NASA TECHNICAL MEMORANDUM 101544

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(NASA-TM-101544) PREDICTION OF FATIGUE-CRACK GROWTH IN A HIGH-STRENGTH ALUMINUM ALLOY UNDER VARIABLE-AMPLITUDE LOADING (NASA. Langley Research Center) 19 p CSCL 20K G3/39

N89-22135

Unclas

0204407

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FEBRUARY 1989

NASA

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Langley Research Center
Hampton, Virginia 23665-5225

PREDICTION OF FATIGUE-CRACK GROWTH IN A HIGH-STRENGTH ALUMINUM ALLOY UNDER VARIABLE-AMPLITUDE LOADING

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ABSTRACT

The present paper is concerned with the application of an analytical crack-closure model to study crack growth under various load histories. The model was based on a crack-tip plasticity concept like the Dugdale model, but modified to leave plastically deformed material in the wake of the advancing crack tip. The effect of material thickness on plasticity was accounted for by using a "constraint" factor on tensile yielding at the crack tip.

The model was used to correlate crack-growth rates under constant-amplitude loading, and to predict crack growth under variable-amplitude loading on a high-strength aluminum alloy (7475-T7351) sheet material. The experimental data were obtained from Zhang et al. Predicted crack-growth lives agreed well with experimental data. For ten crack-growth tests subjected to various variable-amplitude load histories, the ratio of predicted-to-experimental lives ranged from 0.54 to 1.19. The mean value of the ratio of predicted-to-experimental lives was 0.95 and the standard error was 0.2 using a constraint factor of 1.9 in the model. Crack-opening stresses

calculated from the model were significantly different from those determined by Zhang et al. using a striation-based experimental method.

KEYWORDS

Cracks; crack propagation; crack closure; fatigue (materials); fracture; plasticity; stress analysis; stress-intensity factor.

INTRODUCTION

Crack closure during fatigue-crack propagation may be caused by residual plastic deformations, crack-surface roughness, and corrosion- or oxide-products remaining in the wake of an advancing crack. However, in many structural applications, plasticity-induced closure is probably the dominant closure mechanism. The plasticity-induced closure concept, using the effective stress-intensity factor range (Elber, 1971), has been used to correlate crack-growth rates under constant-amplitude loading and to predict load-interaction effects (retardation and acceleration) under variable-amplitude loading. The effective stress-intensity factor range is defined as that part of the applied range for which the crack is fully open.

Plasticity-induced closure models have been developed by Dill and Saff (1976), Budiansky and Hutchinson (1977), Fuhring and Seeger (1979) and Newman (1981). All of these models were based on a crack-tip plasticity concept similar to the Dugdale (1960) model but modified to leave plastically deformed material in the wake of the crack. Budiansky and Hutchinson (1977) and Fuhring and Seeger (1979) studied only the crack-closure behavior. Dill and Saff (1979) and Newman (1981) used the crack-opening stresses from their models to predict crack growth under spectrum loading.

The purpose of this paper is to apply the Newman (1981) crack-closure model, which simulates stress states between plane stress and plane strain, to crack growth in a high-strength aluminum alloy (7475-T7351) under various variable-amplitude load histories. Plane-stress and plane-strain conditions were simulated by using a "constraint" factor on tensile yielding at the crack tip. Experimental crack-growth rate data from 7475-T7351 aluminum alloy sheet material under constant-amplitude loading were correlated with the effective stress-intensity factor range (ΔK_{eff}) for a wide range of stress levels and stress ratios (Zhang et al., 1987). A simple power law was used to relate crack-growth rate to the effective stress-intensity factor range over a wide range in crack-growth rates. The closure model was then used to predict crack growth in the aluminum alloy under ten different variable-amplitude load sequences. The variation of calculated crack-opening stresses with load history are presented for some typical cases. Comparisons between experimental and predicted crack-growth lives were also made.

MATERIAL, SPECIMEN CONFIGURATION AND LOADING

The experimental results were obtained from Zhang et al. (1987, 1988) on 8 mm-thick 7475-T7351 aluminum alloy. The material had a 0.2-percent offset yield stress of 460 MPa and an ultimate tensile strength of 520 MPa. Center-crack tension specimens (w = 80 mm half-width) with a 3 mm-wide starter notch were tested under both constant-amplitude and simple variable-amplitude loading. Constant-amplitude tests were conducted over a wide range in stress ratios (R = 0.8 to -3.33) and stress levels.

Eight variable-amplitude load sequences were tested by Zhang et al. (1987) and two additional ones were tested by Zhang et al. (1988). Herein, these load sequences have been identified as Load Types 1 to 10. A full description of these load types are given in Zhang et al., but a brief description is given herein.

Load Type 1: Single spike overload repeated every 50 cycles.

2: Single spike overload repeated every 100 cycles.

3: Five spike overloads repeated every 50 cycles.

4: Five spike overloads repeated every 100 cycles.

5: Single overload-underload cycle repeated every 39 cycles.

6: Single underload-overload cycle repeated every 39 cycles.

7: Fifty high R-ratio and fifty low R-ratio cycles repeated.

8: Three underload-overload cycles repeated every 40 cycles.

9: Single overload-underload cycle applied at intervals of 40, 100, 1000 and 10,000 cycles repeated.

10: Combination of nine high and low R-ratio 50-cycle sequences and several other load cycles repeated every 453 cycles.

FATIGUE CRACK-GROWTH RATE EQUATION

Newman (1981) showed that the calculated crack-opening stresses under constant-amplitude loading were independent of the constraint factor for stress ratios (R) greater than 0.7 and were equal to the minimum applied stress. Thus, ΔK_{eff} is equal to ΔK for $R \geq 0.7$. This means that the ΔK against crack-growth rates at R = 0.8 from Zhang et al. (1987) are also ΔK_{eff} against rates. Zhang et al. found that a power law would represent the experimental data quite well. The crack-growth rate equation was

$$dc/dN = 4.67 \times 10^{-10} (\Delta K_{eff})^{2.972} \qquad (1)$$

where dc/dN is in m/cycle and ΔK_{eff} is in MPa-$m^{1/2}$ (c is defined as half-length of crack). Using the R = 0.8 data as the baseline ΔK_{eff}rate relation, Zhang et al. estimated K_o/K_{max} values needed to correlate their other R-ratio data with the baseline data. The range of experimental values of K_o/K_{max} are shown as bars in Fig. 1 as a function of stress ratio. The solid and dashed curves in Fig. 1 are calculated results from a crack-opening stress equation, developed by Newman (1984) using the crack-closure model, for constraint factors (α) of 1.7 and 1.9, respectively. (Note that plane-stress conditions are simulated with α = 1 and plane-strain conditions with α = 3.) These curves were calculated for S_{max}/σ_o = 0.2. The flow stress, σ_o, was assumed to be equal to the average between the yield stress and ultimate tensile strength. Experimental results agreed well with the solid curve (α = 1.7). However, the dashed curve (α = 1.9) agreed slightly better with the experiments at low R-ratios than the solid curve.

Because equation (1) fit the R = 0.8 data quite well and applied over a wide range in rates, it was also used in the crack-closure model to calculate fatigue-crack-growth lives for both α = 1.7 and 1.9.

PREDICTION OF CRACK-OPENING STRESSES AND CRACK-GROWTH LIVES

The analytical crack-closure model (Newman, 1981) and the crack-growth program (FASTRAN) was used to calculate crack-opening stresses (S_0) as a function of load history. The program was modified to give crack-opening stresses after every four cycles to give a better description of how the opening stresses change during the variable-amplitude load history. Examples of calculated S_0 as a function of cycle number are presented for some typical load types. The resulting values of S_0 were then used with equation (1) to calculate crack-growth rates and to predict fatigue life from an initial crack size (c_i) to failure. Failure was assumed to occur when the maximum stress-intensity factor reached the fracture toughness (K_c = 100 MPa-$m^{1/2}$). Comparisons were made between experimental and predicted crack-growth lives for all load types using the crack-closure model. Crack-growth lives were also predicted using the linear-damage concept.

Crack-Opening Stresses

Figures 2 and 3 show the crack-opening stresses calculated from the closure model (α = 1.9) for Load Types 2 and 4, respectively. These are identical load types except that Load Type 2 had one spike overload instead of five. These figures show stress plotted against cycle number during the particular load type. The solid and dashed lines denote the maximum and minimum applied stresses, respectively, and the open symbols show the calculated opening stresses. Both results show a sudden drop in opening stress after the application of the overload(s). The opening stresses during the constant-amplitude loading for Load Type 4 (five overloads) were slightly higher than those for Load Type 2. These results show that the closure model predicts more delay in crack growth during the constant-amplitude portion for larger number of overloads. This is because five overloads cause a larger zone of residual plastic deformation to remain along the crack surfaces than a single overload. However, the five overloads are more damaging to crack growth than the single overload. Thus, the overall life for Load Type 4 was shorter than that for Load Type 2 (see test lives in Table 1).

Results for Load Type 5 (single overload-underload repeated every 39 cycles) are shown in Fig. 4. The opening stresses after the overload-underload were lower for Load Type 5 than those for Load Type 6 (not shown) where the overload and underload were reversed. Thus, the underload eliminated some of the plastic deformations that were caused during the overload. In Load Type 6, the deformations that developed during the overload were retained until the underload was applied at the next sequence.

Zhang et al. (1987, 1988) used a "striation" method to estimate the crack-opening stresses for all load types. The solid symbols in Fig. 4 show these experimental results for Load Type 5. During the first 39 cycles, the experimental values were significantly higher than those from the closure model. During the application of the overload, the experimental procedure produced an even higher value compared with the model. If the striation size is a correct indication of the growth rate during the overload, this high value would question the basic ΔK_{eff}-rate relation. The opening value should have been the same as immediately before the overload. After the underload, the experimental value agreed well with the model. These differences in opening stresses, however, would result in over a factor-of-2 difference in crack-growth life. The opening stresses from the model and equation (1) produced a crack-growth life within about 5 percent of the test life (see Table 1).

In Fig. 4, the slight drop in opening stresses around cycle number 20 is believed to have been caused by the "lumping" procedure (Newman, 1981) which was used to minimize the number of elements in the model. This drop was more pronounced, about 7 percent, in Load Type 8 (not shown). This behavior would suggest that a slight modification to the lumping procedure in the model is necessary.

The results for Load Type 9 are shown in Fig. 5. These results show that the overload-underload cycle influenced the opening stress for about 1000 cycles when the crack length (c) was about 30 mm. No closure occurred during 90 percent of the 10,000-block constant-amplitude loading ($R = 0.6$). Using the calculated opening values and equation (1), the predicted crack-growth life was only about 54 percent of the test life. Because the test life should be controlled primarily by the constant-amplitude portion, and the calculated opening stresses are expected to be correct (fully open crack for most of the cycles), the test results are suspect.

Crack-Growth Lives

The test lives and the ratios of predicted life to test life for all ten load types are tabulated in Table 1. The ratios of predicted to test life for all ten load types are also shown in Fig. 6. The solid line represents perfect agreement between test and prediction, and the dashed lines show ±20 percent error bands. Open symbols show results from the linear-damage calculations. The linear-damage results were obtained from Zhang et al. (1987) except for Load Types 9 and 10 (computed herein). Results from the closure model for $\alpha = 1.7$ and 1.9 are also shown. There were large differences between linear-damage results and those from the closure model for Load Types 1 to 4. There was very little difference among all predictions for Load Types 5 to 10. Eight of ten predictions from the closure model ($\alpha = 1.9$) were within 20 percent of the test lives, whereas only four of ten predictions from the linear-damage concept were within 20 percent. The closure model results for $\alpha = 1.7$ produced longer crack-growth lives than those for $\alpha = 1.9$ because opening stresses computed for $\alpha = 1.7$ were consistently higher than those for $\alpha = 1.9$.

CONCLUSIONS

1. The analytical crack-closure model with a constraint factor of 1.9 predicted crack-growth lives in 7475-T7351 aluminum alloy under variable-amplitude loading within 20 percent of test lives for most cases.

2. Significant differences were observed between the crack-opening stresses determined from the "striation" method and the closure model.

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Table 1. Comparison of crack-growth lives among tests, linear-damage and closure model predictions.

Load Type[a]	Initial half-crack length, c_i, mm	Test life, cycles	Linear-damage $\frac{N_{ld}}{N_{test}}$ [b]	Closure model α = 1.7 $\frac{N_{cm}}{N_{test}}$	Closure model α = 1.9 $\frac{N_{cm}}{N_{test}}$
1 (F)	4	474,240	0.59	1.40	1.10
2	4	637,730	0.46	1.19	0.97
3	4	251,210	0.85	1.36	1.19
4	4	409,620	0.61	1.28	1.09
5 (C)	4	179,320	0.88	1.03	0.95
6 (B)	4	251,050	0.63	0.78	0.68
7 (G)	4	253,840	0.95	1.11	1.03
8	4	149,890	0.75	0.92	0.83
9 (D)	2	480,570	0.70	0.62	0.54
10 (E)	28	57,680	1.00	1.18	1.13
		Mean:	0.74	1.09	0.95
		Standard Error:	0.17	0.24	0.20

(a) Numbers are load types in Zhang et al. (1987), except Load Types 9 and 10. Letters are load types in Zhang et al. (1988).

(b) Linear-damage results (N_{ld}) from Zhang et al. (1987), except Load Types 9 and 10 (computed in this paper).

(c) N_{cm} are closure model results for indicated constraint factor.

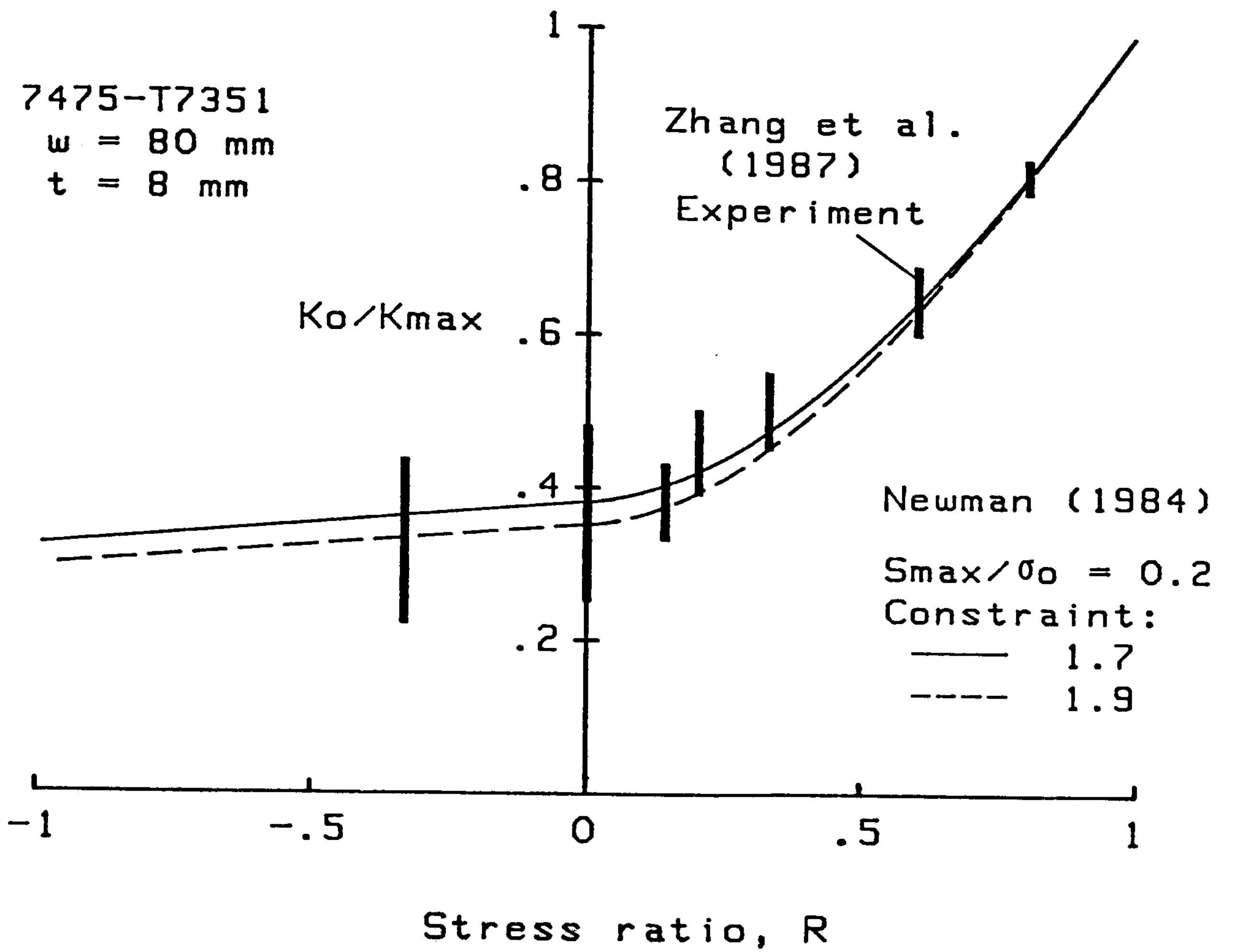

Fig. 1. Comparison of experimental and calculated crack-opening stress as a function of stress ratio.

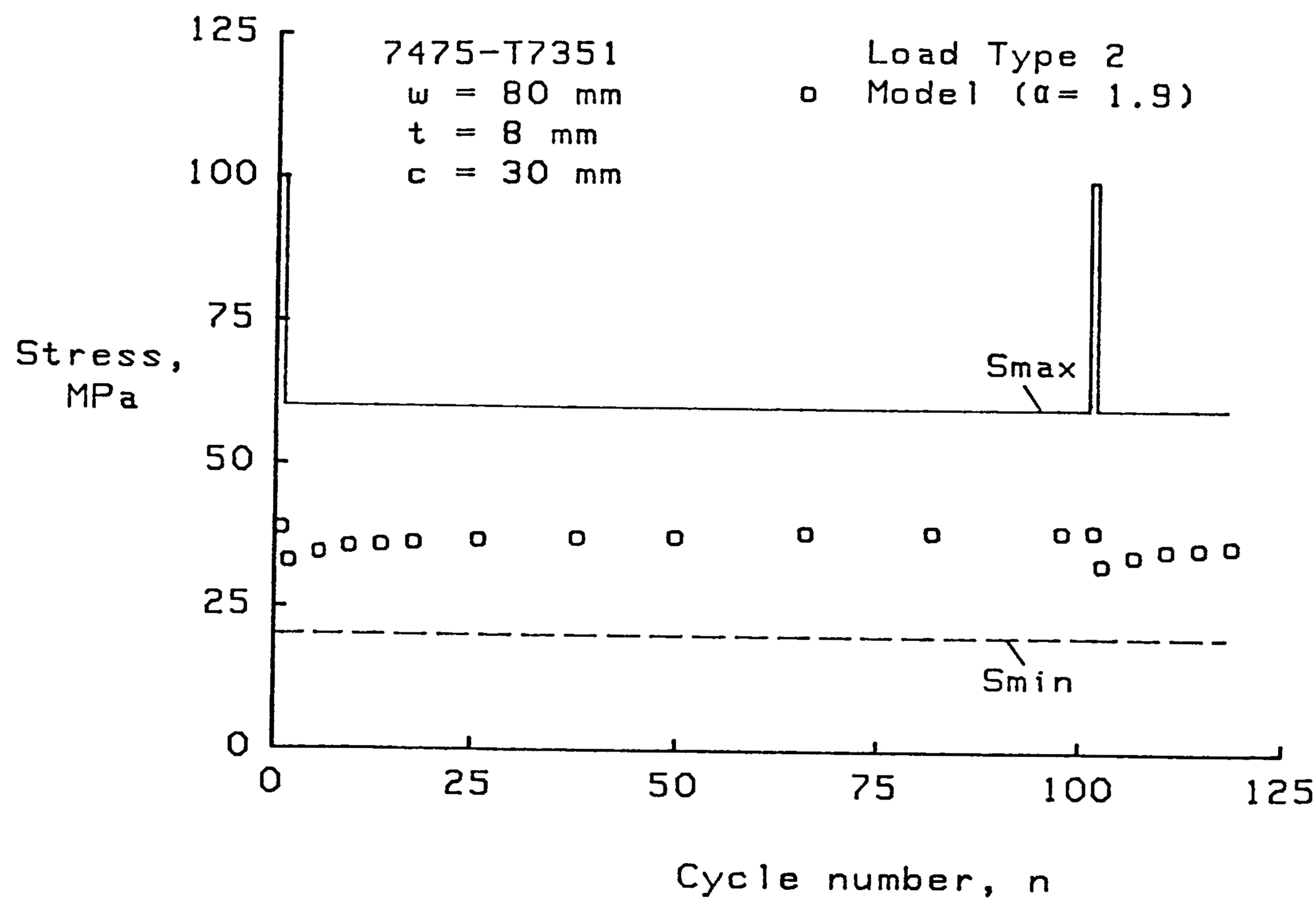

Fig. 2. Calculated crack-opening stresses for Load Type 2 as a function of cycle number.

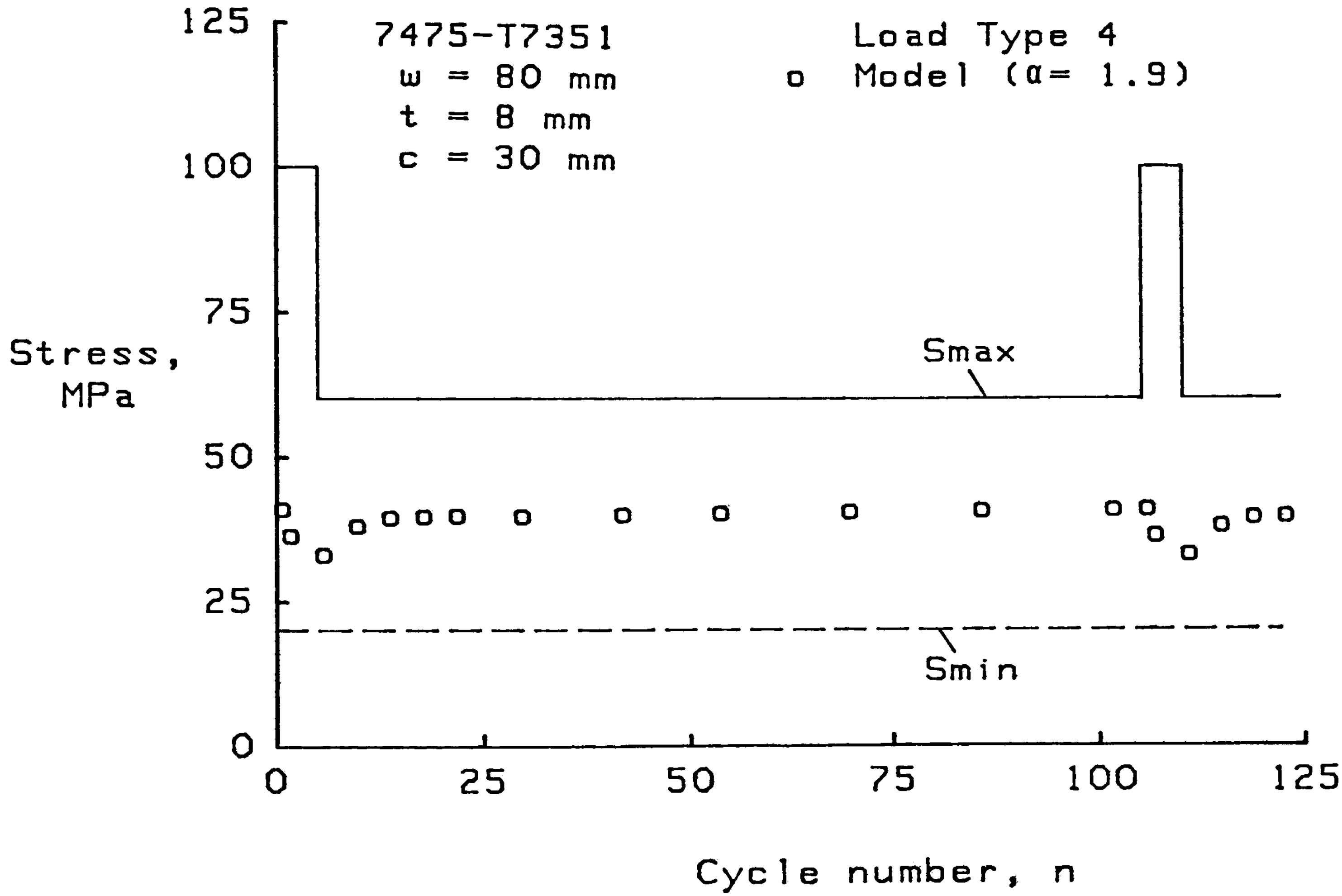

Fig. 3. Calculated crack-opening stresses for Load Type 4 as a function of cycle number.

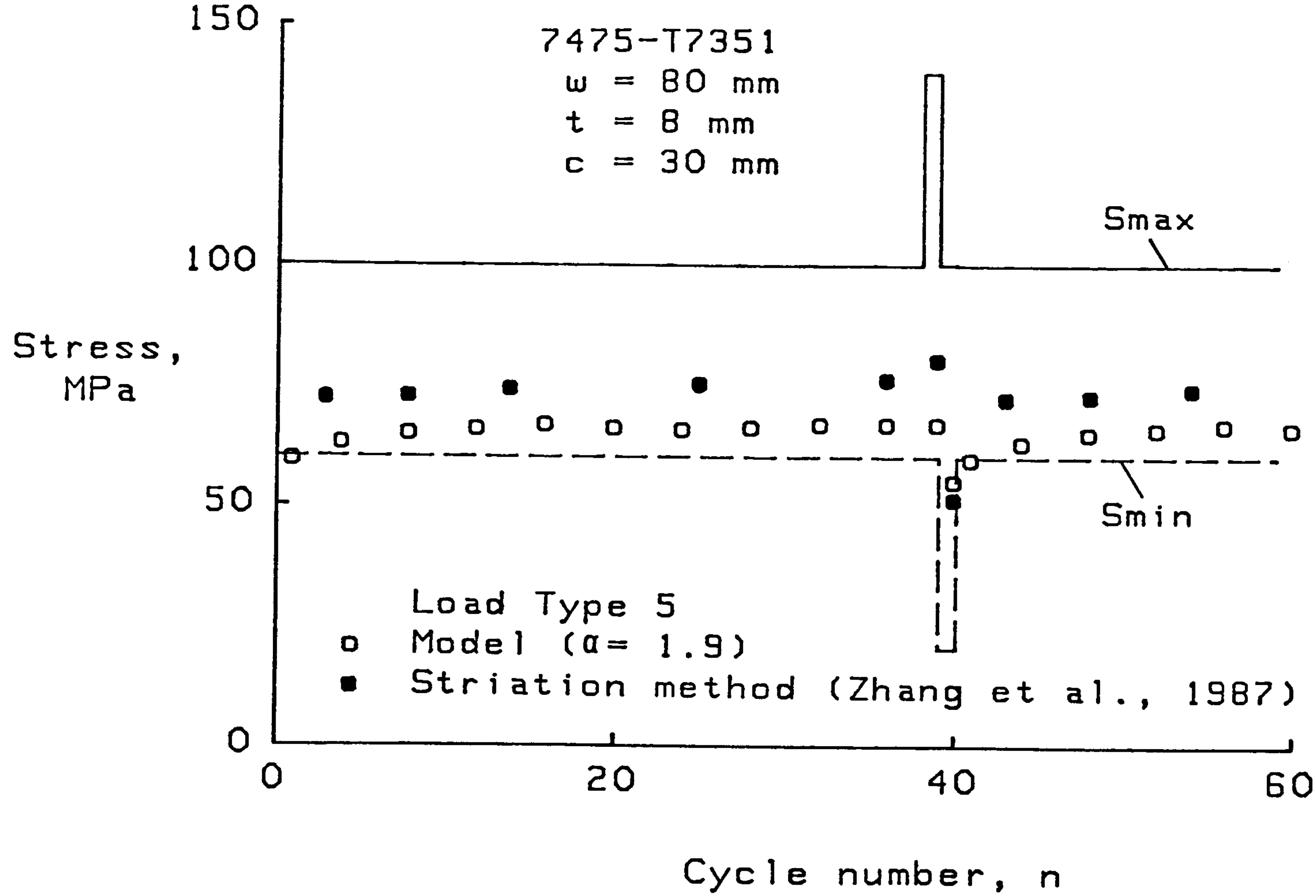

Fig. 4. Calculated and experimental crack-opening stresses for Load Type 5 as a function of cycle number.

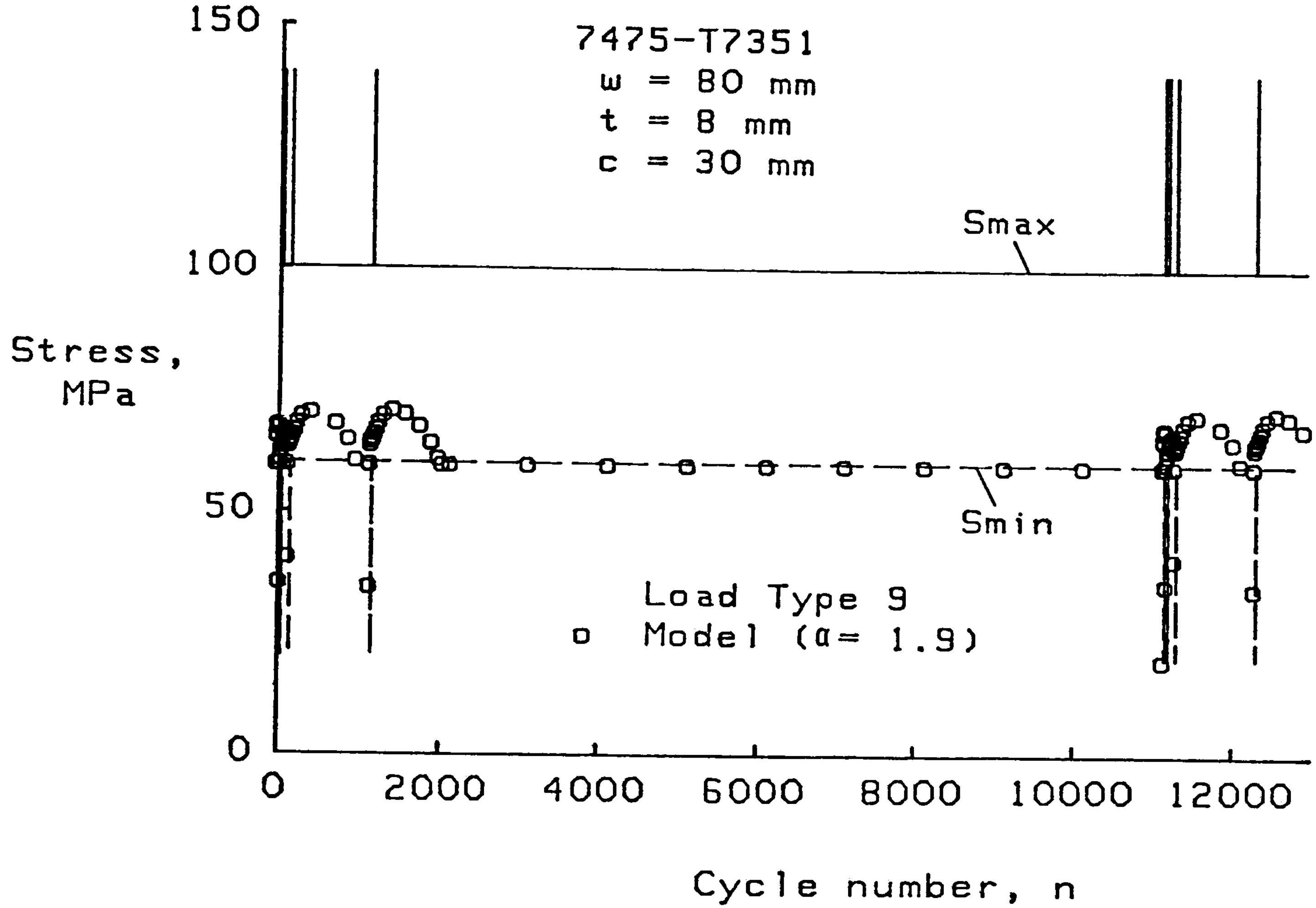

Fig. 5. Calculated crack-opening stresses for Load Type 9 as a function of cycle number.

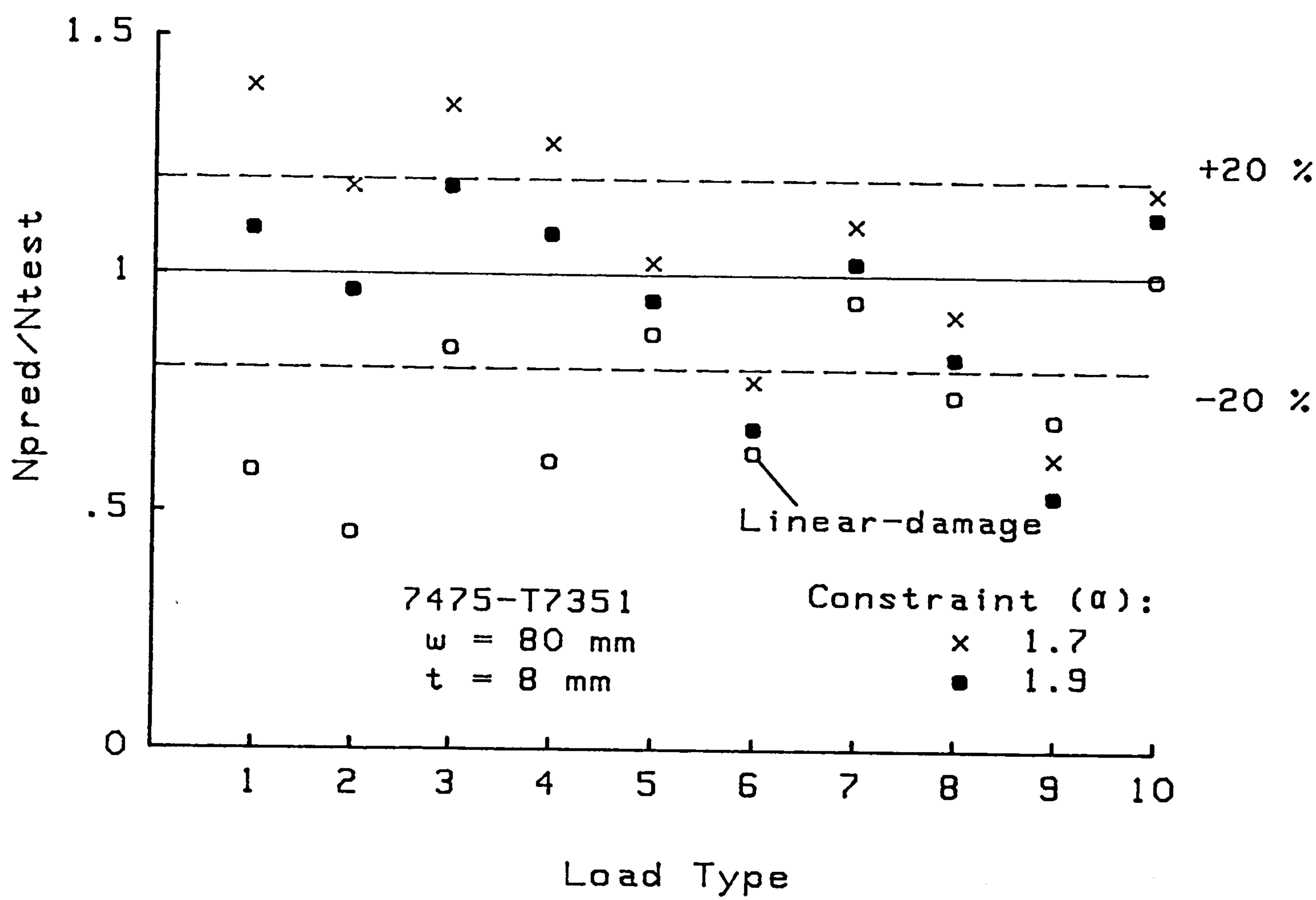

Fig. 6. Comparison of ratio of predicted to experimental cycles to failure for various load types.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-101544		

4. Title and Subtitle	5. Report Date
Prediction of Fatigue-Crack Growth in a High-Strength Aluminum Alloy Under Variable-Amplitude Loading	February 1989
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
J. C. Newman, Jr. and D. S. Dawicke	
	10. Work Unit No.
	505-63-01-05
9. Performing Organization Name and Address	11. Contract or Grant No.
NASA Langley Research Center Hampton, VA 23665-5225	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, DC 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

To be presented at the Seventh International Conference on Fracture, March 20-24, 1989.
J. C. Newman, Jr.: Langley Research Center, Hampton, Virginia.
D. S. Dawicke: Purdue University, West Lafayette, Indiana.

16. Abstract

The present paper is concerned with the application of an analytical crack-closure model to study crack growth under various load histories. The model was based on a concept like the Dugdale model, but modified to leave plastically deformed material in the wake of the advancing crack tip. The thickness effect was accounted for by using a "constraint" factor on tensile yielding at the crack tip.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Cracks; crack propagation; crack closure; fatigue (materials); fracture; plasticity; stress analysis; stress-intensity factor.	Unclassified - Unlimited Subject Category 39

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	18	A03

NASA FORM 1626 OCT 86