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Application of Damage Tolerance to the EH101 Airframe

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Summary

This paper presents the work carried out by GKN Westland Helicopters in the damage tolerance evaluation of the EH101 airframe. A comprehensive programme of crack growth testing and analysis was undertaken and is described in this paper. A simplified analysis method was developed and used to predict flaw growth in the Main Load Path structure of the EH101. The analysis showed that high frequency vibratory loads exceed the crack growth threshold at relatively short crack lengths. This has been confirmed by a full-scale airframe crack growth test in which a 4mm crack was propagated under representative loading. These results have led to the adoption of the 'Flaw Tolerant (Enhanced) Safe Life' approach for fatigue critical components on the EH101 airframe.

1. Introduction

The EH101 is a modern medium/large three engine helicopter that has just entered service with the Royal Navy and will shortly enter service with the RAF. Civil rear-ramp utility variants are also in production. The EH101 has undergone an extensive development programme that included a full-scale factored load fatigue test. Failure modes observed during this test were eliminated from the production standard by design changes. A stand-alone fatigue test of a production standard lift frame, together with analysis using fine mesh finite element modelling, demonstrated the effectiveness of the changes. Safe Lives in excess of 10000 hours have been demonstrated for civil and military variants. Consequently, the EH101 has one of the best qualified helicopter airframes in service today.

As part of the civil certification activity of the EH101-510 variant, the Airworthiness Authorities also required damage tolerance evaluations of all fatigue critical components to be carried out. This is in keeping with the current thinking of regulatory bodies, who favour a flaw growth damage tolerance approach over Safe Life or even Flaw Tolerant Safe Life approaches.

A programme of work and analysis was commissioned to develop a viable approach to flaw growth damage tolerance for the Main Load Path structure of the EH101 Helicopter. Figure 1 shows the cabin fuselage and

highlights the lift frames that form the Main Load Path structure. The frames are machined from cold compressed aluminium lithium forgings (8090 T852).

The programme of work involved a series of crack propagation tests to generate material data and to provide crack growth data that would enable the validation of the analysis method. Crack growth under a realistic usage spectrum at key sites on the Main Load Path was predicted and inspection intervals generated.

This paper presents the manner in which GKN Westland Helicopters have developed crack growth analysis methods for the EH101 Main Load Path. The initial conclusions drawn from applying this method to the EH101 are then discussed.

2. Test Programme

The testing programme involved a series of crack propagation tests. The initial phase of testing generated the required crack growth material data. In subsequent tests, cracks were grown in a variety of specimens ranging from structural elements to a full-scale airframe test.

The principle aims of the test programme were to:-

- Generate crack growth material data.
- Evaluate the crack growth characteristics of the aluminium-lithium Main Load Path components.
- Generate crack growth data under progressively more realistic geometry and loading.

The most effective method for introducing initial flaws in the test specimens was established by a series of coupon tests. Flaws were introduced by spark erosion or by using a 0.5mm grinding wheel. The effect of chemical etching and initial flaw size was also investigated. The main observations were as follows:-

- 25% higher loads were required to initiate cracks from ground flaws compared to spark eroded flaws.
- Chemical etching reduced the load required to initiate cracks by 5% at spark eroded flaws and by 7.5% at ground flaws.

- A higher stress intensity was required to initiate 1.3mm flaws compared with the 2.6mm flaws.

Each of the crack growth tests was modelled using linear elastic fracture mechanics and the analytical predictions compared with the test results. The modelling techniques were refined and the accuracy of the predictions established.

2.1 Generation of Material Data

The Main Load Path structure is machined from aluminium-lithium alloy (8090-T852). This material has been developed specifically to meet the requirements of GKN Westland Helicopters. The crack growth material data required for the damage tolerance evaluation was generated by the GKN Westland Helicopters Materials Laboratory.

Compact tension specimens were machined from production forgings and tested at R-ratios of 0.1, 0.4, 0.7 and 0.9 under constant amplitude load. This testing formed part of the collaborative project 'Robust Crack Growth Model for Rotorcraft Metallic Structures' funded by the UK Department of Trade and Industry as part of the LINK initiative.

The data generated by the testing included:-

- Crack growth rate versus stress intensity range (da/dN versus ΔK)
- Threshold stress intensity range (ΔK_{TH})
- Plane strain / plane stress fracture toughness (K_{IC} & K_C)

2.2 Structural Elements Tests

The purpose of these tests was to prove that the data derived from the CT specimens can be used in the analysis of complex structures. The tests also investigated the crack growth characteristics of the machined aluminium-lithium forgings on the EH101.

The structural element shown in Figure 2 represents the geometry of the roof frames in the region of a lightning hole. Six structural elements were tested under constant amplitude loading. Three structural elements were machined from aluminium-lithium alloy plate (8090 T8771) and three from a cold compressed aluminium-lithium alloy forging (8090 T852). Spark eroded initial flaws were located at either the lightning hole or the corner of the flange. A Potential Drop system was used to monitor crack growth.

A further two lightning hole structural elements were tested by Cranfield University under a complex variable amplitude load spectrum. Crack growth from an initial flaw at the edge of the lightning hole was monitored using a Potential Drop system.

As part of the DTI LINK project, the structural elements have been extensively analysed using various crack growth models. The analysis and conclusions are reported in Reference 1.

2.3 Full-Scale Component Tests

A production roof frame and side frame have also been tested with flaws at four locations (see Figure 3). The load was applied as a block loading programme representing the low frequency manoeuvre loads produced by forward flight, climb, and spot turn conditions. Each flaw site was tested sequentially and the crack growth monitored using crack growth gauges. Each flaw site was repaired using composite patches before beginning testing at the next flaw site.

Cracks were successfully grown at three out of four of the flaw sites. At the first three flaws, elevated loads and large initial flaws were needed to initiate crack growth. At the fourth flaw, located at a bolt hole, crack growth could not be initiated, even when the initial flaw was 5mm deep.

2.4 Full-Scale Complete Airframe Test

The final stage of testing was to grow a crack in the Main Load Path of a complete EH101 airframe (see Figure 4). The aim of this test was to identify the effect of any load redistribution and to more accurately represent the multiple mode loading that occurs in a complete airframe under flight loads.

The development standard fatigue test airframe, used in the safe-life fatigue qualification of the EH101, was retro-fitted with a production roof frame and fore/aft roof beam. High and low frequency loading was applied to the airframe using hydraulic actuators. The flaw was located on the top flange of the roof frame and the flaw growth monitored using crack growth gauges.

A crack was initiated from an initial corner flaw of 4mm with large amplitude crack initiation loads. Once initiated, the crack was grown under high and low frequency loads representative of a level flight cruise condition. At a length of 10.5mm, fast fracture occurred and the crack grew as far as the nearest lightning hole where it arrested. Testing has resumed with the aim of establishing if a crack can be initiated from the lightning hole. A crack self-initiated from and total failure of the frame occurred after very few load cycles. Figure 5 shows the crack propagation up to fast fracture and the final state of the crack.

The test demonstrated that there was very little load redistribution up to the point when fast fracture occurred. After the partial failure to the lightning hole, the load in the adjacent structure increased by about 20%.

3. Analysis Method

The tests described in Section 2 generated a large amount of measured crack growth data with progressively more realistic geometry and loading. The results provided a bench mark to enable fracture mechanics analysis techniques to be developed.

Linear Elastic Fracture Mechanics (LEFM) is used extensively in fixed-wing applications to successfully apply the 'Fail Safe Considering Flaw Growth' approach to damage tolerance. The successful application of this approach to helicopter metallic structures is complicated by a number of factors:-

- Helicopter load spectra contain large amplitude high frequency vibratory loads - fixed wing spectra contain predominantly low frequency manoeuvre loads.
- Critical crack lengths in helicopter components are much shorter than in fixed wing components.
- The versatility of helicopters results in missions that are more complex and involve more manoeuvres than in typical fixed wing operations.

In order to apply the 'Fail Safe Considering Flaw Growth' approach an economically viable analysis method was required that was suitably conservative.

The first step was to select suitable crack growth modelling software with the following features:-

- Commercially available and fully supported
- Allow entry of complex load spectra
- Allow entry of user defined stress intensity solutions
- Retardation and acceleration modelling
- Conservative
- Simple to use

These requirements led to the selection of KRAKEN which is a module of the nSoft software produced by nCode International Ltd. KRAKEN uses a modified Willenber model to model the effect of load interaction on crack growth rates.

The three inputs necessary to predict flaw growth using a model such as KRAKEN are:-

- Material data
- Load Spectrum
- Stress Intensity Factor (Compliance Curve)

The methods used to derive each of these inputs for the analysis of the test results, and in the damage tolerance evaluation of the EH101, are described in the following subsection.

3.1 Material Data

Crack growth material data at R-Ratios of 0.1, 0.4, 0.7, and 0.9 were generated using compact tension specimens. KRAKEN represents the growth rate versus stress intensity range relationship in the following manner (Reference 2):

$$\frac{da}{dN} = C \Delta K_{eff}^m$$

$$\Delta K_{eff} = K_{maxeff} - K_{mineff}$$

$$K_{maxeff} = K_{max} + K_{fs}$$

$$K_{mineff} = \text{Greater of } K_{cl} \text{ or } K_{min}$$

The equations have additional terms to represent retardation, acceleration, short cracks etc.; these have been omitted for clarity.

$$\Delta K_{eff} = \text{Effective stress intensity range}$$

$$K_{fs} = \text{Additional stress intensity from static fracture modes}$$

$$K_{max} = \text{Apparent maximum stress intensity}$$

$$K_{min} = \text{Apparent minimum stress intensity}$$

$$K_{IC} = \text{Material fracture toughness}$$

$$K_{cl} = \text{Stress intensity at crack closure}$$

C and m are material parameters calculated by regression analysis of the growth rate and stress intensity range measured by the CT specimen tests.

The threshold stress intensity range for aluminium-lithium alloy (8090 T852) was measured at R-Ratios of 0.1, 0.4, 0.7 and 0.9 and represented in KRAKEN as shown by Figure 6.

3.2 Stress Intensity Solutions

The most time consuming phase in the analysis process is often the generation of stress intensity solutions. A number of methods have been used to generate stress intensity solutions. Various methods were used in the analysis of the structural elements and 'single frame test'; predicted crack growth was compared with that measured on test to assess the relative accuracy of each method. In Figure 7, stress intensity solutions generated for the lightening hole structural element are compared. It can be seen that the 3D finite element model gives the best representation of the stress intensity solution generated from the test data.

As part of the DTI Link Project, 'Robust Crack Growth Model for Rotorcraft Metallic Structures', the generation of stress intensity solutions using boundary elements was also investigated. This investigation showed that this method is promising but is, at present, very time

consuming and the results too difficult to interpret. For these reasons, boundary element analysis was not used in the analysis of the Main Load Path.

The damage tolerance assessment of the main load path had to be completed in a short time scale. Ideally, each flaw site would have been modelled using fine mesh finite element models and the stress intensity solutions calculated by the strain energy release rate method. This method was used at locations that could not be approximated to a standard solution. Other locations were analysed using standard or test generated stress intensity solutions.

The critical locations of the main load path can be divided into four types of geometric feature. The methods used to derive the stress intensity solution for each type of feature were:

Lightening holes	Calculated from a crack growth test on a structural element by matching growth rates.
Flanges	Derived using standard solutions for a corner crack and through crack.
Cutouts	Fine mesh 2D FE model used to derive solution using the strain energy release rate.
Bolt holes	Derived from standard solutions for loaded bolt holes.

3.3 Load Spectra

A spectrum of low frequency manoeuvre load and high frequency vibratory load was generated for each of the analysed locations. The spectra were derived from measured flight strains. High frequency were those occurring at the blade passing frequency of 17.85 Hertz.

A load survey was undertaken using production EH101 aircraft incorporating comprehensive strain gauge installations. The load survey included each manoeuvre in the civil variant usage spectrum. Conservatively, the maximum vibratory load measured in a manoeuvre was assumed to apply for the whole manoeuvre. In KRAKEN, the load history effect has been shown to have very little influence on crack growth under helicopter load spectra. For this reason, the sequencing of the load spectra was ignored. Figure 8 shows a load spectrum for a typical roof beam strain gauge.

The relationships between the stress at the analysis locations and the stress at the strain gauges were calculated using a fine mesh finite element model of the EH101 airframe. This relationship was used to derive a stress spectrum at the flaw.

4. Analysis of Cabin Main Load Path

The crack growth under the aircraft loads was predicted at each analysis location using KRAKEN. Inspection intervals were calculated based on the predicted flaw growth.

4.1 Selection of Flaw Sites

The selection of flaw sites was based on experience from the Main Load Path airframe fatigue test and by using a fine mesh finite element model of the airframe. The most highly stressed of each type of feature was identified using the finite element model. Typically a flange, lightening hole, and bolt hole were analysed on each component.

4.2 Initial Flaw Size

The crack growth was predicted from 1.3mm (0.05 inch) radial corner cracks. This is in accordance with USAF General Specification for Aircraft Structures, MIL-A87221.

4.3 Failure Criteria

The component was considered to have failed when the first of the following conditions occurred:-

- The crack tip stress intensity at limit load exceeded the fracture toughness, leading to fast fracture.
- Limit load caused nett section yield.

At all of the Main Load Path analysis locations, fast fracture was the critical factor. The limit load at an analysis location was identified using a finite element model of the aircraft that was run with all limit load cases.

4.4 Generation of Inspection Intervals

Threshold and repeat inspection intervals were calculated from the predicted flaw growth. The threshold inspection interval was one-third of the crack growth period from the initial flaw size to the detectable flaw size. The repeat inspection interval was one-third of the crack growth period from the detectable flaw size until failure. The analysis only considered growth in the primary component.

The detectable flaw size was based on an eddy current inspection method.

5. Discussion of Results

The analysis of the EH101 Main Load Path predicted that the vibration levels present in helicopter airframes are sufficient to cause rapid growth at relatively short crack lengths. This has been confirmed by the result from the full-scale airframe test. The lightening holes tended to exhibit slow initial growth because of the thickness of the flange around the hole. Even with the slow initial flaw growth, the time for the cracks to grow to failure was not sufficient to allow the generation of acceptable inspection intervals.

This analysis was conservative on several grounds; these include:-

- The KRAKEN fit to the growth rate versus stress intensity material data can be conservative at high R-Ratios.
- The representation of the vibratory load in the load spectra is conservative for transient manoeuvres where the amplitude does not remain constant.
- No account was made for load redistribution unloading a component as its stiffness reduces.

Refining the analysis would reduce these conservatisms but this would not affect the point at which high frequency load becomes damaging. For the 'fail-safe design considering flaw growth' approach to be viable, high frequency loads must be of a magnitude that ensures that they are not damaging until much greater crack lengths. The point at which the high frequency load exceeds the crack growth threshold is therefore the crucial factor.

The Main Load Path analysis considered flaw growth in the primary load path only. The regulations permit failure of the primary load path if it can be demonstrated that the secondary load path can still sustain limit load. The limit load carrying capability of the EH101 airframe would be compromised by the total failure of the roof frame tested in the full scale airframe test. The full scale test has confirmed that the total failure would occur, a damage tolerance approach based on flaw growth in the secondary load path would therefore not be viable.

6. Conclusions

The EH101 has one of the best qualified helicopter airframes in service today. However, the work reported in this paper shows that the 'Fail Safe Design Considering Flaw Growth' approach to damage tolerance is not viable. It is probable that this conclusion is true for all helicopters and not just the EH101.

The quick and conservative method used to analyse the EH101 Main Load Path generated short inspection intervals. The short inspection intervals were due to high frequency loads causing rapid crack growth at relatively short crack lengths. The full-scale airframe test confirmed that the predicted growth rates are realistic and that the roof frame would completely fail. The complete failure of the roof beam rules out a secondary load path flaw growth approach to damage tolerance. For this reason a 'Fail Safe (Enhanced) Safe Life' approach has been adopted for the EH101 Main Load Path.

GKN Westland Helicopters have demonstrated that accurate predictions of crack growth in helicopter metallic structures are possible. However, due to the complex nature of helicopter structures and load spectra, the generation of accurate predictions is very time consuming.

The DTI LINK Project 'Robust Crack Growth in Rotorcraft Metallic Structures' (Reference 1) has demonstrated that crack growth models need to be developed further before they can be reliably applied to helicopter structures. A number of issues are being addressed by a collaborative project with the same partners as the DTI LINK Project. The project will focus on the following:-

- Stress intensity solution generation.
Existing generation methods involving fine mesh finite element or boundary element analysis are very labour intensive.
- Crack growth model
Models need to accurately predict growth rates over a range of R-Ratios. KRAKEN, for instance, can be very conservative with high R-Ratio loads.
- Threshold stress intensity
Little is known about the scatter that can be expected in threshold data. Also, the threshold behaviour of shorter cracks is not fully understood.

7. References

1. DTI LINK Project - "Robust Crack Growth Model for Rotorcraft Metallic Structures" - Final Report GKN Westland Helicopters Ltd. Research Paper RP1011 June 1998
2. nSoft Version 4 "KRAKEN Users Manual" 1996 nCode International Ltd., Sheffield UK.

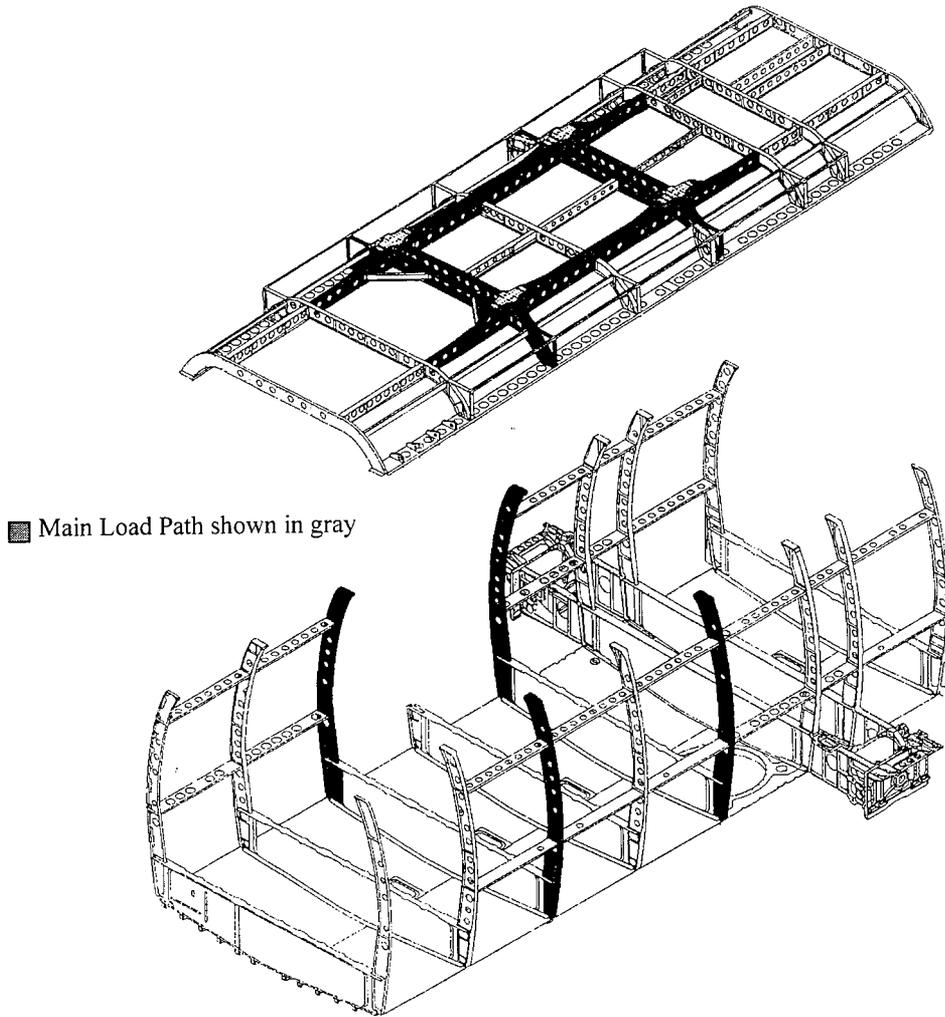


Figure 1 Main Load Path Structure

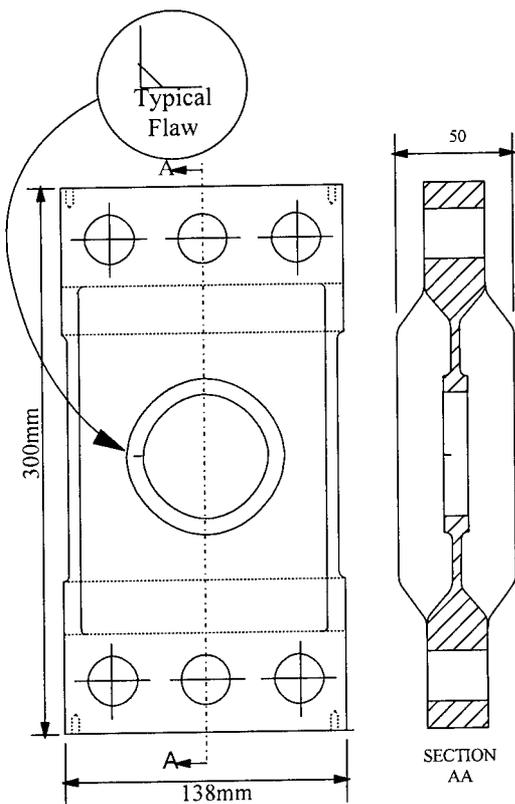


Figure 2 Lightning Hole Structural Element

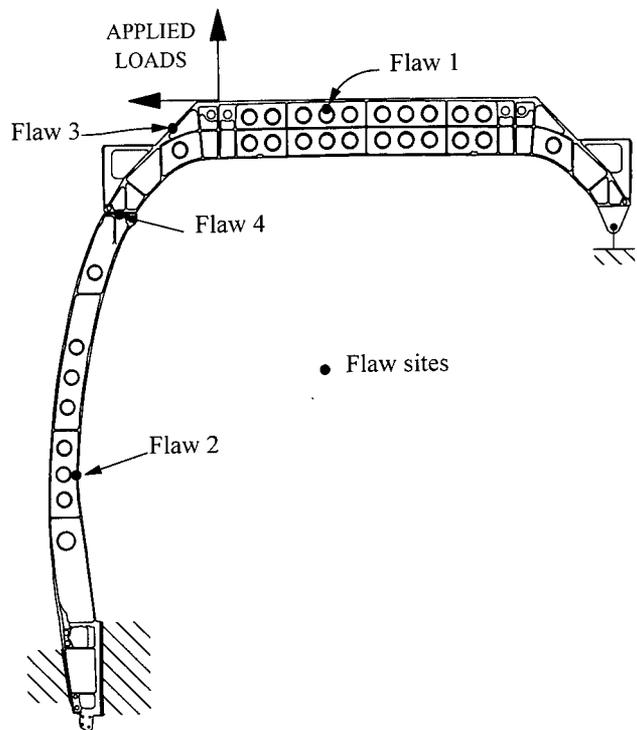


Figure 3 Single Frame Crack Growth Test

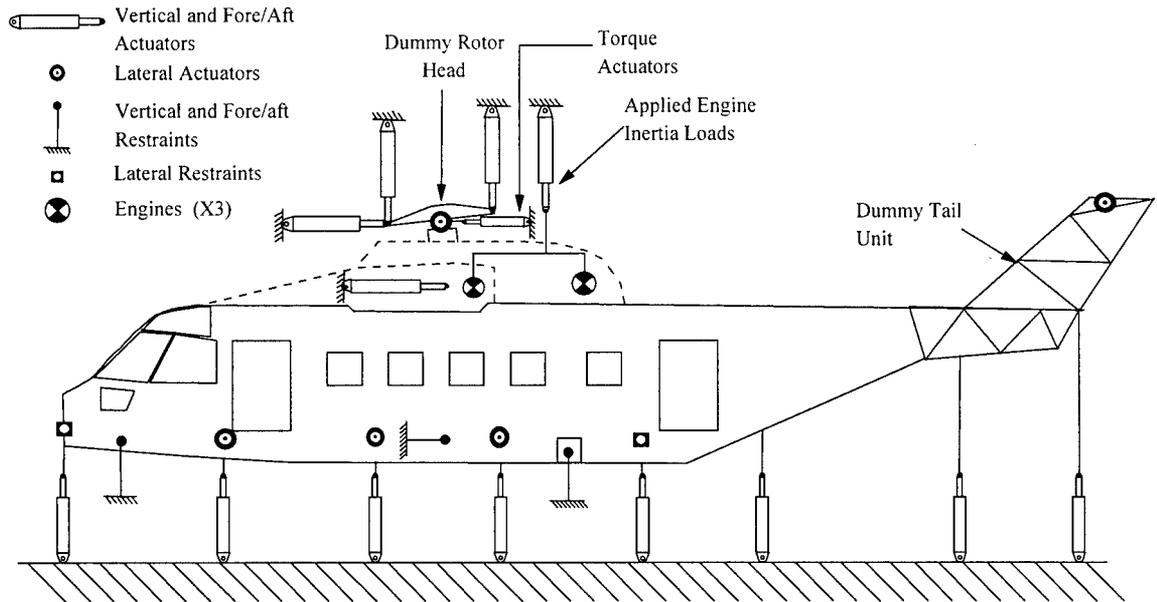


Figure 4 Full Airframe Fatigue Test Rig

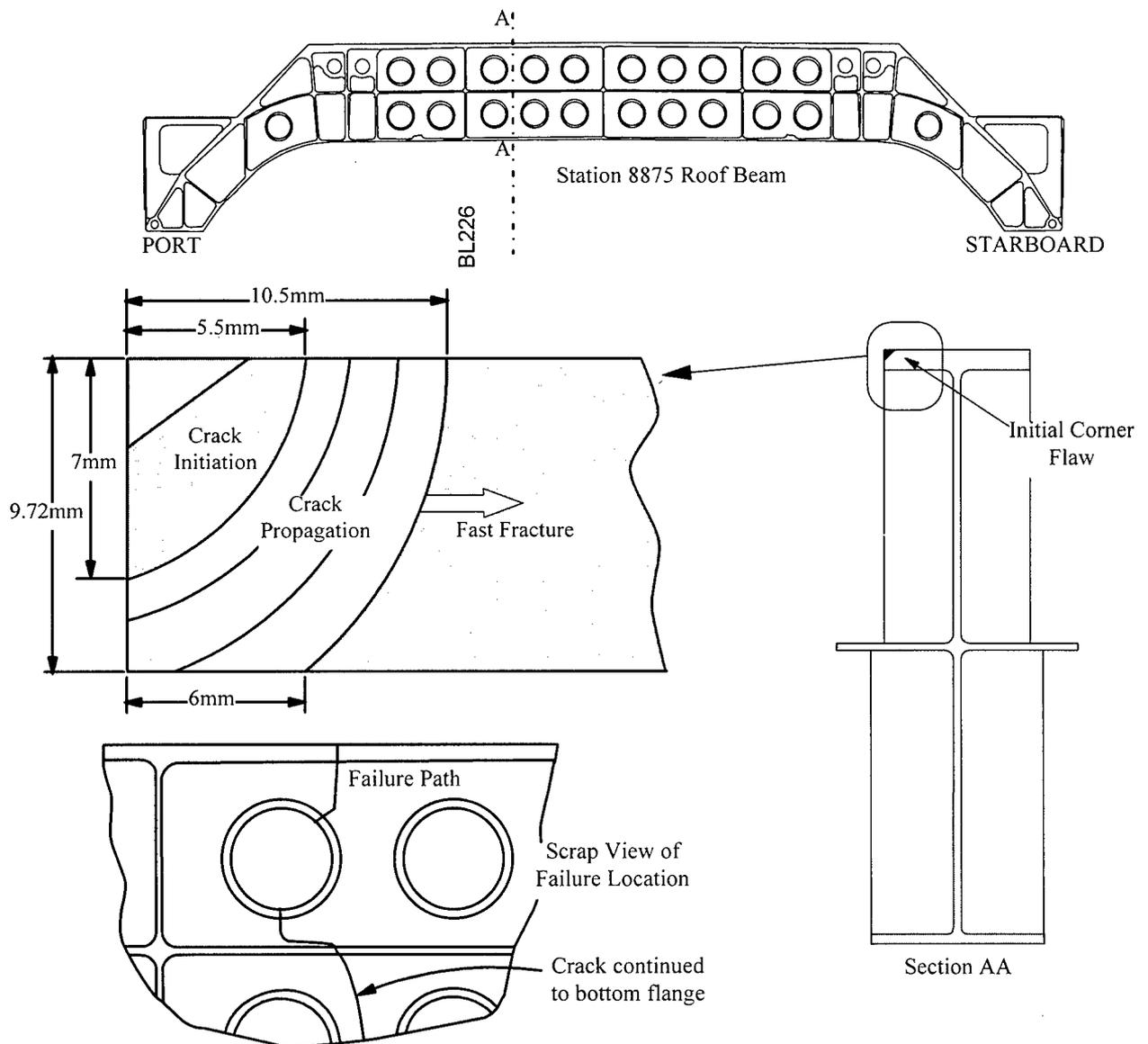


Figure 5 Full Airframe Fatigue Test - Crack Propagation

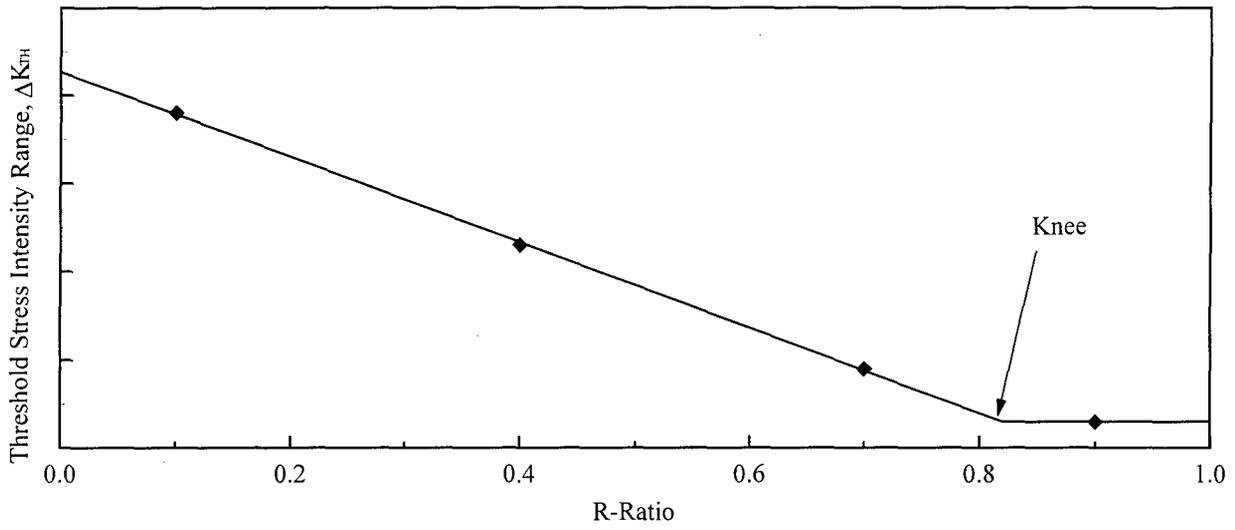


Figure 6 Kraken Representation of ΔK_{TH}

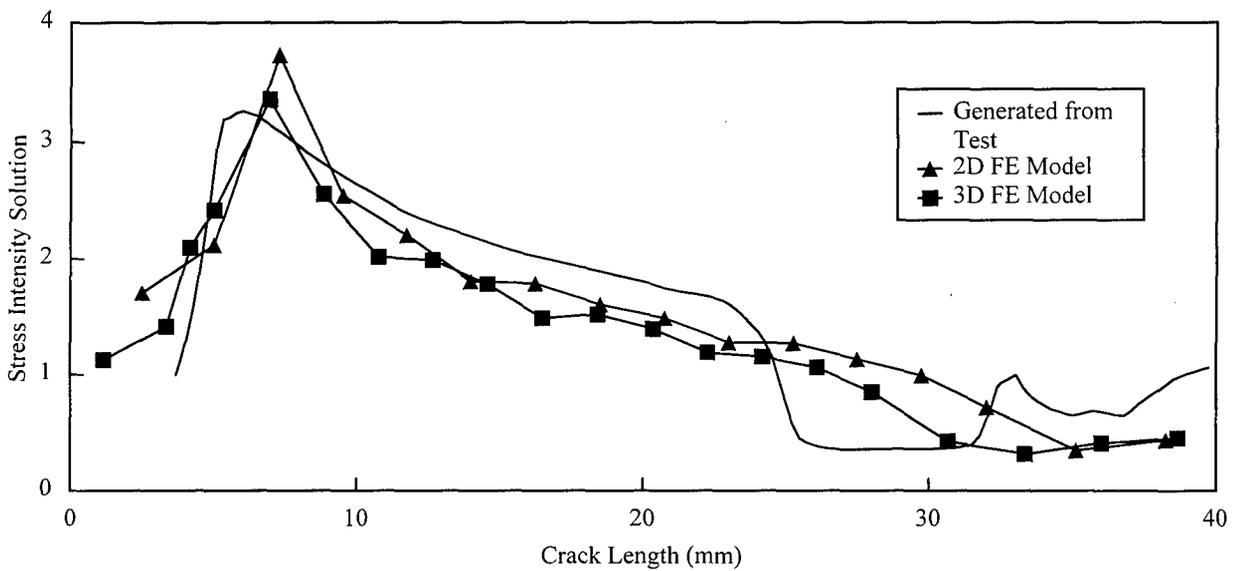


Figure 7 Stress Intensity Solutions for a Flanged Lightening Hole

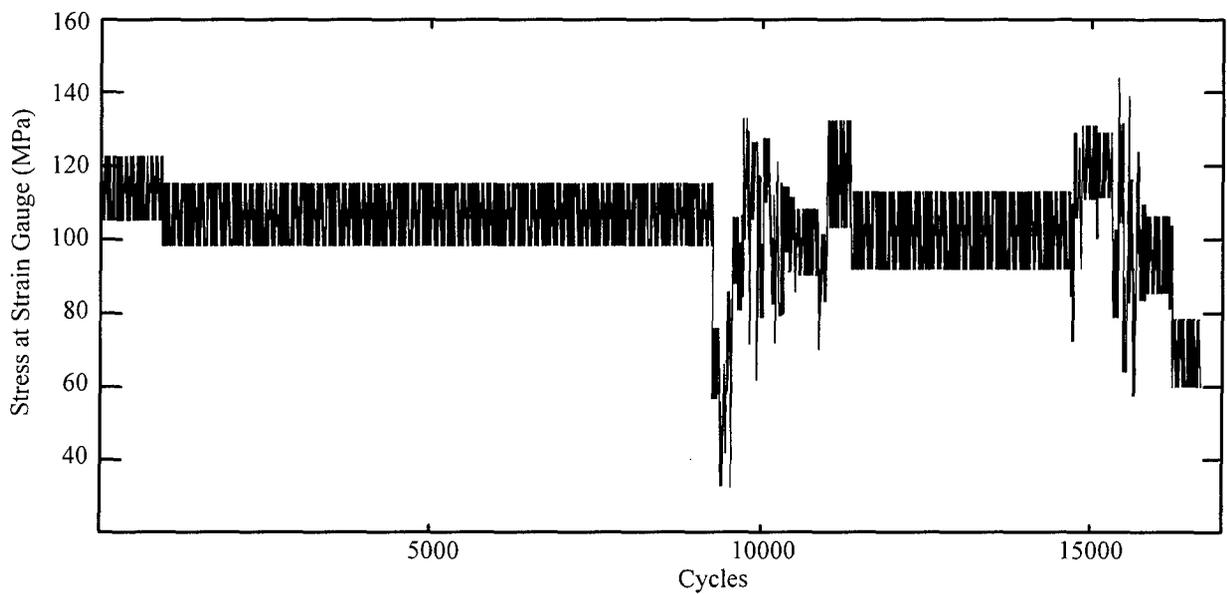


Figure 8 Typical Load Spectrum