CRACK PROPAGATION ANALYSES OF BUILT-UP STRUCTURES

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Abstract

In this paper results from crack propagation analyses of built-up structures are reported. The structures considered are panels with riveted stringers manufactured from alum.-alloy 2024 T3. The loading condition is a constant amplitude loading. Analytical investigations are based on the concept of the linear-elastic stress intensity factor. The influence of stiffeners on the stress intensity factor is predicted by using the FINITE ELEMENT METHOD. FORMAN-equation is used to describe the material crack propagation behaviour. Comparisons of analytical results with corresponding test results show good agreement.

I. Introduction

Up to a few years ago aircraft structures were designed using the FAIL-SAFE CONCEPT or the SAFE-LIFE CONCEPT. The behaviour of a cracked structure due to static or dynamic loads (DAMAGE TOLERANCE CONCEPT) were not studied in detail. This procedure might lead to following problem areas

- o A crack-free structure due to possible defective manufacturing processes or due to local fatigue problems cannot be guaranteed.
- o No statements can be made about a catastrophical failure of a cracked component during service life.
- o Undetectable cracks may cause a catastrophical failure and a loss of the aircraft.
- o Changing a cracked component is sometimes uneconomical.

Therefore great emphasis has been put on the DAMAGE TOLERANCE DESIGN PHILOSOPHY, for example see fig. 1. Damage tolerance analyses require the investigation of a cracked component due to dynamic loads (crack propagation problem) and to static loads (residual strength problem). The linear elastic fracture mechanics, i.e. the concept of the stress intensity factor, gives a good tool to analyse the crack propagation behaviour of structures [(1),(2)].

II. Damage Tolerance Concept

The DAMAGE TOLERANCE CONCEPT is based on the assumption that cracks are present in the structure during operational service. Specific information about the behaviour of these cracks due to corresponding loading conditions are required. Therefore detailed specifications have been established for the damage tolerance analyses of civil and military aircraft, respectively [(3),(4)]. Herein various damage tolerance structures are defined, for example see fig. 2, where the different types of stiffened panels are considered.

The behaviour of a cracked component can be described as following, fig. 3:

- o Starting from an initial length the crack will reach a detectable length. The detectable crack length depends on the accessibility and the inspectibility of the component.
- o Due to service load conditions the crack will increase, until it reach-

es its critical value, where the component fails.

The time from the detectable crack length up to the critical crack length is available for inspecting the component. In order to define appropriate inspection intervals the crack propagation behaviour of the component must be known.

III. Crack Propagation Analyses

The calculation model to predict the crack propagation behaviour of components is based on the concept of the linear-elastic stress intensity factor, [(2),(5)]. The crack length, depending on the applied load cycles, can be calculated by summing up the crack propagation rates, see eqn. (1) in fig. 4. The crack propagation rate is the increase of crack length per load cycles and depends on the range of the applied stress intensity factor. For high-strength alum.-alloys this dependency can be given by the socalled FORMAN-constants, which are derived from test results. It follows from the equations given in fig. 4, that for a given material the same crack propagation rate is expected, when the same range of stress intensity factor is applied.

For crack propagation analyses of stiffened panels the following procedure should be adhered to:

- For an unstiffened panel the crack propagation behaviour will be determined experimentally. From these test results the FORMAN-constants will be derived, [(7)]. For the alum.-alloy 2024 T3 the results are given in fig. 5.

- For the stiffened panel the correcting function of the stress intensity factor, see eqn.(3) in fig. 4, will be calculated. This correcting function takes the presence of the stiffening elements into account.

- The dependency of the crack length from the applied load cycles for the stiffened panel will be calculated by using eqn.(1) through (4).

IV. Correcting Function

For several simple structures the correcting function can be taken from corresponding handbooks, [(8),(9)]. For other structures various methods are applied to determine the correcting function, see fig. 6. The application of the simple methods is limited to simple crack configurations, whereas the advanced methods can be used for the analyses of complicated, cracked structures. The FINITE ELEMENT METHOD is the best candidate at the present time for obtaining correcting functions, whenever other solutions are not available, [(10), (11),(12)]. Two different approaches are possible:

- The correcting function will be derived from computed stresses (force method).

- The correcting function will be derived from computed displacements (displacement method).

The displacement method seems to be superior to the force method as far as analyses of cracked structures are concerned, [(13)]. The application of the displacement method for analyses of cracked structures are described in the literature and will not be repeated in this paper, [(11)]. However, a brief summary of this method is given in fig. 7, since this method will be applied to determine the correcting functions of the stiffened panels, which are defined in fig. 8. Three different types of stiffened panels will be considered. All panels have the same dimensions, except the geometry of the stiffeners, which leads to different stiffening ratios. Local effects, i.e. the presence of residual stresses due to riveting, are neglected in the following analyses.

The correcting function are calculated using the method described in fig. 7 for the two cases

- o the central stiffener is intact,
- o the central stiffener is broken.

The results of this calculation are given in fig. 9. From this figure following conclusions can be made:

- o Intact stiffeners reduce the stress intensity factor as compared with the unstiffened panel, i.e. $Y < 1$. This can be explained by the additional load carrying capacity of the intact stiffeners, which leads to a relief of the cracked sheet.

- o Broken central stiffeners increase the stress intensity factor as compared with the unstiffened panel, i.e. $Y > 1$. This is due to the additional crack opening forces, which are present, when the central stiffener is loaded and totally broken.

Thus, increasing the stiffening ratios leads to the case of an intact stiffener having a reduction of the stress intensity factor, whereas for the case of a broken central stiffener this leads to an increase of the stress intensity factor.

V. Crack Propagation Results

Knowing the material law for the crack propagation behaviour, see fig. 5, and the correcting function of the considered structure, see fig. 9, one can predict the crack propagation behaviour of the structure by using eqn.(1) through (4). The results of these predictions are given in fig. 10. For the reason of comparison corresponding test results are shown in fig. 10, too,[14]. From fig. 10 following statements can be made:

- o The analytical results predict the general behaviour of stiffened panels.

- o The analytical results correlate reasonably with the test results.

- o Intact stiffeners increase the crack life as compared with the unstiffened panel. The crack life increases with increasing stiffening ratio.

- o Broken central stiffener reduces the crack life as compared with the unstiffened panel. The crack life decreases with increasing stiffening ratio.

The method described herein has been used to predict the crack propagation behaviour of a pressurized fuselage structure. The fuselage (radius of curvature = 1435 mm) was loaded by cyclic internal pressure (upper pressure level = 470 mbar, lower pressure level = 0 mbar). Two different crack configurations have been considered:

CRACK A	The longitudinal crack is located in the middle of a curved panel between two intact frames.
CRACK B	The longitudinal crack is located under a partly broken frame.

For these cases the influence of curvature on the stress intensity factor has been taken into account,[15]. The analytical results are given in fig. 11, together with corresponding test results [16]. For these cases good agreement between analytical results and test results is found.

VI. Conclusions

Crack propagation behaviour of built-up structures due to constant amplitude loadings can be reasonably predicted, provided that:

- Appropriate material data are available. For thin-walled, high strength alum.-alloy the FORMAN-law gives a good description of the material behaviour as far as crack propagation due to constant amplitude loading conditions is concerned.

- Correcting functions of the stress intensity factor are known. The FINITE ELEMENT METHOD described herein to obtain correcting functions of stiffened panels leads to nearly the same results as using the COMPATIBLE DISPLACEMENT METHOD, of which the author has reported previously, [17],[18].

For the case of stiffened panels the intact stiffeners increase the crack life, whereas the broken central stiffener reduces the crack life as compared with the unstiffened panel. This fact has to be taken into account, when designing stiffened panels as far as damage tolerance aspects are concerned.

VII. References

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PRE 1970 SAFE LIFE CONCEPT

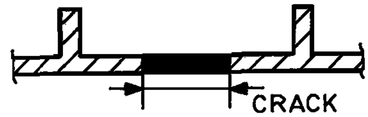
- UNFLAWED STRUCTURE ASSUMED
- MEAN LIFE DEMONSTRATED BY TESTS AND ANALYSES (MINER'S RULE) INCLUDING SCATTER FACTOR
- NO DAMAGE TOLERANCE REQ.

POST 1970 DAMAGE TOLERANCE CONCEPT

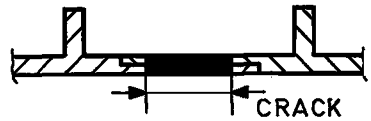
- INITIAL FLAWS ASSUMED
- DEFINITION OF STRUCTURES
  - •• SLOW CRACK GROWTH
  - •• FAIL SAFE
- ANALYSES OF
  - •• CRACK PROPAGATION
  - •• RESIDUAL STRENGTH
- CONTROL OF CRITICAL PARTS BY INSPECTION METHODS
- DEFINITION OF
  - •• INSPECTION INTERVALS
  - •• REPAIR SOLUTIONS

FIG.1 SAFETY DESIGN PHILOSOPHIES (USAF)

- SLOW CRACK GROWTH STRUCTURE



- FAIL SAFE STRUCTURE
  - •• MULTIPLE LOAD PATH STRUCTURE



  - •• CRACK ARREST STRUCTURE

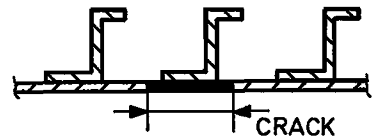
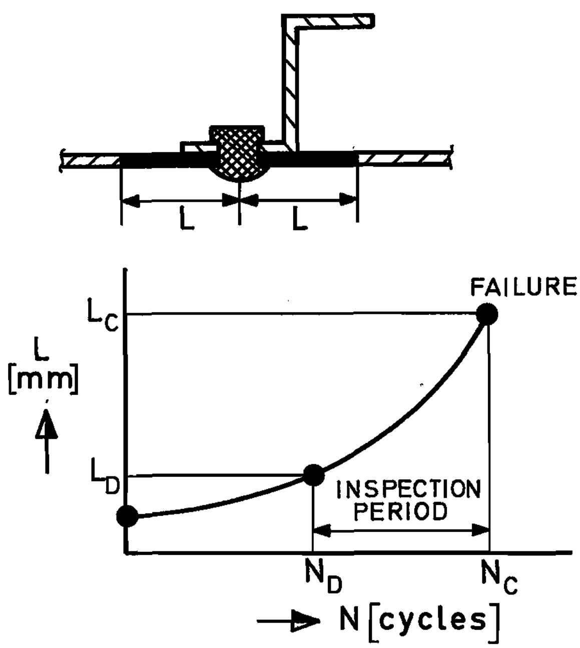


FIG. 2 DEFINITION OF DAMAGE TOLERANT STRUCTURES (MIL 83444)



L_D = DETECTABLE, L_C = CRITICAL } CRACK LENGTH

FIG.3 CRACK PROPAGATION BEHAVIOUR

$$L = f(N) = L_D + \sum \frac{\Delta L}{\Delta N} \Delta N \tag{1}$$

$$\frac{\Delta L}{\Delta N} = \frac{C_F (\Delta K)^{n_F}}{(1-R) K_{C_F} - \Delta K} \tag{2}$$

$$\Delta K = \sigma_U (1-R) \sqrt{\pi L}\ Y \tag{3}$$

$$R = \sigma_L / \sigma_U \tag{4}$$

σ_U = UPPER, σ_L = LOWER } STRESS LEVEL OF A LOAD CYCLE

n_F, C_F, K_{C_F} } CRACK PROPAGATION MATERIAL DATA (FORMAN CONSTANTS)

Y = CORRECTING FUNCTION OF STRESS INTENSITY FACTOR

FIG. 4 CRACK PROPAGATION ANALYSIS FOR HIGH-STRENGTH ALUM-ALLOYS

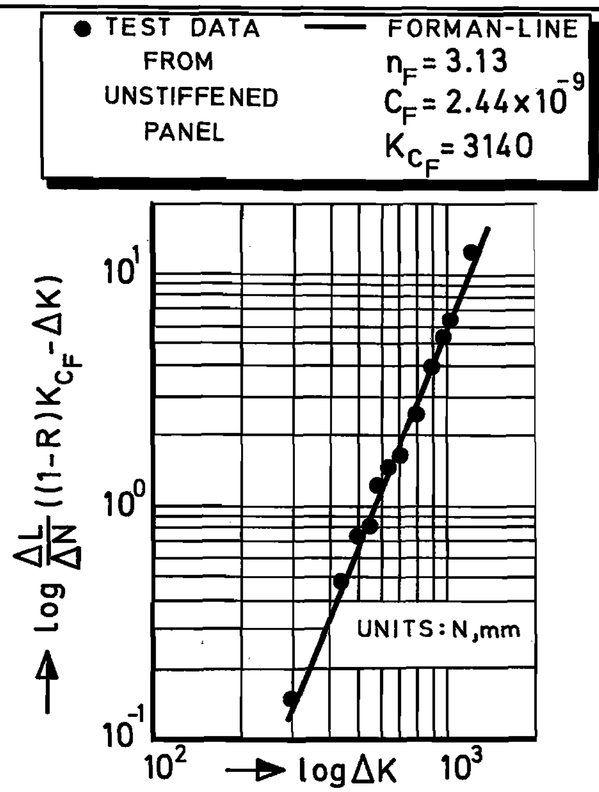


FIG. 5 FORMAN DIAGRAM FOR ALUM 2024T3 T = 2 mm

- SIMPLE METHODS
  - SOLUTION FROM HANDBOOKS
  - SUPERPOSITION
  - COMPOUNDING TECHNIQUE
  - WEIGHT FUNCTION
- ADVANCED METHODS
  - COLLOCATION
  - COMPATIBLE DISPLACEMENTS
  - FINITE ELEMENT METHOD (FEM)
  - EXPERIMENTAL METHODS

FIG. 6 METHODS TO DETERMINE CORRECTING FUNCTION Y

- USE A FINE MESH IN THE CRACK TIP REGION TO SIMULATE SINGULARITY
- CALCULATE THE DISPLACEMENT V_j OF A NODAL POINT j, WHICH IS LOCATED ON THE CRACK SURFACE AND HAS A DISTANCE R_j FROM THE CRACK TIP
- CALCULATE

$$K_j = \frac{\sqrt{2\pi}}{4} \frac{E V_j}{\sqrt{R_j}} \qquad (5)$$

AND PLOT K_j VS. R_j
- APPROXIMATE K_j-VALUES THROUGH A STRAIGHT LINE. THE INTERSECTION OF THIS LINE WITH THE LINE $R_j = 0$ GIVES THE STRESS INTENSITY FACTOR
- APPLY THIS PROCEDURE FOR THE UNSTIFFENED AND STIFFENED PANEL (SAME LOADING CONDITIONS AND SAME CRACK LENGTH) TO DEFINE CORRECTING FUNCTION Y

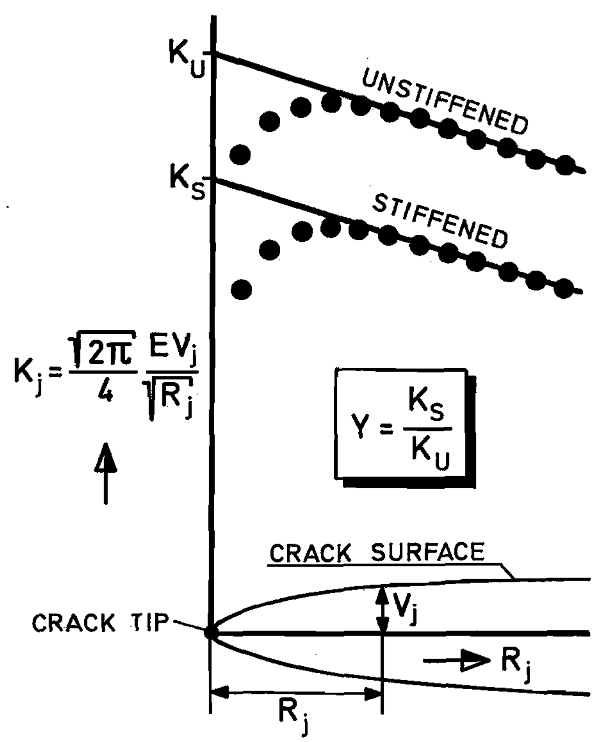
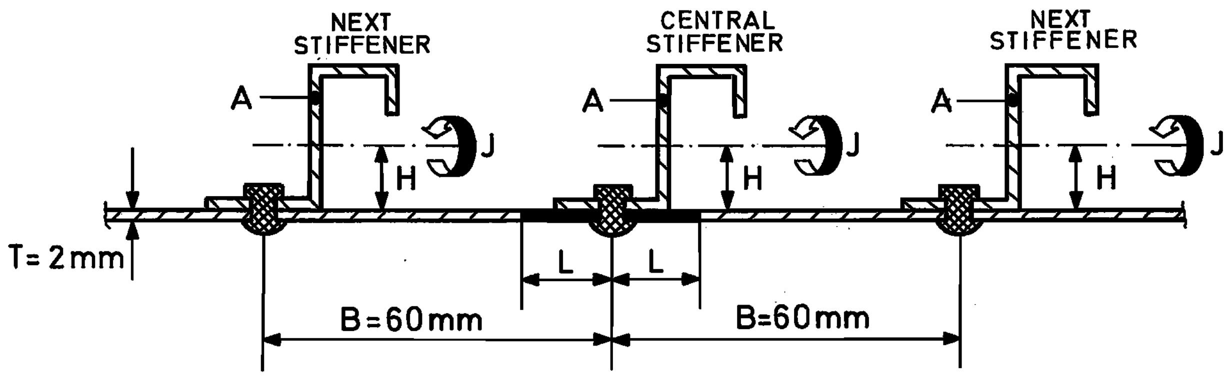


FIG. 7 DETERMINATION OF CORRECTING FUNCTION Y FOR STIFFENED PANELS USING DISPLACEMENT METHOD (FEM) WITH STANDARD ELEMENTS



PANEL	GROSS SECTIONAL AREA A	MOMENT OF INERTIA J	ECCENTRICITY H	RIVET DIAMETER	STIFFENER PROFILE	STIFFENING RATIO
	mm^2	mm^4	mm	mm		$\mu = \frac{A}{A+BT}$
1	44	4200	13.1	4.0	Z 25x15x0.8	0.27
2	101	13400	15.6	4.0	Z 30x20x1.5	0.46
3	190	67500	25.8	4.0	Z 50x25x2.0	0.61

FIG.8 DATA OF CONSIDERED STIFFENED PANELS

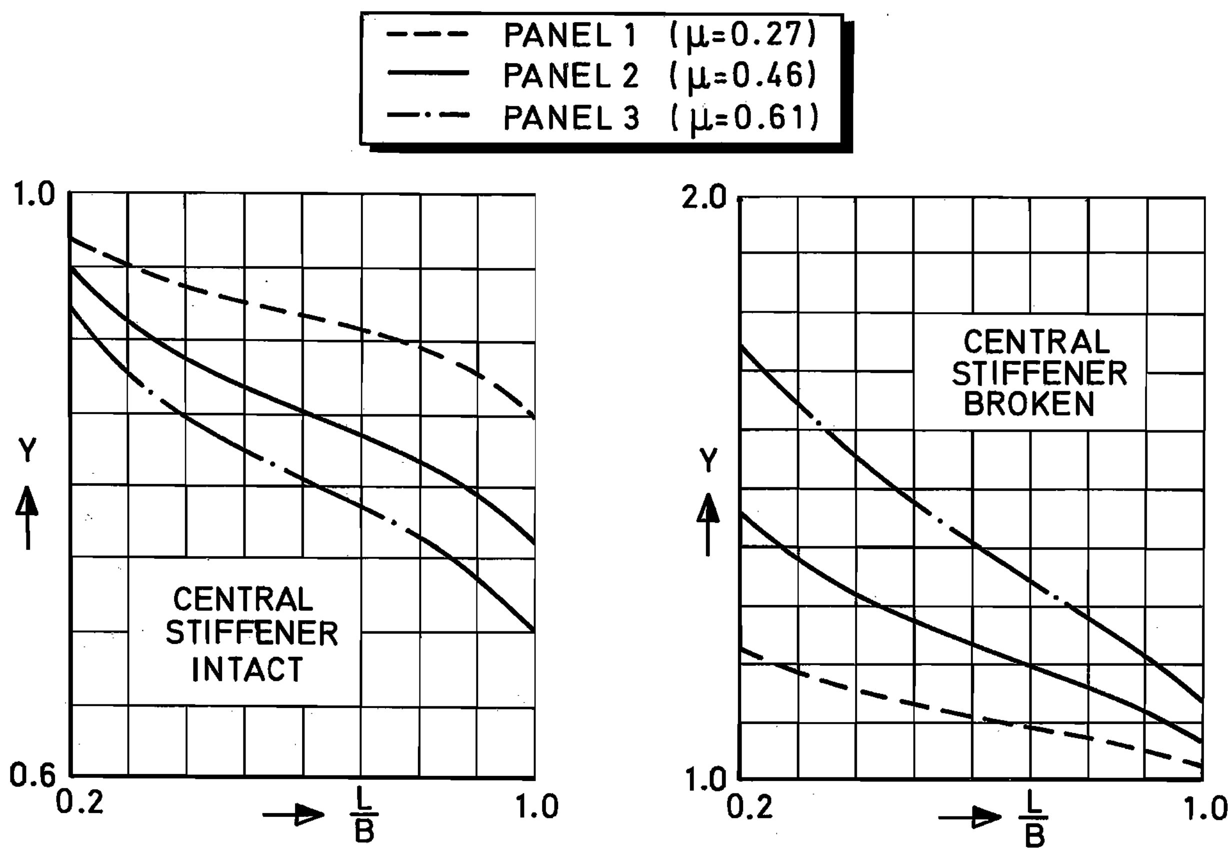


FIG.9 CORRECTING FUNCTIONS

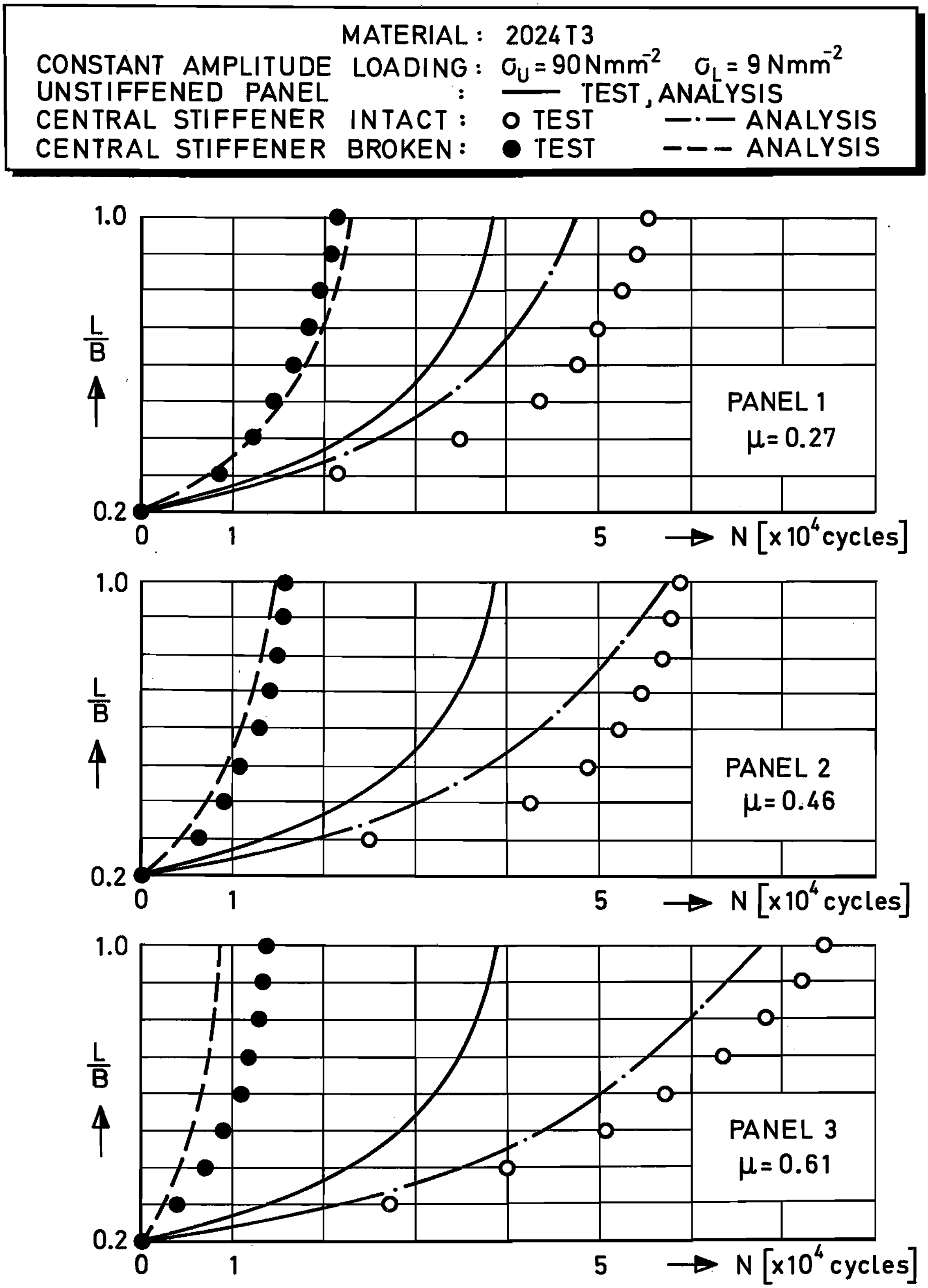


FIG. 10 CRACK PROPAGATION TEST RESULTS COMPARED WITH ANALYTICAL RESULTS. STIFFENED PANELS

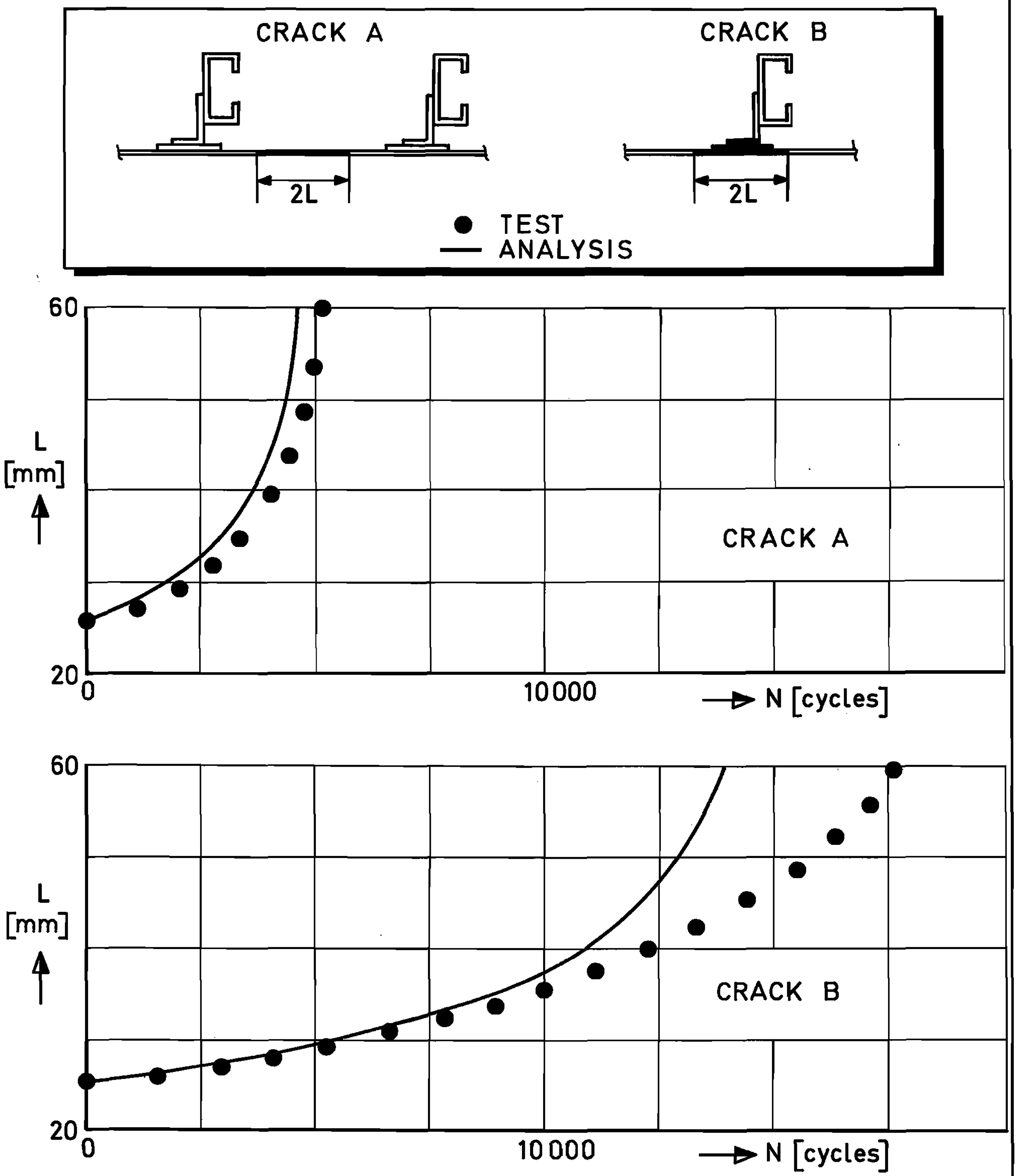


FIG.11 CRACK PROPAGATION TEST RESULTS COMPARED WITH ANALYTICAL RESULTS. FUSELAGE STRUCTURE