FATIGUE CRACK PROPAGATION IN LIGHT ALLOY SHEET MATERIAL AND STRUCTURES

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Summary—Several test series on crack propagation in light alloy specimens were performed at a positive mean stress and axial loading. Results are presented on the following aspects: (1) The frequency effect was studied by comparing the crack rate at a low and a high frequency, viz. about 20 and 2000 c/min respectively. Some fractographical observations were made. (2) The effect of varying the stress amplitude and applying high peak loads on the crack propagation was studied in comparison with constant-amplitude data. (3) The results of stiffened panels were compared with the results of a complete structure and the results of small sheet specimens. At the end of the paper the conclusions are summarized.

1. INTRODUCTION

NOWADAYS it is generally recognized that the design of the structure of a commercial aircraft cannot be considered to be complete without a thorough treatment of the fatigue aspect. This, however, does not imply that such a treatment is easily possible nor that a straightforward procedure is available. Many people still feel that handling the fatigue problem is still more an art than a science, the art being guided by the bulk of fatigue data in the literature and the designer's experience.

The available data on crack propagation are fairly scanty in the literature. Still, crack propagation in aircraft structures is now felt to be important. Since the best possible estimate of the life until a crack will appear in an aircraft structure may err a factor of, say, two, even if it is based on full-scale testing, the designer has to face the problem that fatigue cracks may occur in his structure at a moment when they are not yet expected. He then has to be sure that crack growth and reduction of static strength will be sufficiently low to leave a high probability of detecting the cracks during scheduled inspections. This implies that cracks cannot be allowed in certain components, but cracks do not need to be catastrophic in stiffened sheet structures. To make an estimation of the crack rate in such structures it has to be realized that many parameters are involved. Some of them have been studied in this investigation and the results are presented. Aspects being studied are (1) the effect of frequency on the crack rate, (2) the crack rate at variable-amplitude loading and (3) the comparison of crack rate in small and large specimens. Obviously this list of parameters is not at all complete. Most of the parameters affecting the fatigue life until crack initiation have some bearing on the crack propagation. However, the notch effect has lost much of its importance. Once a crack has started and grown for some length there will be hardly any effect left of the geometry of the notch at which it was nucleated. This justifies the use of sharp notches in studies of crack propagation. Cracks are then initiated in a conveniently small number of cycles.

The specimens used were sheet specimens or panels stiffened by a number of stringers. The materials involved were light alloys of the 2024 and 7075 type.

Fatigue test results dealt with in this paper were obtained under contract with the Netherlands Aircraft Development Board (NIV). Permission for publication is acknowledged here.

2. NOTATION AND UNITS

l = half length of crack from tip to tip, including the notch, see Fig. 1
n = number of cycles
dl/dn = crack rate
kc = kilocycle = 1000 cycles
S = stress
S_a = stress amplitude
S_m = mean stress

All stresses are based on the gross area, including the notch and the cracks. Stresses are expressed in kg/mm^2 (1 kg/mm^2 = 1422 p.s.i.) and dimensions in mm (1 inch = 25·4 mm).

3. THE EFFECT OF LOADING FREQUENCY ON THE CRACK RATE

The sheet specimen is shown in Fig. 1. The material was 2024 Alclad and the static properties were $S_{0\cdot2} = 36\cdot9$ kg/mm^2, $S_u = 48\cdot5$ kg/mm^2 and $\delta = 16\%$. The geometry of the small central notch had been proposed by Weibull$^{(1)}$ and proved to be effective to initiate cracks at both sides of the notch after a small number of load cycles. The specimen surface was locally polished. The highly reflecting surface allowed an easy observation of the crack length through a large magnifying glass with a low magnification (2 ×). Fine lines were inscribed on the surface for this purpose.

The fatigue machine was a horizontal Schenck-pulsator, type PPD 6. It has been equipped with installations for both a high and a low frequency⁽²⁾. The specimen is directly coupled to the optical dynamometer. The high frequency is in the order of 2000 c/min and the machine is operating near resonance frequency, involving a pure sinusoidal stress wave. The low frequency is in the order of 20 c/min and is generated by a reversible screw drive. This induces a triangular wave form.

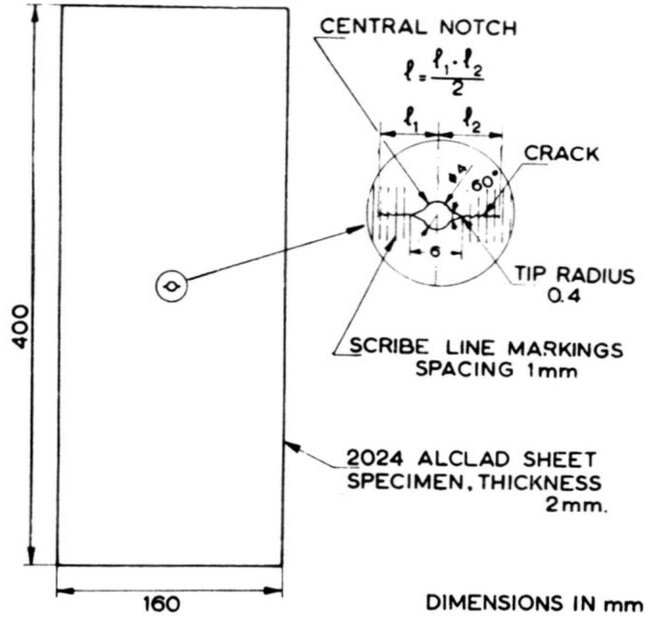

FIG. 1. Sheet specimen for crack propagation.

All tests were run at a constant mean load, corresponding to $S_m = 8{\cdot}18$ kg/mm². Three different stress amplitudes were used and each

TABLE 1

S_a (kg/mm²)	Frequency (c/min)	Cycles to increase l from 5 to 30mm (kc)	Mean (kc)	Ratio
2·41	2170	95 –99 –115·5	103·2	1·19
,,	14	83·5–86·5–89·5	86·5	
3·27	2200	45·2–51·9–58·9	52·0	1·32
,,	26	34·0–41·4–42·6	39·3	
5·49	2230	11·85–15·05–15·6	14·17	1·31
,,	17	10·1–11·0–11·35	10·82	

test was repeated three times. Both cracks in one specimen grew almost perfectly symmetrically and their results were averaged. The scatter between three similarly tested specimens was small as usual for crack propagation(3). This is illustrated by Table 1.

It should be noted that l is the length of the crack to the center line (see Fig. 1). It was felt that the most appropriate and instructive comparison was obtained by comparing crack rates. This has been done in Figs. 2 and 3 to show the effect of crack length and stress amplitude respectively. In Fig. 2 each curve is the mean result of three tests. Figure 3 has been derived from Fig. 2. Figure 2 shows that the crack rate at the higher frequency is consistently lower than at the low frequency, on the average about 30%. There is a tendency to a reduced difference at higher values of the crack length. From Fig. 3 the difference in S_a-values to obtain the same crack rate at the high and the low frequency is on the average 11%. This is too much to be explained by machine errors which might account for 2 to 3% only. So it seems that a small but definite frequency effect on the crack rate has been found. A more detailed account of the

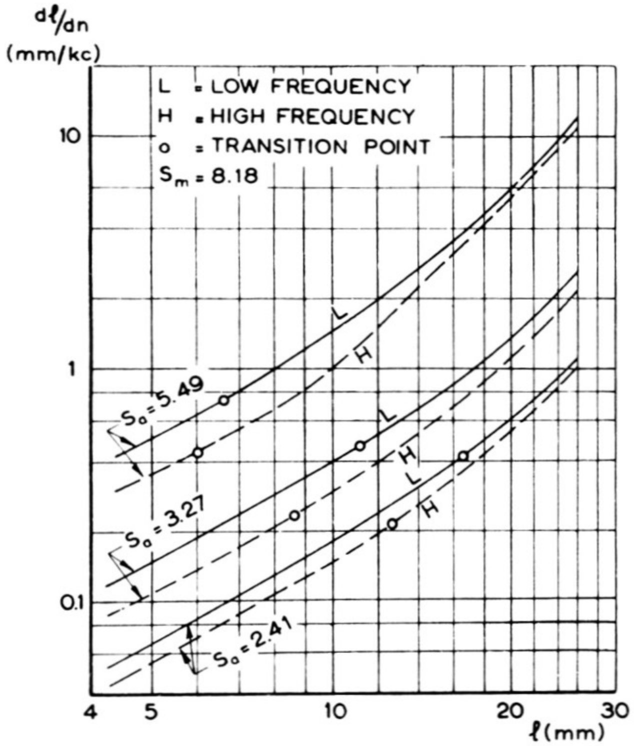

FIG. 2. Crack rate as a function of crack length for specimen of Fig. 1.

test results will be presented in ref. 4. In the literature some results about the frequency effect on crack propagation were found[5, 6, 7]. In general the effect was of the same order; however, the number of tests was very small.

Fractographical observations revealed some interesting features. In light alloy sheets the fatigue crack on a macro scale starts in a plane perpendicular to the sheet surface and the loading direction. When the crack length has sufficiently increased the plane of the crack starts to rotate around the growing direction as an axis until the angle with the sheet surface is about 45°, as it is for static failures of sheet material. This is well known to those who have tested light alloy sheet material in fatigue. Frost and Dugdale[8] noted that the transition did not affect the crack propagation curve to a noticeable extent. This was confirmed by the present investigation. The crack length at which the transition occured has been indicated in Fig. 2. It is somewhat surprising to see that the transition at the low frequency occurred at higher cracklengths than at the high frequency. So the low frequency seems to emphasize the fatigue character of the failure. It is thought that the maximum stress of the load cycle may govern the crack length at which the transition occurs, however, also the frequency of loading is of some importance as shown in Fig. 2.

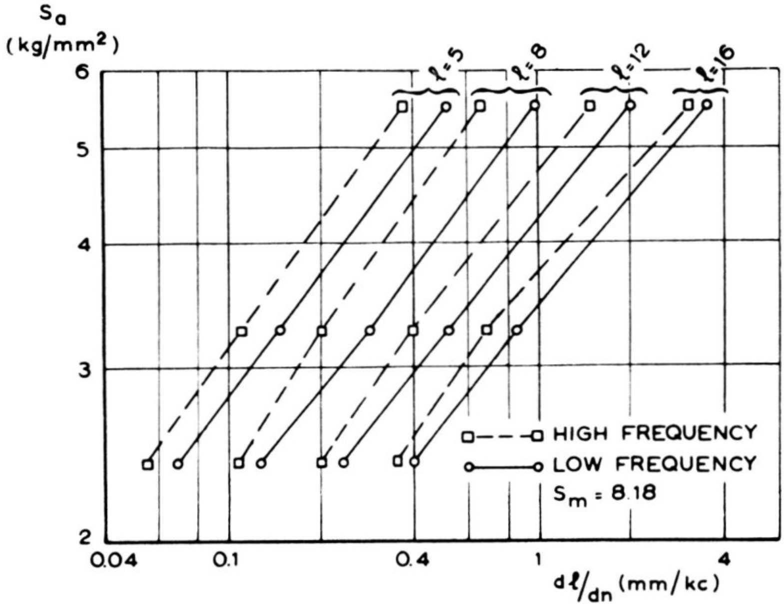

FIG. 3. Crack rate as a function of stress amplitude for specimen of Fig. 1.

By microscopical examination growth lines were found (see Figs. 4 and 5). By comparing the spacing of these lines with the corresponding crack

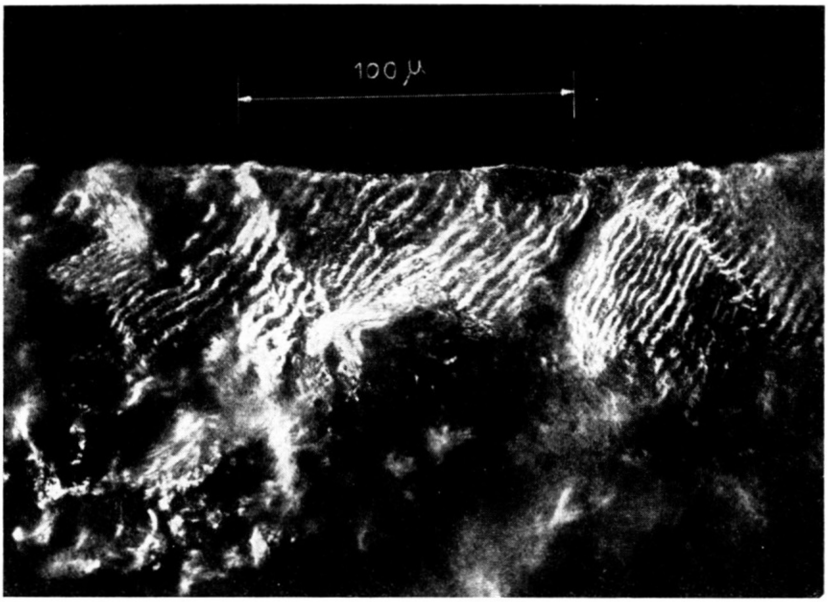

FIG. 4. Growth lines in the cladding layer. Propagation from right to left, $l=17{\cdot}3$ mm.

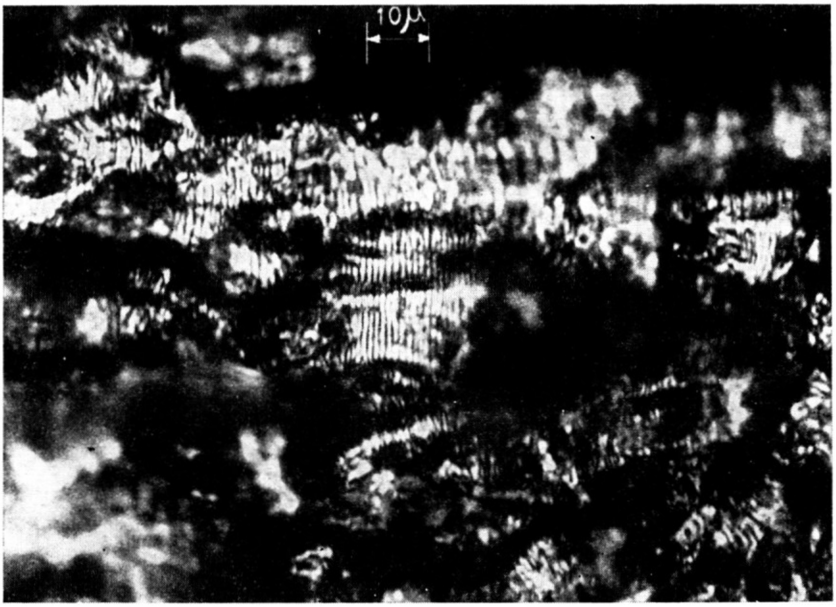

FIG. 5. Growth lines in the core. $l=7{\cdot}3$ mm.

rate it could be proved that one such line corresponds to the crack extension of one load cycle. This confirms the findings of Ryder and Forsyth(9). In general the growth lines in the cladding layer were found in the region for which the transition, discussed above, had already occurred. They were easily found there. The growth lines in the core were met in the region for which this transition had not yet occurred. Their detection was more difficult since they did not occur so abundantly and are near to the limit of the optical microscope.

Local variations of the spacing of the lines were common. Still it is felt that the lines showed that fatigue crack propagation is a fairly continuous process. No obvious differences with respect to the growth lines were found between specimens tested at the high and the low frequency. So it seems that fatigue crack propagation at both frequencies is not essentially different.

An explanation of the frequency effect might prove to be difficult. Due to the large difference in frequency the low-frequency tests involve a much longer time per cycle at a high load level than the high-frequency tests. The triangular wave form of the low-frequency loading does not affect this statement. Since the result was a larger crack extension one might be inclined to say that creep has been active. However, since the low frequency seems to emphasize the fatigue character and since fatigue is generally associated with slip it is probably better to say that some time-dependent phenomenon which increases the amount of slip has been active. Dislocation theory may offer a number of mechanisms which will do so. Another complicating aspect is that the precipitation in the light alloy has not yet reached a stable condition. There may be an interaction with the dislocation movements which is time dependent. No further discussion will be presented here.

A first approximation of Figs. 2 and 3 is to consider the curves as straight and parallel. Since both Figures have been plotted on a double-logarithmic scale the following relation should then be valid:

$$\frac{\mathrm{d}l}{\mathrm{d}n} = k l^{\alpha} S_a^{\beta} \tag{1}$$

α and β are constants, k is a factor depending on the frequency. A similar relation was found by Frost and Dugdale(8). On the basis of geometrical similarity of small cracks they concluded that $\alpha = 1$, which was in agreement with their results on sheet specimens of different materials. For the present investigation the average value for $l \leqslant 12$ mm was $\alpha = 1{\cdot}5$, a value derived analytically by Head(10). Strictly Head's analysis is not applicable here due to the assumptions he made. Shanley(11) also assumes a relation similar to eq. (1) with $\alpha = 1$.

For a light alloy, B.S. L71 (~ 2024), sheet material, loaded at $S_m = 3{\cdot}15$ kg/mm² and $6{\cdot}3$ kg/mm². Frost and Dugdale found $\beta = 3$. For this investigation the value is $\beta = 2{\cdot}6$ which may be felt to be a reasonable agreement.

Probably eq. (1) may be of some use for interpolation purposes (see also Chapter 5). It has to be noted that k, α and β may still depend on the dimensions of the specimen, its material and the mean stress. The results of Frost and Dugdale on sheet material of a light alloy, mild steel and copper suggest that α and β do not depend on the type of material and that the mean stress might affect k only.

With respect to the technical implications of the frequency effect it is fortunate that only a relatively small influence has been found. For quantitative information on inspection periods of an aircraft, tests should preferably be carried out at a realistic test frequency. If carried out at a higher frequency some allowance should be made for this frequency effect.

4. CRACK PROPAGATION UNDER VARIABLE-AMPLITUDE LOADING

Two different types of tests were performed until now: (1) tests in which two values of the stress amplitude have been applied and (2) tests with a constant stress amplitude to which single peak-loads of different types have been added several times during the crack growth. A third test series will involve program-fatigue tests.

Tests with two values of S_a.—The stress-time history has been indicated schematically in Fig. 6. The purpose of the tests was to study the effect of cyclic loading at one value of S_a on the subsequent crack propagation at an other value of S_a. To obtain a sufficiently long propagation curve at each value of S_a only 3 or 4 changes of S_a were made during a single test. The specimen shown in Fig. 1 was used again and also the material was the same as in the previous tests. So the crack propagation curves

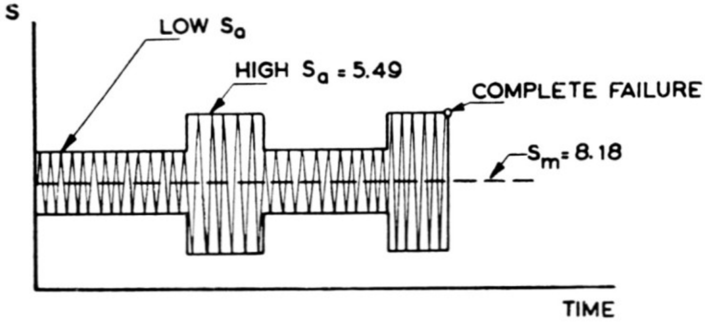

FIG. 6. Load sequence in a test with 2 different stress amplitudes.

obtained during the study of the frequency effect could be used as a reference. Also the same fatigue machine was employed. Tests were started at the high frequency (~ 2000 c/min) and sometimes continued at the low frequency (~ 20 c/min) if the crack rate became too high for an accurate observation of the crack growth. About 200 cycles were involved in changing the load level at the high frequency and only a few cycles at the low frequency. The same three values of S_a mentioned in the previous section were applied. In all tests the high S_a-value was 5·49 kg/mm². Both values 2·41 and 3·27 kg/mm² have been used for the lower stress amplitude. Four test series of three identical tests each have been conducted.

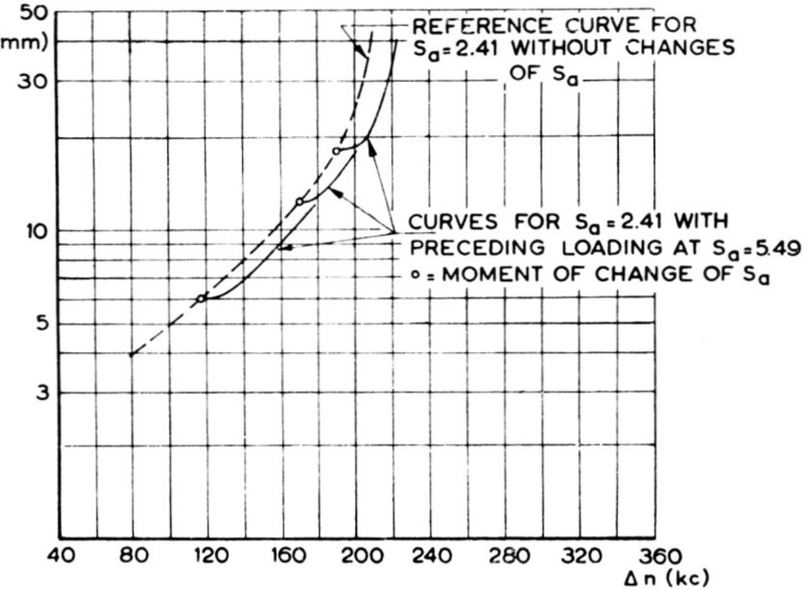

FIG. 7. The effect of cyclic loading at a high S_a-value on the subsequent crack propagation at a low S_a-value.

The results can be summarized as follows: After a change of S_a has been made the preceding loading had a temporary effect on the subsequent crack propagation. This effect disappeared after some extension of the crack length. The high S_a-value followed by a low S_a-value induced a noticeable retardation of the crack propagation at the lower S_a-value. This is shown in Fig. 7 showing average results. After the initial period of retardation the propagation curves resume the original shape from the reference curve, horizontal shifts being in the order from 10 to 14 kilocycles. For tests with $S_a = 3{\cdot}27$ kg/mm² as the lower stress amplitude the results were similar; however, the shifts were smaller, i.e. in the order of 1·5 to 3·5 kc.

Plotting the results for changes of S_a from 2·41 or 3·27 kg/mm^2 to the high S_a-value, 5·49 kg/mm^2, and comparing this with the reference curve for testing at $S_a = 5{\cdot}49$, gave the impression that stressing at the low amplitude did not affect the subsequent crack propagation at the high amplitude. However, a careful study of the numerical data revealed that a small acceleration of the crack growth at the high S_a was induced by the preceding loading at the low S_a. This acceleration effect was indeed much smaller than the retardation effect as shown in Fig. 7 and it might easily escape attention. Moreover it is possible that the small acceleration effect is a fictitious result due to a better and more easy observation of the tip of the crack at the higher S_a-value.

Tests with peak loads.—In ref. 12 it had been found that the fatigue life of a notched specimen until the occurrence of a macroscopically visible crack is largely influenced by periodic high peak loads. A more or less similar study is made here for crack propagation. For all tests $S_m = 8{\cdot}18$ kg/mm^2 and $S_a = 3{\cdot}27$ kg/mm^2. In one test series a positive peak load had been inserted three times as shown schematically in Fig. 8. The effect on the crack propagation is very large. Initially the crack practically refuses to grow. After some time it resumes propagation and finally the original shape of the crack propagation curve without peak loads will be obtained again. Figure 8 shows the effect to be larger at higher values of l. This will be due to the higher net stress at the peak for larger cracks.

Tests with negative peak loads were also carried out. The value of S_m-$S_{\min}$ for the negative peak loads was the same as $S_{\max}$-S_m for the positive peak loads. This led to $S_{\min} = -2{\cdot}9$ kg/mm^2. Buckling of the specimen was prevented by attaching two steel covers to the specimen. The covers had felt at the inside. Strain-gage measurements showed that no load transmission occurred through the covers. In the first test negative peak loads were applied at $l = 6$, 13 and 23 mm respectively. Since this did not affect the crack propagation to a noticeable extent more negative peak loads were applied in two other tests, viz. at $l = 5$, 6, 7, 8, 9, 11, 13, 15, 19, 23 and 29 mm respectively. No effect on the propagation could be found in this case either.

A third test series was performed with positive peak loads immediately followed by negative peak loads as indicated schematically in Fig. 9. If this figure is compared with Fig. 8, taking into consideration the different horizontal scales, it is clear that the large effect of the positive peak-loads is drastically reduced by the subsequent negative peak loads. It is, however, not completely obliterated. Some retardation of the crack growth remains. It is noteworthy that this retardation is not a maximum directly after the application of the peak-load cycle but somewhat later (see Fig. 9).

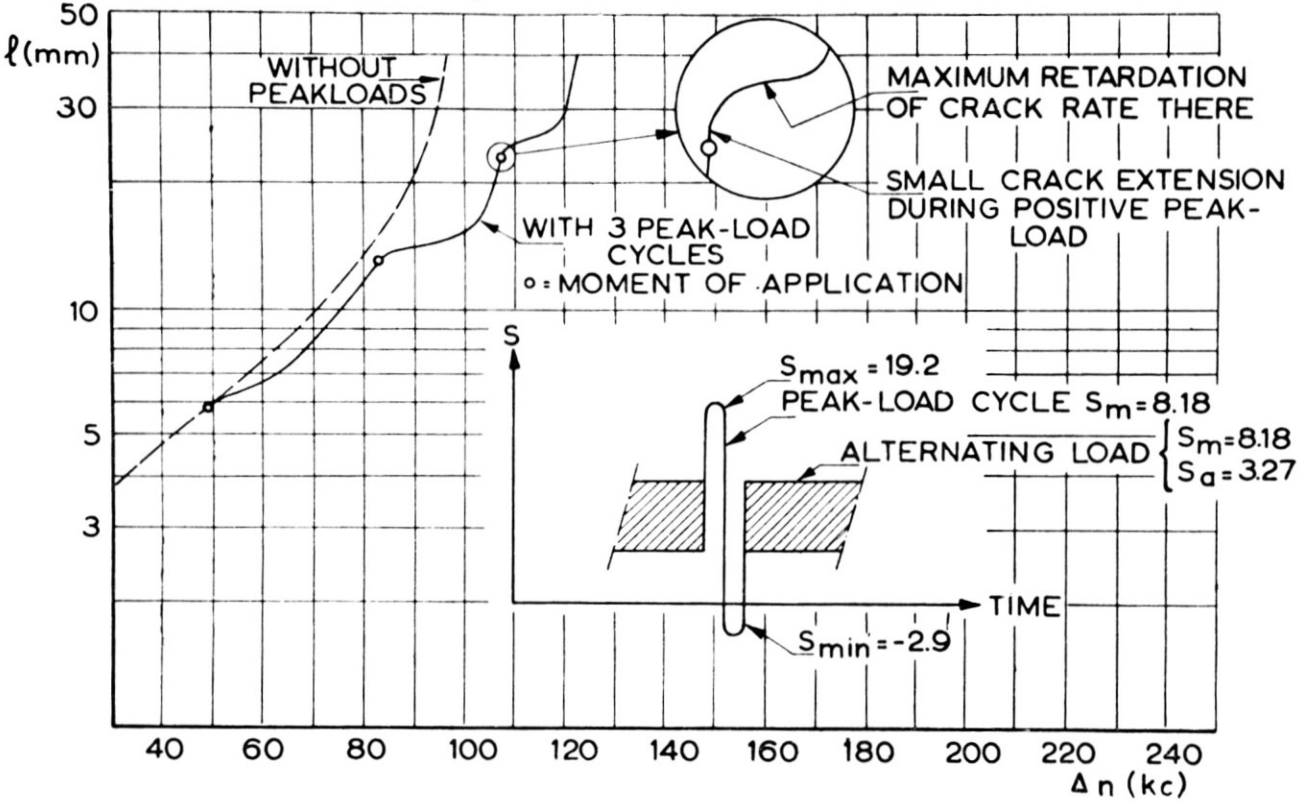

FIG. 8. The effect of positive peak loads on the crack propagation at $S_a = 3{\cdot}27$ kg/mm².

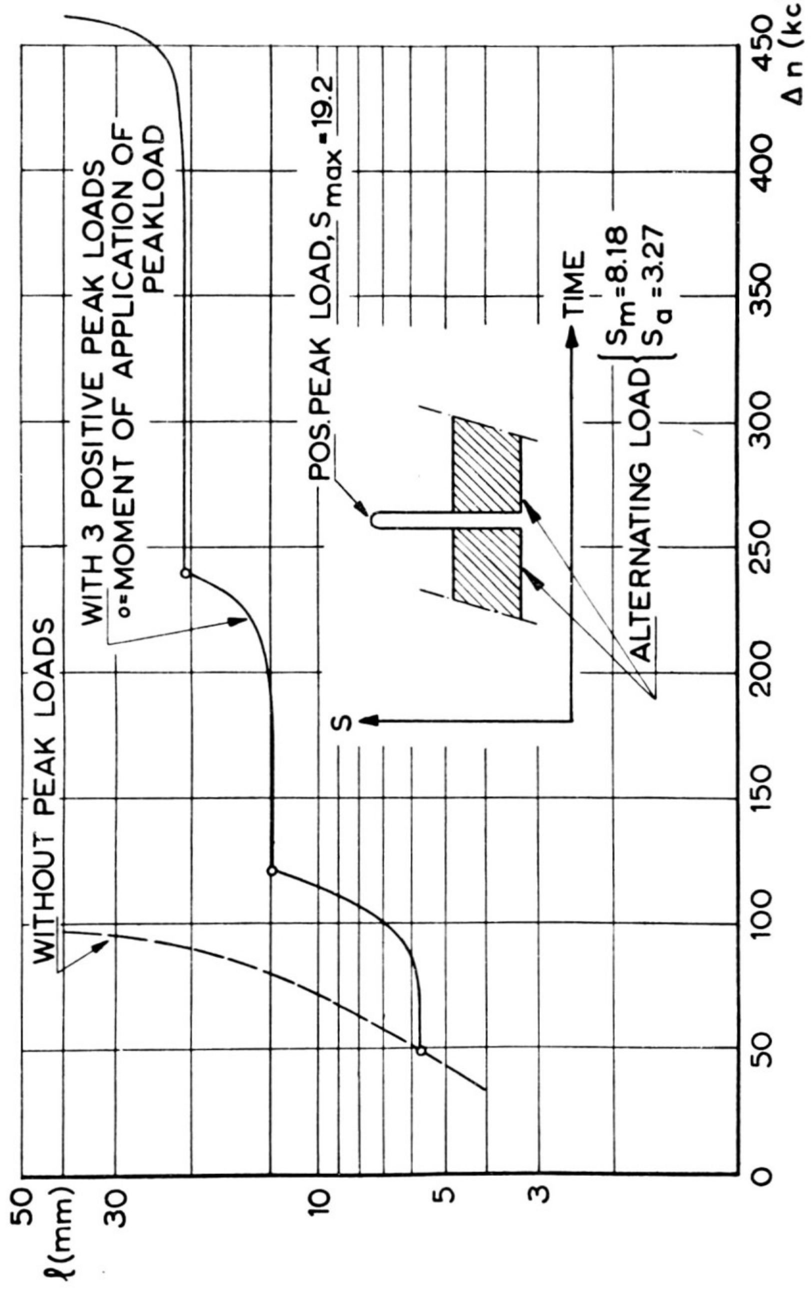

FIG. 9. The effect of peak-load cycles on the crack propagation at $S_a = 3{\cdot}27$ kg/mm^2.

Two important arguments can be raised in order to explain the results described in this section. (1) Around the tip of a crack there will be severe plastic deformation and residual stresses are easily built up. (2) A crack is not the same stress raiser in tension as in compression. During compression the crack may be partly closed and thus the stress concentration will be decreased.

In ref. 12, reviewing the available data on variable-amplitude loading of notched light-alloy specimens, residual stresses were found to be a powerful tool in explaining much of the empirical results. Also here it must be expected that negative residual stresses will decrease the crack rate, whereas positive residual stresses will do the opposite. The effect of negative residual stresses may be called favourable since they slow down the crack propagation. This effect is clearly demonstrated in Fig. 8 for the tests with the positive peak loads. The crack has apparently to break through a barrier of negative residual stresses. After it has succeeded in doing so the effect of the peak-load is vanishing.

It is believed that the trend of Fig. 7 which was also found by Christensen(13) and Haas(14) may be explained equally well on the basis of favourable residual stresses.

Positive residual stresses should imply an unfavourable effect on the crack rate, however, they are not so easily built up due to closing of the crack. In ref. 7 it was shown by Illg and McEvily that closing of the crack occurs. The tests with the complete peak-loads cycles show that the favourable negative residual stresses are easily wiped out by the negative peak loads. As has been reasoned in ref. 7 a crack which is opened in tension by plastic deformation at the tip is not directly closed by a negative load. So an effective wiping out of the favourable residual stresses around the tip of the crack may occur. However, at a certain moment the crack will still close more or less and a further increase of the compressive load will leave the favourable residual stresses at some distance from the tip of the crack unaffected. In other words the plastic region associated with the negative peak loads will be smaller than the plastic region associated with the preceding positive peak loads. The result is that the crack propagation is retarded most effectively after it has passed the small region in which the residual compressive stresses were wiped out and it enters the region in which this has not occurred. It is felt that this explains the trend shown in Fig. 9.

The small acceleration of the crack growth after a change from a low to a high S_a-value cannot be explained on the basis of residual stresses. This acceleration was also found by Christensen(13) and Haas(14). According to Christensen, cracks being formed at a low S_a-value are much finer and sharper than cracks formed at a high S_a-value and they are therefore more severe stress raisers. This should explain the acceleration effect. It is felt that this explanation can hardly be complete since a few cycles at the high S_a-value must be sufficient to give the tip of the crack the geometrical appearance associated with that stress amplitude. Christensen and Haas did not offer quantitative data on the acceleration effect. In the present investigation the effect was found to be very small and it even might be a fictitious result. From practical point of view it is fortunate that this acceleration effect was very small. A detailed account of the test results will be presented in the future as an NLL-report.

Summarizing the results of this section it can be said that residual stresses have an important effect on the crack propagation which is favourable for residual compressive stresses and unfavourable for residual tensile stresses. The first can be built up easily by positive loads. They are easily diminished, but not fully eliminated by negative loads, thus reducing the favourable effect. On the other hand the unfavourable residual tensile stresses cannot be built up very effectively due to closing of the crack at negative loads and can be eliminated easily by positive loads.

There are now some consequences for crack propagation in service. In practice fatigue trouble is mainly associated with positive mean stresses and then favourable residual stresses are more likely to be present than unfavourable residual stresses if the distribution function of load amplitudes is symmetric around the mean stress. So as an average a favourable interaction of different load amplitudes may be expected. Periodic negative loads may occur on a wing structure due to landings. They are suspected to be fairly damaging with respect to fatigue life until cracks are visible(12); however, during crack propagation its effect need not to be feared very much. It is true that they may cancel a favourable residual stress but that is easily built up again. In general the landings are not expected to induce a stable unfavourable residual stress field. So the average crack rate under service loadings at a certain crack length is expected to be equal to or lower than the calculated average crack rate based on constant-amplitude test data and weighted according to the probability of occurrence of all S_a-values involved. Obviously any environmental effects on crack propagation have been neglected in this conclusion. The procedure of calculating a crack rate averaged over all S_a-values actually involved a "cumulative damage" concept with the crack lengths as the only damage-parameter. This is a simplification, (see ref. 15), however, for crack propagation is expected to be on the safe side due to interaction of different stress amplitudes, which on the average is expected to be favourable.

5. COMPARISON OF THE CRACK PROPAGATION IN PANELS OF DIFFERENT WIDTHS

The fatigue crack propagation in stiffened panels will be compared with the propagation in a complete structure and with the sheet specimens discussed in Sec. 3. The aim of the tests on the panels was to compare the fatigue performance of 2024 and 7075 material with respect to the crack rate and the remaining static strength when cracks were present. Only the rates of crack propagation will be presented.

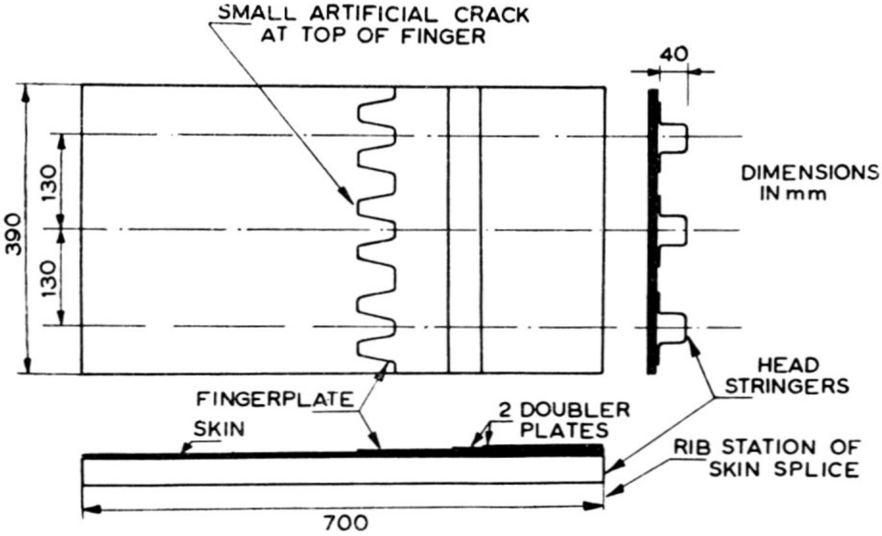

FIG. 10. Stiffened panel with 3 stringers for crack propagation tests.

The type of panel is given in Fig. 10. It represents the skin splice of the tension skin of the wing of the Fokker Friendship near the fuselage. The skin is spliced there, the stringers are continuous. Three doubler plates, one of them being a finger plate have been bonded to the skin the stringers were riveted to the skin. Thicknesses are given below. Panels of both materials were tested at the same mean load and the same 3 values of the alternating load. Values of S_m were 8·5 and 5·7 kg/mm^2 for 7075 and 2024 panels respectively. Crack growth was promoted by

TABLE 2

Material	Thickness (mm)			Cross-section (mm^2)
	skin	stringer	doublers	
7075	2	1·6	0·6	1554
2024	3	2	0·6	2130

cutting a sharp artificial crack at the top of a finger of the finger plate (see Fig. 10). For each material 3 tests were performed at each load amplitude. All stresses were measured with strain gages. A very slight bending of the specimen occured. Values of the stress quoted refer to the skin. The frequency of the alternating load was 500 c/min. The crack propagation was observed visually. Sometimes a crack ran into a rivet hole and was arrested there for a considerable time. In general both sides of the crack grew symmetrically in the skin and no cracks were found in the stringers until late in the test. Some tests were stopped at a small crack length for a subsequent static test. Considering the tests in which a large symmetrically growing crack was obtained, fairly smooth propagation curves were found. The scatter was low, as shown in Table 3.

TABLE 3

Material	S_a (kg/mm^2)	Observed crack extension (mm)	Number of cycles involved (kc)
7075	2·60	l= 6 to 50	72 –75·5–79
	3·56	ditto	22·5–29·8–33·2
	6·01	ditto	7·5–8·4
2024	1·98	l=12 to 50	174–190·5
	2·85	ditto	74–77

Also here, it was felt more appropriate to plot the crack rate as a function of the crack length (Fig. 11) and the stress amplitude (Fig. 12) rather than presenting crack propagation curves. Obviously the crack rate in the 2024 panels was much lower than in the 7075 panels, the ratio being 2·5 to 3. However, the mean stress was lower for the 2024 panels. Data on the effect of mean stress on the crack rate are very scanty. Frost and Dugdale(8) compared the crack rate for a light alloy at $S_m = 3{\cdot}15$ and 6·3 kg/mm^2 and they found an effect on the crack rate amounting to a factor of about 2. The difference in mean stress here is 2·8 kg/mm^2 instead of 3·15 kg/mm^2 and the resulting difference in crack rate may be a factor of about 1·75. That means that the difference found in the panels of both materials would reduce to a factor of 1·4 to 1·7 at the same S_a and S_m. Hardrath, Leybold *et al.* studied the crack rate in a stiffened tension skin of a box beam for both materials(16, 17). As an average result they found the crack rate in 7075 to be about 1·85 times faster than in 2024 material, the geometry of box beams and the loading being the same for both materials. Differences of the same order of magnitude were found by others on unstiffened sheet specimens(6, 13).

The results of the 7075 panels could be compared with a crack propagation curve obtained on the complete wing structure with a premodification type tension skin. This structure had exactly the same skin, stringers and doublers. The only difference between the panel and the wing structure is the width of the specimen. For the wing structure this is the chord distance between front spar and rear spare, being 1467 mm, i.e. 3·8 × the width of the panel. The mean stress in the wing structure was slightly higher than in the panel, viz. 9·4 kg/mm^2 instead of 8·5 kg/mm^2 for the panel. The wing structure was loaded with gust cycles of a constant amplitude, $S_a = 3{\cdot}07$ kg/mm^2, at a frequency of 10 c/min. In addition landing cycles were inserted, thus simulating flights. Each flight consisted of 10 gust cycles and one landing cycle(18). The minimum stress during the landing cycle was $-0{\cdot}7$ kg/mm^2. From fractographical studies on the cladding layer it became clear that at the macro-stage of the crack there was not much difference between the crack extension during the

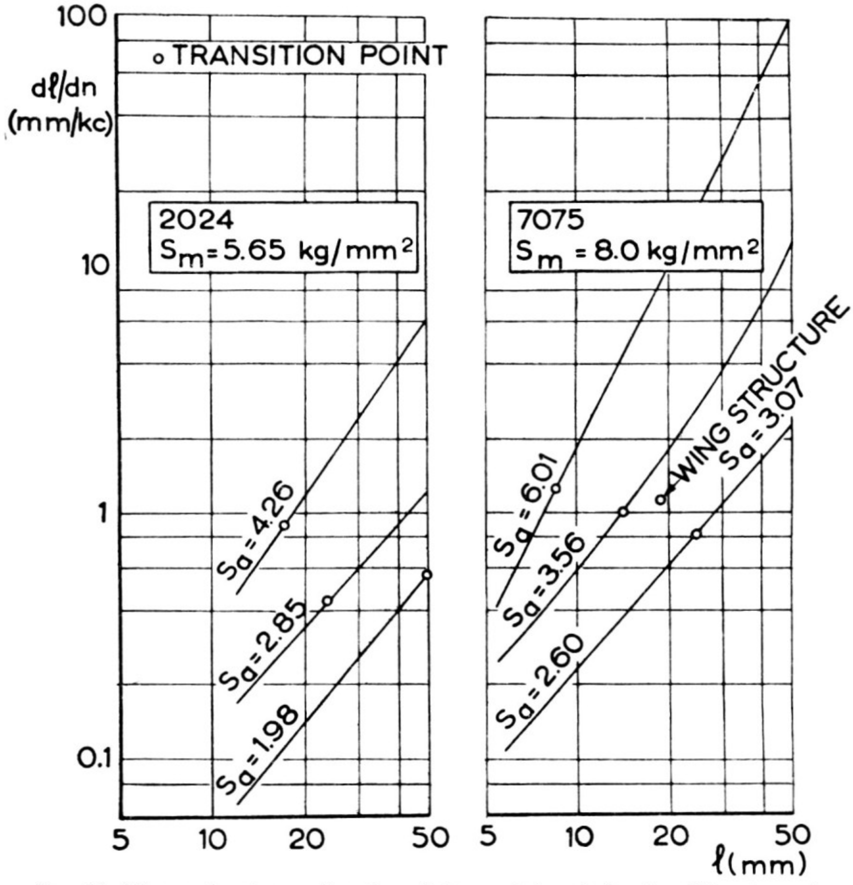

FIG. 11. The crack rate as a function of the crack length for the stiffened panels of Fig. 10.

landing and during one gust cycle. Taking the landing equivalent to one gust cycle the crack rate was derived from the crack propagation curve for $l = 20$ mm and $l = 40$ mm. Values have been plotted in Fig. 12. They are in good agreement with the panel test. If the small difference in mean stress and the different loading rate are taken into account the agreement is felt to be excellent. So the comparison suggests that the crack rate was correlated to the absolute length of the crack and any size effect based on the specimen width is not supported here. Additional evidence is offered by comparing the transition point as discussed in Sec. 3 for the panel and the wing structure (see Fig. 11). Also here a good agreement on the basis of absolute crack length was reached.

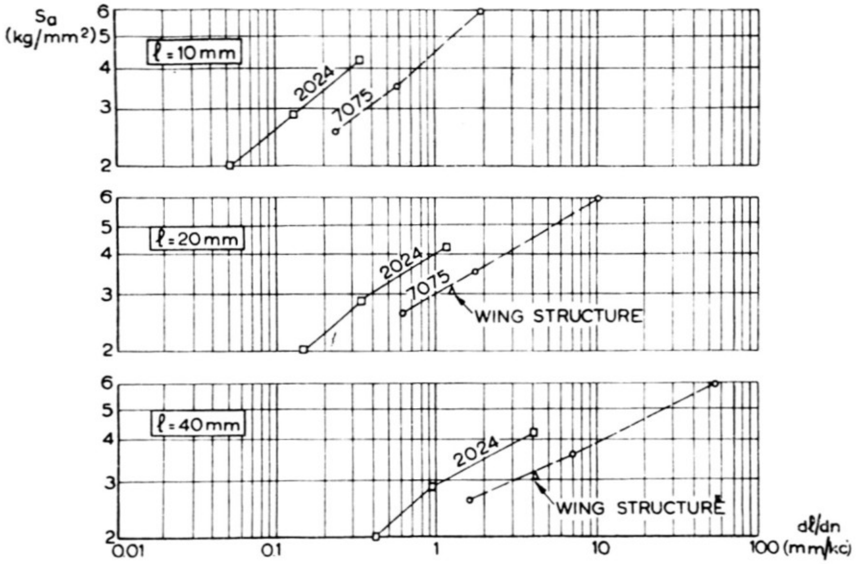

FIG. 12. The crack rate as a function of the stress amplitude for the stiffened panels of Fig. 10.

The 2024 panels, which are identical to the production type wing structure, might be compared with the 2024 sheet specimens discussed in Sec. 3. Such a comparison is fairly ambitious in view of the difference in mean stress, 5·7 kg/mm² for the panel and 8·18 kg/mm² for the sheet specimen. Moreover, the panel is stiffened whereas the sheet specimen is not. The stringers will lower the crack rate in the skin considerably. A tentative comparison is offered in Fig. 13, on the basis of absolute crack length and on the basis of the crack length as a percentage of the specimen width. The better agreement obtained in the latter case is felt to be accidental since the panel was stiffend and had a lower mean stress. If this could have been accounted for the curves for the panel would have moved to the right considerably and it might well have turned out that a better agreement was obtained by comparing on the basis of absolute crack length. Actually such a comparison will be only allowed for cracks which are small enough to have a negligible effect on the net stress. The value of $l = 20$ mm in the sheet specimen employed for Fig. 13 was already too large in this respect.

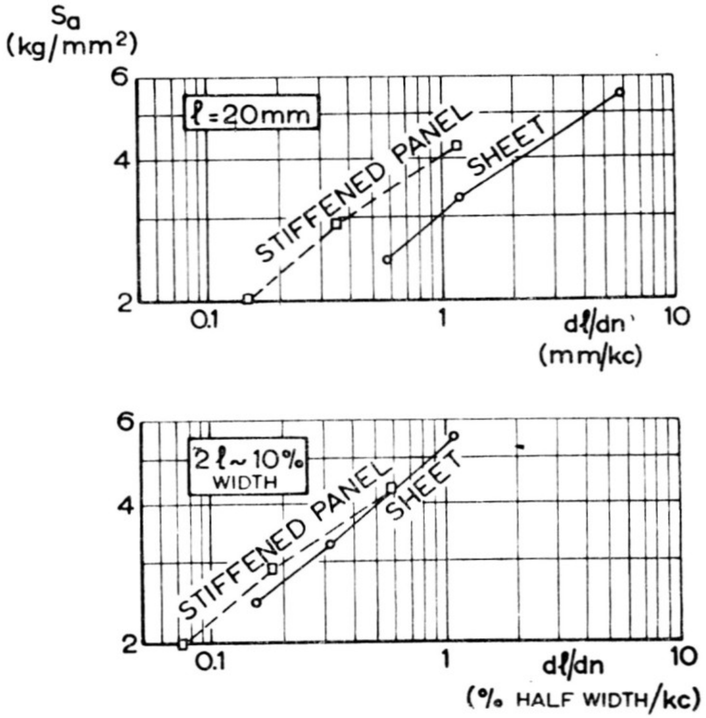

FIG. 13. Comparison of the crack rate in the specimens of Figs. 1 and 10.

It is clear that the comparison is far from satisfactory in order to make a statement with respect to size effect. A systematical study on unstiffened sheet specimens was started by McEvily and Illg(6), and, contrary to the evidence found here, their results suggest that the specimen width is an important parameter. So, further research on the size effect seems to be highly desirable. Moreover it is felt that the complete problem of estimating crack rates in sheet structures, now that much data is becoming available, is ripe for a combined analytical and empirical approach. The potentialities of such concepts as the stress concentration factor of a crack(6, 7) or the stress intensity factor of a crack(19) should be further explored.

6. CONCLUSIONS

1. Testing 2024—Alclad sheet specimens at a positive mean stress and three values of the stress amplitude showed that the crack rate at 20 c/min was on the average about 30% higher than at 2000 c/min. The scatter of the crack rate was low. The effects of the stress amplitude and the crack length on the crack rate could be represented by a simple power function. Fractographical observations revealed growth lines in the cladding layer and in the core. The spacing of the lines corresponds to the crack extension per cycle.
2. Testing 2024—Alclad sheet specimens at a positive mean stress showed that a variation of the stress amplitude or an application of a single positive and/or negative peak load had a temporary effect on the crack growth which varied from a large retardation to a very small acceleration. The results could be explained by considering the residual stress field around the tip of the crack. Residual compressive stresses are easily built up by positive loads and slow down the crack rate. However, they are fairly easily wiped out by negative loads. Building up residual tensile stresses by negative loads is not easy, due to closing of the crack. Moreover also these stresses are easily wiped out by subsequent positive loads.
3. Testing 2024 and 7075—Stiffened panels at a positive mean stress and three values of the stress amplitude showed that the crack rate in the 7075 panels was about 1·5 times as large as in the 2024 panels. Scatter was low. Comparing the results of the 7075 panels with the crack propagation in a complete wing structure of the same material and geometry, with the exception of the width, which was 4 times as large, showed a good agreement if the comparison was based on the absolute crack length and not on the crack length as a percentage of the specimen width. A similar but far less clear indication was obtained by comparing the results of the 2024 panels with the crack propagation in sheet specimens of the same material, but of a 2·5 times smaller width.

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DISCUSSION

J. Cuss: The author has stated that his tests were over a frequency range of 20 to 2000 cycles per minute and has shown the difference he gets in fatigue endurance for the two cases. The fact that there is a difference is an important conclusion, but does he think that the result would have been the same if the ratio had been maintained but the rate had been, say, per hour, instead of per minute?

J. Schijve: The question raised by Mr. Cuss is of special interest with respect to pressurisation cycles for a fuselage. Tests were performed at two different values of the frequency only, i.e. 20 and 2000 c/min. The lower value may be associated with wing bending due to gusts and the upper value is in the range of test frequencies obtained in many commercial fatigue machines. The results do not allow quantitative extrapolation to lower loading rates.

The explanation of the frequency effect is felt to be some time-dependent mechanism occurring on a microscale in the material. Consequently, a frequency effect may be expected for still lower values of the frequency. The magnitude of this effect cannot be estimated from the present test results. It might seem desirable to study the frequency effect at loading rates as low as 1 c/min to 1 c/hour; however, such tests would involve very large testing times.