Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

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FRACTOGRAPHIC INVESTIGATION OF PRESSURE CABIN MSD

Dr. R.J.H. Wanhill, ir. W. van der Hoeven, ir. H.J. ten Hoeve, ir H.H. Ottens*

The characteristics of MSD fatigue initiation and early crack growth in transport aircraft fuselage longitudinal lap splices were determined fractographically for samples from three aircraft types, of which two from service and one from a full-scale test. The results are compared with NASA data from a full-scale test. The most MSD-susceptible rivet row was the upper one in the outer sheets of the lap splices. Cracks initiated mainly at faying surfaces near or at rivet hole corners. There was no evidence from the service aircraft that corrosion was involved in crack initiation. Early crack growth rates, from cracks 30 μm – 5 mm in size, were above 10^{-8} m/cycle (or flight), which means one should not expect "short" crack behaviour. This facilitates crack growth modelling. However, it also makes questionable the usefulness of testing sub-scale specimens. For the service aircraft the environmental effects on crack growth were mild, if any. All the results are placed in the context of MSD fatigue modelling.

INTRODUCTION

As part of a European programme the NLR undertook fractographic investigation of Multiple Site Damage (MSD) fatigue cracks in longitudinal lap splices of transport aircraft pressure cabins. The investigation concentrated on initiation and growth of small fatigue cracks with dimensions less than 5 mm, with the intent of establishing the crack initiation lives and early growth rates. Furthermore, the lap splices from service aircraft were scrutinised for any environmental influences on crack initiation and growth.

The lap splices examined by the NLR were from three service aircraft, two Fokker F28s and a British Aerospace BAC 1-11, and the Fokker F100 full-scale fuselage test. The results are compared in this paper with NASA data from a Boeing B 747-400 forward fuselage full-scale test (1, 2). The histories of all five pressure cabins are summarised in table 1.

Table 1 Service or test histories of the pressure cabins

Aircraft type	Flights	Flight hours	Simulated flights
F28 [1]	43,870	28,694	
F28 [2]	43,323	unknown	
F100			126,250 @ 110 % design load
BAC 1-11	75,158	52,000	
B 747-400			60,000 @ 100 % design load

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MSD LOCATIONS AND LAP SPLICE CONFIGURATIONS

Figures 1-3 show the positions and configurations of the MSD-fatigue cracked lap splices. The positions varied widely, as do the joint designs. The single common feature is the sheet material, 2024-T3 Alclad.

As expected (3), the most MSD-susceptible rivet row was the upper one in the outer sheets of the lap splices. However, other rivet rows were also susceptible, notably the lower one in the inner sheets.

OBSERVATIONAL ASPECTS OF SMALL CRACK MSD

Table 2 lists the observational aspects of small crack MSD for fuselage longitudinal lap splices. The qualification “small” means crack sizes less than 5 mm. Beyond this the crack front shapes are of less interest. Also, and more importantly, the cracks will eventually link up, possibly resulting in fracture surface damage and obscuration owing to out-of-plane movement.

The most significant general aspect of table 2 is the distinction between fatigue initiation and crack growth. It has become *bon ton* to do damage tolerance analyses as if fatigue is a regular crack growth process that begins during the first load cycle. However, this is physically incorrect.

Table 2 Observational aspects of small crack MSD in fuselage longitudinal lap splices

MSD characteristics	**Service aircraft**	**Full-scale test**
• Fatigue initiation		
• locations		
- macroscopic : outer and inner sheets, rivet rows	•	•
- mesoscopic : rivet hole vicinities	•	•
• single or multiple initiation sites	•	•
- “initiation length” for multiple initiation sites	•	•
• specific causes		
- corrosion pits	•	–
- fretting, material or fabrication defects (“high K_t regions”)	•	•
• obscuration		
- corrosion, e.g. “mud cracking”, “cauliflower growth”	•	–
- fretting products (“oxide debris”)	•	•
• Fatigue crack growth		
• multiple site initiation: coalescence to form continuous crack fronts	•	•
• crack front shapes and sizes	•	•
• overall topography: semi-faceted, continuum-mode	•	•
• striation spacings: transverse and longitudinal crack growth rates	•	•
• marker bands: crack length versus cycles, crack growth rates	–	•
• environmental effects on crack growth: “beach marks”	•	–
• obscuration by corrosion, e.g. “mud cracking”, “cauliflower growth”	•	–

Table 2 shows also that there are differences in what is observable from service aircraft and full-scale tests. Most notably, tests cannot account for environmental effects even if done outdoors. One reason is that the test duration is too short to result in corrosion damage in the lap splices.

Another is that the exterior of the test article is not cooled to cruise altitude temperatures during each pressurization cycle. This means that any transpiration is unlikely to result in moisture condensation and entrapment within the lap splices.

FATIGUE INITIATION CHARACTERISTICS

Figure 4 shows the characteristic MSD fatigue crack locations and shapes in the cracked lap splices. These will be discussed separately, followed by a summary.

F28 service aircraft

The total lengths of MSD were 530 mm and 330 mm for aircraft [1] and [2] respectively. The fatigue cracks initiated at numerous sites along the faying surface edges of the outer sheet dimpling cones, see figures 3 and 4. The cracks were mechanically induced: there was no evidence that corrosion played a role in initiation. The large number of initiation sites (many cracks initiating at each dimpling cone) suggests that fatigue cracking began soon after the aircraft entered service.

F100 full-scale test (indoors)

The MSD extended over several frame bays having poor adhesive bond quality. The fatigue cracks initiated from the faying surfaces, mostly at multiple sites close to the rivet holes, see figure 4. There was no evidence of corrosion, as expected from a test indoors.

BAC 1-11 service aircraft

Two sections, port and starboard, of lap splices suspected to contain MSD were disassembled and the rivet holes *carefully* opened up (4). The MSD was found along about 500 mm of the lap splices. The fatigue cracks initiated at a variety of locations, see figure 4, though mainly at faying surfaces close to the rivet holes (types A, C and D). There was no evidence that corrosion played a role in initiation.

B 747-400 full-scale test (outdoors)

The MSD extended over several frame bays, see figure 2. The fatigue cracks initiated at a variety of locations, see figure 4, though mainly at faying surfaces and rivet hole/faying surface corners. There was no evidence of corrosion, even though the test was done outdoors.

Summary

Bearing in mind that the F28 dimpled lap splices are uncustomary, the investigation of in-service and full-scale test MSD showed that fatigue initiation occurred mostly from faying surfaces near or at the rivet hole corners. This means that the faying surface condition (cladding, anodising, priming, interfay sealant, adhesive bonding) and rivet hole corner quality are very important. Also, fretting must play a role, if not always during crack initiation, then probably during early crack growth (5).

The fatigue fracture surfaces from the F28 and BAC 1-11 service aircraft showed varying amounts of post-cracking corrosion. This partially obscured the fractographic characteristics, for example making it difficult to measure fatigue striation spacings near the crack initiation sites, but on the whole it may be concluded that the local environments within the lap splices were mild.

Of more interest is a possible effect of the local environment on fatigue crack growth. Some evidence for this was found, namely the occurrence of fracture surface “beach marks” during early crack growth in the F28 and BAC 1-11 lap splices. Figure 7 is a particularly clear example. The “beach marks” could well indicate periodic changes in the local environment (8). They are *not* due to variable amplitude loading, since it is known that the F28 fuselages were subjected to the maximum cabin pressure differential in each flight. Also the MSD position, see figure 1, would not have been sensitive to gust loads.

Additional evidence is provided by figure 8, which shows the effect of changing from “dry” to “wet” air on the fatigue fracture behaviour of 2024-T3 cycled at a low frequency of the same order as in-service cabin pressure cycling, and at overall crack growth rates similar to those for early crack growth in the lap splices.

More than six hundred measurements of striation spacings were made for the light and dark bands of eleven “beach marks” on the F28 fatigue fracture surfaces. The results have been shown already in figure 5, and there appears to be no systematic difference in crack growth rates for the light and dark bands. However, the data scatter gives differences in crack growth rates of ± 20 % about the average, and this could be enough to mask a mild environmental effect on crack growth rates.

MSD FATIGUE MODELLING AND SIMULATION

General remarks

The fatigue behaviour of pressure cabin longitudinal lap splices is determined by complex load and stress distributions that are very difficult to analyse (3,7,10). In particular, this means realistic stress intensity factor solutions are not available for cracks with dimensions less than the sheet thicknesses. And one may doubt the usefulness, through lack of accuracy, of solutions for cracks with dimensions less than the rivet hole diameters.

Nor does it seem possible to model fatigue initiation by analysis. This is not only because of the complex stress fields, but also because fatigue initiation in lap splices depends strongly – if not totally – on the local behaviour of various materials (aluminium alloy matrix, cladding and anodising layers, primers and sealants) at the faying surfaces and near or at rivet hole corners (7,11). We note, in passing, that models based on fatigue initiation at corrosion pits (12) or inclusions (13) are most probably irrelevant and anyway too simple for 2024-T3 Alclad lap splices: the F28 and BAC 1-11 service aircraft samples showed no evidence of corrosion pitting, and tests have shown time and again that fatigue cracks initiate in the cladding, not the 2024-T3 matrix (4, 11, 14, 15).

Instead, and at least for the present, recourse must be made to empirical modelling that describes the *actual fatigue behaviour* of lap splices from service aircraft and full-scale test articles. One such model, due to Eijkhout (6), is described and illustrated next.

Empirical model for crack growth and determination of crack growth and crack initiation lives

Eijkhout's model is based on the following observations:

(1) MSD fatigue cracks tend to initiate at several sites near or at rivet hole corners and grow in directions varying gradually from transverse to longitudinal, see figure 9.

(2) The transverse (through-thickness) fatigue crack growth rates are nearly constant, e.g. figure 5.

(3) The transverse and longitudinal fatigue crack growth rates are similar for cracks with dimensions less than twice the sheet thickness, compare figures 5 and 6 (sheet thicknesses 1.2–1.6 mm, see figure 3).

Figure 10 is a schematic of the model. There are three main assumptions, the first two being derived from the foregoing observations. These assumptions are:

- Constant crack growth rate in the transverse direction, in general equal to the *initial* crack growth rate in the longitudinal direction, i.e. $dc/dN = Ae^{Ba_i}$
- Crack depth $c = 0$ at a_i , the "initiation length".
- Quarter-circular crack fronts in the transition from transverse to longitudinal crack growth.

These assumptions are convenient but not essential. For example, the model can be used for non-constant dc/dN and for crack initiation at rivet hole corners, i.e. $a_i = 0$ in figure 10. Also the model can be used for both non-countersunk and countersunk lap splice sheets.

Figure 11 gives examples of the model's use. It is seen that besides providing estimates of the fatigue crack growth lives and hence the fatigue initiation lives, the model also enables estimates of the lives at which cracks become through-thickness. This information is potentially useful for in-service NDI.

Another interesting point is that the model can be made compatible with marker bands on the fatigue fracture surface of full-scale test articles, as in the case of the B 747-400 forward fuselage (1). When determining the striation-based crack growth rate equations, $da/dN = Ae^{Ba}$, for individual cracks one can check the equations' compatibility with the distances between marker bands, adjusting the equations if necessary.

Fatigue initiation lives

Table 3 gives estimates of the fatigue initiation lives for all four types of aircraft. The F28 estimate is no more than a reasonable guess. The F100 and BAC 1-11 estimates were obtained using Eijkhout's model (6). The B 747-400 estimates were made from marker band analyses (1).

Table 3 Estimates of MSD fatigue initiation lives in fuselage longitudinal lap splices

Aircraft type	**MSD rivet row**	**Lives to first crack initiations**	
		Flights	**Simulated flights**
F28	outer sheet upper row	a few thousand?	
F100	outer sheet upper row		60,000 } @ 110 % design load
	inner sheet lower row		70,000 } @ 110 % design load
BAC 1-11	outer sheet upper row	60,000	
	inner sheet lower row	50,000	
B 747-400	outer sheet upper row		5,000–15,000 @ 100 % design load

Table 3 shows that there is considerable variation in the estimated fatigue initiation lives, although the F28 lap splices are not of general interest. Actually, the total variation is greater: for the F100 full-scale test the estimates ranged from 60,000 – 97,000 simulated flights, and for the BAC 1-11 the estimates ranged from 50,000 – 74,000 flights.

Fatigue crack growth behaviour

From the section of this paper on early fatigue crack growth and figures 5 and 6 it is apparent that the transverse and longitudinal fatigue crack growth rates were above 10^{-8} m/cycle for crack sizes ranging from 30 μm to 5 mm. This result has to be compared with figure 12, which shows the short and long fatigue crack growth behaviour of 2024-T3 for two stress ratios covering the range to be expected in fuselage longitudinal lap splices (10). Figure 12 shows that at crack growth rates above 10^{-8} m/cycle there is only long crack growth behaviour. In other words, one should not expect any difference between short and long fatigue crack growth behaviour in fuselage longitudinal lap splices, which facilitates crack growth modelling.

However, the relatively high early crack growth rates in actual fuselage longitudinal lap splices make questionable the usefulness and relevance of sub-scale specimen tests. Uniaxial specimens “simulating” the F100 fuselage longitudinal lap splice had early crack growth rates far too low compared with the full-scale test results (17). This was also true for biaxial specimens (18). This situation may change when improved stress analyses become available and are used for improving sub-scale specimen design and testing. On the other hand, it may turn out that reliance will still have to be made mainly on full-scale fuselage section or panel tests (19,20).

DISCUSSION: LAP SPLICE FATIGUE ANALYSES

Survey of analyses

Figure 13 shows the “traditional” and developing fatigue analysis methods for transport aircraft fuselage lap splices:

(1) In the “traditional” methods the inspection threshold is established using fatigue life S-N data, cumulative linear damage analysis (if deemed necessary) and scatter factors. Subsequent inspection intervals are based on a safe fatigue crack growth period using da/dN

versus ΔK_{eff} long crack growth data, crack growth models for spectrum loading (if deemed necessary) and scatter factors.

(2) In the developing methods the inspection threshold is intended to be established using fatigue crack growth analysis and tests, whereby it is assumed the structure contains initial flaws (Initial Quality Flaw Sizes, IQFS). Subsequent inspection intervals are based on a safe fatigue crack growth period that accounts for MSD essentially as a refinement – however important – to the “traditional” analyses.

Analysis problems: actual versus predicted behaviour

Figure 14 is a schematic of the likely differences between actual early fatigue crack growth behaviour, as described in the present paper, and predictions using macroscopic (long) crack growth modelling, whereby the IQFS values are obtained either from actual data for manufacturing flaws or by back-extrapolation using a long crack growth model.

In both cases the long crack growth model is used to make an empirical fit such that the fatigue life is represented as a continuous crack growth process, beginning as soon as the aircraft enters service. This premise is incorrect: crack initiation is a physical reality. The fitted model therefore has limited transferability, and in general should not be used for “blind” predictions of crack growth in other structural areas with differing lap splice geometries and – most importantly – differing faying surface conditions. Nor should the fitted model be used for predicting crack growth at different (local) stress levels. This latter point is significant for two reasons:

(1) The stress-dependence of fatigue initiation life will probably be very different to that of fatigue crack growth, e.g. (21).

(2) Actual fatigue crack growth rates could be in a different “Paris Law” regime, i.e. the exponent m in the relation $da/dN = C(\Delta K)^m$ could be different. An example of a surprisingly high but realistic exponent was mentioned under the sub-heading of transverse (through-thickness) crack growth rates and is shown in figure 12.

There would seem to be no solution to the above problems so long as it is assumed that crack growth begins as soon as the aircraft enters service. One alternative is to further investigate the usefulness of Eijkhout’s model. This possibility has much to recommend it. The model is based on physical reality: it takes account of actual lap splice fatigue initiation and crack growth behaviour, and the present paper has shown much commonality in this behaviour for several aircraft types and different positions of the lap splices. Also, as mentioned under the sub-heading of fatigue crack growth behaviour, it may turn out that fatigue crack growth analyses will have to rely mainly on full-scale fatigue testing. If so, then Eijkhout’s model provides a way of describing crack growth, notably the all-important early crack growth through the sheet thickness, and a way of estimating the fatigue initiation life. Of course, since the model is empirical, the parameters in the model have to be determined for each type of aircraft, and also – possibly – for fuselage areas where the design stress levels are significantly different, e.g. varying by more than 10 % from the average.

CONCLUSIONS

This paper describes and discusses the characteristics of MSD fatigue initiation and early crack growth in transport aircraft fuselage longitudinal lap splices, using examples from four aircraft types. These are two Fokker F28s and a British Aerospace BAC 1-11 from service, the Fokker F100 full-scale fuselage test, and a Boeing B 747-400 full-scale forward fuselage test (1). The following conclusions are drawn:

(1) A distinction should be made between fatigue initiation and fatigue crack growth. It is physically incorrect to consider lap splice fatigue solely as a regular crack growth process that begins as soon as the aircraft enters service.

(2) There was a strong tendency for fatigue cracks to initiate at faying surfaces near or at rivet hole corners. The cracks were mechanically induced. There was no evidence from the service aircraft that corrosion was involved in crack initiation.

(3) There are indications of considerable variation in fatigue initiation lives, both in the range of lives for each aircraft type and between aircraft types.

(4) The most MSD-susceptible rivet row was the upper one in the outer sheets of the lap splices. However, other rivet rows were susceptible, notably the lower one in the inner sheets.

(5) Early fatigue crack growth rates, for crack sizes 30 μm – 5 mm, were above 10^{-8} m/cycle (or flight), which means one should not expect any difference between short and long fatigue crack behaviour in the lap splices. However, the relatively high crack growth rates make questionable the usefulness and relevance of sub-scale specimen tests.

(6) For the service aircraft the local environmental effects on crack growth were mild, if any. It is as yet uncertain whether the fatigue crack growth rates in service are significantly different, owing to environmental effects, from those determined by testing in laboratory air.

The foregoing conclusions should be taken into account during further development of fatigue analysis methods for transport aircraft fuselage lap splices.

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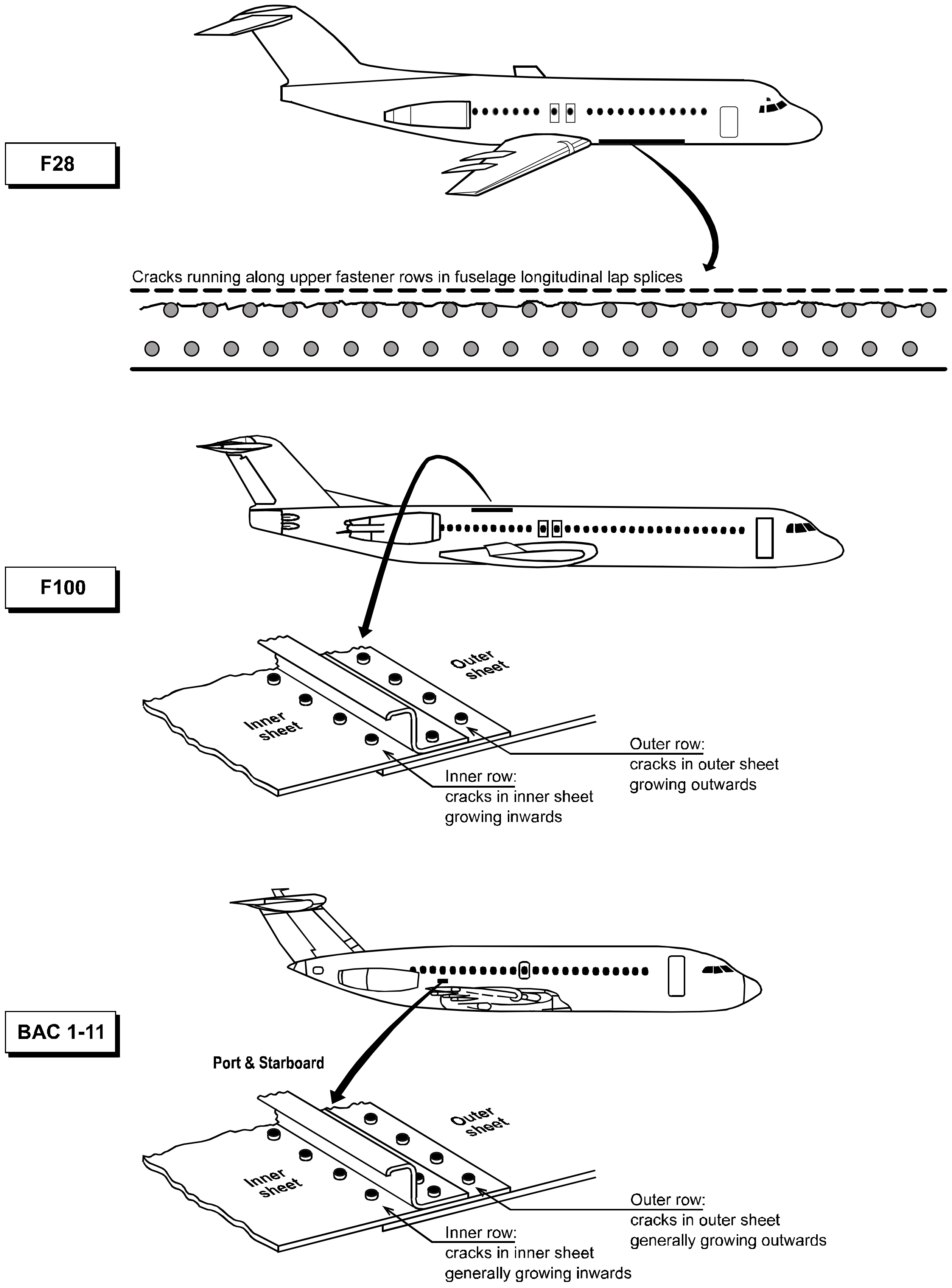


Fig. 1 Positions of the MSD fatigue cracked lap splices investigated by the NLR

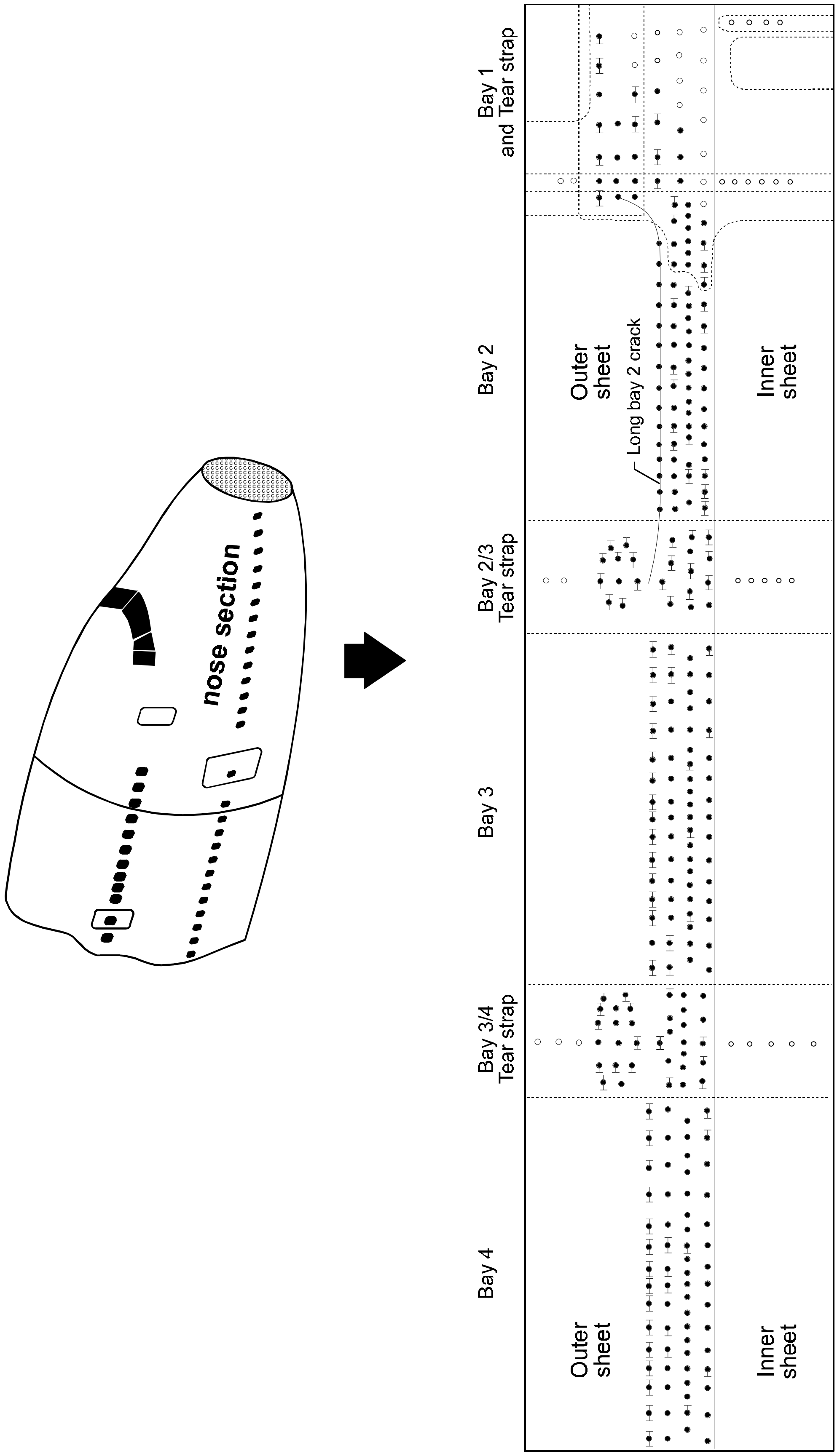
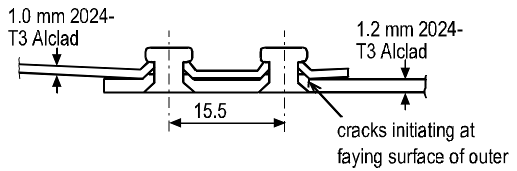


Fig. 2 Positions of the MSD fatigue cracks in the B 747-400 lap splice investigated by NASA (1, 2)

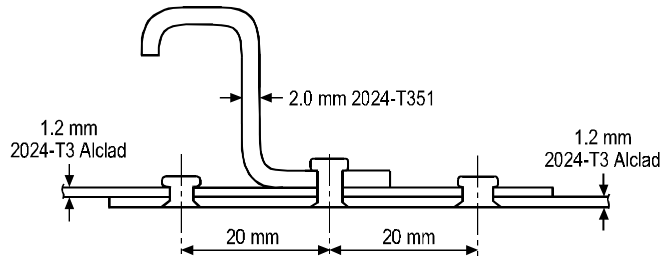
F28

- **rivet pitch 16.6 mm**
- **rivet diameter 4 mm**
- **sheets chromic acid anodised and primed**



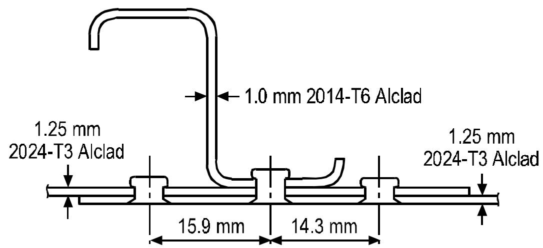
F100

- **rivet pitch 20 mm**
- **rivet diameter 3.2 mm**
- **sheets chromic acid anodised, primed and cold bonded**



BAC 1-11

- **stiffener rivet pitch 12.7 mm**
- **sheet rivet pitch 25.4 mm**
- **rivet diameter 3.2 mm**
- **sheets chromic acid anodised and primed**
- **interfay sealant**



B 747-400

- **stiffener rivet pitch 20 mm**
- **sheet rivet pitch 30 mm**
- **rivet diameter 4.8 mm**
- **interfay sealant**

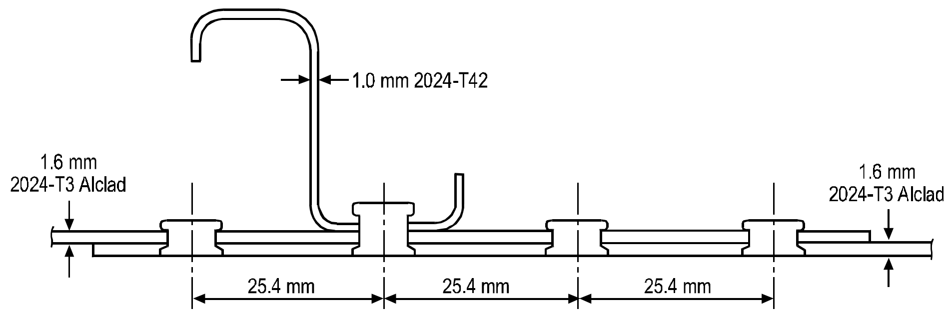


Fig. 3 Configurations of the cracked lap splices looking FORWARD

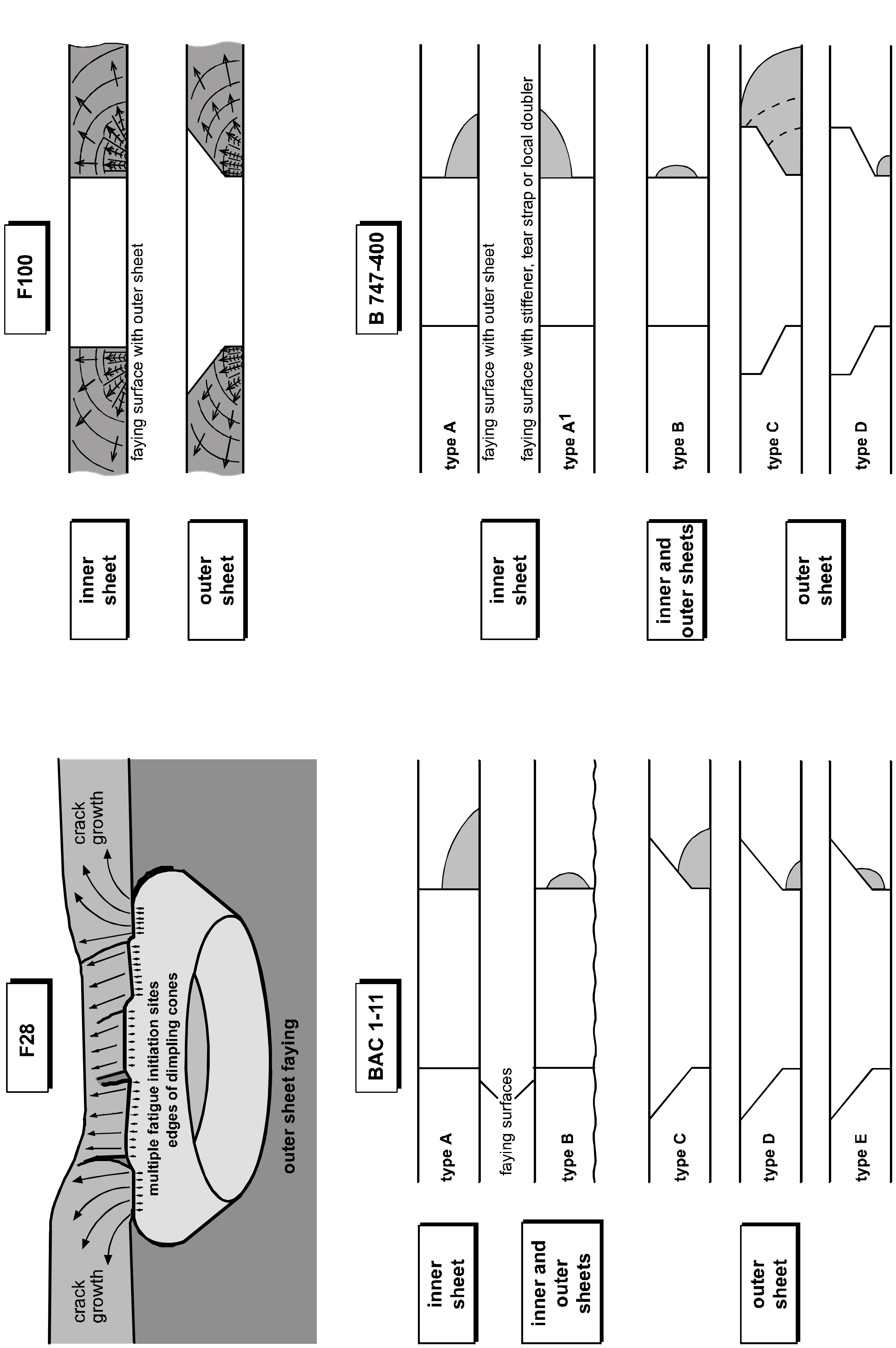


Fig. 4 MSD fatigue crack locations and shapes in the cracked lap splices

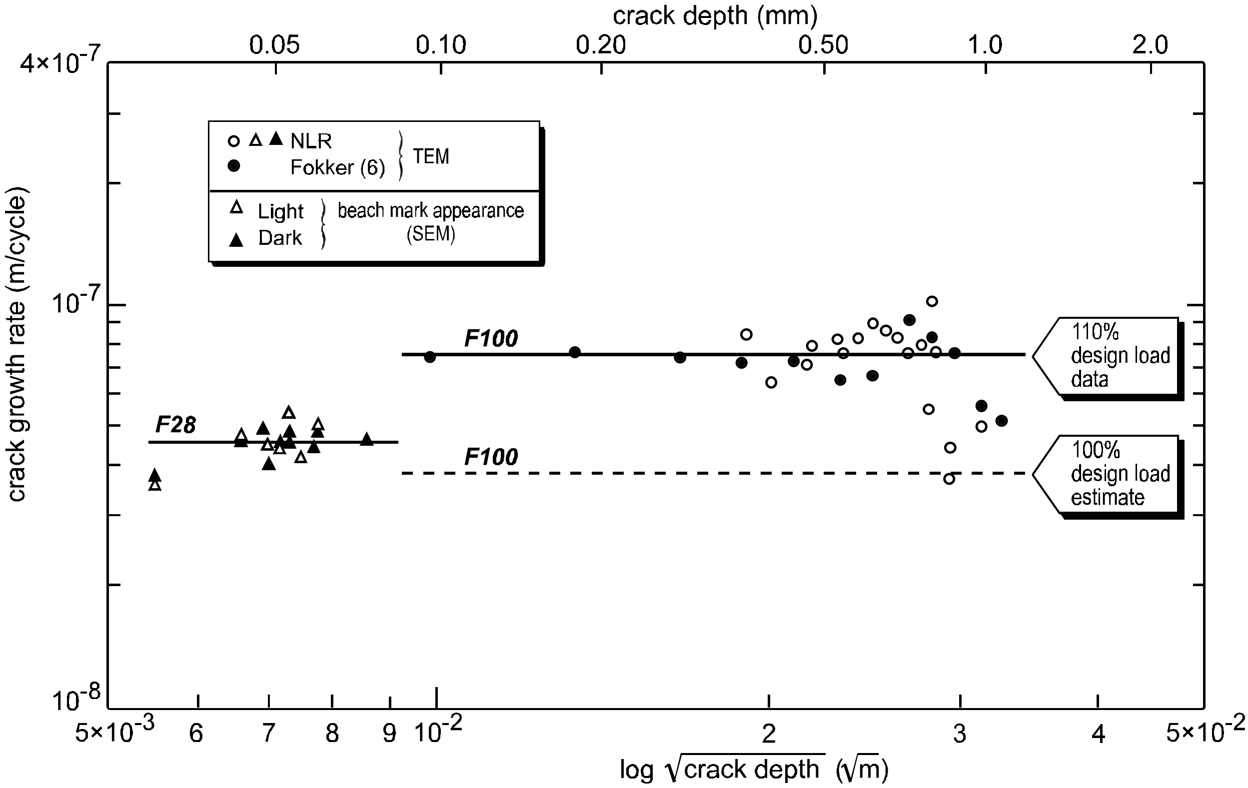


Fig. 5 Summary of transverse (through-thickness) fatigue crack growth rates: TEM = Transmission Electron Microscopy of replicas; SEM = Scanning Electron Microscopy

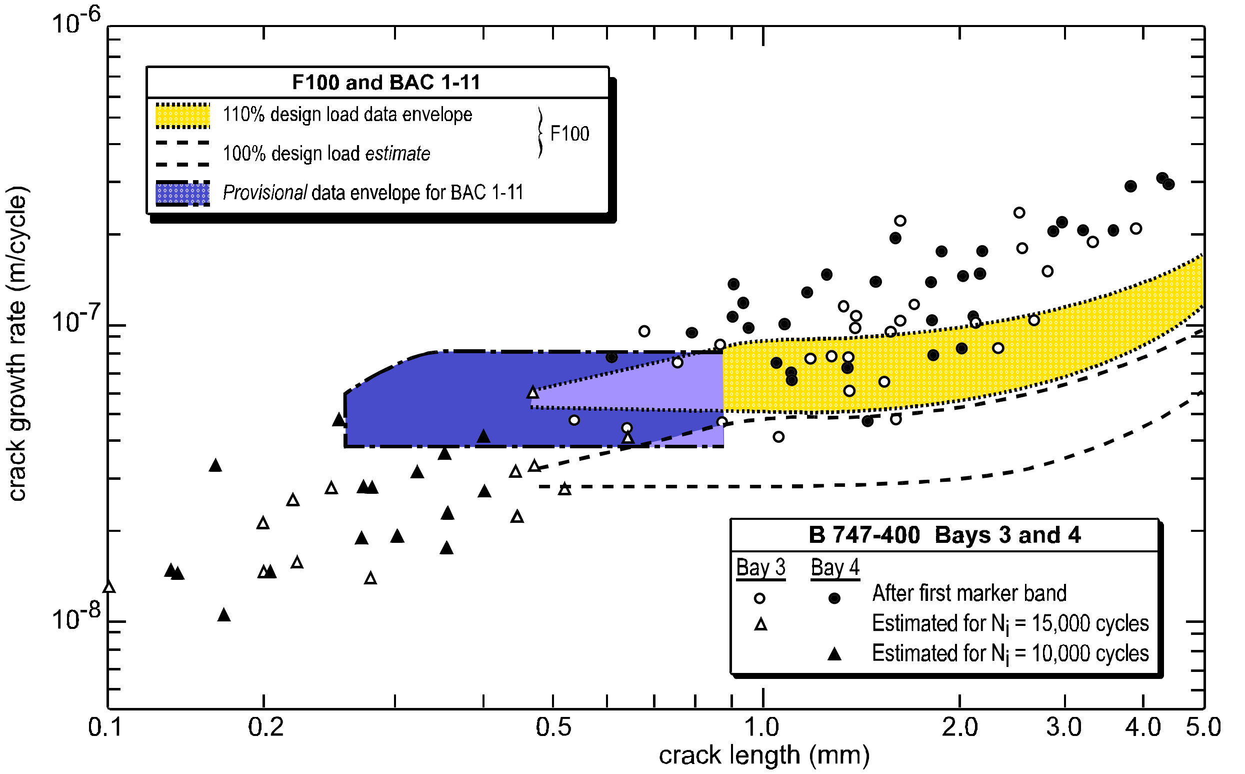


Fig. 6 Summary of longitudinal fatigue crack growth rates: B 747-400 data from (1)

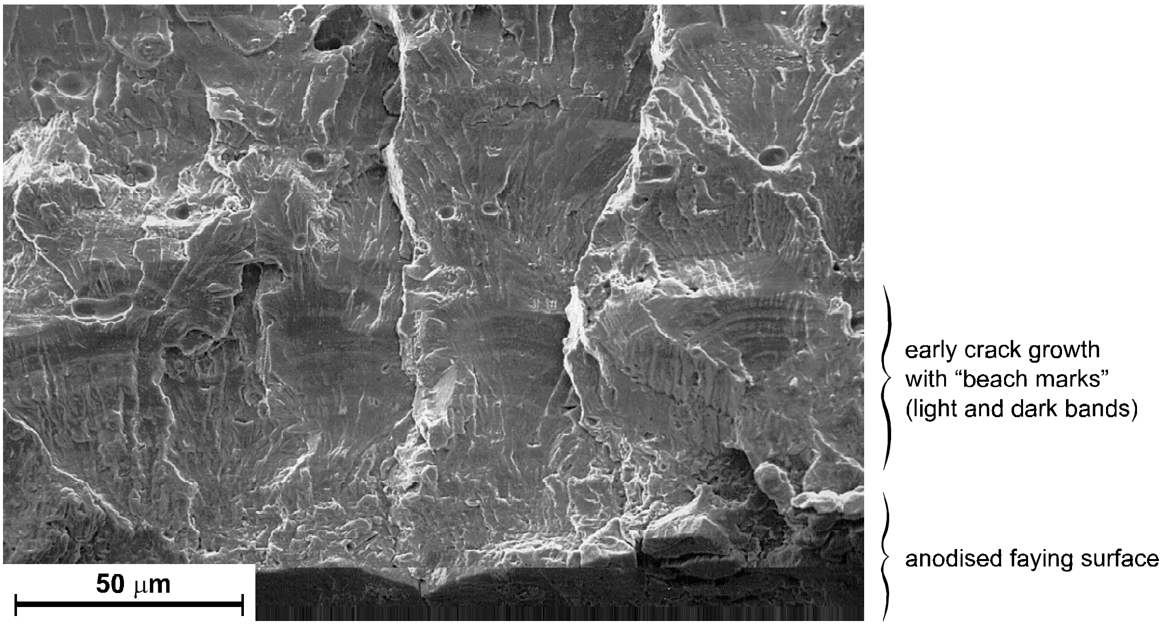


Fig. 7 Multiple site fatigue initiation and early crack growth in an F28 lap splice

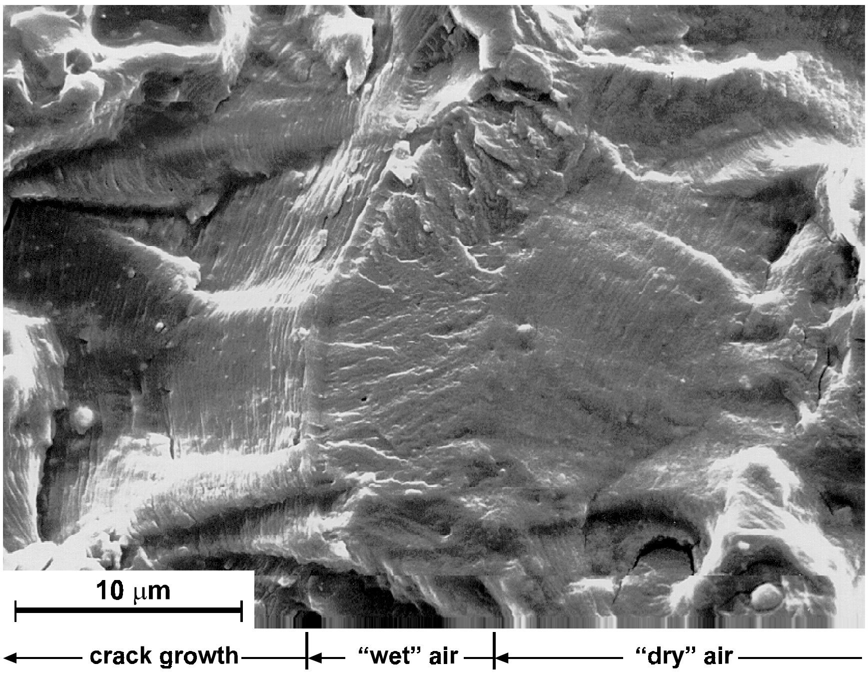


Fig. 8 Fatigue fracture topographical change for 2024-T3 cycled at 0.003 Hz in "dry" and "wet" air: R = 0.05, $\Delta K \sim 8.5\ MPa\sqrt{m}$ (9)

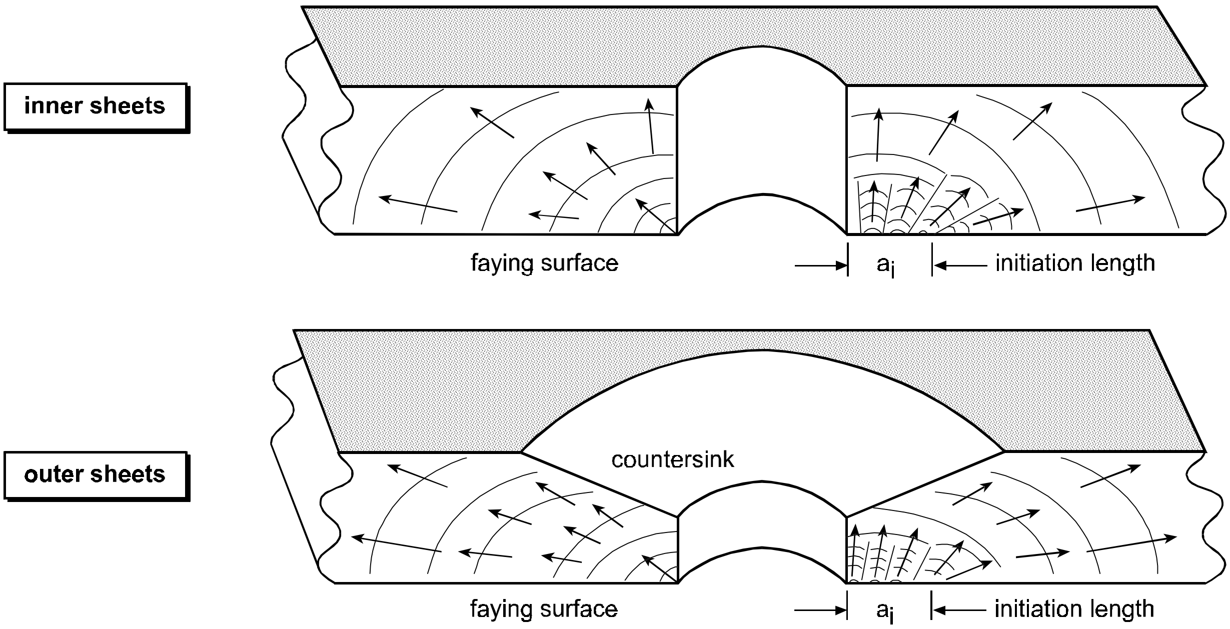
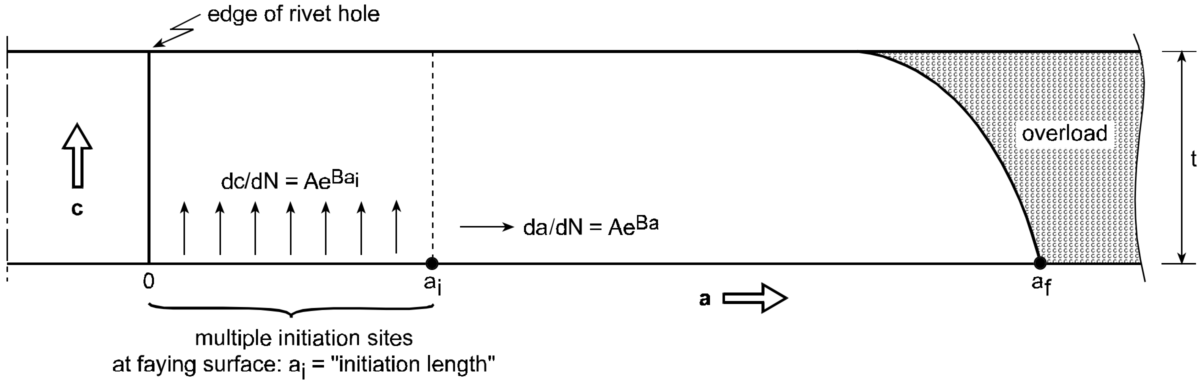


Fig. 9 Most common MSD fatigue initiation sites from service experience and full-scale testing

- **From fractographic observations and striation spacings:**



- **a_i, a_f and N_f are known. Calculate N_i from:** $N_f - N_i = \frac{1}{AB}\left(e^{-Ba_i} - e^{-Ba_f}\right)$
- **Calculate intermediate values of a for given values of n:** $a_{int} = -\frac{1}{B}\ln\left[e^{-Ba_i} - AB(N_{int} - N_i)\right]$
- **For each a_{int} calculate c_{int} from:** $c_{int} = (N_{int} - N_i)\,Ae^{Ba_i}$
- **Construct crack fronts as follows:**

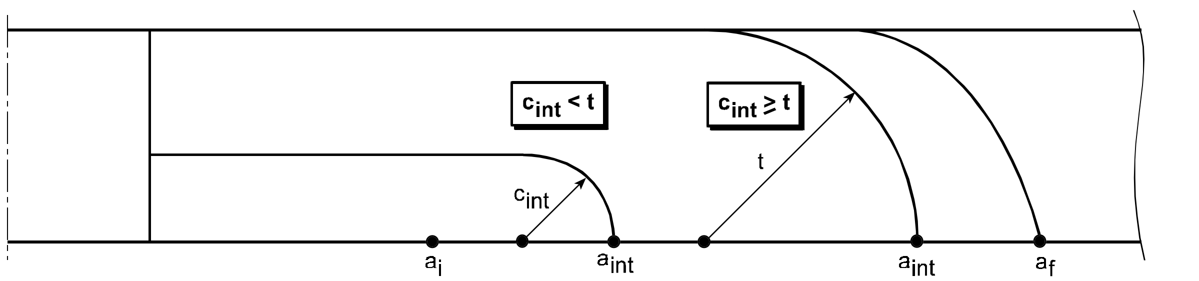
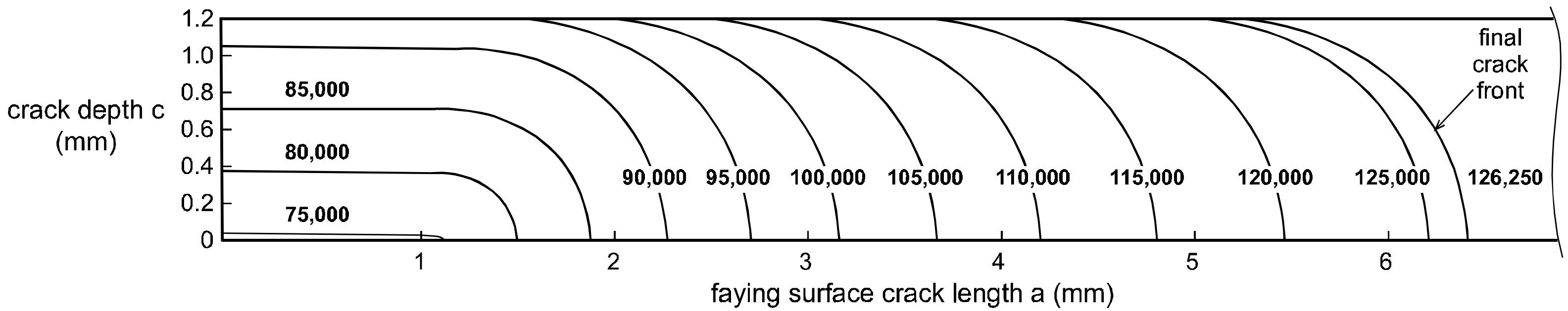


Fig. 10 Eijkhout's empirical model illustrated for a non-countersunk sheet and multiple fatigue initiation sites

inner sheet rivet hole 19391T DOF				
a_i (mm)	a_f (mm)	da/dN (μm/cycle)	N_f-N_i (cycles)	N_i (cycles)
1.1	6.4	$0.05721e^{0.1673a}$	51,700	74,550



outer sheet rivet hole 17981P nDOF				
a_i (mm)	a_f (mm)	da/dN (μm/cycle)	N_f-N_i (cycles)	N_i (cycles)
0	5.2	$0.05311e^{0.1593a}$	67,000	59,250

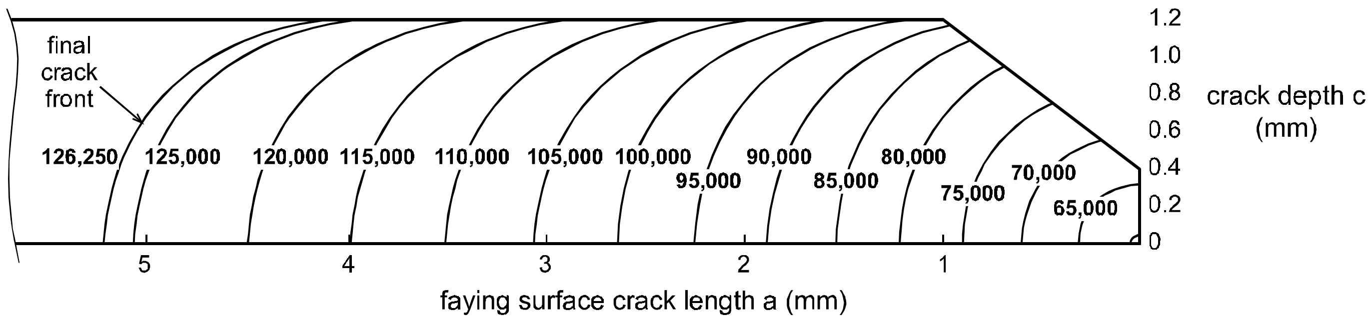


Fig. 11 Examples of the use of Eijkhout's empirical model to predict "iso-life" fatigue crack fronts for two MSD fatigue cracks in the F100 full-scale test lap splice (6): DOF = Direction Of Flight; nDOF = opposite to Direction Of Flight

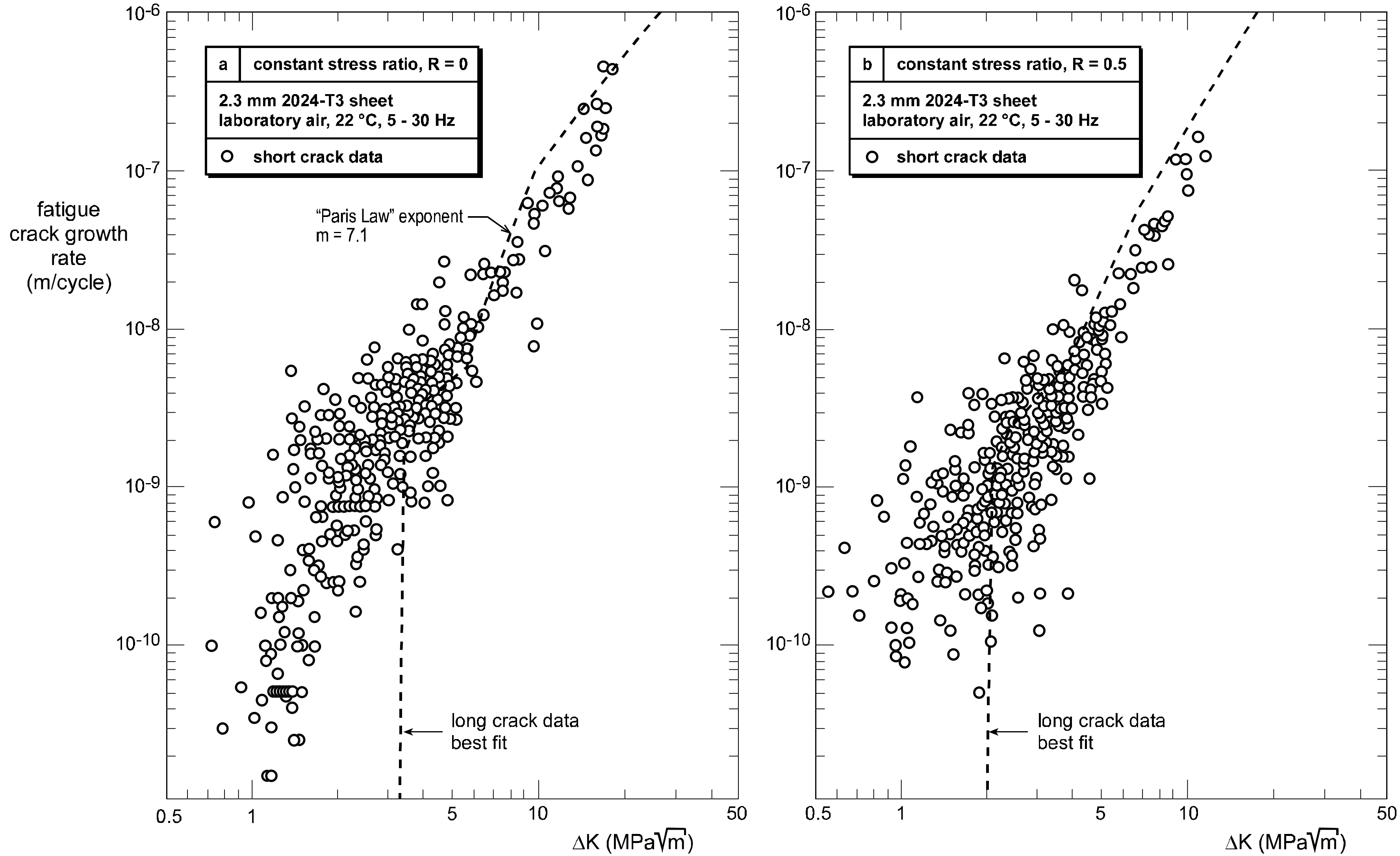


Fig. 12 Comparisons of short and long fatigue crack growth rates for 2024-T3 aluminium alloy sheet: data for specimens loaded parallel to the sheet rolling direction (16)

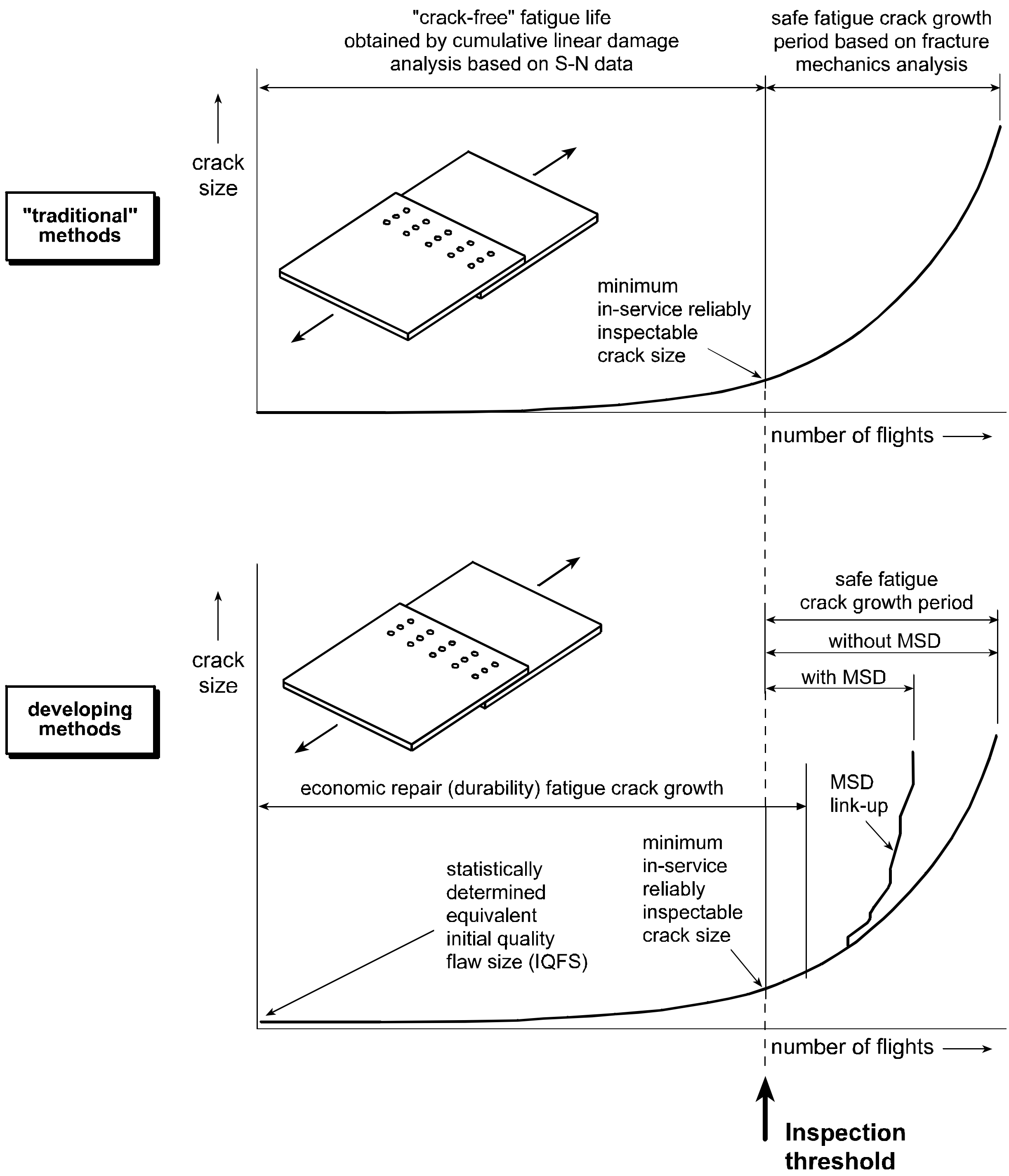


Fig. 13 Fatigue analyses for transport aircraft fuselage lap splices

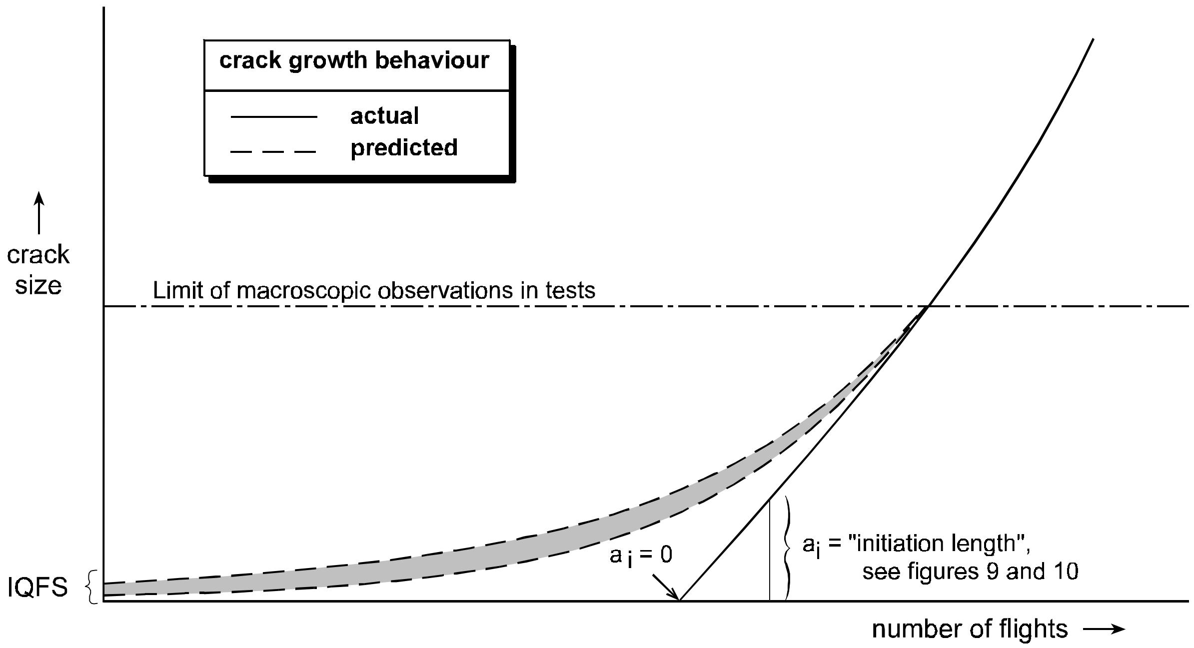


Fig. 14 Schematic of differences between actual and predicted early crack growth behaviour in transport aircraft fuselage longitudinal lap splices: the predictions are fitted to the macroscopic observations and the IQFS values are obtained from actual manufacturing flaws or by back-extrapolation using a macroscopic (long) crack growth model