	12.70	6.985	58.141	0.99	2.7
2324	T39	82.8	0.1	3.175	14.808	102.438	0.93	1.0
	T39	82.8	0.1	7.087	16.866	114.071	0.95	2.7
	T39	82.8	0.1	12.649	25.375	112.293	0.99	2.7
7150	T39	82.8	0.1	3.302	15.773	111.836	0.95	1.0
	T39	82.8	0.1	6.350	15.926	87.401	0.96	2.7
	T39	82.8	0.1	12.70	17.475	117.450	0.99	2.7

Table 4. Comparison of Experimental and Predicted Crack Growth Lives for 2024 Aluminum Material under Transport Spectrum Loading

Temper	t (mm)	a_i (mm)	a_f (mm)	Np/Nt
T3	3.175	6.528	25.349	1.52
T351	6.350	5.842	60.198	0.30

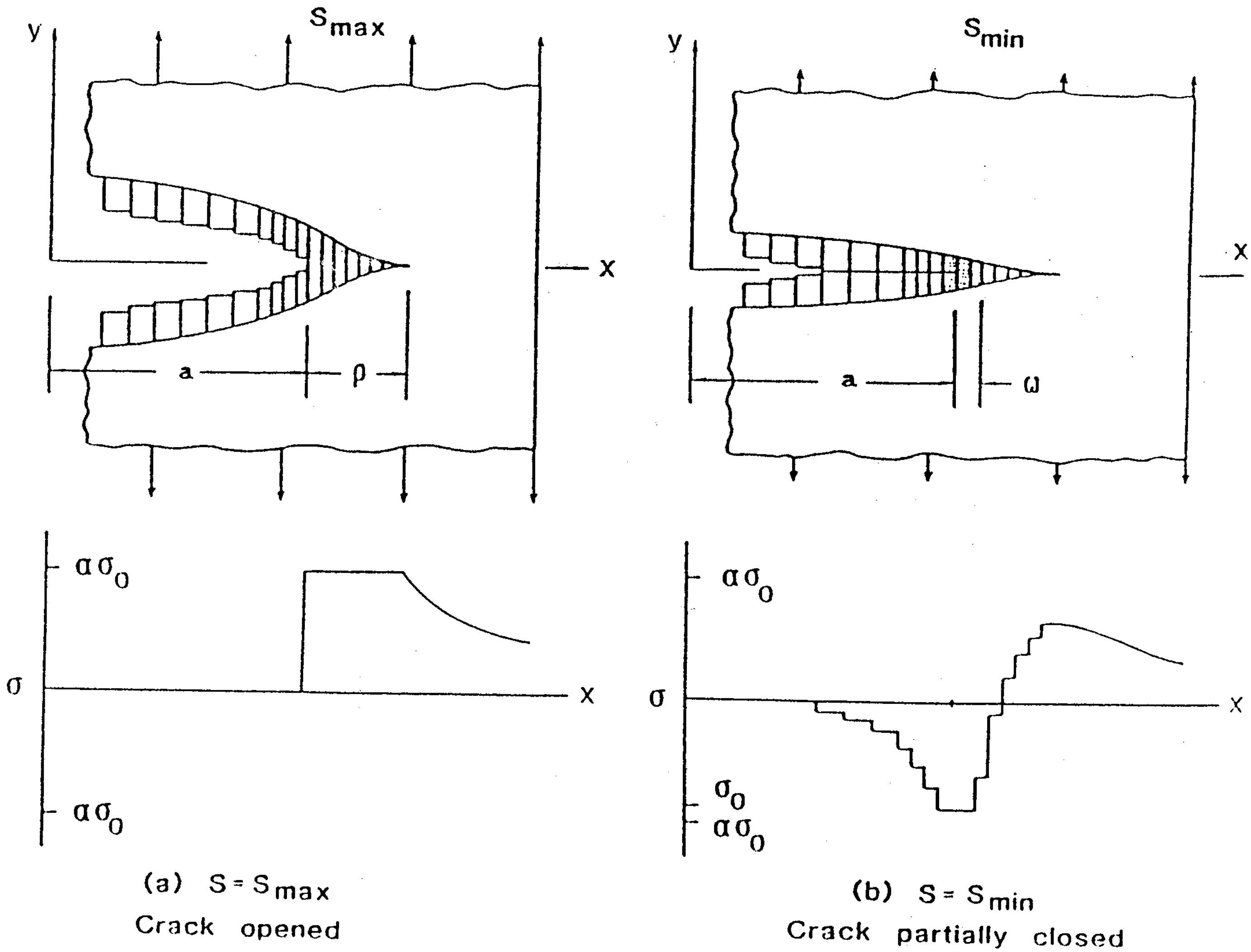

Figure 1. Schematic of crack closure model.

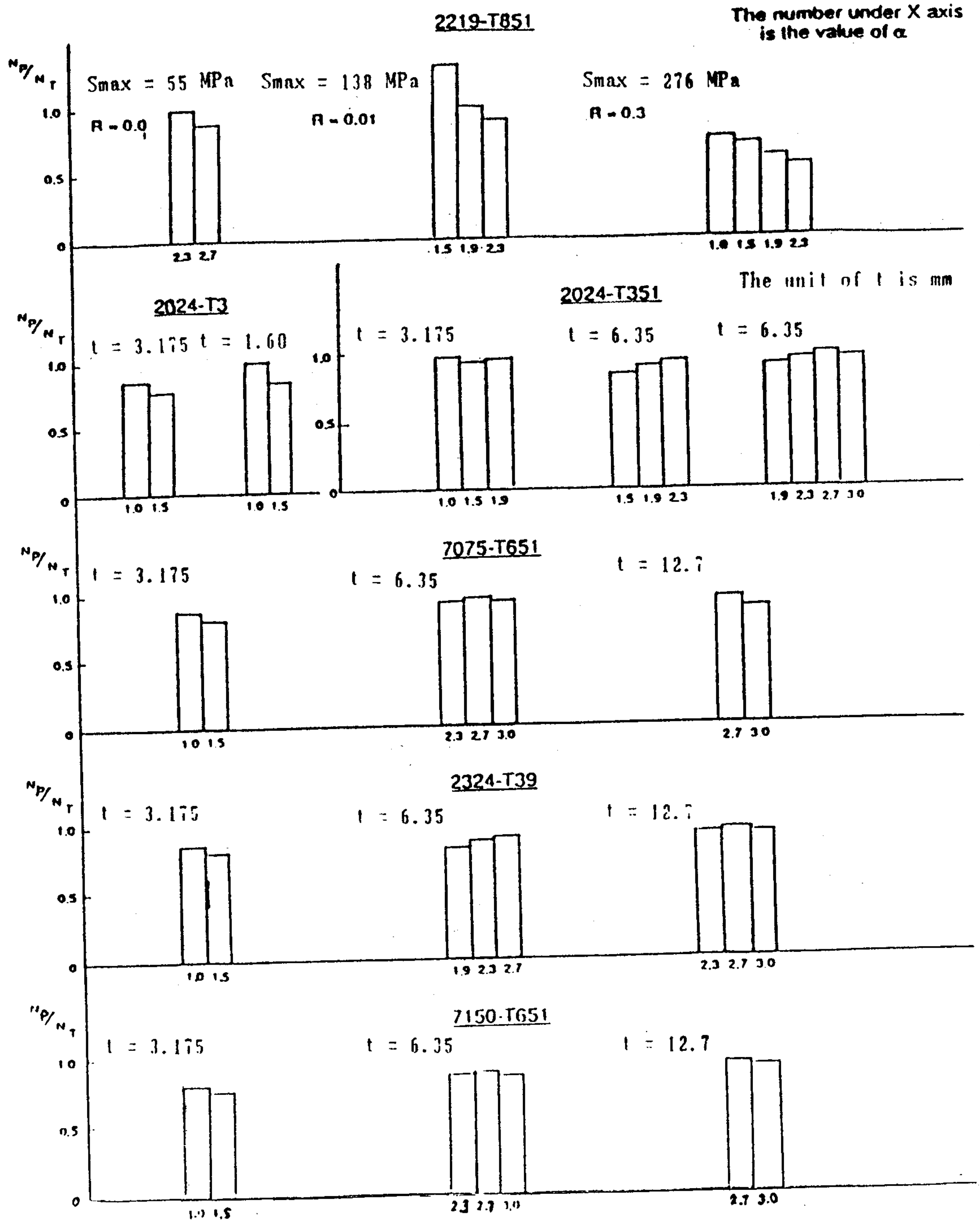

Figure 2. The effect of the constraint factor α on predicted lives.

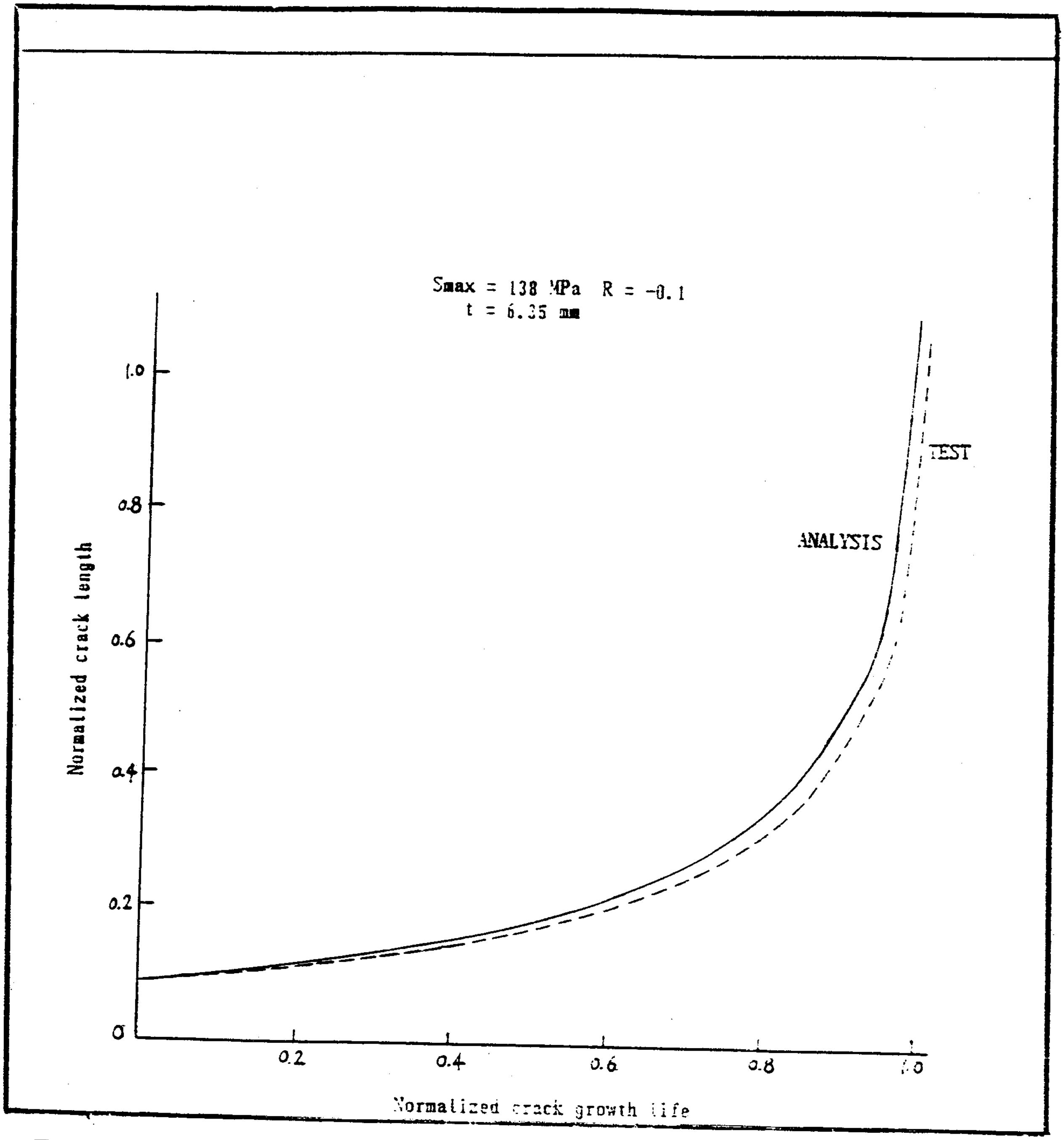

Figure 3. Crack growth comparison between prediction and test for 2219 - T851.

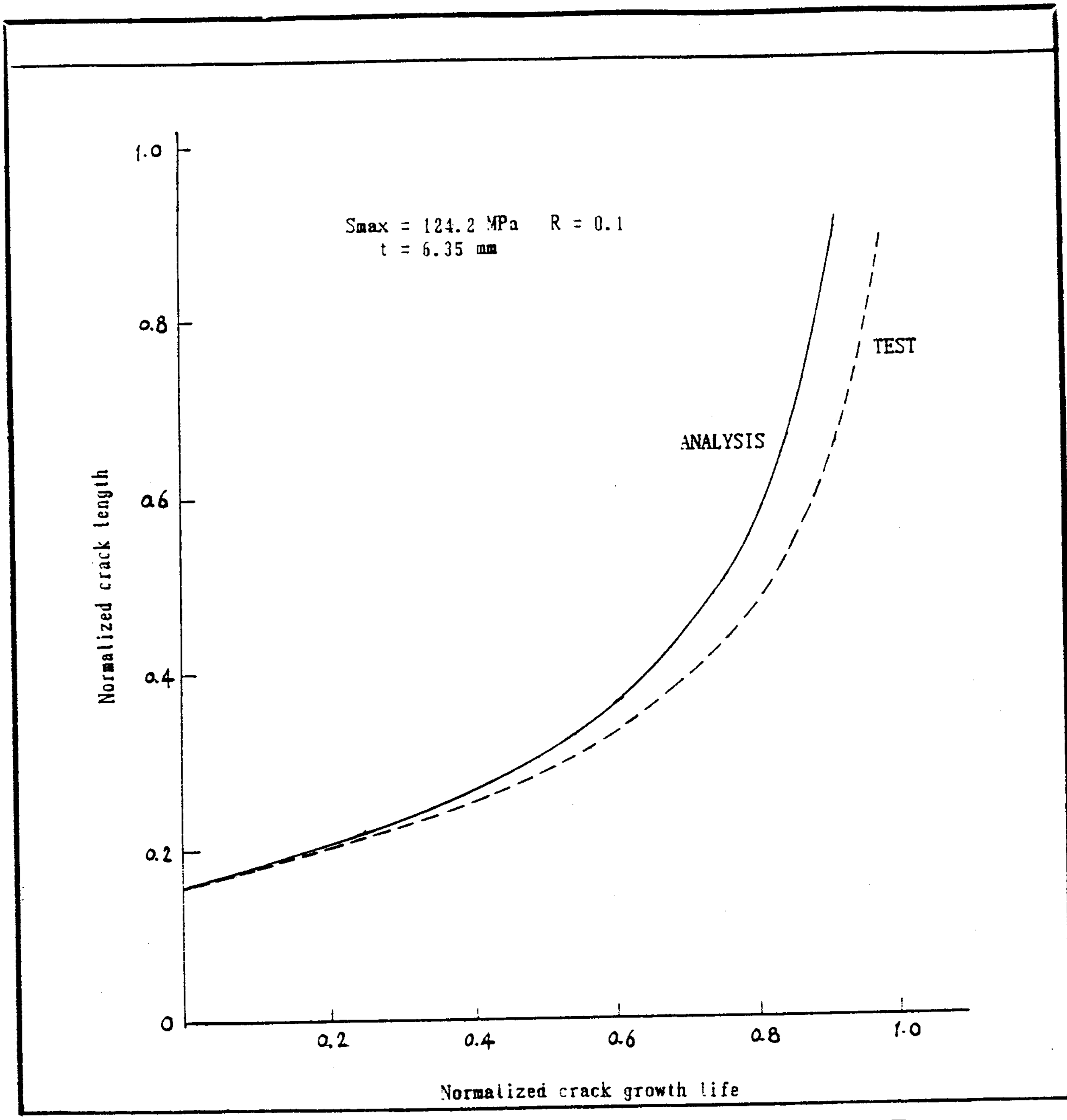

Figure 4. Crack growth comparison between prediction and test for 2024 - T351.

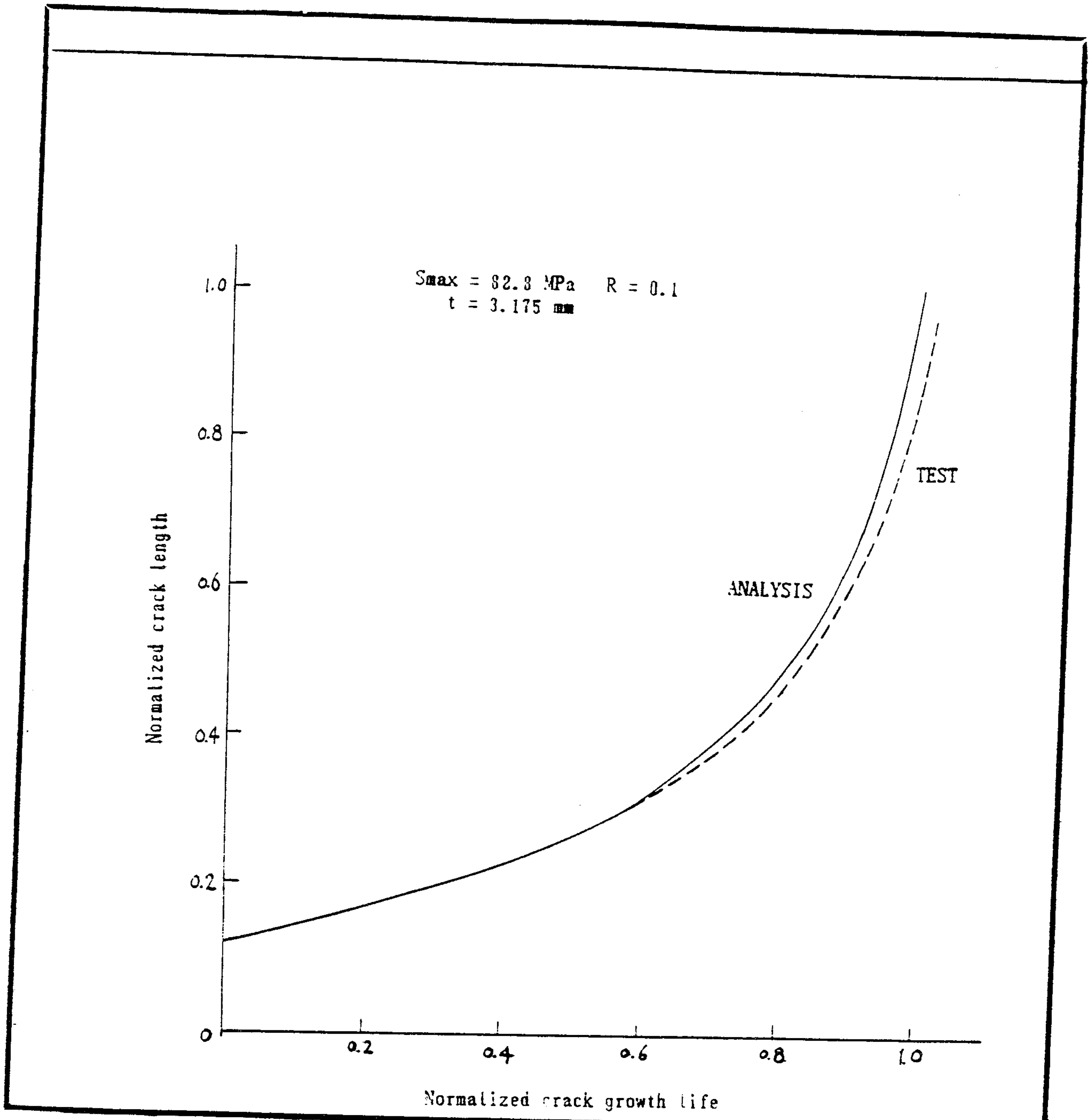

Figure 5. Crack growth comparison between prediction and test for 7075 - T651.