# Computer Aided Fatigue and Damage Tolerance Sizing

by

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## ABSTRACT

The software system for fatigue and damage tolerance sizing at Saab Aircraft Division is demonstrated. The need for fatigue and damage tolerance predictions in the design work of a new aircraft is emphasized. Computer programs for this purpose and for the loads spectrum handling work are described through an example from the Saab JAS39 Gripen aircraft, all from a stressmans point of view. The sizing approach including prediction and verification of structural integrity through testing is described.

## INTRODUCTION

### The sizing aims

Aircraft structure should be designed for a low risk of fatigue crack initiation throughout the operational life. However, it can not be guaranteed that fatigue cracking will not occur in at least some aircraft of the fleet. Aircraft structure may also be cracked due to corrosion, incorrect maintenance or impact damages from accidents, such as turbine disc desintegration or propeller break-up.

One example of this, simple but illustrative, emerged in the fatigue laboratory. Cupons with edge notches were fatigue tested with a transport wing loading spectra. In one series, which simulated a structural member of good fatigue performance, the average time to fatigue crack initiation was approximately 350,000 flights. Suddenly one specimen failed after 37,000 flights i.e. approximately one-tenth of the expected life. A closer examination of the notch area of the specimen showed that a damage was present at the most highly stressed point, see figure 1.

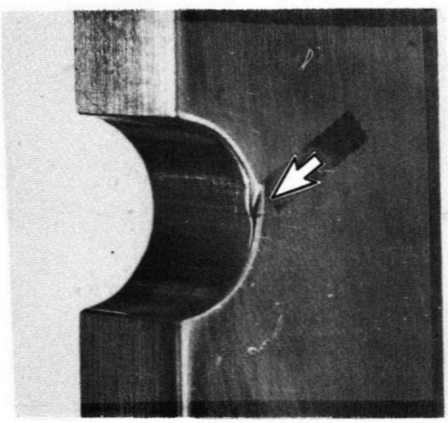

Figure 1. Specimen with impact damage.

The damage was assumed to be an impact damage from which a fatigue crack was initiated. This type of damage which might have been expected to produce some compressive residual stress in the damaged area, acted as a stress raiser and so reduced the fatigue life.

This simple example shows that, besides an overall high fatigue quality, the structure must be designed also with damage tolerance capabilities in order to avoid any catastrophic failure due to accidental causes. A damage tolerant structure should maintain sufficient residual strength until any cracks or damages are detected during scheduled inspections.

The damage tolerance capability does not necessarily imply delayed fatigue crack initiation. Delayed initiation and slow crack propagation are sometimes contradictory. High stress concentration and steep stress gradient are usually very severe for crack initiation but the crack growth rate becomes slow as the crack advances. This behaviour is amplified if high compressive peak stresses are present. On the other hand, a smooth member with no stress concentration is usually not a fatigue problem but if a crack or a defect appears the growth rate is high and accelerating. The conclusion of this is that both classical fatigue and damage tolerance sizing is required.

The sizing aim is to design the structure with a low risk of crack initiation and with damage tolerance capacity. This should be achieved at a minimum weight. These two goals can not be met independently. Accurate stressing methods are needed in order to fulfill both these requirements on an optimal design. The methods and procedures must also be rational and easy-to-use since the sizing work of a new aircraft, civil or military, is made on a short time period. The analysis procedures ought also to be robust so that predictions made early in the design phase can, as an option, be reproduced later despite of developments and modifications of the design data.

### The sizing system

The aims above are met at Saab Aircraft Division through a fatigue sizing system based on what we refer to as the Global Spectrum Approach and computerized conventional fatigue and fracture mechanic principles. A block scheme of that system is shown in figure 2.

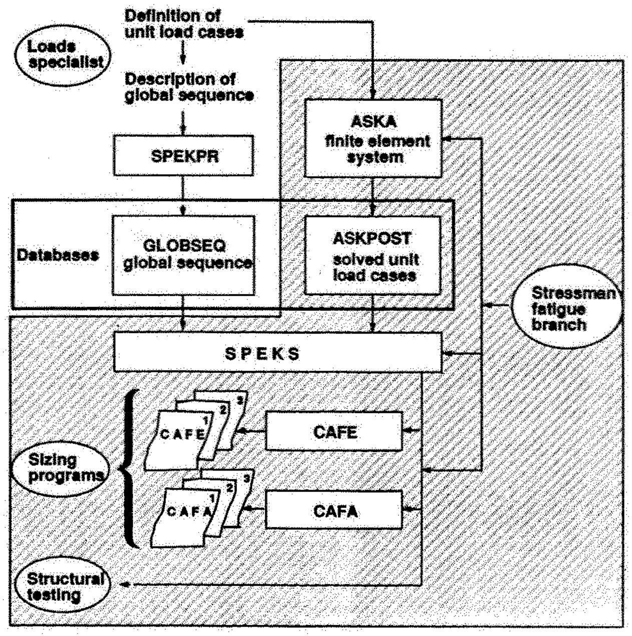


Figure 2. The sizing system

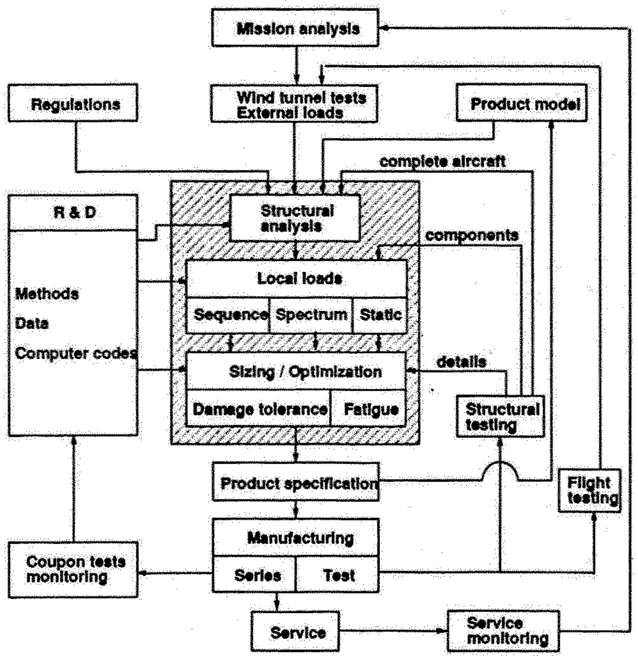


Figure 3. The sizing concept.

A prerequesite for all fatigue and crack growth work is access to local load spectra or load sequences for any part of the structure. This important part of the sizing work is in this system carried out by the program SPEKS. The program requires a description of significant load cases and their appearance in a global sequence and numerical values of the load cases for selected entity. This information, which is related to a specific aircraft, is stored in databases GLOBSEQ and ASKPOST respectively. When this prework is done the stressman is able to obtain local spectra for any member of the finite element model for fatigue and fracture mechanic analysis.

### The sizing concept

For each aircraft project, the sizing system consisting of SPEKS and GLOBSEQ/ASKPOST and the programs CAFA for fatigue analysis and CAFE for fracture mechanic analysis is also a part of a sizing concept which involves applied regulations, feedback from structural and flight testing and follow-up of service experiences. This concept is schematically shown in figure 3.

In the following chapters, the use of the system will be described from a stressmans point of view. The development of the global sequence as well as some applications will be shown.

## THE GLOBAL SEQUENCE

From figure 2 it is apparent that the key to the sizing system is access to internal loads through the global sequence and the finite element solution. The global spectrum approach implies that the design loading of the aircraft is defined as a sequence of instantaneus load cases defined for the aicraft as a whole. The load cases which are expressed in terms of ordinary flight parameters such as configuration, thrust, speed, acceleration, altitude etc have reference to solved unit load cases for the finite element model of the complete airframe.

### Structure of the global sequence

The efficiency of SPEKS to handle and process load cases is based on the hierarchic structure of information in the global sequence. Five main levels plus one additional level containing unit load cases are available for definition of the content of the global sequence. Each item on one level refers to a number of items on the next lower defined level according to figure 4.

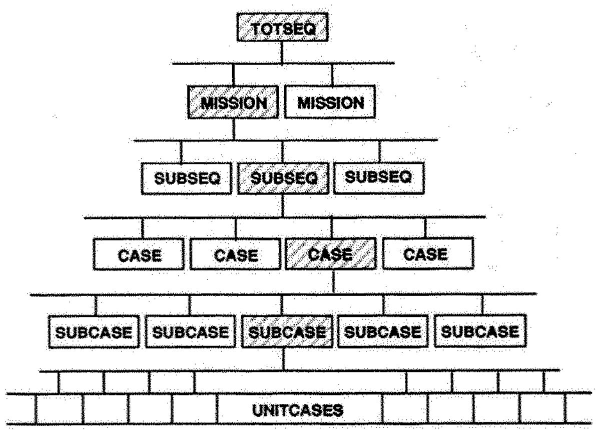


Figure 4. Structure of the global sequence.

## Composition of load cases

Load cases which are significant from a fatigue viewpoint are composed from unbalanced unit load cases (level UNITCASE). The balanced design load cases (level CASE) are obtained as linear combinations of the unit load cases or as linear combinations of interim cases (level SUBCASE) which also are combined from unit cases. The balance is obtained through equilibrium of forces and moments in all directions with regard to boundary conditions such as maximum roll velocity, limitations of the control system etc. For the JAS39 Gripen, the current global sequence contains 1866 cases, each consisting of 50 to 100 unit load cases. Every unique load case of the sequence is also assigned a code number to a systematic scheme. These code numbers are used for identification and are important for certain work tasks.

## Composition of sequences of load states

Once the load cases are established the mission profile defines in which order they shall appear. SPEKS has three levels for sequences of load cases. The lowest one, SUBSEQ represents parts of a mission. Load case sequences for ground conditions consisting of turns, bumps, breaking, towing etc manoeuver and gust conditions for different configurations of the aircraft and landing conditions are defined here. Having this library of subsequences, a number of complete missions can be defined as sequences of SUBSEQ´s. For the JAS39 a/c 35 different MISSION´s are defined from a total of 60 unique SUBSEQ´s. At the top level (TOTSEQ) the mix of missions are defined. It is not necessary to define a unique global sequence for the whole life time. TOTSEQ is often a repetative sequence representing approximately 5 to 10 percent of the total service period. For JAS39 a total sequence of 313 missions are defined.

Once it has been defined, the global sequence is deterministic. This means that stochastic courses of events such as gusts and missions mix etc are always the same once they are feed into the global sequence data base. The loading of the data base is maintained by SPEKPR, a preprogram which decodes a user friendly command language into a fast access format for SPEKS.

## THE LOCAL SPECTRUM

The sizing system is ready when the global sequence and the finite element solution data bases are created. Local sequences and spectra for any calculated quantity for any location of the finite element model can now be momentarily created by the stressman through the use of SPEKS.

## Example for demonstration

The features of SPEKS will be demonstrated for a JAS39 application. Figure 5 shows the ASKA finite element model of the aircraft and a substructure of a half wing attachment frame.

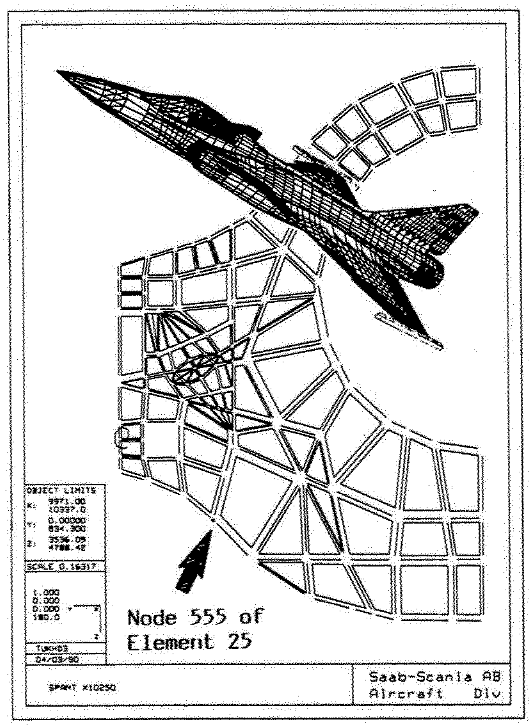


Figure 5. The finite element model.

The structural member to be analysed is the lower flange of a frame close to one of the wing attachments (note the marked position in fig. 5). The flange is modelled by flange elements and the quantity to be extracted is the axial force.

## Definition of a quantity

SPEKS is executed through a high level command language. Below are the commands given for allocation of databases and selection of the above defined quantity.

```
SET GLOBAL SEQUENCE ID = 39SEK43
SET ASKPOST = 320NPOST
SET NET = 320 EGID = 9200 ELEMENT = 25
QUANTITY FLAFORC = QUANTITY (NODE = 555,K1)
```

This is an example of the most elementary way to define a quantity when it can be extracted directly from the finite element model. For more complex situations, SPEKS has features to facilitate a number of operations on finite element results. Loads, stresses, displacements etc can be arbitrarily factorized and superimposed and principal stresses and effective stresses can be derived.

## Local spectra and sequences

Coming so far the local sequence of the flange force is defined and can be printed on a direct access file for cycle-by-cycle crack growth analyses or testing. For such purposes it is sometimes advisable to omit certain small cycles which from a fatigue viewpoint have no practical meaning. SPEKS contains interactive facilities to remove insignificant states. By defining omission conditions connected to the earlier defined sequences the reduction of the sequences is immediately displayed. For the example above, the original sequence consists of 5,843,925 states. By omitting cycles with ranges smaller than 20 kN (approximately 10% of the maximum range) the total sequence is reduced by approx 96 % to 236,685 states. The omission technique adopted in SPEKS works also when more than one load sequencies considered through a lowest common denominator scheme.

Selected parts of the total sequence can be plotted in a variety of forms and on different devices. In figure 6 a plot of the beginning of the unreduced sequence is shown on a screen format. The sequence shown In figure 7 has the above defined omission condition applied. The triangular marks shows where each mission ends.

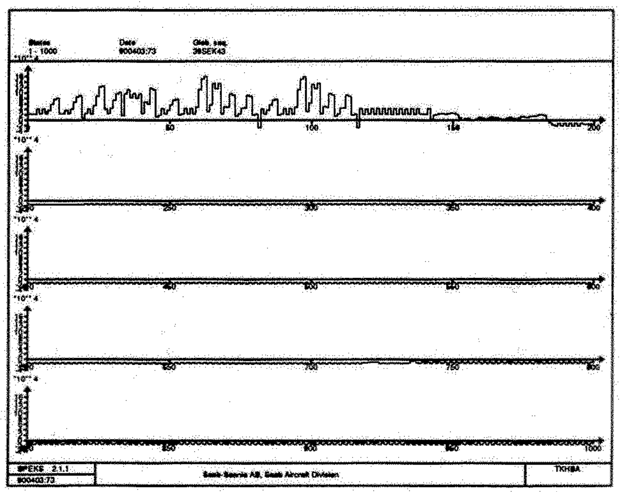

Figure 6. Part of the unreduced local flange force sequence.

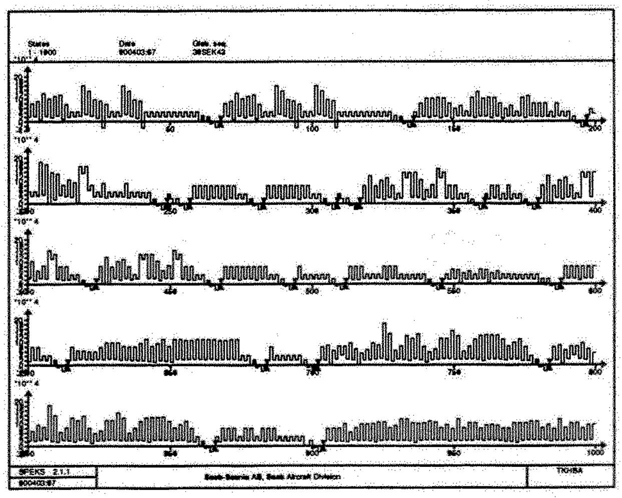

Figure 7. Part of the reduced local flange force sequence

Another plot form which marks out the states that can be removed due to a proposed omission condition is also available and shown for a flight manoeuvre part in figure 8.

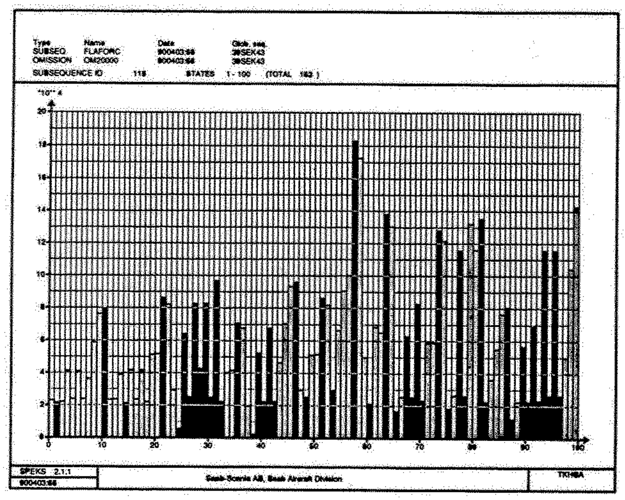

Figure 8. Bar chart showing states that will be omitted according to a proposed omission condition.

For very long irregular sequences like this the rain-flow counting algorithm that in a relevant way combines load states into cycles is available. The counting is performed on the subseq-level with intermediate states treated afterwards. This procedure has proven to be very CPU time efficient so that almost immediate response has been achieved. The RFC-matrix of associated peaks and troughs can be printed on sequential files as input to fatigue and crack growth calculations. By connecting an omission vector, generated by the above described omission procedure, to the RFC-counting, reduced spectra can be created.

Spectra can be plotted in two forms, either the distribution of ranges or the distributions of peaks and troughs. In figure 9, the distributions of ranges are shown for both the original spectrum and the reduced spectrum.

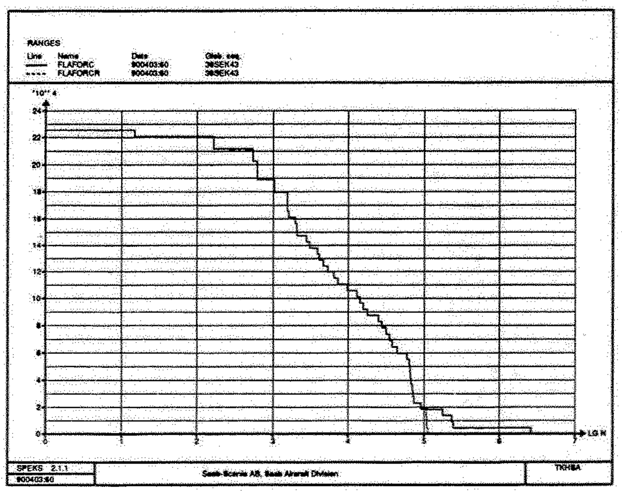

Figure 9. The distributions of ranges for the original and the reduced spectrum.

The SPEKS software has features to facilitate identification of load cases. This can be done by retaining load case identification numbers all the way through the rain flow count operations, omission procedures etc. This technique has proven to be most important when planning for structural testing. For JAS39 every unique load case of the global sequence has been assigned a 9 digits code number according to a systematic scheme. Below is shown a part of a list from a RFC-matrix with load case identification conditions added.

```
*------------------------------------------------------------------------------
SPEKS   Version 2.1.1          DATE  900409:35
RFCDUMP  FLAFORC               DATE  900409:35
GLOBAL SEQUENCE ID   39SEK43
*------------------------------------------------------------------------------
*   Rows     Min          Max              Service    Total number
*            Trough       Peak             Period     of cycles
    872    -33067.     0.19249E+06         3000        2739795
*------------------------------------------------------------------------------
*    Cycles    Range        Trough          Peak        ID-trough    ID-peak

        15   0.22556E+06   -33067.       0.19249E+06   338100001    197002030
        60   0.22011E+06   -27617.       0.19249E+06   100100000    197002030
        90   0.21967E+06   -27179.       0.19249E+06   338000001    197002030
        45   0.21064E+06   -27617.       0.18303E+06   100100000    197102030
       165   0.21021E+06   -27179.       0.18303E+06   338000001    197102030
       135   0.20983E+06   -27179.       0.18265E+06   338000001    187002037
        30   0.20900E+06   -26351.       0.18265E+06   338700001    187002037
        75   0.20211E+06   -27179.       0.17493E+06   338000001    195000007
       120   0.18843E+06   -27179.       0.16125E+06   338000001    170802047
       195   0.18754E+06   -27617.       0.15992E+06   100100000    195102040
```

The systematics of the code give the stressman direct indication of the origins of the load cases. When this is not enough, SPEKS has facilities to track a load case through its hierarchic structure, back to basic unit load cases and flight mechanic parameters.

## THE FATIGUE ANALYSIS

### The program CAFA

The program CAFA (Computer Aided Fatigue Analysis) has been used at Saab for fatigue sizing for more than twenty years in several versions. See reference (1). The latest version is a command driven program with access to materials data from commercial databases and compatible to the loads handling program SPEKS. See figure 10.

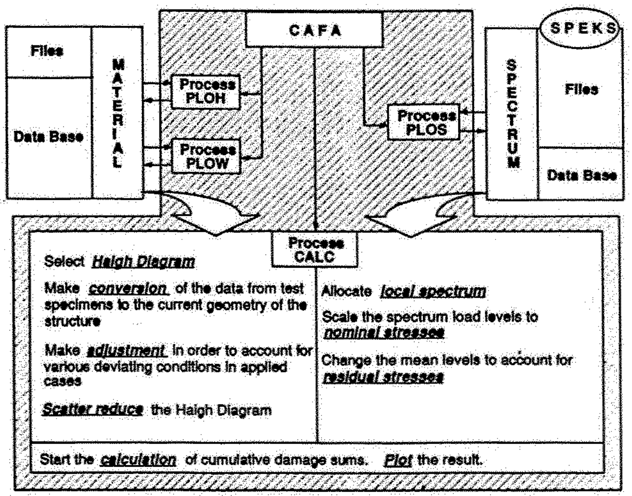


Figure 10. The program CAFA

### Materials data

The fatigue strength data are formatted as Haigh diagrams. Four classes of diagrams are available.

- Stress concentrations
- Lugs
- Joints
- Various structural elements e.g. threads

The first type is used for stress concentrations in general e.g. groves, notches, open holes, cut-outs. For each combination of material, condition etc a set of 3 or 4 haigh diagrams for the stress concentration factors 1, 1.5, 2.5 and 4 are used. Procedures to interpolate and extrapolate between stress concentration factors are available. Lugs data are related to a reference lug and converted to represent the current lug through mapping formulas i.e. "the Saab method". A similar procedure for riveted and bolted joints is also available. The idea to compare lugs with lugs and joints with joints is that fretting effects which are difficult to quantify are accounted for directly in the data.

### Adjustment correction and scatter factors

Reduction is made to account for scatter between different populations of the same kind. This "normal correction" to a lower quartile value is usually included in the basic curves of the database. Additionally, adjustments are often made in order to account for various deviating conditions in the applied cases, e.g. size effect, surface roughness, surface treatments etc. A database of adjustment factors for simple cases as well as combined cases are available. The adjustment factor, less or greater than unit, are defined in the high cycle regime. Smooth adjustment of the factor to unit value in the low cycle regime is made. The fatigue strength curves used for sizing are also reduced to account for scatter within the population. A factor on life in the low cycle regime and a factor on stress in the high cycle regime are used. The numerical values of the scatter factors depends on type of element, material, environment etc and their use will result in a low probability of failure.

### Cumulative calculation

The cumulative fatigue calculation method is of some "Relative Miner" type.

$$\sum_i (n/N) = C < D \; ; \qquad T = \frac{T_o \cdot D}{\sum (n/N)_i}$$

This approach means that the allowable damage sum D is not always equal to one. Numerical values of D depends on both type of structural element and the loading spectrum and are obtained from spectrum testing.

Executing CAFA

The execution of CAFA is shown through the example outlined before. The local geometry of the lower flange is shown in figure 11.

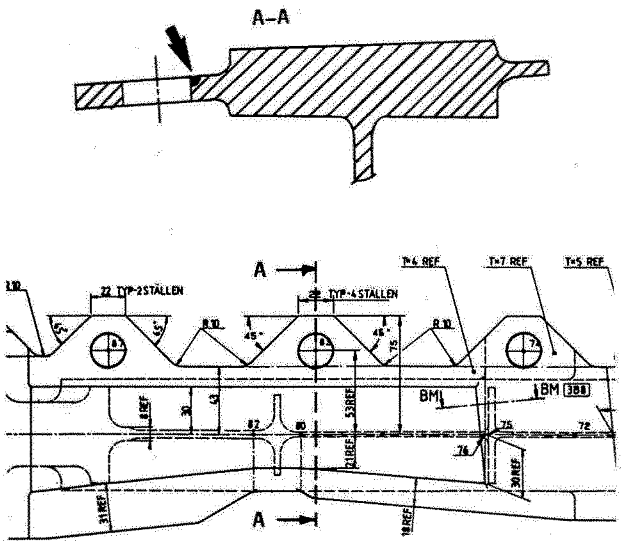


Figure 11 Local geometry of the lower flange

The stress concentration factor at the notch is estimated to 2. The max spectrum peak load is 192490 N giving a net section stress of 148 MPa. The material is forged aluminium AA 7010-T73651 (Saab designation 3644-74). An adjustment factor (PSI) equal to 0.80 is used to account for the current surface condition (hole reamed after anodization and size correction) and scatter factors 3 and 1.3 are used to reduce the fatigue strength curves to meet a specified failure risk. This information and the RFC-spectra from SPEKS are fed into CAFA through the following batch of commands.

```
SPECTRUM FLAFORC = FLSPE.RFC
HAIGH 3644-74-FORG-L
PSI 0.80
STRESS 148
SRED 3 1.3
ALFA 2
```

CAFA present input data used and results on list file and plotted diagrams. If extrapolations of the haigh diagrams have been made during the damage summation, the amount of damage from the extrapolated cases will be listed as percent of the total cumulative damage. Below is a part of the list for the example given in which severe load cases can be identified through their case-id numbers.

```
HAIGHDIAGRAM= 3644_74_HFORG_L  (MPA)
SPECTRUM    =  FLAFORC  (Period:  3000 (hours) )
Load        :  0.19249E+06
ADD         =  0.00
ALFA        =  2.00
ADJUSTMENT  :  PSI = 0.800
REDUCTION   :  fn= 3.00   fs= 1.30
STRESS      =  148.00

===============================================================
 row      n     SIG min    SIG max       n/N        cum(n/N)
===============================================================
  1      15    -25.424     27.665     0.000000     0.000000
  2      15    -25.424    148.000     0.000663     0.000663
  3     510    -21.885     31.204     0.000000     0.000663
  4     120    -21.885     52.439     0.000000     0.000663
  5     990    -21.885     63.057     0.000004     0.000666
                  ********************
                  *** List cut off ***
                  ********************
189     720     87.828    101.991     0.000000     0.046338
190    1050     87.828    105.528     0.000000     0.046338
191     150     91.373    101.991     0.000000     0.046338
192      75    101.991    109.064     0.000000     0.046338
193     630    101.991    123.227     0.000000     0.046338
                        Cumulative Damage          0.046338
```

The calculated damage sum C is here 0.046338 which is less than the allowed sum, D = 0.7. Thus the achieved fatigue strength is far on the safe side.

It is often of great importance and in general advisible to study the effect on damage sum from a change in the input data. Particularly in the early phase of design, when the configuration is still flexible. For this purpose CAFA can produce plot pictures which give the cumulative damage sum as function of stress level and stress concentration factor. In figure 12 is such a plot for our example given.

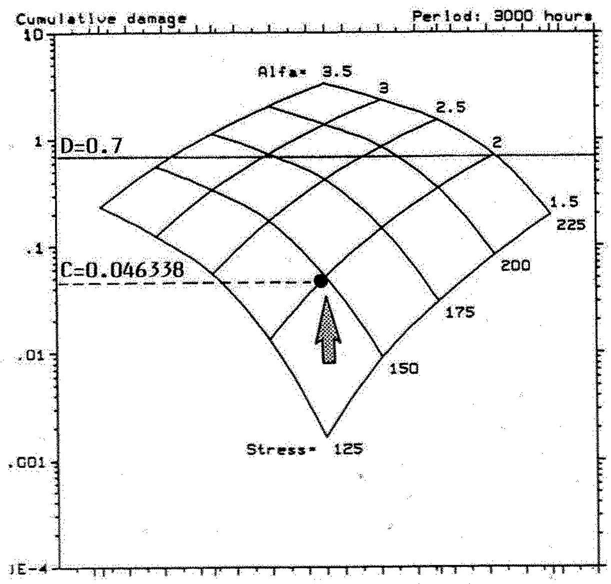


Figure 12. Plot of the cumulative damage sum.

## THE DAMAGE TOLERANCE ANALYSIS

### The program CAFE

In the previous section the fatigue calculation showed that the analysed item has a potentional for weight saving. However, besides static strength also damage tolerance capabilities need to be fulfilled. For that purpose the program CAFE (Computer Aided Fracture Engineering) is available. Like CAFA this program is also command driven through a similar language and has also access to materials data from a database and is compatible to the loads handling program SPEKS. In addition to materials data the database contains also nondimensional stress intensity factor solutions. The structure of CAFE is shown in figure 13.

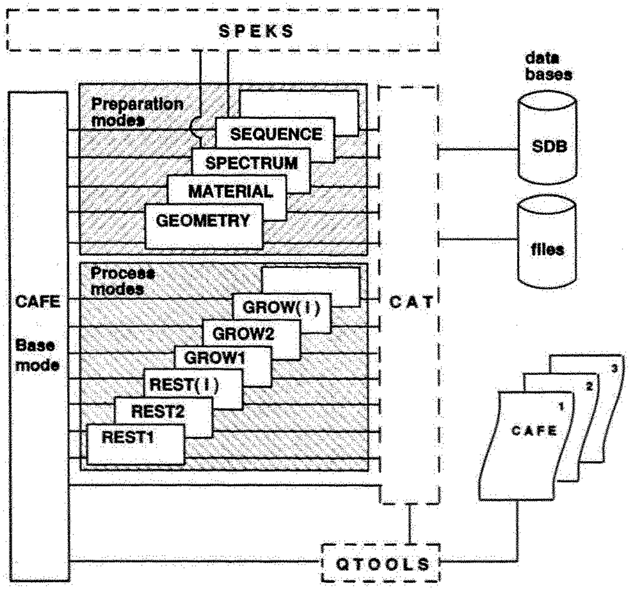


Figure 13. The program CAFE

Like CAFA, this program is also supported by the programs CAT and QTOOLS. CAFE is built-up around a base mode from which preparation modes and process modes can be entered. The preparation modes are used for construction of the fracture mechanic model which means call for and preparation of materials data, stress intensity factors and local spectra or local sequences. When this is done appropriate fracture mechanic procedures can be selected. These are residual strength and crack growth models. For residual strength prediction, classical models for plane strain and plane stress conditions e.g. KIc, Kc and R-curves are available. For crack growth predictions both continuous integration models and incremental cycle-by-cycle models like Willenborg, Wheeler and crack closure are available. Lug joints with the load direction varying from load case to load case can also be analysed through a special process.

### Preparation of input data

Load geometry functions i.e. non-dimensional stress intensity factors can be constructed in several ways e.g. from

- Formulas entered directly and treated by the command interpretor
- Point curves from external files
- Point surfaces from external files
- Database call
- Weight function technique
- Arithmetric operations on functions

Three dimensional crack problems are treated in a special way which means that all information about the stress intensity along the whole crack front is considered. The local virtual growth of the curved crack front is calculated by use of a Paris type of power law. The error is then minimized when constraining the crack front to remain elliptic. All this is done when the call to the database for the selected crack case is made and a crack shape curve and a shape dependent nondimensional stress intensity factor curve is created simultaneously. This load geometry curve can be used for further compounding with other curves.

For the current problem of an assumed corner crack at the edge of a hole growing towards a thickness step, the following calls to the database is made in the GEOMETRY mode.

```
GLIB 3DIM 330 (A,1.27,295,9.25,4,2,Y1)
GLIB SHEET 410 (A,4,19,10,60,Y2)
GLIB SHEET 141 (A,70,Y3)
```

The final solution of the load geometry function Y is obtained through the following arithmetric command (similarity relation)

```
Y=Y1*Y2/Y3
```

The material data i.e. crack growth rate (da/dN) and fracture toughness (KIc) are defined in the MATERIAL mode. Numerical values to several formulas such as PARIS, WALKER, FORMAN etc can be set or data can be assigned from the database using a materials code similar to the one used in CAFA for fatigue strength data.

### Executing CAFE processes

Having the input data prepared in the GEOMETRY, MATERIAL and SPECTRUM modes, any process mode can be selected. In our example, the simple continuous integration model is selected for the crack growth prediction. The crack growth time is calculated according to the following formulas.

$$dT = \frac{To \cdot da}{\sum_i \left[(da/dN) \cdot n\right]_i} \qquad T = \int_{a_i}^{a_c} \frac{da}{(da/dT)_{mean}}$$

Entering commands to scale the spectrum and to give additional input data, the selected process can be executed. The result is given on list files and can be graphically displayed. A part of the listed results is given below

GEOMETRY: Y

MATERIAL: 3644_74_DFG_LT_HHA;DADN

SPECTRUM: S1 Max peak level = 148.00

| Cycles | Troughs | Peaks |
|---|---|---|
| 15 | -25.42 | 27.66 |
| 15 | -25.42 | 148.00 |
| 510 | -21.89 | 31.20 |
| 120 | -21.89 | 52.44 |
| 990 | -21.89 | 63.06 |
| *** SPECTRUM LIST CUT OFF *** | | |
| 720 | 87.83 | 101.99 |
| 1050 | 87.83 | 105.53 |
| 150 | 91.37 | 101.99 |
| 75 | 101.99 | 109.06 |
| 630 | 101.99 | 123.23 |

| CRACK LENGTH | GEOMETRY FACTOR | PEAK STRESS INTENSITY | CRACK GROWTH LIFE (Hours) |
|---|---|---|---|
| 1.27 | 1.209 | 357. | 0 |
| 1.77 | 1.116 | 390. | 1422 |
| 2.27 | 1.037 | 410. | 2557 |
| 2.78 | 0.976 | 427. | 3544 |
| 3.28 | 0.957 | 454. | 4388 |
| 3.78 | 1.045 | 533. | 4971 |
| 4.28 | 1.146 | 622. | 5259 |
| 4.79 | 1.085 | 622. | 5489 |
| 5.29 | 1.023 | 617. | 5728 |
| 5.79 | 0.975 | 616. | 5971 |
| 6.29 | 0.958 | 630. | 6204 |
| 6.79 | 0.938 | 641. | 6422 |
| 7.30 | 0.914 | 648. | 6630 |
| 7.80 | 0.886 | 649. | 6835 |
| 8.30 | 0.853 | 645. | 7040 |
| 8.80 | 0.811 | 631. | 7254 |
| 9.31 | 0.755 | 604. | 7493 |
| 9.81 | 0.545 | 448. | 7884 |
| 10.31 | 0.424 | 357. | 9680 |
| 10.81 | 0.503 | 434. | 10905 |
| 11.31 | 0.583 | 514. | 11544 |
| 11.82 | 0.636 | 573. | 11923 |
| 12.32 | 0.675 | 622. | 12192 |
| 12.82 | 0.708 | 665. | 12402 |
| 13.32 | 0.738 | 707. | 12574 |

This prediction shows that the analysed section is damage tolerant according to the slow crack growth principle and need not to be inspected since the stable crack growth time is greater than two service lives i.e. 2 4000 hours.

## TEST VERIFICATION

The fatigue and damage tolerance analyses create the necessary conditions for high structural integrity. This integrity need also to be demonstrated in testing according to the sizing approach shown in figure 3. For this purpose the loads handling program SPEKS takes a principal part. SPEKS contain a large number of facilities which are necessary in the test planning work. One of those options, elimination of insignificant states, was shown earlier. This procedure works also when more than one sequence (hydraulic actuator channel) are considered. A description of the fatigue test planning work with SPEKS is given in reference (2)-(3).

Besides the testing for obtaining materials data for predictions, three levels of testing are identified.

### Detail testing

Detail testing is mainly performed early in the sizing work. It is used to verify detail design of vital structural members and to qualify the application of prediction methods to typical structural configurations.

The lower flange configurations of frames were studied in that way. Six different crack/geometry configurations were tested with the load sequence having the small cycles omitted as described in the second chapter. The specimen for our example is shown in figure 14.

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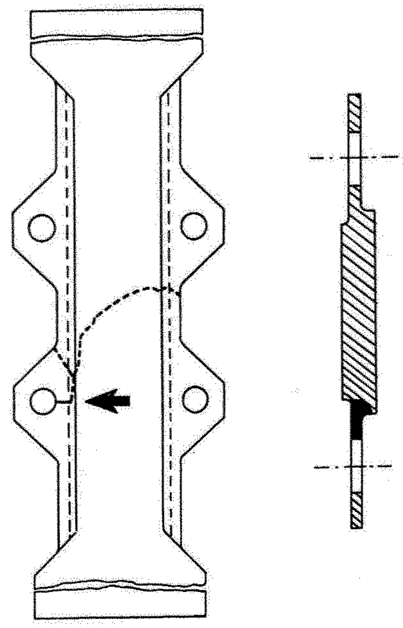

Figure 14. Lower flange test specimen

The results from the testing and predition are compared in figure 15. The outcome of this are that the design has sufficient damage tolerant capability and that the prediction technique is well qualified for this type of structure.

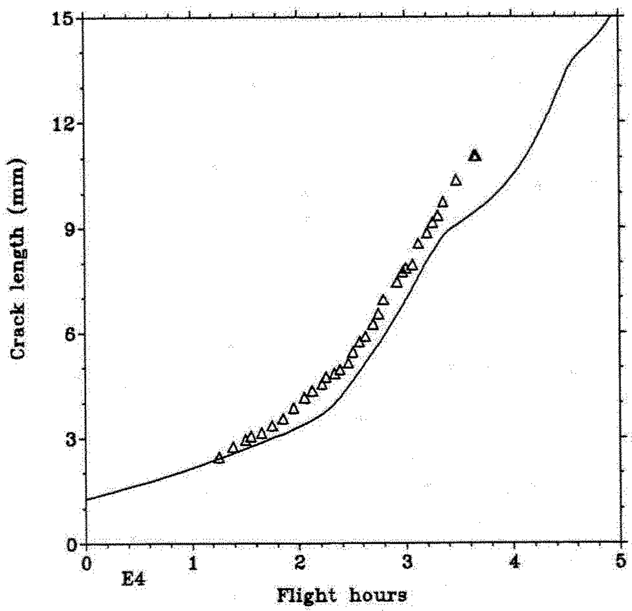


Figure 15. Comparison between detail testing and prediction

### Major component testing

Major component testing is done for early fatigue and damage tolerance verification. The key point in these tests is that a critical part is tested while properly installed in its nearest boundary structure. This type of testing will verify the structural integrity and the prediction of internal loads.

An early design of the wing attachment frame, examplified in this paper, has been fatigue tested for four service life times. Figure 16 shows a photograph of the half frame being rigged up for testing.

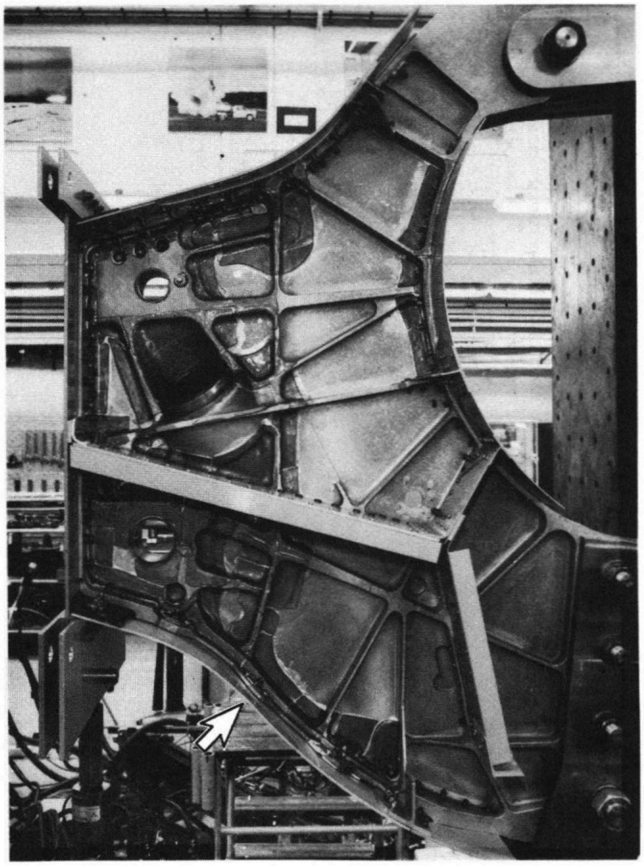

Figure 16. Frame rigged up for testing.

This test will be followed by a second one with a series version of the wing attachment frame. The second fatigue test will consist of two parts. First a conventional fatigue test will be made for 2 service lives. A damage tolerance test with artifical damages introduced at critical locations will then be made for an additional test period of 2 life times.

Full scale testing of complete airframe

The final check of the fatigue and damage tolerance performance is made with a complete airframe tested for several service lives. This test will spot fatigue critical areas and demonstrate the stable growth of those natural cracks that may initiate or of any artificially made cracks. The JAS39 a/c will be subjected to such a fatigue test for at least 4 lifetimes.

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