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Fatigue Life Predictions of Aluminium Structures

Estimation de la durée de vie de fatigue des structures en aluminium

Vorhersage der Lebensdauer von Aluminium-Tragwerken

R. JACCARD
Dr., Ph.D.
Swiss Aluminum Ltd.
Zürich, Switzerland

SUMMARY

The fatigue life prediction of aluminum structures have to be based on SN data that have been collected in full scale fatigue tests. Since such tests are expensive and time consuming in most cases, only a limited number of data points can be accumulated. Simulated SN curves based on simple fracture mechanics models and the physical appearance of crack growth are suitable to fill the data gap. Such curves are a lower bound of SN data if the appropriate fracture mechanics model is selected and the curves are calibrated at the lowest data points of the considered test series.

RESUME

L'estimation de la durée de vie des structures en aluminium doit être basée sur des données de Wöhler déterminées par des essais de fatigue en vraie grandeur. Vu le coût et le temps exigés pour de tels essais, on ne peut en général rassembler qu'un nombre limité de points de données. Des courbes de Wöhler simulées par des modèles simples de la mécanique de rupture sont susceptibles de combler ce manque de données. Ces courbes simulées sont une limite inférieure des données de Wöhler, pour autant qu'un modèle approprié de la mécanique de rupture soit choisi et que les courbes soient calibrées par le point de donnée le plus bas de la série d'essais considérés.

ZUSAMMENFASSUNG

Zur Vorhersage der Lebensdauer von Aluminium-Tragwerken sind Wöhlerkurven an Testkörpern in natürlicher Grösse durchzuführen. Derartige Grossversuche sind zeit- und kostenaufwendig, so dass Messwerte nur in beschränktem Umfange ermittelt werden können. Aus diesem Grund fällt den Wöhlersimulationen, welche mit einfachen bruchmechanischen Modellen und den Gesetzen der Rissausbreitung vorgenommen werden, eine grosse wirtschaftliche Bedeutung zu. Eine Wöhlerlinie, die aufgrund eines Kantenrisses berechnet und mit einem Messpunkt einer Wöhler-Versuchsserie geeicht wird, stellt dann einen unteren Grenzwert für alle Wöhlerdaten mit höheren oder gleichen Spannungsdifferenzen dar, falls der Eichpunkt jenem Masspunkt entspricht, welcher die geringste Lastspielzahl der betrachteten Spannungsdifferenz aufweist.

1. INTRODUCTION

SN testing or the Wöhler procedure is the traditional approach to investigate the fatigue behavior of materials. It is a one parametric description of the materials behavior under cyclic loading. The results are often depicted in a double logarithmic plot with the number of cycles to failure on the X axis and the stress ranges on the Y axis. SN data are collected on small specimens subjected either to cyclic loading in tension, bending or torsion. Such tests are inexpensive and quite useful for alloy development. To design structures and vehicles, especially in the case of welded components, SN data found for small test specimens are not conservative as shown in Fig. 1 where the 95.5 % lower confidence limits of beam and tensile specimen tests are plotted. Some of the main reasons for the lower beam life might be the variation in flaw size and the existence of residual stress.

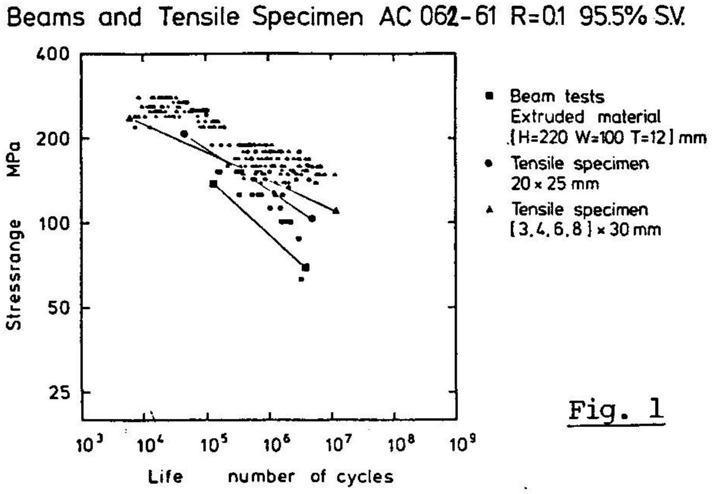


Fig. 1

It is obvious that the safe fatigue design of any large structure requires full scale testing of beams, components or even the structure or vehicle itself. Such tests are expensive and since in most cases only low frequencies can be used, they are time consuming. As it will be shown, it is possible to simulate SN curves by using Linear Elastic Fracture Mechanics models (LEFM). The fracture mechanics approach is based on the physical phenomenon of crack growth. It is a three parametric description of the fatigue problem. The parameters are crack growth rate, defect geometry, and stress range.

The crack growth rate depends on the stress intensity range ΔK, the material, the load history, and the environment. It is determined on calibrated test specimens by standardized test procedures [1,2]. Figure 2 contains the crack growth rate, da/dN, of the aluminum alloy AlMg0.7Si at four different R-ratios ($R=\sigma_{min}/\sigma_{max}$). The typical polygonal shape of the da/dN vs ΔK curve is quite obvious. The crack growth rate is higher at larger R-ratios. In the threshold regime this difference is significant, while at growth rates above 10^{-7} m/cycle all the curves lie close together. There are basically three branches. As confirmed by [3], each branch is associated with a typical fractographic appearance.

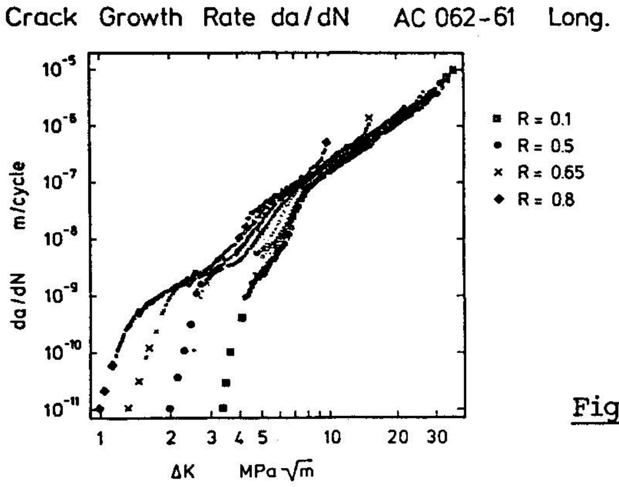


Fig. 2

In the lowest branch, the threshold regime from 10^{-11} up to 10^{-9} m/cycle, the fracture surface exhibits a cleavage-like highly faceted appearance. In the mid range, up to 10^{-6} m/cycle, striations can be observed. Above 10^{-6} the branch of faster fracture is reached. In this region the fracture surface depicts dimples, particle rupture, and occasionally few very large striations.

The crack growth rate or the da/dN data are statistically treated by a regression analysis to determine the crack growth constant C and the exponent n. These two parameters are the basic input to the fatigue equation. Figures 3 and 4.

The defect geometry is evaluated by the defect analysis leading to the selection of the appropriate fracture mechanics model, the crack geometry function y, and the initial crack size a. [5]

The third parameter in the LEFM approach, the stress range, is controlled by the design, the geometry of structural detail, the stress-strain relationship (plastic deformation), temperature effects and secondary deformations such as out of plane bending. As mentioned before, the stress ratio R, that is the quotient minimum stress divided by maximum stress, has to be considered as well. The R-ratio is important to select the associated crack growth rate polygon.

2.FATIGUE LIFE PREDICTION BASED ON LEFM MODELS

Fatigue life predictions of components (Figure 3) depends on the fatigue equations and the stress intensity range or the effect of the LEFM model. The life or the number of cycles to propagate a crack from the initial crack size a_1 to the final size a_2 is determined by integrating the fatigue equation (Figure 4).

Fig. 3 Fatigue Life Prediction of Components (1)

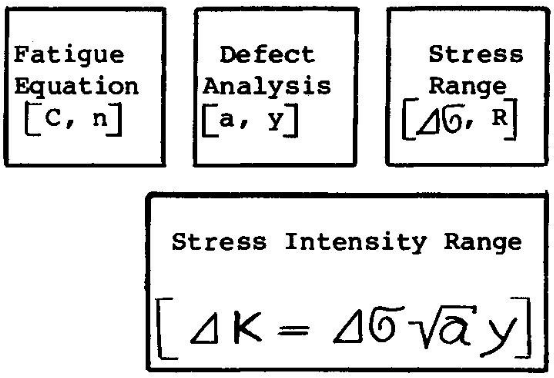


Fig. 4 Fatigue Life Prediction of Components (2)

$$da/dN = C\,[\Delta K]^n$$

or integrated Fatigue Equation:

$$\boxed{\Delta N = \int_{a_1}^{a_2} \frac{da}{C\,(\Delta K)^n}}$$

In the case of aluminum alloys this procedure has to be carried out taking into account the R-ratio (selection of appropriate da/dN values) and the polygonal shape of the da/dN curve (multiple regression intervals). The results reported in this paper have been calculated by the computer program FAGRO [6] that includes a library of LEFM models and a data base of fatigue equations of various aluminum alloys. The LEFM model most frequently used is the surface crack by J.C. Newman [7].

Figure 5 contains the result of defect analysis that has been performed on extruded beams. The number of estimated cycles using the surface crack model [7] corresponds well with the life determined in the SN tests. Thus the dimensions of the initial crack size (a = half minor, c = half major axis) determined from macroprints and a light microscope of 50 x seem to be adequate.

Fig. 5 Defect Analysis Examples

Material: ANTICORODAL 062-61

Beams H = 220 mm W = 100 mm T = 12 mm
Stress Range : 100 N/mm2

Spec. No.	a mm	c mm	$N_{estim.}$ Cycles	N_{tested} Cycles
J131	0.15	3.0	747'000	873'000
J128	0.25	0.5	234'000	230'000
J124	0.14	0.72	227'000	202'000
J125	0.30	0.55	2'970'000	2'744'000

Macro - Prints, Microscope 50 x

Figures 6 and 7 illustrate typical crack growth behavior at a low and a high number of cycles. In both cases the number of cycles consumed to grow the crack from its initial size to twice that size, is at least 50 %. In the case of a low number of cycles, the life elapsed in the interval between 1.0 mm and 11.5 mm is still 30 % of the total life. Whereas in the case of high cycles the corresponding life is just 2.4 %.

Fig. 6 Crack Growth (Low Cycle)

Crack Size mm	Δ K MPA $\sqrt{m}$	Increm. Life %	Total Life Cycles
11.50	38.00		0
		30.0	
1.05	13.04		8'378
		19.2	
0.30	7.83		13'738
		50.8	
0.15	5.28		27'944

Fig. 7 Crack Crowth (High Cycle)

Crack Size mm	Δ K MPA $\sqrt{m}$	Increm. Life %	Total Life Cycles
11.50	22.20		0
		2.4	
1.05	7.58		55'800
		10.4	
0.30	4.57		288'800
		87.6	
0.15	3.08		2'511'200

The effect of finite specimen dimensions is, in the case of high cycle fatigue, neglectable (Figure 8).

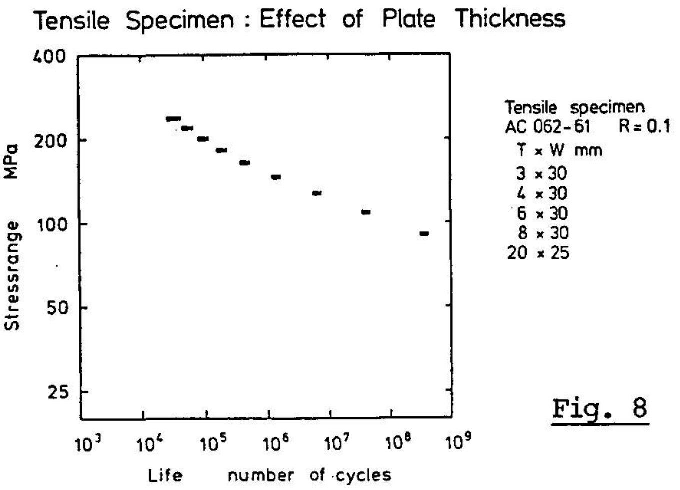
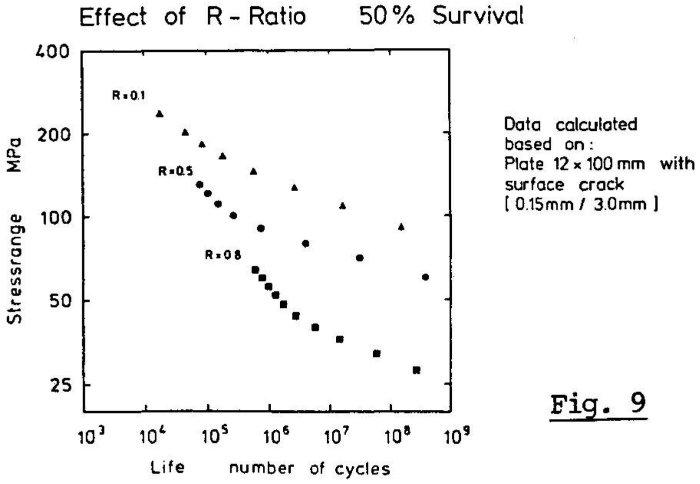


Fig. 8

Existence of residual stress yields a significant reduction of the fatigue life (Figures 9 and 10). In Figure 10 it is demonstrated how a designer can include the residual stress in his calculations.



Data calculated based on:
Plate 12 × 100 mm with surface crack
[0.15mm / 3.0mm]

Fig. 9

Fig. 10 Life Prediction Examples

Effect of Residual Stress:

σ max = 67 N/mm2
σ res. = 130 N/mm2
σ max e = 197 N/mm2
σ min = 6 N/mm2
$\Delta\sigma$ = 61 N/mm2
σ min e = 136 N/mm2

R - Ratio:	Life:
0.1	4'464'760'000
0.7	1'384'000

Considering Figure 11, another important observation can be made: Assume two structural components, the first one with a small, the second one with a larger initial crack, are dimensioned according to a given stress intensity range ΔK e.g. the threshold value ΔK_{TH}. The one with the larger crack exhibits a lower stress range than the one with the smaller crack, but both are subjected to the same stress intensity range ΔK. By computing the lives of both components one realizes that the component with the larger crack size has a considerable longer life than the one with the smaller crack.

Fig. 11 Effect of Crack Size

Halfcircular Crack			
Initial Crack mm	Final Crack mm	Initial ΔK MPA $\sqrt{m}$	Life Cycles
0.2	15.0	2.47	44'482'400
0.4	15.0	2.48	82'097'400

Same Initial Stress Intensity Range Does Not Yield Same Life!

3. SN DATA SIMULATIONS

The main advantage and economic efficiency of LEFM models are SN data simulations and the inter- or extrapolation of SN test results.

Figure 12 contains three SN curves that have been generated using a surface crack with an a/c ratio approximating an edge crack condition. The reason why an edge crack was selected rather than a penny shape crack was the fact that the edge crack yields a life a little more conservative than the penny shape crack.Various calculations have comfirmed this.

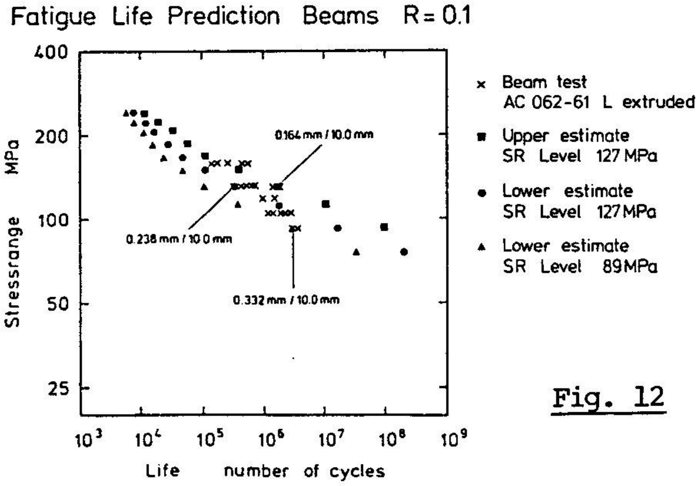


Fig. 12

Considering the data on Figure 12, it becomes obvious that the SN curve computed using the single edge crack model and calibrated at a data point of a SN test series, is a lower bound to all SN data at equal or higher stress range levels if the data point of calibration represents the lowest life of the tested stress levels. This observation is of great economic importance for SN testing. It is no longer necessary to fabricate thirty or more expensive full scale test specimens to generate SN data over several stress ranges. With about one fifth of the number of specimens and the SN simulation, a conservative lower bound can be determined if the specimens are tested at the lowest stress range level.

4. SUMMARY AND CONCLUSIONS

- The fatigue behavior of aluminum structures can be described by fracture mechanics models.
- These models are useful to inter- and extrapolate SN DATA.
- In the case of Anticorodal-062 the upper limit of crack propagation resistance of tensile specimen can be calculated by the SN curve generated, based on the halfcircular surface crack model and the average threshold defect size.
- The SN curve, computed using the single edge crack model and calibrated at a data point of a test series, is a lower bound to all SN data at equal or higher stress range levels, if the data point of calibration represented the lowest life of the tested stress level.
- A structure with a small initial crack length and the same initial stress intensity range as a second structure with a large initial crack length will have a smaller fatigue life. The fatigue life reduction is approximately proportional to the ratio of the initial crack size.
- The number of cycles consumed to propagate a fatigue crack from the initial crack size to the double size is at least 50 % of the total life.
- The effect of residual stress can be taken into account by adding the residual stress to the maximum and to the minimum stress. The fatigue equations have then to be selected according to R-ratio based on these effective stresses.

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