NLR-TR M.2145

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NATIONAL AEROSPACE LABORATORY NLR

AMSTERDAM

NLR-TR M.2145

The residual strength of cracked sheet - Tests interrupted after intermediate slow crack growth

by

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July 1965

Prepared for Reports and Transactions Vol. XXXIII

C.C.L. Class. G 311: G 331

REPORT NLR-TR M.2145

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Summary

Residual strength tests were performed on 2024-T3 and 7075-T6 aluminium alloy sheet specimens of 600 mm width. After the cracks had shown some stable slow growth the specimens were unloaded and then reloaded. Unloading appeared to have no effect on the residual strength.

Contents

Symbols

$2l$ — crack length
$2l_0$ — initial crack length
$2l_{01}$ — crack length at first interruption of the test
$2l_{02}$ — crack length at second interruption of the test
$2l_c$ — crack length at fracture instability
U — elastic energy
W — plastic energy
α, p — numerical constants
δ — elongation
$\sigma_{0.2}$ — 0.2% yield strength
σ_c — critical fracture stress (residual strength)
σ_i — stress to initiate slow crack growth
σ_{i1} — stress to re-initiate crack growth after first interruption of test
σ_{i2} — stress to re-initiate crack growth after second interruption of test
σ_{r1} — stress at first interruption of test
σ_{r2} — stress at second interruption of test
σ_u — ultimate tensile strength
σ_y — yield strength
All stresses are based on gross area

Units

length mm (1inch = 25.4 mm)
force kg (1 lb = 0.454 kg)
stress kg/mm² (1000 psi = 0.703 kg/mm²)

1 Introduction

Consider a sheet containing a central transverse crack (of length $2l_0$) loaded in tension. At a certain value σ_i of the gross stress the crack will start to extend slowly. The stress can still be increased under continuous gradual slow crack growth until at a certain crack length $2l_c$ and a gross stress σ_c fracture instability occurs. Both the stress σ_i to initiate crack growth and the fracture stress σ_c are lower if the initial crack is longer. The amount of slow crack growth is larger for longer initial cracks.

The slow crack growth preceding fracture is interesting from a theoretical point of view and is not well understood. From an engineering point of view the phenomenon gives rise to an important problem: A high load in service may induce slow growth of an existing crack. A longer crack then remains, having possibly a lower residual strength. Several of such loads

This investigation has been performed under contract with the Netherlands Aircraft Development Board (N.I.V.)

might impair the residual strength so much that fracture might occur at loads which previously only induced slow crack growth.

It seemed worthwhile to investigate the effect of high preloads on the residual strength. Therefore tests were carried out on large aluminium alloy sheet specimens. Firstly the residual strength curve was determined. In a second test series the specimens were loaded until the cracks had shown a certain amount of slow crack growth. The tests were then interrupted by fully unloading the specimens, after which the specimens were fractured by reloading. A number of tests were interrupted twice in this way.

This report gives the results of the tests and a discussion from a technical point of view. The results are also used to check the criteria for slow crack growth and fracture as presented in ref. 1 and 2.

2 Experimental details

The materials tested were 2024-T3 Alclad and 7075-T6 Clad sheets of 2 mm thickness, having the following static properties (averages of 8 tests):

	$\sigma_{0.2}$ (kg/mm^2)	σ_u (kg/mm^2)	δ_{2in}%
2024-T3	$36.4^{+1.4}_{-1.6}$	$47.6^{+0.6}_{-1.0}$	18
7075-T6	$51.4^{+0.8}_{-0.9}$	$55.2^{+0.4}_{-0.4}$	12

The specimens were cut to a size of 1280 × 600 mm (51 × 24 in, see fig. 1) and provided with a fine central transverse saw cut, made by means of a jeweller's fret saw. It was shown in ref. 3 for aluminium alloy sheet that this saw cut can simulate a fatigue crack for the purpose of residual strength tests. The stress to initiate slow crack growth was slightly higher for a saw cut than for a fatigue crack, but once slow crack growth had started the behaviour was the same (same σ_c and l_c).

The residual strength tests were carried out in an ad hoc test set-up. The specimens were loaded in tension by means of a hydraulic jack of 50 tons capacity. A strain gauge dynamometer in combination with a strip chart recorder provided the load records. During the test the specimen was filmed continuously (at 14 frames per second) to record the slow crack growth. Through a mirror arrangement the load recorder was filmed simultaneously (fig. 1). From the cinematographic records the relation between stress and crack length during slow growth and the crack length at the interruption of the tests could be determined. As was pointed out in ref. 3 for the thin sheets used in the present investigation filming gives reliable crack growth records.

3 Test results

The test results are collected in table 1 for the 2024-T3 alloy and in table 2 for the 7075-T6 alloy. In these tables the results of the interrupted tests are compared with two series of continuous tests. As appears from tables 1 and 2 a number of tests were interrupted twice. The residual strength curves (the fracture stress as a function of initial crack length) are plotted in figs. 2 and 3. In these figures the results of the interrupted tests are also shown, again as a function of initial crack length.

The slow crack growth curves are given in figs. 4 and 5. For the continuous tests only average curves are given in order to avoid confusion. Only two curves of each series of 4 interrupted tests are plotted (The results of the other tests are similar and the characteristic points of these curves are given in tables 1 and 2).

Finally in figs. 6 and 7 the critical crack length is plotted as a function of the initial crack length.

4 Discussion

From the residual strength curves in figs. 2 and 3 it can be concluded that one or two interruptions of a residual strength test have no influence on the residual strength. A better appreciation of the results can be obtained from figs. 4 and 5. For the discussion of these

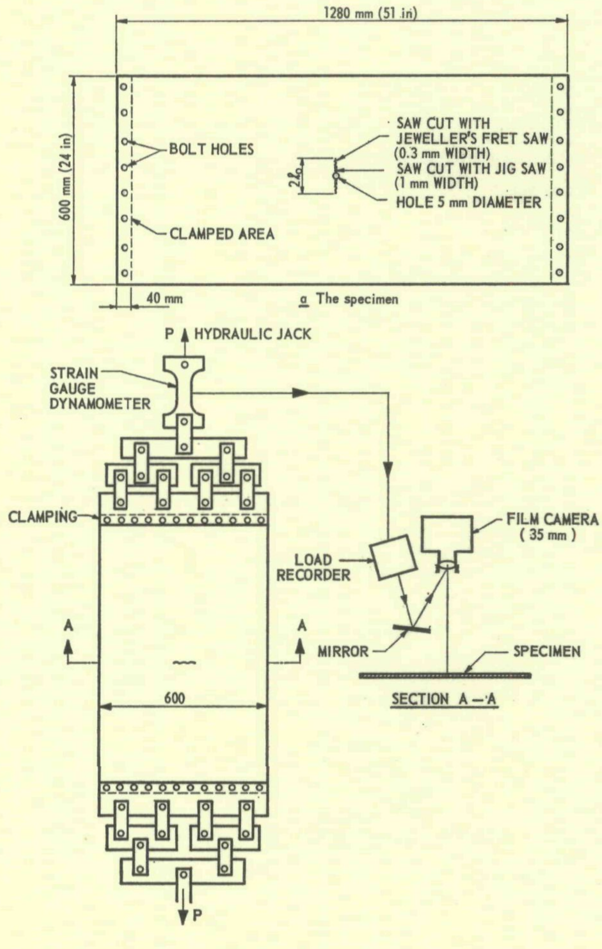

Fig. 1 Test arrangement.

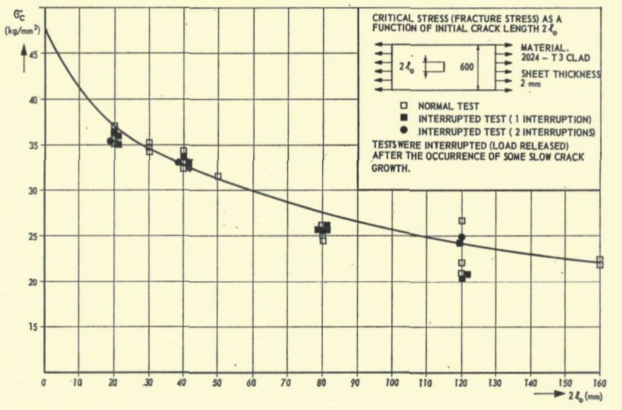

Fig. 2 Influence of unloading and reloading on the residual strength.

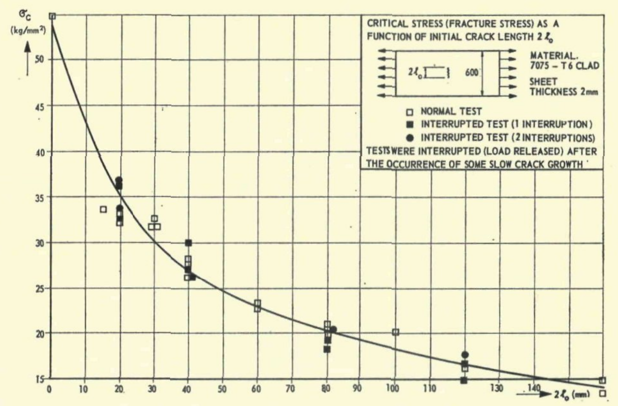

Fig. 3 Influence of unloading and reloading on the residual strength.

figures reference is made also to fig. 8. There are two distinct ways in which a specimen might behave when it is reloaded after a load release to $\sigma = 0$.

Suppose the initial crack length is $2l_0$ (fig. 8) and the specimen is unloaded after the crack has grown to a length $2l_{01}$. At reloading, one of the following two extreme possibilities can happen:

a. The specimen behaves as a new specimen with an initial crack length $2l_{01}$. Consequently, slow crack growth is initiated at a stress σ_i* in accordance with the curve for the start of slow crack growth (fig. 8) and fracture occurs at a stress σ_c*, wich is the fracture stress belonging to an initial crack length $2l_{01}$ (fig. 8).
b. There is no influence of unloading and the crack continues to grow as soon as the stress σ_r is reached, σ_r being the stress at which the test was interrupted.

Figs. 4 and 5 show that after an interruption there is *no initiation of slow crack growth in accordance* with the curve for the start of slow crack growth, though crack growth is continued at a stress somewhat below σ_r.

Soon after the re-initiation of crack growth the original slow growth curve is followed again. The specimen apparently "remembers its load history and ignores the unloading".

It seems reasonable to conclude that if the interrupted tests had been carried out as continuous tests crack propagation curves would have been obtained similar to the dotted curves given in figs. 4 and 5.

At the moment of the interruption of the test a plastic zone of a certain size has formed at the crack tip (fig.

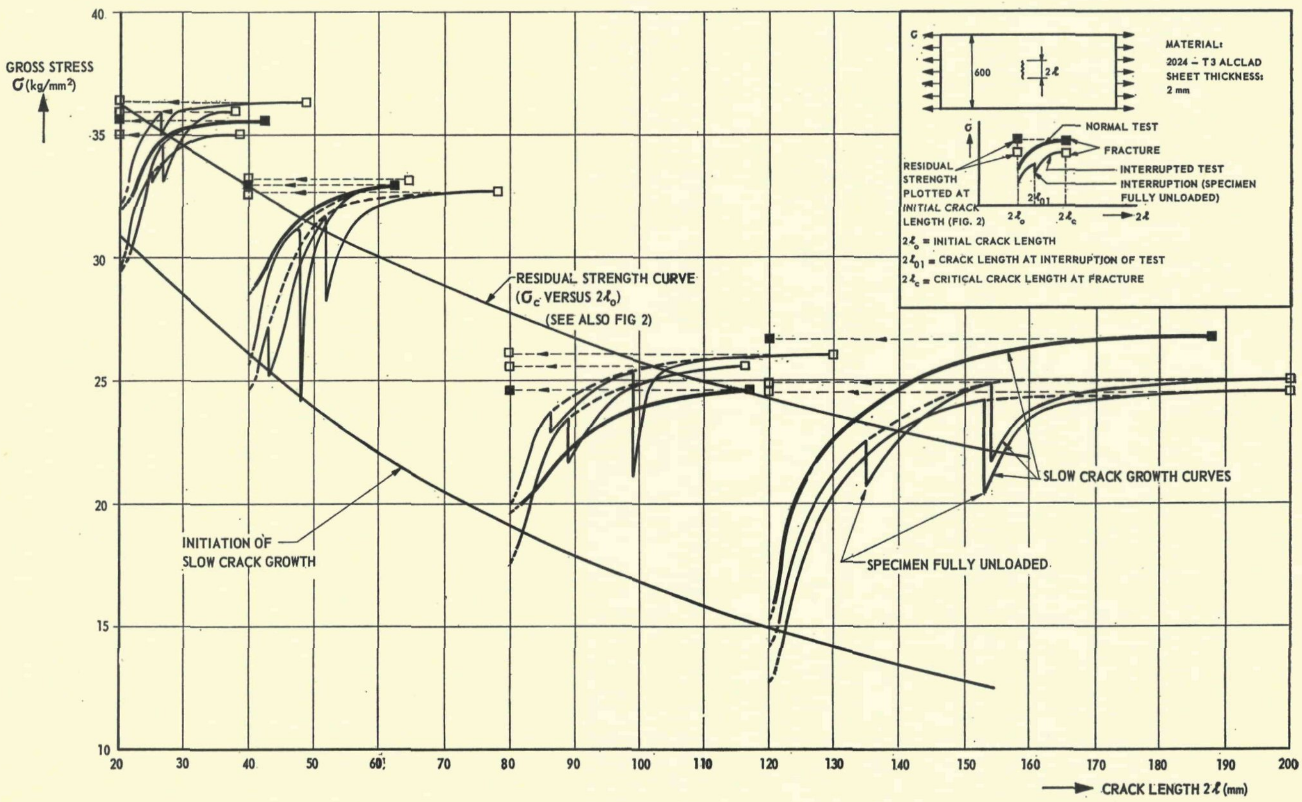

Fig. 4 Influence of unloading to zero stress on slow crack growth.

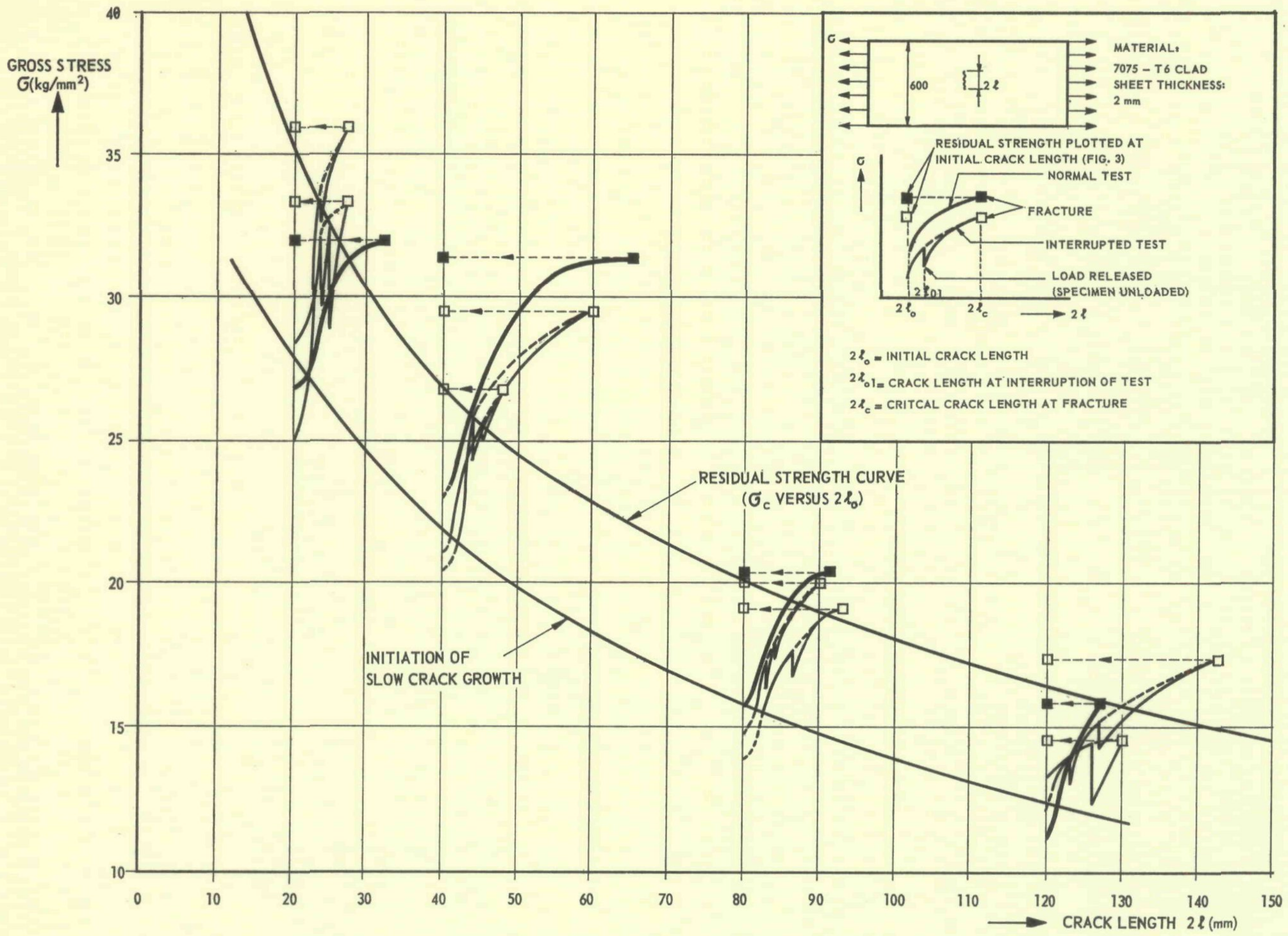

Fig. 5 Influence of unloading to zero stress on slow crack growth.

9a). Now it is assumed for a moment that at unloading only elastic deformations take place. The stress distribution at the crack tip in an unloaded specimen then is as shown diagrammatically in fig. 9b. At reloading the stresses at the crack tip are lower than in fig. 9a, as long as the nominal stress is below σ_r. At a stress σ_r the stress distribution of fig. 9a is again obtained. The stresses at the crack tip are highly decisive for the occurrance of crack growth and before unloading the stress distribution of fig. 9a was necessary to maintain crack growth. Then it is plausible that at reloading the re-initiation of crack growth is postponed until the stress distribution is the same as before unloading, i.e. until the stress σ_r is reached.

Of course unloading is not fully elastic. Reversed plastic flow will take place in a small region at the crack

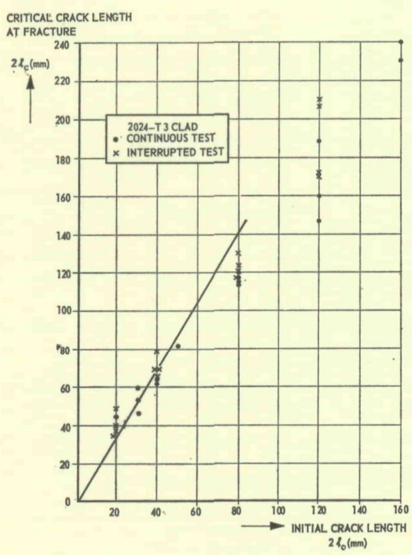

Fig. 6 Relation between critical crack length and initial crack length.

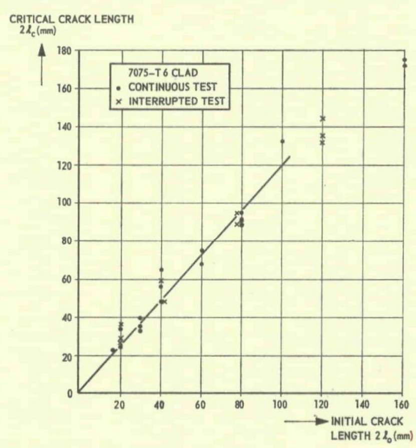

Fig. 7 Relation between critical crack length and initial crack length.

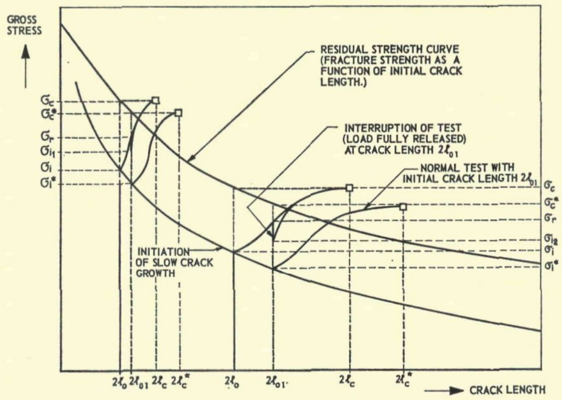

Fig. 8 Possible crack propagation curves at reloading after interruption of residual strength tests.

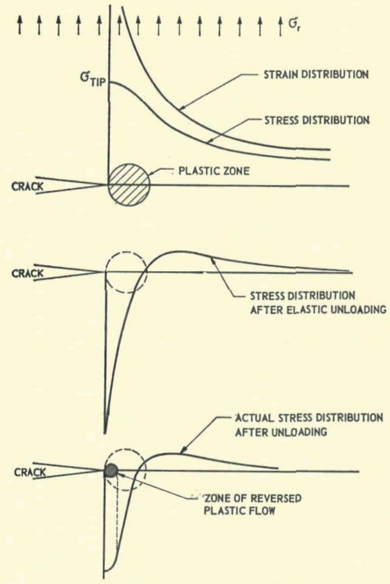

Fig. 9 Stress distribution at crack tip after unloading.

tip and the stress distribution will resemble that in fig. 9c. At reloading the stress at the crack tip will reach the value of fig. 9a at a nominal stress lower than σ_r. Then it may be expected that the re-initiation of crack growth also takes place at a stress below σ_r. When the crack has grown through the small region in which reversed plastic flow has occurred there is no longer an influence of the unloading on the stress distribution and the situation is similar again to the situation in a continuous test. This might explain why at reloading slow crack growth started at a stress somewhat below σ_r and why soon after re-initiation of crack growth the original crack propagation curve was followed again.

5 Technical implication of the test results

The fail-safe qualities of an aircraft include that under the presence of a crack of a certain length a certain high load can be safely resisted. When a crack of this ultimate length is actually present in service it may show some slow growth if a high load, lower than the failsafe load, is met. Though the ultimate crack length is exceeded now the residual strength is still sufficient as may be concluded from the present test results. The high load that induced slow crack growth has introduced residual compressive stresses at the crack tip (fig. 9c) which are known (refs. 4, 5) to slow down the rate of crack propagation under subsequent fatigue loading. Therefore it may be expected that during some time after the occurrence of slow static crack growth the residual strength is not impaired, not even if a second high load induces some further slow crack growth.

Though this conclusion may be reassuring it must be expected that a number of successive high loads could well affect the residual strength. This is a consequence of the fact that in the present tests slow crack growth was re-initiated at a stress lower than the stress at which the test was interrupted (figs. 4 and 5). Now consider the case when previous loads have extended the crack to a length almost equal to the critical crack length. At subsequent loading and initiation of crack growth the crack length will exceed the critical crack length already at stresses lower than the fracture stress. Then fracture might occur at a lower stress. It is not likely, however, that between two inspections so many high loads are met. The same situation will be obtained if one single high load extends the crack to almost the critical length but it is a case of low probability that then before the next inspection a second high load of the magnitude of the fail-safe load would occur.

It should be concluded that high preloads generally will not affect the residual strength, but that in certain extreme cases a reduction of the strength must be expected.

6 The present results and the energy criterion for fracture

In refs. 1 and 2 it was concluded that the energy criterion for fracture reads:

$$\left.\begin{aligned} \frac{\partial U}{\partial l} + \frac{\mathrm{d}W}{\mathrm{d}l} &= 0 \\ \frac{\partial^2 U}{\partial l^2} + \frac{\mathrm{d}^2 W}{\mathrm{d}l^2} &= 0 \end{aligned}\right\} \qquad (1)$$

in which $\frac{\partial U}{\partial l}$ is the energy released during a crack extension $\mathrm{d}l$ and $\frac{\mathrm{d}W}{\mathrm{d}l}$ is the energy consumed during a crack extension $\mathrm{d}l$.

Eqs. (1) could be evaluated by-making use the observation that critical crack length l_c is proportional to the initial crack length l_0, i.e.:

$$l_c = \alpha l_0 \qquad (2)$$

As a result of this the following relation was obtained between the fracture stress σ_c and the initial crack length l_0:

$$\sigma_c l_0^p = \text{constant} \quad (3)$$

in which

$$p = \frac{1}{2\alpha} \quad (4)$$

For the stress σ_i at the onset of slow crack growth the following condition was obtained:

$$\sigma_i l_0^{0.5} = \text{constant} \quad (5)$$

Eqs. (2)–(5) can be checked with the results of the present tests. Figs. 6 and 7 indicate that eq. (2) is reasonably true for small cracks.

The validity of eqs. (3) and (5) is also reasonable as is shown in fig. 10, where both σ_c and σ_i are plotted versus l_0 on a double-logarithmic scale. For very small cracks the results deviate from the straight lines; this is because the residual strength should tend to σ_u for a crack length approaching zero, whereas eqs. (3) and (5) predict infinite stresses at zero crack length. The criteria of eqs. (3) and (5) cannot be valid, however, when the nominal stress is close to or higher than the yield stress, since general yielding will seriously alter the stress distribution. Also for very large cracks the results deviate from the straight lines. This is due to the effect of finite sheet width (ref. 6). For an important range of crack lengths, however, the criteria are reasonably obeyed.

According to fig. 10 the exponent p in eq. (3) appears to be 0.27 for the 2024-T3 alloy and 0.41 for the 7075-T6 alloy. Then eq. (4) predicts values for α of 1.85 and 1.22 respectively. The lines drawn in figs. 6 and 7 give values of 1.75 and 1.20 respectively, which is felt to be a very good agreement. Also in figs. 6 and 7 deviations from the straight lines occur at large values of the crack length. This may again be due to a width effect (ref. 6).

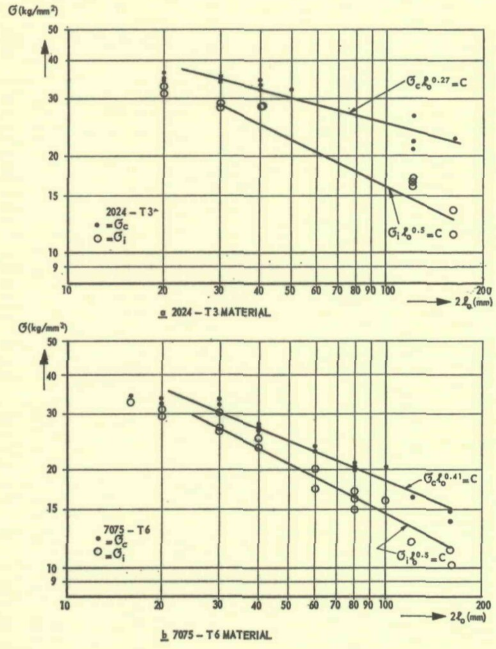

Fig. 10 Check of crack growth and fracture criteria.

7 Conclusions

Residual strength tests were performed on 2024-T3 and 7075-T6 aluminium alloy sheet specimens of 600 mm width and 2 mm thickness. In one test series the specimens were unloaded after a certain amount of stable crack growth had occurred and then reloaded. The following conclusions can be drawn from the test results:

a. The interruption of a residual strength test by unloading to zero stress and reloading has no influence on the residual strength. At reloading slow crack growth starts at a stress somewhat below the stress at which the test was interrupted but soon after the reinitiation of crack growth the original crack propagation curve is followed again. The critical fracture stress and the critical crack length are the same for a continuous test and an interrupted test on specimens with the same initial crack length.

b. The residual strength of structures containing service cracks will not be impaired by one or two high loads which cause a small amount of stable crack extension.

c. The test results reasonably obeyed the fracture criterion

$$\sigma_c l_0^p = \text{constant}$$

and the criterion for slow crack growth:

$$\sigma_i l_0^{0.5} = \text{constant.}$$

8 References

1 BROEK, D. The residual strength of cracked sheet and structures NLR report TM-M.2135, Aug. 1964.

2 BROEK, D. The energy criterion for fracture of sheets containing cracks.
Applied Materials Research, 4, 3 (July 1965) pp. 188–189.

3 BROEK, D. The residual strength of aluminium alloy sheet specimens containing fatigue cracks or saw cuts.
NLR report TR-M.2143, Febr. 1965.

4 SCHIJVE, J., BROEK, D. Fatigue-crack propagation under variable amplitude loading.
NLR report TN-M.2094, Dec. 1961.

5 SCHIJVE, J., BROEK, D. Crack propagation under variable amplitude loading. Aircraft Engineering, Vol. 34 (Nov. 1962) pp. 314–316.

6 BROEK, D. The effect of finite specimen width on the residual strength of light alloy sheet.
NLR report TR-M.2152, Sept. 1965

TABLE 1

Test results for 2024-T3 clad material

		First interruption			Second interruption			End of test		Continuous test		
$2l_0$	σ_i	σ_{r1}	$2l_{01}$	σ_{i1}	σ_{r2}	$2l_{02}$	σ_{i2}	$2l_c$	σ_c	σ_i	$2l_c$	σ_c
20	29.5	33.5	26	33.0				39	35.0	*)	37	35.0
	32.0	35.8	27	35.0				49	36.1	32.5	43	35.4
	29.5	34.7	27	33.0				38	35.8	20.3	36	36.8
	30.5	33.9	24	28.3	34.6	26	30.7	36	35.2			
30										26.6	59	34.6
										29.4	47	34.1
										29.3	53	35.1
40	25.8	31.1	48	24.2				65	33.0	28.6	64	34.2
	24.5	27.1	43	24.9	31.7	52	28.0	78	32.5	28.6	62	33.0
	26.0	28.9	46	26.7	31.8	52	28.6	68	33.0	*)	*)	32.5
	26.5	32.2	49	25.4				68	33.6			
50										22.9	81	31.7
80	17.5	23.4	89	21.7				117	25.4	19.7	117	24.3
	18.0	24.6	96	23.8				124	25.3	18.0	113	24.9
	20.0	23.6	87	22.8	25.4	99	20.9	130	25.6	17.8	114	26.0
	19.6	25.7	103	23.5				121	25.7			
120	14.4	20.9	150	19.4				172	20.4	16.8	188	26.6
	14.3	20.8	145	14.5				170	20.6	16.6	160	22.0
	13.0	24.2	153	20.4				205	24.2	15.6	146	20.9
	14.0	22.4	135	20.8	24.7	154	21.8	209	24.8			
160										13.2	240	21.7
										11.2	230	22.4

*) No value obtained due to fail of motion picture.

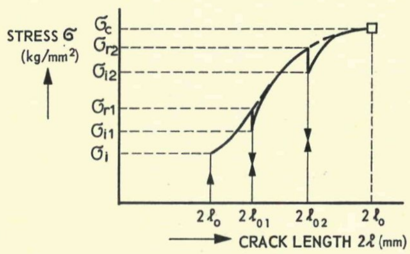

TABLE 2

Test results for 7075-T6 clad material

		First interruption			Second interruption			End of test		Continuous test		
$2l_0$	σ_i	σ_{r1}	$2l_{01}$	σ_{i1}	σ_{r2}	$2l_{02}$	σ_{i2}	$2l_c$	σ_c	σ_i	$2l_c$	σ_c
16										32.4	22	33.7
20	28.5	32.4	24	29.7	32.5	25	29.1	27	33.6	*)	25	33.4
	31.4	31.9	22	31.5	34.3	23	31.3	35	36.8		33	32.0
	24.5	33.3	24	33.3				28	36.1			
	26.6	32.1	26	31.1				28	33.0			
30										26.8	39	31.7
										26.7	35	31.7
										31.1	34	32.7
40	21.3	25.4	46	25.1				48	26.9	*)	57	28.0
	20.5	25.9	45	24.2				59	30.1	23.7	65	26.1
	20.6	23.0	44	22.3				53	26.1	25.0	48	27.9
60										17.2	75	22.6
										20.0	68	23.2
80	16.6	18.9	88	17.4				88	18.2	14.8	94	19.9
	15.0	17.7	87	17.7				94	19.2	16.9	88	20.9
	16.0	17.6	84	16.4	18.2	85	17.7	90	20.0	15.9	91	20.6
100										15.6	132	20.3
120	13.7	14.7	127	12.8				131	14.7	11.7	127	16.0
	13.0	14.4	124	13.3	15.5	128	15.1	143	17.6			
	13.5	17.2	133	15.5				135	16.5			
160										11.2	174	14.9
										10.0	170	13.3

*) No value obtained due to fail of motion picture.