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Variation in load factor experience - a re-analysis of Fokker F27 and F28 operational acceleration data -

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Variation in load experience - A re-analysis of Fokker F27 and Foker F28 operational acceleration data -

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ABSTRACT
Fatigue meter data obtained during operational flights of Fokker F27 and Fokker F28 aircraft were re-processed and analyzed to study the variation in load experience between different aircraft of the same type.
The Data covered about 470000 flights, made by 101 aircraft of 51 different operators. A simple algorithm was developed to quantify the load factor experience in terms of fatigue damage per flight. The data were subjected to a statistical analysis. Considerable variations in load experience were found. The results give an indication of the profits that can be gained from individual aircraft load monitoring.

Summary

Fatigue meter data obtained during operational flights of Fokker F27 and Fokker F28 aircraft were re-processed and analyzed to study the variation in load experience between different aircraft of the same type.

The Data covered about 470000 flights, made by 101 aircraft of 51 different operators. A simple algorithm was developed to quantify the load factor experience in terms of fatigue damage per flight. The data were subjected to a statistical analysis. Considerable variations in load experience were found. The results give an indication of the profits that can be gained from individual aircraft load monitoring.

Contents

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List of symbols

cg	= centre of gravity	
fl(j)	= number of flights	
fn(j)	= number of flight hours	(hrs)
$exp(x_i)_j$	= positive incremental exceeding level	
$exn(x_i)_j$	= negative incremental exceeding level	
$yp(x_i)_j$	= positive incremental exceeding per flight level	(hrs^{-1})
$yn(x_i)_j$	= negative incremental exceeding per flight level	(hrs^{-1})
$y(x_i)_j$	= logarithmic mean incremental exceeding per flight level	(hrs^{-1})
DI	= damage index	
DH	= damage per hour	(hrs^{-1})
μ	= mean	
σ, std	= standard deviation	
dur	= average flight duration	(hrs)
GAG	= Ground Air Grand cycle	

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1 Introduction

Design Fatigue Load Spectra, and the associated safe service lives and the inspection periods for transport aircraft are usually based on an estimated average usage of the aircraft. As the usage, and associated fatigue load experience of an individual aircraft may deviate from this average, adequate safety factors must be applied to the determined service lives in order to cover scatter in load experience.

Unfortunately, relatively little quantitative information about the magnitude of this load experience is available for civil transport aircraft.

In the mid-fifties, the Fokker F27 twin turboprop short haul transport aircraft entered service, followed at the end of the sixties by the Fokker F28 twin jet short haul aircraft. Both aircraft types were bound to be flown by a wide variety of operators with a variety of networks.

In order to check the validity of the Design Fatigue Spectra assumed for these aircraft, the Netherlands Civil Airworthiness Authorities required counting accelerometers to be installed in at least two aircraft of each operator. These meters were read out at weekly or monthly intervals and the results sent to Fokker for further processing and analysis.

The measurements started in 1961 and continued until 1976, when it became clear that the fatigue design assumptions for both aircraft types were conservative indeed: design spectra roughly corresponded with the load experience observed for the most severe operator.

By that time a very large set of recorded data had been accumulated. Although the information is limited (only cg vertical acceleration exceeding, number of flights and number of flight hours) it was felt that the data provide highly useful information about scatter in load experience occurring in service.

On request of the Netherlands Civil Airworthiness Authority RLD, the Fokker Aircraft Company made the original data available for re-analysis, within the framework of the FAA program on Continuing Airworthiness of aging aircraft.

The present report describes the re-analysis of these data, covering about 470000 flights, made by 101 different aircraft belonging to 51 different operators.

Chapter 2 gives an overview of the recorded data.

The data analysis procedures are presented in chapter 3, including the definition of a "damage index" related to a measured spectrum as a means to quantify the variation in observed usage in terms of fatigue damage.

The actual analysis is presented in chapter 4, followed by a discussion of the results.

It is concluded that even for typical short-haul aircraft considerable variations in load experience occur, resulting in differences in average damage per flight from operator to operator of about a factor up to ten.

The results support the usefulness of in-service load monitoring as a means to optimize maintenance and enhance safety.

2 Overview of available data

The counting accelerometers used were of the so-called "Fatigue meter"-type, produced by Mechanism Ltd, UK. These devices count the number of exceeding of eight predetermined acceleration levels, four above the one-g level and for below the one-g level. These levels were 1.25g, 1.55g, 1.95g and 2.35g "upward" and 0.75g, 0.45g, 0.05g and -0.35g "downward" respectively. (A limited number of the earlier measurements were done with meters having only six counting levels: in that case no 2.35g and -0.35g exceedance counts were made).
The meters were read out at monthly or weekly intervals and the counts were filled out on special forms, together with the number of flight hours and the number of flights of the aircraft over that period.
These forms were sent to Fokker's for processing and analysis.
It should be noted that no information is recorded with regard to speed altitude and aircraft weight at the instant of acceleration occurrence, and that the acceleration data, as they refer to groups of flights, only present average data per flight.

In the present study, the original data forms were re-analyzed. Table 1 gives a general overview of the available data. As data capture for the F28 took place during about 5 years compared to 13 years for the F27, the total batch for the F28 is smaller but still covers 150000 flights, distributed over 38 aircraft, pertaining to 25 operators. For the F27, these figures are 320000 flights, 63 aircraft and 29 operators.
The tables 2 and 3 give a complete overview of the available data for the F27 and F28 respectively. Note that the data have been "sanitized" by replacing the name of the operator by a code. Information on the "Continent of operation", however, has been maintained (For two aircraft, the country of origin is unknown: their "continent" has been indicated in the tables as UNO).
In order to be statistically relevant, the data batch for each aircraft should be sufficiently large. The distributions of the number of recorded flights per aircraft are presented in the figure 1 . In case of the F27, for only three aircraft the batch is smaller than 1000 flights, while the median batch size is about 4000 flights.
For the F28, ten aircraft have a data batch smaller than 1000 flights, but the median batch size is also about 4000 flights.
A careful analysis of the data pertaining to these small batches led to the conclusion that they could be considered as representative, and hence they were included in the full statistical analysis.

Both the F27 and F28 are typical short haul transport aircraft, with an average recorded flight duration (airborne time) of 55 and 49 minutes respectively, but of course with very different performance characteristics.

Figure 2 presents the average load factor spectrum as recorded for both aircraft. It is remarkable to note that these spectra largely coincide, at least for the load factor range between 2g and 0g.

3 Data analysis procedures

It may be recalled that the data recorded for each individual aircraft j (j=1,...m), consist of 10 figures, namely:

1. Total number of flights, fl(j)
2. Total number of flight hours, fh(j)
3. Total number of exceeding (level crossings) of:
   a. four upward incremental load levels, $exp(x_i)_j$ (i=1...4)
   b. four downward incremental load levels, $exn(x_i)_j$ (i=1...4)

whereby x_1=0.25g, x_2=0.55g, x_3=0.95g and x_4=1.35g.

The purpose of the present analysis is to study the difference in load experience between different aircraft. It is a known fact that generally speaking the load spectra of different aircraft types when expressed in terms of "per flight" show better agreement, that means less difference, than when expressed in terms of "per flight Hour". Also, most maintenance schedules are defined in terms of "flights" rather than flight hours.
Hence, it was decided to perform the comparative analysis in this report primarily on a "per flight" basis.

For this, the "overall" data recorded were first reduced to data per flight by division by the number of flights. This results for each aircraft j in:

1. Average flight duration dur(j)= fh(j)/fl(j)
2. Average number of exceeding per flight
   a. for upward levels $yp(x_i)_j=exp(x_i)_j/fl(j)$ (i=1...4)
   b. for downward levels $yn(x_i)_j=exn(x_i)_j/fl(j)$ (i=1...4)

Usually, the number of crossings of a certain incremental load factor
is larger for the levels larger than 1g than for the levels below 1g: $yp(x_i)>yn(x_i)$ for all i.
The reason for this is that the total load factor experience consists of a combination of loads due to turbulence (largely symmetrical with respect to 1g), and manoeuvre loads, which are predominantly associated with positive incremental loads (all turning manoeuvres and pull-up manoeuvres go with positive load factor increments; only push-down manoeuvre cause a negative load factor increment).
In order eliminate the manoeuvre effect, it is often customary to "symmetrize" the spectrum by calculating the logarithmic mean of the exceeding of corresponding positive and negative load

factor increments:

$$y(x_i)_j = \sqrt{yp(x_i)_j * yn(x_i)_j} \qquad (i=1...4)$$

The relation between the quantities yp, yn,and y is illustrated in figure 3.

The statistical variables defined sofar describe the load factor spectrum, and the variation in severity of this spectrum from aircraft to aircraft.
In order to have a quantitative measure in terms of potential fatigue damage, a quantity has been defined, indicated as Damage Index or DI, which provides a relative figure for "the damage per flight" inflicted in the lower wing skin near the wing root. The derivation of this Damage Index is given in Appendix A. The Damage Index DI for aircraft j is a function of the spectrum variates defined above:

$$DI(j)= Function(yp(x_i)_j, yn(x_i)_j,\ i=1...4).$$

The Damage Index DI is a relative measure for the fatigue damage per flight. In addition, a variable DH, describing the fatigue damage per flight hour will be defined:

$$DH(j)= DI(j)/dur(j)$$

In summary, we have now defined 15 variables, defining the average load experience per flight for our set of aircraft.

In the next chapter, we will study the statistical behaviour of these variables .
For each variable, the mean and standard deviation are calculated.
For example, the mean and standard deviation for the average flight duration are calculated from:

$$\mu(dur) = \frac{1}{m} \sum_{j=1}^{m} dur(j)$$

$$\sigma(dur) = \sqrt{\frac{1}{m} \sum_{j=1}^{m} \left(dur(j) - \mu(dur)\right)^2}$$

It should be realized that thus equal weight is given to the value dur(j) for each aircraft j, independent of the batch size (nr of recorded flights) of that aircraft j.
It may be recalled from the previous chapter that specifically for the F28 data a number of data batches were relatively small, but analysis of these small batches led to the conclusion that even

these small batches may be considered as representative samples to describe the average load experience of that individual aircraft.

Probability distributions of a variable will be determined by sorting the respective observed values in ascending order, and plotting these against their "plotting position" j/(m+1).
Correlation between variables will be studied by plotting the respective values of the variables against each other.

4 Data analysis

In the previous chapter, 15 statistical variables were defined. Thirteen of these are directly derived from the recorded data presented in the tables 2 and 3. The two damage parameters DI and DH are calculated using the algorithm derived in appendix A.
The tables 4 and 5 present the results of the damage calculations for all F27 aircraft and F28 aircraft respectively.
It may be recalled that the "total damage" of a flight is thought to consist of two parts, namely the "spectrum damage" and the "GAG" damage.
The "total damage" for each aircraft is normalized by division by the value found for "all aircraft", resulting in the damage index DI. The damage per hour is found by dividing DI by the average flight duration for that aircraft.
Figure 4 presents the calculated damage values for each aircraft. It may be noted that the damage associated with the Ground-Air-Ground cycle constitutes more than 50 percent of the total damage: this is one of the reasons why the number of flights tends to be more descriptive for the accumulated fatigue damage than the number of flight hours.

The figures 5a and 5b show for F27 and F28 respectively the acceleration spectra per flight for the aircraft with the highest DI, the lowest DI, and
the average spectrum pertaining to all recorded flights.

Tables 6 and 7 summarize some statistical properties of the fifteen defined variables for the F27 and F28 respectively.
As expected, all variables display considerable scatter.
It is interesting to note that the variables dur, DI and DH all have a coefficient of variation of about 0.35 for both aircraft types.
In the following, some statistical properties will be analysed in more detail.

a. Probability distributions: Probability distributions for the different variables were determined. Results for the most relevant parameters are presented in the following figures:

    - Figure 6: Average Flight Duration.
      We may note that for the F27 only ten percent of the aircraft have an average flight duration of less than 0.7 hours; for about 60 percent, the flight duration lies in a relatively narrow band between 0.7 and 1.0 hours while about 25 percent have a relatively long flight duration of more than 1.4 hours. The flight duration distribution for the F28 appears more "smooth", the mean flight duration of 0.91 hours is slightly less than that of the F27 (1.03 hours).

- Figure 7: Damage Index DI
  Both for the F27 and the F28 the majority of aircraft have a DI which falls in a relatively narrow band. For the f27 e.g. about 70 percent of the aircraft have a DI between 0.8 and 1.2, for the F28 70 percent have a DI between 0.7 and 1.2. On the other hand, for both aircraft types a limited number of aircraft experienced considerably higher DI values, up to about 3 and 2 for F27 and F28 respectively. These "severely flown" aircraft will be subject to a detail review furtheron in this chapter

- Figure 8: Damage per Hour DH
  As expected, the DH appears to show more scatter than the DI. For example for the F28 70 percent of the aircraft have a DH between 0.7 and 1.6, thus covering a DH range with ratio 1.6/0.7 =2.1 , compared to a DI range of 1.2/0.7=1.7.
  Specifically for the F28 the distribution curve approaches a straight line for DH values between 0.6 and 1.7, covering 85 percent of all aircraft. This means that over this range the probability density distribution is flat; all DI values in this range are equally probable.

- Figure 9: Number of exceeding of 1.25g
  The number of exceeding has been plotted on a logarithmic scale.
  It may be observed that the distribution for the F27 is wider than for the F28. The shape of the distribution pertaining to the F27 slightly resembles the well-known shape pertaining to a normal distribution; for this reason the distribution for the F27 has also been plotted on log-normal probability paper, see figure 10. The resulting plot is still far away from a straight line, indicating that the resemblance with a normal distribution is only superficial.

- Figure 11: Number of exceeding of 1.95g
  These distributions have been presented for illustrative purposes only. Keeping in mind that the exceeding of 1.95g is a "rare" event, happening on the average say once in thousand flights in case of the F28, it must be clear that a data batch of at least a few thousand flights is required to get a reliable estimate of the average 1.95g exceedance frequency for a particular aircraft. As shown in figure 1 and figure 2, several aircraft in the data base do not comply with this requirement, and only limited value can be attributed to the derived 1.95g exceedance statistics.

b. <u>Correlations:</u> The statistical variables defined in this study are not necessarily independent: it may even be expected that several variables are highly correlated. In the following figures some of these correlations will be presented.

- Figure 12: Correlation between flight duration and damage index DI.
  The two variables are hardly correlated, with very low figures for the square of the correlation coefficient R^2. The "best fit" linear regression line suggests in accordance with expectations a certain positive correlation: an increase in flight duration by a factor 10 results in a DI increase of a factor 2.4 for the F27 and 1.9 for the F28.

- Figure 13: Correlation between flight duration and damage per hour DH.
  The correlation coefficient remains low, but is higher than in the previous case. Again in accordance with expectations, the linear regression curve indicates a negative correlation: e.g. for the F28 an increase of flight duration by a factor 10 leads to a decrease in DH from 1.8 to appr. 0.25

- Figure 14: Correlation between damage index DI and number of 1.25g exceeding per flight.
  As might be expected, the correlation coefficient is high, with a value R^2= 0.932 in case of the F27 and 0.837 for the F28. The best fit regression line has an offset of about 0.5: even if the number of 1.25g exceeding is zero, the damage index is non-zero, because of the damage due to the ground-air-ground cycle.

- Figure 15: Correlation between number of 1.55g exceeding and 1.25g exceeding.
  In a flight with many 1.25 exceeding, one expects also a relatively large number of 1.55g exceeding. In other words, one expects these exceedance numbers to be correlated. The figure shows this expectation to be reasonably fulfilled: the correlation coefficient R being in the order of 0.8 for both aircraft types.

- Figure 16: Correlation between damage index DI and number of flights in badge.
  Fortunately, figure 16 shows that such a correlation does not exist: values for R^2 are very low and regression lines are practically horizontal.
  Yet, it may be observed that for the F27 aircraft with exceptionally high DI values only a relatively small data batch existed. This was not the case for the F28, where the high DI values were associated with medium sized batches. Furtheron, the properties of these data sets with high DI values will be further investigated.

c. <u>Variations per continent of operation.</u>

The data for F27 and F28 pertain to operations in all parts of the world. It is useful to investigate whether a systematic difference in usage severity between different part of the world exists.

Figure 17 shows the DI values per aircraft, arranged in ascending order, per continent of operation.

For the F27, the differences per continent are remarkably small but the average DI value for Australia is about 20 percent higher than in other continents due to the high DI values observed for four specific aircraft. For the F28, the DI-values for Europe appear a little bit higher than for other parts of the world, but this effect is largely due to three specific aircraft included in the data that have a DI value higher than 1.5.

In the following paragraph, the data batches associated with high DI values will be considered in some more detail.

d. Very severe data batches:

Figure 18 shows the Identification numbers of the 10 aircraft in each data set having the highest damage index DI as shown already in figure 17, the four F27 aircraft with a DI value larger than 2 were operated in Australia. For these aircraft the data batches are of a relatively limited size. These aircraft were flown by operators, indicated in table 2 under the code AUS2 and NZE2 respectively. Actually, these were not "normal" commercial operators, but government agencies: the aircraft were used to check the ILS systems at various airports. This obviously explains the very high load experience: the operation will have been characterized by many turns, and a relatively high proportion of the total flight time was spent at low altitude. At the same time, the utilization of these aircraft was relatively low, in the order of 50 flights per month. This explains the relatively small batch sizes. It is interesting to note that a third aircraft of AUS2, aircraft 10120, experienced a DI of 1.28 which is not extremely high. However, this aircraft made flights of relatively short duration (40 minutes), resulting in a relatively very high damage per hour DH of 1.93.

For the F28, three aircraft operated in Europe have a damage index which is well above the fleet average. These three aircraft belong to the same (commercial) operator, and the data batches for each aircraft are larger than 5000 flights. A review of the original data showed that the high load experience was not "incidental", but remained relatively high throughout the whole recording period for this aircraft. The explanation for this relatively severe usage is that these aircraft were probably used for a specific (relatively long) inland stretch over a mountaneous area with high turbulence activity, in combination with a relatively long average flight duration of about 1.2 hours compared to the average of 0.8 hours.

5 Discussion

The main purpose of the present investigation was to get quantitative information about the difference in load experience between aircraft of the same type, but operated by different operators. The only loading parameter for which statistical data were available is the cg. acceleration and although this may be a very relevant parameter one must keep in mind that for certain parts of the structure c.g. acceleration has no relevance at all. For example for the pressure cabin the pressurization cycle is the determining fatigue loading case. For other parts like the wing the aircraft weight, weight distribution, speed etc. also determine the actual loading severity. Hence, one must be careful not to attach absolute value to the damage figures derived in this report. Yet it is felt that the information obtained is very relevant, specifically because of the very large size in terms of flights of the data batch available.

For the pressure cabin the number of pressurization cycles and hence the total number of flights determines the accumulated fatigue damage. Hence, the damage per flight for such structure may be considered as a constant. It is interesting to note from figure 6 that even for typical short haul aircraft like F27 and F28 considerable differences in average flight duration occur; for the F28 all durations between 0.6 and 1.2 hours have about the same probability. In other words, the damage per hour may easily vary from aircraft to aircraft over a factor 2!

Loading in flight of the wing structure is due to gusts and manoeuvres. It is well known that the frequency of these loads does not increase proportionally with flight duration: the majority of gust- and manoeuvre loads occur at low altitude, during climb and descent, and the time spent in these flight phases hardly changes with total flight duration (except for very short flights). Hence, the cg-acceleration experience variation per flight may be expected to be smaller than per flight hour, and this expectation was confirmed by the present data. Still, the difference in average c.g acceleration experience per flight from aircraft to aircraft is considerable, as shown in figure 5. An interesting fact to be noted is that the differences in load factor experience between aircraft operated by the same operator appear small: differences between operators are a result of the differences in network (e.g. mountainous versus overseas stretches) and possibly differences in loading. The latter factor, however, is expected to be of minor importance for the type of aircraft involved.

In this study, a damage index DI was defined to get a quantitative "one figure" measure of the severity of a measured spectrum in terms of fatigue damage. The underlying algorithm is simple, and no absolute accuracy should be expected, but it is felt the DI value is a fair measure.
In the derivation of the DI, and in the selection of the material constant k, care was taken not to "overestimate" the variation in damage with variation of acceleration experience. Hence, the

following figures are felt to be no "exaggerations":

- Both for the F27 and the F28, about 80 percent of the aircraft have DI between approximately 0.7 and 1.3, thus covering a range with a width of nearly a factor 2.
- A limited number of F27 aircraft, being used in a very specific role, were subject to a load experience resulting in a DI- value more than two times the fleet average.
- One specific "normal" F28 operator was subjected to a load experience resulting in DI values about 1.8 times the fleet average.

These figures show that inspection intervals and component replacement times, if they are based on an "average" load experience plus an adequate "safety factor" to cover also severely loaded aircraft, must necessarily be very conservative for a large part of the fleet that is subjected to average or "below average" load experience. This implies that considerable advantage could be obtained if inspection schedules for individual aircraft are adapted on the basis of individual aircraft load monitoring data.

6 Conclusions

- Fatigue meter data, obtained during operational flights of Fokker F27 and Fokker F28 aircraft were analysed to study variation in load experience between aircraft.
- The data covered about 470000 flights, made by 101 aircraft owned by 51 operators in different parts of the world.
- The measured average load factor experience per flight was expressed in terms of fatigue damage by means of a derived Damage Index DI. The Damage Index found showed considerable variations from aircraft to aircraft: eighty percent of all aircraft had a DI-value between 0.7 and 1.3, thus covering a range of a factor of about two.
- A limited number of aircraft experienced a DI- value that was more than two times the fleet average.
- The data illustrate the reduction in inspection effort that could be obtained if inspection schemes are be adapted on the basis of individual aircraft load monitoring.

7 Reference

1. Schijve, J., The significance of Flight-Simulation Fatigue Tests.
   Proceedings of the 13th ICAF Symposium, 22-24 May 1985, Pisa, Italy.

Table 1 General Overview of recorded data

Aircraft Type	Fokker F27	Fokker F28
number of operators	29	25
number of aircraft	63	38
number of recorded flights	319259	149744
number of flight hours	291357	122298

Table 2 Overview of F27 fatigue meter data

Aircraft	Operator	Cont	Flights	Hours	Flight duration	-0.35g	0.05g	0.45g	0.75g	1.25g	1.55g	1.95g	2.35g
10192	SUD1	AFR	2772	3810	1.374	0	5	119	7643	15767	275	1	0
10193	SUD1	AFR	1490	2297	1.542	0	2	123	1071	845	167	4	1
10204	ANG1	AFR	4498	6427	1.429	0	9	250	9493	23021	483	27	0
10205	ANG1	AFR	4011	6145	1.532	3	4	245	9999	25666	586	18	0
10207	ANG2	AFR	1484	1682	1.133	0	4	65	3162	18245	168	4	0
10217	NIG1	AFR	8707	7603	0.873	5	22	457	15045	25614	819	27	1
10275	LIB1	AFR	4194	6171	1.471	0	7	484	19657	23730	907	8	0
10342	LIB2	AFR	1765	3037	1.721	0	2	148	7955	14100	238	2	0
10436	LIB1	AFR	1222	1786	1.462	0	3	106	5298	10567	211	4	0
10450	IVC1	AFR	1072	1527	1.424	2	7	81	3203	3956	114	5	0
10469	IVC1	AFR	834	874	1.048	0	1	38	2342	3874	113	7	0
10150	JOR1	ASI	361	190	0.526	1	2	37	1304	2841	121	10	1
10226	SIN1	ASI	2959	2195	0.742	2	4	162	5719	11906	310	4	0
10239	KOR1	ASI	5157	4905	0.951	2	21	722	10592	43712	1635	34	2
10240	KOR1	ASI	5092	4857	0.954	1	15	589	16580	43431	1381	42	5
10290	NEP1	ASI	2474	4354	1.760	0	10	265	8825	17159	494	15	0
10316	EMI1	ASI	5864	4275	0.729	1	5	419	10159	30362	306	27	0
10325	EMI1	ASI	3927	2772	0.706	0	1	74	4171	8894	168	12	2
10111	AUS1	AUS	6722	5003	0.744	0	1	354	22345	36227	765	2	0
10113	AUS1	AUS	6216	5084	0.818	0	0	349	15762	32520	633	0	0
10114	AUS1	AUS	6116	4737	0.775	0	0	329	16097	36377	860	2	0
10120	AUS2	AUS	2490	1645	0.661	0	1	307	10613	24862	988	1	0
10121	AUS1	AUS	6308	5154	0.817	0	0	347	17172	39808	881	5	0
10122	AUS1	AUS	6480	5163	0.797	0	2	358	17283	31320	985	4	0
10127	AUS3	AUS	7822	5861	0.749	0	0	280	10576	43570	972	0	0
10131	AUS2	AUS	1399	2205	1.576	0	0	245	14444	40093	1082	4	0
10132	AUS2	AUS	1244	2024	1.627	0	0	221	12315	32194	868	1	0
10134	AUS1	AUS	3677	3628	0.987	0	0	102	4087	7769	169	0	0
10135	AUS1	AUS	3720	3599	0.967	0	0	103	3519	3654	225	2	0
10138	AUS1	AUS	4822	4708	0.976	0	2	212	10693	38447	931	4	0
10139	AUS4	AUS	5597	9647	1.724	0	1	296	14568	28509	555	1	0
10166	NZE1	AUS	14453	12224	0.846	0	99	1802	57719	78648	2354	64	0
10167	NZE1	AUS	13144	11310	0.860	0	50	1845	65332	73546	2147	55	0
10168	NZE1	AUS	14384	12327	0.857	0	101	1709	55883	74431	2353	64	0
10169	NZE1	AUS	13265	9383	0.707	0	63	1559	45810	73575	2529	62	0
10184	NZE1	AUS	12120	10504	0.867	0	150	1997	52257	71838	3523	86	0
10185	NZE1	AUS	11171	9651	0.864	0	53	1737	48483	78460	2752	65	0
10189	NZE1	AUS	12906	11476	0.889	0	66	1569	53642	71784	2089	54	0
10190	NZE1	AUS	11599	9657	0.833	0	50	1819	47970	55463	1791	82	0
10284	AUS1	AUS	5059	4627	0.915	0	0	167	8943	22066	435	0	0
10329	AUS1	AUS	4561	4876	1.069	0	1	1277	15900	22125	600	2	0
10444	NZE2	AUS	1030	1765	1.714	0	0	185	10034	21201	968	19	0
10445	NZE2	AUS	713	1220	1.711	0	6	187	11460	21286	641	7	0

Aircraft	Operator	Cont	Flights	Hours	Flight duration	-0.35g	0.05g	0.45g	0.75g	1.25g	1.55g	1.95g	2.35g
10102	GER1	EUR	3871	4164	1.076	0	10	334	11822	20520	776	20	1
10108	NOR1	EUR	4674	3479	0.744	0	10	331	7510	9187	651	19	0
10116	NOR1	EUR	1992	3051	1.532	0	7	276	2643	1844	1118	14	0
10186	GER1	EUR	1459	2602	1.783	0	8	135	4106	10470	331	17	0
10224	LUX1	EUR	7179	4176	0.582	0	11	797	31007	58508	1894	31	1
10268	GER2	EUR	1537	1409	0.917	0	0	96	3610	7132	192	8	0
10269	LUX1	EUR	8201	5759	0.702	1	10	489	16479	20101	782	23	0
10270	GER2	EUR	1412	1375	0.974	0	8	132	4121	6278	176	9	0
10274	ICE1	EUR	12494	9356	0.749	4	59	1098	45023	88067	5482	250	22
10300	ICE1	EUR	10840	9256	0.854	9	82	1719	41606	90523	5346	280	28
10332	SPA1	EUR	2487	1795	0.722	0	2	121	7480	13339	295	8	0
10341	DAN1	EUR	1335	2193	1.643	1	6	71	2602	7124	268	6	0
10343	SPA1	EUR	2053	1827	0.890	0	5	100	6325	10022	210	5	0
10360	BEL1	EUR	7284	5829	0.800	1	8	401	15245	32277	514	7	1
10366	FRA1	EUR	5844	4381	0.750	2	4	168	7915	40365	2614	85	14
10367	FRA1	EUR	2915	2645	0.907	0	1	180	5705	16238	706	28	4
10369	FRA2	EUR	1011	604	0.597	0	1	78	3181	5712	377	14	1
10370	FRA2	EUR	809	568	0.702	0	3	71	2174	4014	152	10	3
10364	NAN1	SAM	4816	3338	0.693	0	2	103	5193	29481	816	10	1
10365	NAN1	SAM	2145	1165	0.543	0	4	53	2366	6997	208	5	0
all aircraft (63)			319259	291357	0.913	35	1011	30493	1011238	1861662	63500	1686	88

Table 3 Overview of F28 fatigue meter data

Aircraft	Operator	Cont	Flights	Hours	Flight duration	-0.35 g	0.05 g	0.45 g	0.75 g	1.25 g	1.55 g	1.95 g	2.35 g
11053	NIG1	AFR	4274	3322	0.777	2	2	236	9382	9987	476	11	1
11079	UNO2	AFR	374	212	0.567	0	2	9	228	3294	212	4	0
11993	NIG1	AFR	8695	6799	0.782	3	12	357	16442	32181	1170	30	2
12001	GHA1	AFR	2752	1781	0.647	2	13	180	5620	8314	240	12	1
12002	GHA1	AFR	264	357	1.352	0	1	17	851	1430	43	1	0
12003	NIG1	AFR	208	322	1.548	0	0	10	371	1464	41	3	0
12005	GAB1	AFR	4262	2171	0.509	0	5	203	6849	15255	399	13	0
12006	GAB1	AFR	4569	2337	0.511	1	1	172	6208	15110	277	15	1
12007	GAB1	AFR	262	430	1.641	0	1	19	760	955	19	2	0
11033	CAN1	AME	8466	7500	0.886	0	1	120	10013	15642	504	34	5
11038	CAN1	AME	7326	6406	0.874	1	5	133	10902	18978	804	38	5
11059	PER1	AME	9563	9149	0.957	5	18	391	21402	33160	1138	52	6
11085	ARG1	AME	6863	4178	0.609	3	26	650	19612	19750	1410	64	7
12010	PER1	AME	188	225	1.197	0	0	7	543	710	14	1	0
12011	UNO2	AME	180	165	0.917	0	1	16	606	2505	54	1	0
11035	INO1	ASI	7271	7156	0.984	0	7	282	11372	14751	587	14	0
11042	INO2	ASI	303	263	0.868	0	1	34	517	1341	54	0	0
12004	BIR1	ASI	2488	2287	0.919	2	12	193	6638	8733	485	20	1
12008	BAD1	ASI	2044	1300	0.636	2	10	109	4446	8433	100	15	0
12009	BAD1	ASI	649	364	0.561	0	1	12	551	1914	69	0	0
11026	AUS5	AUS	1466	953	0.650	4	7	133	6107	8665	266	9	0
11001	HOL1	EUR	2642	1101	0.417	0	28	943	7179	16006	1367	170	19
11003	HOL1	EUR	6920	4959	0.717	2	18	439	16314	32065	1185	56	12
11004	GER1	EUR	307	432	1.407	0	0	9	1361	1942	47	0	0
11008	HOL2	EUR	4082	4898	1.200	1	9	305	11427	23733	1605	28	0
11009	NOR1	EUR	17101	8487	0.496	0	19	652	35964	62320	2031	36	1
11014	ITA1	EUR	9742	8281	0.850	4	40	850	32499	67069	2475	65	2
11017	SPA1	EUR	5837	7394	1.267	3	71	1510	43207	66788	4028	308	35
11019	SPA1	EUR	5114	6222	1.217	4	33	1102	45223	70785	3198	218	27
11023	SPA1	EUR	5534	6364	1.150	4	44	1269	31327	62537	3860	215	24
11027	GER4	EUR	1897	2782	1.467	1	5	101	4113	16163	901	54	12
11046	GER3	EUR	963	963	1.000	3	8	36	1308	2577	102	2	0
11057	TUR1	EUR	2963	2123	0.717	0	1	126	7103	13126	564	6	1
11067	SWE1	EUR	11170	7366	0.659	3	16	429	23972	31020	2233	23	0
12013	SWE1	EUR	974	678	0.696	0	15	80	1290	2773	30	0	0
12014	SWE1	EUR	480	380	0.792	0	0	10	1145	2325	37	0	0
11041	UNO1	UNO	1186	1956	1.649	2	4	78	2710	6315	158	5	1
12012	UNO3	UNO	365	235	0.644	0	2	44	1577	2936	90	3	0
all aircraft (38)			149744	122298	0.817	52	439	11266	407139	703052	32273	1528	163

Table 4 Calculation of damage index F27 fatigue meter damage

Aircraft	Operator	Cont	Damage GAG	Damage SPEC	Damage TOT	Damage Index	Damage/hour
10192	SUD1	AFR	0.3277	0.2688	0.5964	0.9251	0.6707
10193	SUD1	AFR	0.1877	0.0600	0.2476	0.3841	0.2483
10204	ANG1	AFR	0.3262	0.2222	0.5484	0.8505	0.5932
10205	ANG1	AFR	0.3410	0.2687	0.6098	0.9457	0.6151
10207	ANG2	AFR	0.3508	0.3539	0.7047	1.0930	0.9609
10217	NIG1	AFR	0.3035	0.1567	0.4602	0.7137	0.8145
10275	LIB1	AFR	0.3499	0.3462	0.6961	1.0796	0.7312
10342	LIB2	AFR	0.3450	0.4052	0.7503	1.1636	0.6739
10436	LIB1	AFR	0.3544	0.4132	0.7676	1.1905	2.0627
10450	IVC1	AFR	0.3147	0.2254	0.5401	0.8377	0.5881
10469	IVC1	AFR	0.3288	0.2441	0.5729	0.8885	0.6216
10150	JOR1	ASI	0.3780	0.3802	0.7582	1.1759	2.2264
10226	SIN1	ASI	0.3176	0.1875	0.5051	0.7834	1.0523
10239	KOR1	ASI	0.3772	0.3025	0.6798	1.0543	1.1046
10240	KOR1	ASI	0.3705	0.3647	0.7353	1.1404	1.1914
10290	NEP1	ASI	0.3532	0.3371	0.6903	1.0707	0.6062
10316	EMI1	ASI	0.3126	0.2024	0.5150	0.7987	1.0917
10325	EMI1	ASI	0.2822	0.1052	0.3873	0.6007	0.8481
10111	AUS1	AUS	0.3292	0.2837	0.6129	0.9506	1.2727
10113	AUS1	AUS	0.3257	0.2244	0.5501	0.8532	1.0395
10114	AUS1	AUS	0.3378	0.2421	0.5799	0.8994	1.1572
10120	AUS2	AUS	0.3922	0.4344	0.8267	1.2822	1.9340
10121	AUS1	AUS	0.3394	0.2548	0.5942	0.9216	1.1239
10122	AUS1	AUS	0.3333	0.2391	0.5723	0.8877	1.1102
10127	AUS3	AUS	0.3324	0.1661	0.4985	0.7732	1.0283
10131	AUS2	AUS	0.4465	1.0561	1.5026	2.3305	1.4734
10132	AUS2	AUS	0.4391	0.9795	1.4186	2.2002	1.3476
10134	AUS1	AUS	0.2801	0.0932	0.3733	0.5790	0.5847
10135	AUS1	AUS	0.2430	0.0556	0.2986	0.4631	0.4770
10138	AUS1	AUS	0.3559	0.2809	0.6369	0.9878	1.0081
10139	AUS4	AUS	0.3242	0.2430	0.5672	0.8797	0.5086
10166	NZE1	AUS	0.3392	0.3168	0.6561	1.0175	1.1989
10167	NZE1	AUS	0.3402	0.3563	0.6965	1.0803	1.2511
10168	NZE1	AUS	0.3377	0.3051	0.6428	0.9970	1.1593
10169	NZE1	AUS	0.3448	0.2989	0.6437	0.9983	1.4064
10184	NZE1	AUS	0.3633	0.3548	0.7181	1.1137	1.2805
10185	NZE1	AUS	0.3614	0.3774	0.7387	1.1457	1.3215
10189	NZE1	AUS	0.3397	0.3257	0.6654	1.0321	1.1566

Aircraft	Operator	Cont	Damage GAG	Damage SPEC	Damage TOT	Damage Index	Damage/hour
10190	NZE1	AUS	0.3334	0.3045	0.6379	0.9893	1.1841
10284	AUS1	AUS	0.3162	0.1728	0.4890	0.7584	0.8262
10329	AUS1	AUS	0.3295	0.2805	0.6100	0.9461	0.8818
10444	NZE2	AUS	0.4601	0.8414	1.3015	2.0186	1.3763
10445	NZE2	AUS	0.4573	1.4728	1.9301	2.9935	1.7408
10102	GER1	EUR	0.3451	0.2736	0.6187	0.9596	0.8889
10108	NOR1	EUR	0.2918	0.1286	0.4204	0.6521	0.8730
10116	NOR1	EUR	0.2180	0.1298	0.3478	0.5394	0.3509
10186	GER1	EUR	0.3588	0.3072	0.6660	1.0330	0.5772
10224	LUX1	EUR	0.3682	0.3990	0.7672	1.1899	2.0385
10268	GER2	EUR	0.3266	0.1978	0.5244	0.8133	0.8841
10269	LUX1	EUR	0.2960	0.1511	0.4471	0.6934	0.9839
10270	GER2	EUR	0.3251	0.2453	0.5704	0.8847	0.9053
10274	ICE1	EUR	0.3898	0.3617	0.7516	1.1656	1.5511
10300	ICE1	EUR	0.4012	0.4211	0.8223	1.2753	1.4883
10332	SPA1	EUR	0.3301	0.2714	0.6015	0.9329	1.2880
10341	DAN1	EUR	0.3453	0.2200	0.5653	0.8768	0.5319
10343	SPA1	EUR	0.3236	0.2632	0.5868	0.9100	1.0190
10360	BEL1	EUR	0.3130	0.2061	0.5191	0.8051	1.0025
10366	FRA1	EUR	0.3905	0.2130	0.6035	0.9360	1.2442
10367	FRA1	EUR	0.3536	0.2250	0.5786	0.8974	0.9856
10369	FRA2	EUR	0.3741	0.2913	0.6655	1.0321	1.7215
10370	FRA2	EUR	0.3406	0.2511	0.5917	0.9177	1.3025
10364	NAN1	SAM	0.3441	0.1724	0.5165	0.8011	1.1518
10365	NAN1	SAM	0.3082	0.1283	0.4365	0.6769	1.2420
all a/c			0.3479	0.2969	0.6448	1.0000	1.0958

Table 5 Calculation of damage index F28 fatigue meter data

Aircraft	Operator	Cont	Damage GAG	Damage SPEC	Damage TOT	Damage Index	Damage/hour
11053	NIG1	AFR	0.2965	0.1546	0.4511	0.7579	0.9749
11079	UNO2	AFR	0.4118	0.1667	0.5784	0.9718	1.7140
11993	NIG1	AFR	0.3203	0.1813	0.5016	0.8428	1.0775
12001	GHA1	AFR	0.3032	0.1746	0.4778	0.8027	1.2400
12002	GHA1	AFR	0.3391	0.2822	0.6212	1.0437	0.7717
12003	NIG1	AFR	0.3532	0.2117	0.5649	0.9490	0.6129
12005	GAB1	AFR	0.3110	0.1620	0.4730	0.7946	1.5596
12006	GAB1	AFR	0.3006	0.1433	0.4439	0.7458	1.4577
12007	GAB1	AFR	0.3069	0.2204	0.5273	0.8859	0.5397
11033	CAN1	AME	0.2769	0.0998	0.3767	0.6330	0.7143
11038	CAN1	AME	0.3010	0.1348	0.4358	0.7321	0.8371
11059	PER1	AME	0.3149	0.1920	0.5069	0.8516	0.8899
11085	ARG1	AME	0.3215	0.2111	0.5326	0.8949	1.4696
12010	PER1	AME	0.3086	0.2106	0.5192	0.8723	0.7287
12011	UNO2	AME	0.3857	0.4619	0.8476	1.4241	1.5531
11035	INO1	ASI	0.2848	0.1207	0.4055	0.6813	0.6921
11042	INO2	ASI	0.3349	0.1562	0.4911	0.8251	0.9503
12004	BIR1	ASI	0.3287	0.2207	0.5494	0.9231	1.0040
12008	BAD1	ASI	0.3047	0.2047	0.5094	0.8559	1.3454
12009	BAD1	ASI	0.3059	0.0943	0.4003	0.6725	1.1988
11026	AUS5	AUS	0.3452	0.3356	0.6808	1.1439	1.7592
11001	HOL1	EUR	0.3968	0.3470	0.7438	1.2497	2.9981
11003	HOL1	EUR	0.3353	0.2304	0.5658	0.9505	1.3261
11004	GER1	EUR	0.3421	0.3496	0.6917	1.1620	0.8256
11008	HOL2	EUR	0.3780	0.2804	0.6584	1.1061	0.9216
11009	NOR1	EUR	0.3167	0.1863	0.5030	0.8451	1.7024
11014	ITA1	EUR	0.3620	0.3318	0.6939	1.1657	1.3711
11017	SPA1	EUR	0.4307	0.6825	1.1132	1.8703	1.4761
11019	SPA1	EUR	0.4257	0.7756	1.2013	2.0183	1.6585
11023	SPA1	EUR	0.4314	0.5925	1.0239	1.7203	1.4955
11027	GER4	EUR	0.3992	0.3062	0.7054	1.1852	0.8080
11046	GER3	EUR	0.3017	0.1307	0.4324	0.7265	0.7264
11057	TUR1	EUR	0.3371	0.2181	0.5552	0.9327	1.3014
11067	SWE1	EUR	0.3189	0.1665	0.4854	0.8155	1.2363
12013	SWE1	EUR	0.2871	0.1167	0.4038	0.6784	0.9743
12014	SWE1	EUR	0.3174	0.2270	0.5444	0.9147	1.1551
11041	UNO1	UNO	0.3328	0.2397	0.5725	0.9619	0.5831
12012	UNO3	UNO	0.3651	0.3999	0.7650	1.2853	1.9959
all a/c			0.3434	0.2518	0.5952	1.0000	1.2243

Table 6 Statistical properties F27 fatigue meter date

Variable	Average	Standard dev	Coef. of var	Maximum	Minimum
Flight duration	1.0299	0.3661	0.3555	1.7834	0.5263
-0.35g/fl	0.0002	0.0004	2.8569	0.0028	0
0.05g/fl	0.0024	0.0026	1.0565	0.0124	0
0.45g/fl	0.0891	0.0541	0.6069	0.2800	0.0188
0.75g/fl	3.3125	2.4709	0.7459	16.0729	0.7188
1.25g/fl	6.8020	5.5504	0.8160	29.8541	0.5671
1.55g/fl	0.2233	0.1927	0.8630	0.9398	0.0428
1.95g/fl	0.0053	0.0058	1.1033	0.0277	0
2.35g/fl	0.0003	0.0008	2.5104	0.0037	0
|0.25g|/fl	4.6750	3.6065	0.7714	21.9053	0.6385
|0.55g|/fl	0.1356	0.0902	0.6647	0.4856	0.0284
|0.95g|/fl	0.0031	0.0031	0.9940	0.0140	0
|1.35g|/fl	0.0001	0.0004	3.6724	0.0028	0
Damage Index	1.0090	0.4115	0.4078	2.9830	0.3827
Damage/Hour	1.0532	0.3886	0.3690	2.2264	0.2483

Table 7 Statistical properties F28 fatigue meter data

Variable	Average	Standard dev	Coef. of var	Maximum	Minimum
Flight duration	0.9141	0.3359	0.3674	1.6492	0.4167
-0.35g/fl	0.0004	0.0007	1.6592	0.0031	0
0.05g/fl	0.0036	0.0035	0.9744	0.0154	0
0.45g/fl	0.0778	0.0714	0.9177	0.3569	0.0142
0.75g/fl	2.7052	1.6404	0.6064	8.8430	0.6096
1.25g/fl	5.3075	3.0820	0.5807	13.9167	1.8476
1.55g/fl	0.2164	0.1820	0.8408	0.6975	0.0308
1.95g/fl	0.0100	0.0148	1.4773	0.0643	0
2.35g/fl	0.0010	0.0020	2.0278	0.0072	0
|0.25g|/fl	3.7032	2.0755	0.5605	11.0634	1.4783
|0.55g|/fl	0.1239	0.1042	0.8406	0.4297	0.0290
|0.95g|/fl	0.0050	0.0063	1.2523	0.0261	0
|1.35g|/fl	0.0003	0.0006	1.6992	0.0020	0
Damage Index	0.9969	0.3152	0.3162	2.0178	0.6328
Damage/hour	1.2012	0.4770	0.3971	2.9981	0.5397

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Appendix

A Development of a damage index DI

In the following, an algorithm will be derived to calculate a relative damage figure associated with a measured load factor spectrum per flight.

The basic assumptions that underlay this derivation are as follows:

a. "Damage rule": The fatigue damage (or inherent crack growth damage) of a load cycle is proportional to the amplitude to the power k:

$$D(\text{cycle } dS) \div (dS)^k. \qquad \text{(A.1)}$$

The value of the slope factor k is a material-dependent constant.

b. "Load cycle content": The load cycle content of a flight consists of two parts, namely the "g-spectrum loads", associated with gusts and manoeuvres, and the "Ground-Air-Ground" or GAG cycle.

The GAG cycle is defined by the lowest stress occurring once per flight while the aircraft is standing on the ground (S_{gr}), and the highest stress reached on the average once per flight (S_{once}).

The load cycles associated with the g-spectrum are defined by the "symmetrized" load factor exceedance data. The number of load cycles with an amplitude equal to dn or larger is taken equal to the symmetrized number of exceedings of dn, y(dn).
The smallest load cycles to be included in the damage calculation have an amplitude corresponding with dn=0.1

c. "Normalization": The Damage Index must give a relative measure of the damage associated with a specific load spectrum: its absolute value is irrelevant: For this reason, calculated damages will be "normalized" by division by the Damage corresponding to the average spectrum pertaining to "all flights" for the specific aircraft type.

d. "Structural Location": In principle, the Damage Index refers to one specific structural location. In the present study, the DI-values for both the F27 and the F28 refer to the lower wing skin near the wing root.

In the present study, the following numerical values were adopted:

Ground stress level: The lowest stress reached on the ground is just equal to zero.

The slope factor k has been taken as k=3; this value lies in the lower band of the values found in flight simulation fatigue and crack growth tests under transport aircraft wing test spectra (ref. 1)

The mathematical derivation of the DI- equation is given below

i) Calculation of GAG damage

Load factor level exceeded once per flight:

X_{once} is found by log-linear interpolation between the exceedance frequencies of the acceleration levels x_1 ($\Delta n = 0.25$) and x_2 ($\Delta n = 0.55$):

$$x_{once} = \frac{x_2 * \log yp(x_1) - x_1 * \log yp(x_2)}{\log yp(x_1) - \log yp(x_2)} \qquad \text{(A.2)}$$

Amplitude of the GAG cycle:

$$S_{GAG} = \frac{x_{once} + 1 - x_{ground}}{2} \qquad \text{(A.3)}$$

With $x_{ground} = o$

Damage due to GAG cycle: $D_{GAG} = (S_{GAG})^k$ (A.4)

ii) Calculation of damage of spectrum loads

Number of cycles with amplitude equal to or larger than $x = y(x)$.

Number of cycles with amplitude x*, x < x* < x + dx is equal to

$$y'(x) = -\frac{d(y)}{dx}$$

Damage due to cycles with amplitude between x_ℓ and x_u:

$$SD = \int_{x_\ell}^{x_u} D(x)\ y'(x)dx \qquad \text{(A.5)}$$

with $D(x) = x^k$

y(x) is an exponential function between x_i and x_{i+1}

$$\log y(x) = \log y(x_i) + a_i(x - x_i)$$

$$a_i = \frac{\log y(x_{i+1}) - \log y(x_i)}{x_{i+1} - x_i} \qquad \text{(A.6)}$$

y'(x) between x_i and x_{i+1} can be written:

$$y'(x) = -y(x_i)e^{-a_i x_i} \cdot a_i\ e^{a_{ix}} \qquad \text{(A.7)}$$

or $y'(x) = b_i\ e^{a_i x}$

$$\text{with } b_i = -a_i\ e^{-a_i x_i}\ y(x_i) \qquad \text{(A.8)}$$

The spectrum damage SD may now be calculated from:

$$SD = \sum_{i=1}^{3} SD_i$$

$$SD_1 = b_1 \int_{x_\ell}^{x_2} x^k e^{+a_1 x} dx, \qquad x_\ell = 0.10$$

$$SD_2 = b_2 \int_{x_2}^{x_3} x^k e^{+a_2 x} dx, \qquad \text{if } y(x_3) \neq 0$$

$$SD_2 = b_1 \int_{x_2}^{x_3} x^k e^{+a_1 x} dx, \qquad \text{if } y(x_3) = 0 \tag{A.9}$$

$$SD_3 = b_3 \int_{x_3}^{x_4} x^k e^{+a_3 x} dx, \qquad \text{if } y(x_4) \neq 0$$

$$SD_3 = 0 \qquad \text{if } y(x_4) = 0$$

iii) <u>Calculation of total damage</u>

The total damage is equal to

$$D_{tot} = SD + D_{GAG} \tag{A.10}$$

iv) <u>Calculation of damage index DI</u>

The total damage per flight pertaining to <u>all</u> aircraft is called $D_{tot,all}$.
The <u>Damage Index</u> for aircraft j is calculated from:

$$DI_j = \frac{(D_{tot})_j}{D_{tot,all}} \tag{A.11}$$