Development of Load Spectra for Airbus A330/A340 Full Scale Fatigue Tests

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Summary

For substantiation of the recently certified medium range Airbus A330 and long range A340 the full scale fatigue tests are in progress. The airframe structures of both aircraft types are tested by one set of A340 specimens.

The development of the fatigue test spectra for the two major test specimens which are the center fuselage and wing test and the rear fuselage test is described. The applied test load spectra allow a realistic simulation of flight, ground and pressurization loads and the finalization of the tests within the pre–defined test period.

The paper contains details about the 1g and incremental flight and ground loads and the establishment of the flight–by–flight test program, i.e. the definition of flight types, distribution of loads within the flights and randomization of flight types in repeated blocks. Special attention is given to procedures applied for acceleration of the tests, e.g. omission of lower spectrum loads and a general increase of all loads by ten percent.

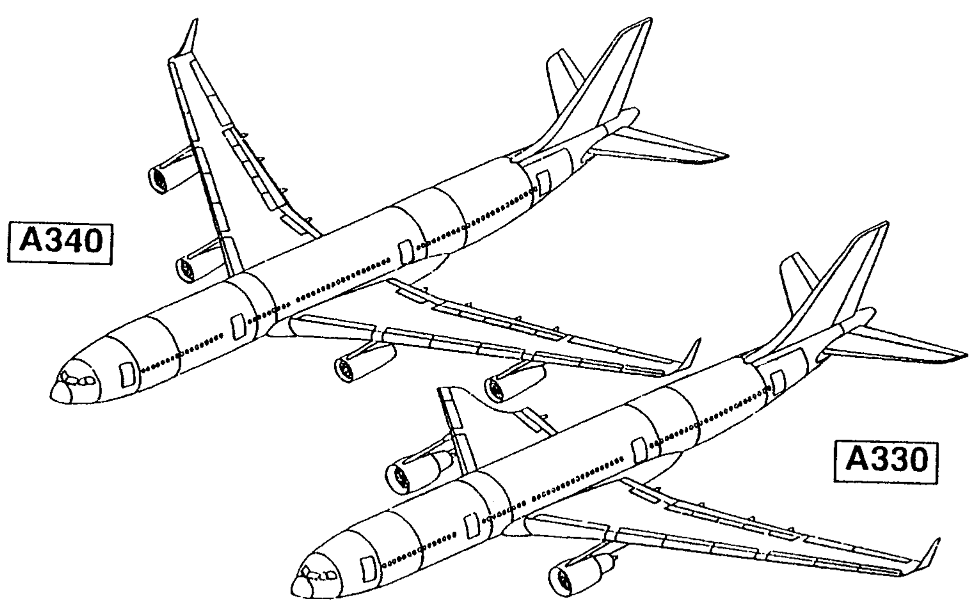

Fig. 1 Airbus aircraft.

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1. Introduction

The newest Airbus products, the medium range A330 and the long range A340 have been certified in 1992 and 1993, respectively. The structure of both aircraft types is very similar (Fig. 1). However, the A340 is equipped with 4 engines with a maximum thrust of 130.000 lbs and the A330 with 2 engines with a maximum thrust of 136.000 lbs. Furthermore the A340 contains a center undercarriage in addition. With respect to this similarity both aircraft types are justified by one set of specimens using the A340–300 structure for the multi-section full scale fatigue test. Four major specimens are tested which are the forward fuselage, the center fuselage and wing, the rear fuselage and the horizontal tailplane.

The development of the load spectra for the two major tests, i.e. center fuselage and wing test and rear fuselage test, is described. These load spectra allow a realistic simulation of all flight, ground and pressurization loads to achieve the most accurate prediction of the fatigue and damage tolerance behavior. The major differences between A330 and A340 regarding design service goals, mission profiles and resulting external loads are considered.

2. Operational Conditions and Representation

All Airbus aircraft are designed for an in–service life of more than 20 years. With respect to earlier Airbus experience and the customers' requirements typical A330 and A340 mission profiles have been defined which were the basis for type certification and have been used for test load spectra definition, see Fig. 2. The typical A330 mission contains an average block time of 90 min. and an operation altitude of 35.000 ft. For A340 two typical mission profiles are defined, i.e. a short range mission with 75 min./35.000 ft and a medium range mission with 405 min./39.000 ft. With respect to the planned service time of more than 20 years the design service goals are 40 000 flights for the A330 and 20 000 flights for the A340; the latter figure consists of 10 000 short range plus 10 000 medium range flights.
Since the real operation may deviate from the typical mission profiles the fatigue and damage tolerance behavior of additional mission profiles will be evaluated to allow an adaptation of the structural inspection program.

65 percent payload fatigue mission			
units	A330 SR	A340 SR	A340 MR
flight time [min]	90	75	405
distance [nm]	500	380	2960
max. alt. [ft]	35000	35000	39000

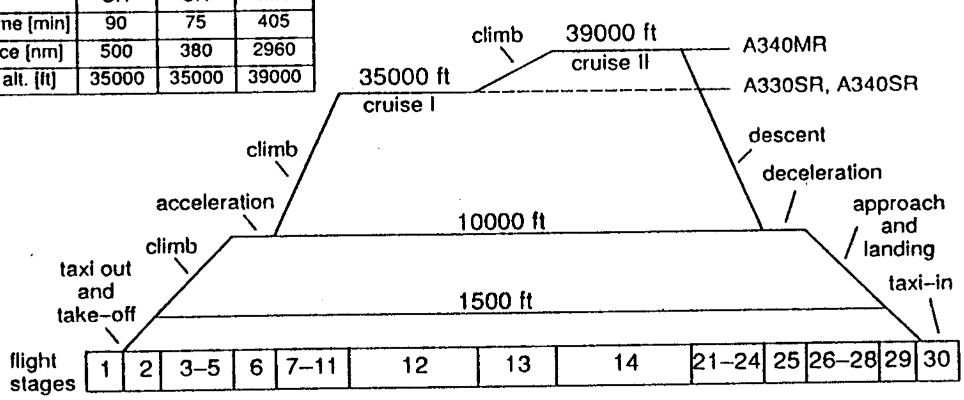

Fig. 2 Mission profiles.

The mission profiles have been divided in more than 30 flight stages for which all relevant flight and ground loads and the corresponding internal pressure have been determined, see. Fig. 3. The splitting of the structure in more than one test specimen allows an optimized representation of the operational loads by consideration of their effect on the fatigue and damage tolerance behavior. Insignificant load cases are deleted for one or the other test specimen which saves test time for the exact representation of the significant load cases.

The major differences between the center fuselage and wing test compared with the rear fuselage test are the representation of the lateral gusts and lateral and vertical manoeuvre which are only applied to the rear fuselage specimen. On the other side the ground loads for the rear fuselage specimen are limited to taxi–in and taxi–out, take off, landing run and touch down.

This approach has been used for all previous Airbus full scale fatigue tests and the correctness is confirmed by the in–service experience.

operational basic condition	loading component	centre fuselage / wing	rear fuselage	representation
standing		X	X	steady case
taxi–out		X	X	two cycles per flight
preflight braking		X	–	one cycle per flight
ground turning		X	–	two cycles per flight
take–off run		X	X	two cycles per flight
rotation		X	X	steady case
initial climb climb cruise I cruise II initial descent descent approach	vertical gust	X	X	stepped spectra
	vertical manoeuvre	–	X	stepped spectra
	lateral gust	–	X	stepped spectra
	lateral manoeuvre	–	X	stepped spectra
	Δp	X	X	stepped spectra
	temperature loads	–	X	stepped spectra
touch down		X,	X	one cycle per flight
landing roll		X	X	two cycles per flight
braking		X	–	one cycle per flight
ground turning		X	–	two cycles per flight
taxi–in		X	X	two cycles per flight

Fig. 3 Application and representation of operational condition.

3. Development of Load Spectra for Center Fuselage and Wing Test

The center fuselage and wing specimen EF2 is identical to the A340–300 and contains 31 m of the fuselage structure as well as the center and outer wings without movable surfaces; see Fig. 4. All attachments to movable surfaces, undercarriages, pylons and winglets are original structures. Pylons, undercarriages and winglets are dummies for load introduction purposes. The specimen is supported by 6 links at the forward and rear dummy steel bulkheads and is loaded by 92 hydraulic jacks and internal pressure.

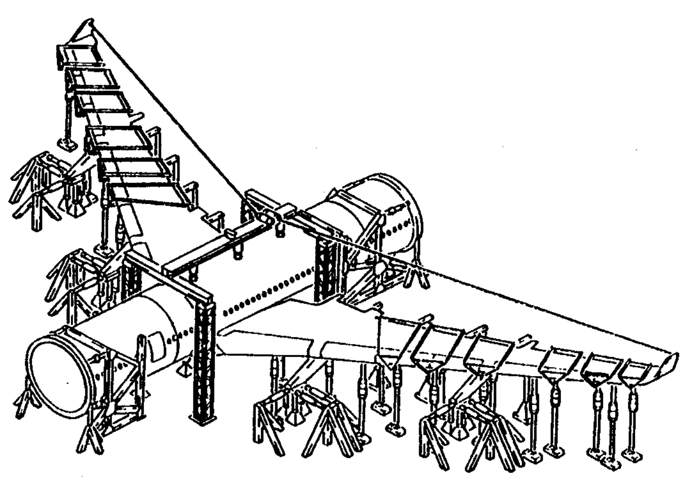

Fig. 4 Full scale fatigue test EF2 "center fuselage and wing".

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The goal of the EF2 test is the simulation of 80 000 test flights considering the increase of all test loads by 10 percent and the simulation of A340 loads in phase I and A330 loads in phase II; see Fig. 5. The design service goal of the A340 is verified after reaching 40 000 test flights, whereby the A330 service goal needs a demonstration of 80 000 test flights. The insertion of artificial damages is scheduled latest at 1.5 times of the design service goals.

The reason for increasing all test loads by 10 percent is to save test time which is mainly influenced by the high deflection of the outer wings. An increase of test loads leads to a decrease of the number of flights to be simulated.

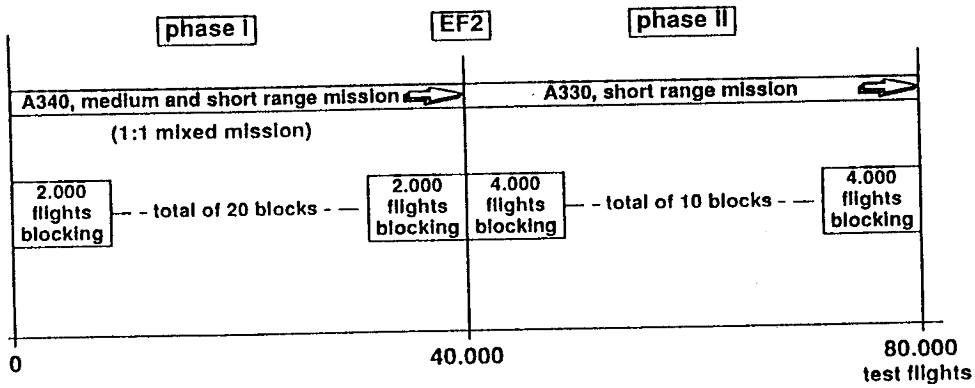


Fig. 5 Test phases and sequence of blocks.

3.1 Flight Load Spectra Representation

Each typical mission profile includes more than 30 flight stages; see Fig. 6. For representative fuselage and wing sections the 1g load time histories are plotted and up to nine representative test flight segments are selected for simplification of the load spectra. The selection considers four criteria:

- maintaining maximum original 1g variation
- maintaining maximum original 1g wing and fuselage bending moments
- representing original flap and slat conditions
- representing the cruise flight stage in a separate segment

The simplification described above leads to an adequate representation of the 1g variation which is important for the correct fatigue damage in test.

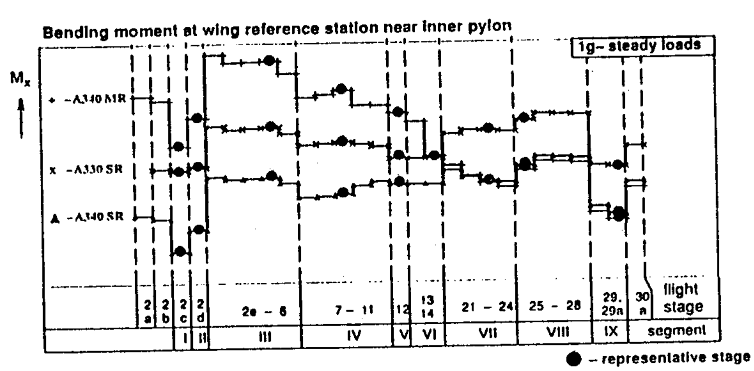


Fig. 6 Representation of 1g– condition.

For each of the segments vertical gust load spectra are calculated. Instead of using ESDU 69023 as done for previous tests the vertical gust load spectra are based on the data presented in the AGARD report No. 605. A new interpretation of this data was focussed on the high levels of gust velocity and presented in the CAA report NPA25C–205. Since the equation leads to a single slope curve which gives an insufficient agreement with the measured data for low gust velocities, a second slope has been introduced by Airbus Industrie in the gust statistical data. The gust modeling used for A330/A340 gust spectra is described by the following equation:

$$n_{\mu_0} = A \times e^{\frac{-B\mu_0}{K_0}} \times K_1$$

where:

- n_{μ_0} : number of exceedences of gust velocity μ_0 (ft/s) per nautical mile
- μ_0 : gust velocity in ft/s EAS
- A,B : function of altitude different for $\mu_0 < 10$ ft/s EAS and $\mu_0 > 10$ ft/s EAS
- K_0 : factor 1.00 for vertical gust
  1.15 for lateral gust
- K_1 : ratio of upgust or downgust to total gusts (function of altitude) where K_1 up + K_1 down = 1.0.

The application of the equation given above leads to the vertical gust spectra for the wing rib 10 shown in Fig. 7 LH side. The spectra include the 1g loads which are defined for the segments. The RH side of Fig. 7 shows the ground–air–ground spectra (GAG) which were developed using the method of ESDU 79024.

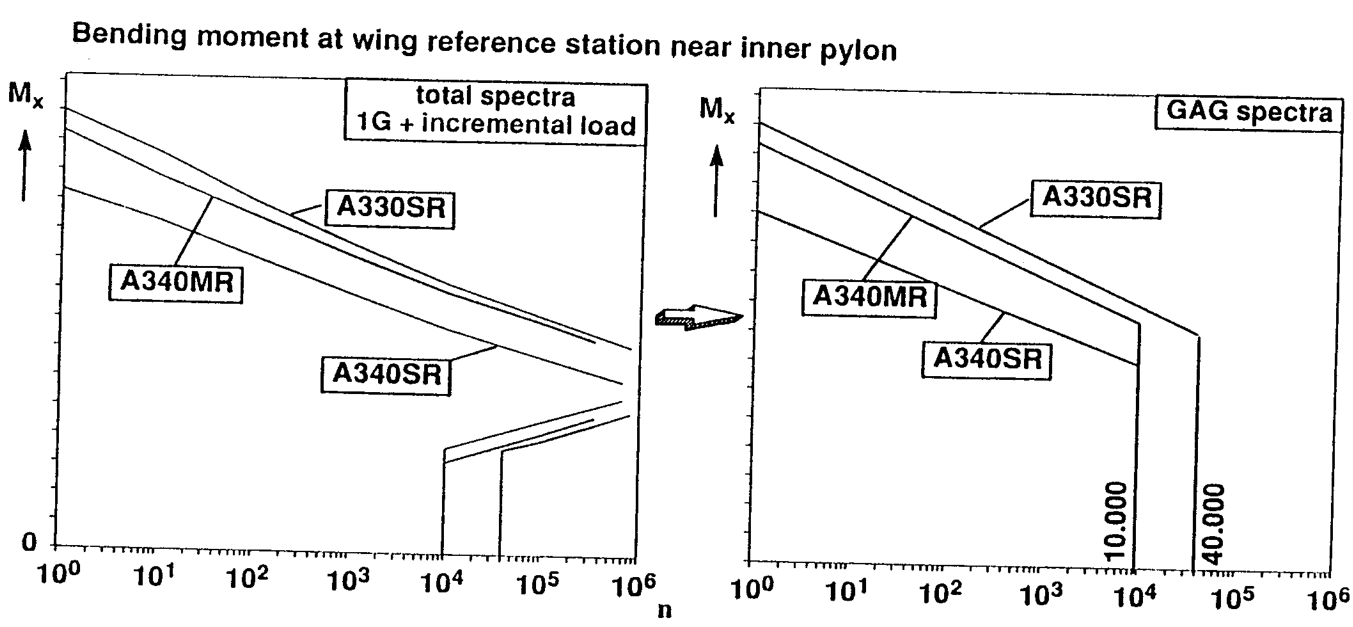
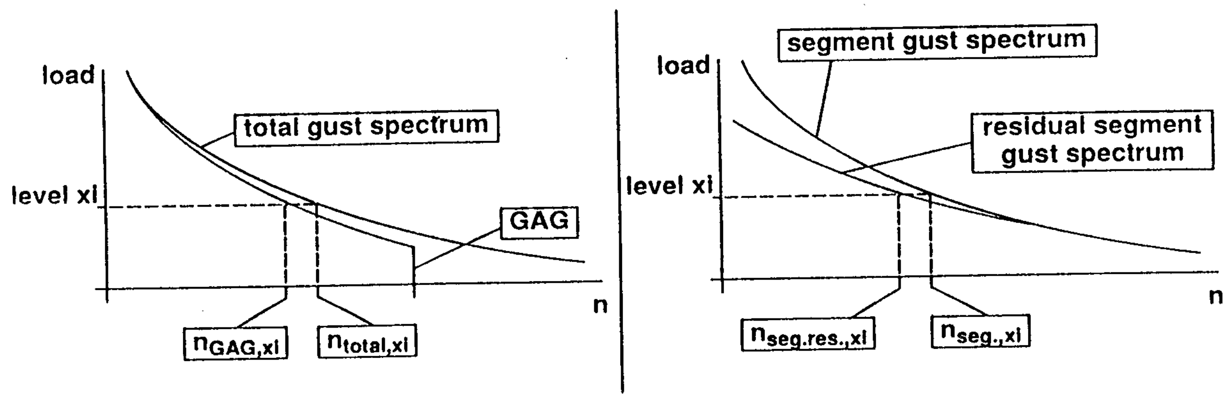


Fig. 7 Total vertical gust spectra and ground air ground spectra (GAG).

The simulation of the GAG spectrum is applied during the cruise stage, since the gust loads with the highest load levels occur during the cruise stage. However, this type of application is conservative for the pressurized fuselage. The simulation of the GAG spectrum during cruise has to be considered by a reduction of the segment spectra as described in Fig. 8.



For the different load levels x_i the number of cycles for the residual gust spectrum $n_{seg.res.,xi}$ has to be calculated as follows:

$$n_{seg.res.,xi} = n_{seg.,xi} - \frac{n_{seg.,xi}}{n_{total,xi}} \times n_{GAG,xi}$$

Fig. 8 Determination of residual gust spectra.

The load spectra for the individual segments and for the GAG spectrum are stepped into six to nine load levels and distributed to eight basic flight types, i.e. A to H. These flight types occur with different frequencies in repeated blocks of 2.000 flights (A340 SR and MR) and 4.000 flights (A330 SR), and are supposed to represent different weather conditions.

An example for the described procedure is shown in Fig. 9 which represents the total gust spectrum, the resulting GAG, the original gust spectrum for cruise and the residual gust spectrum for cruise.

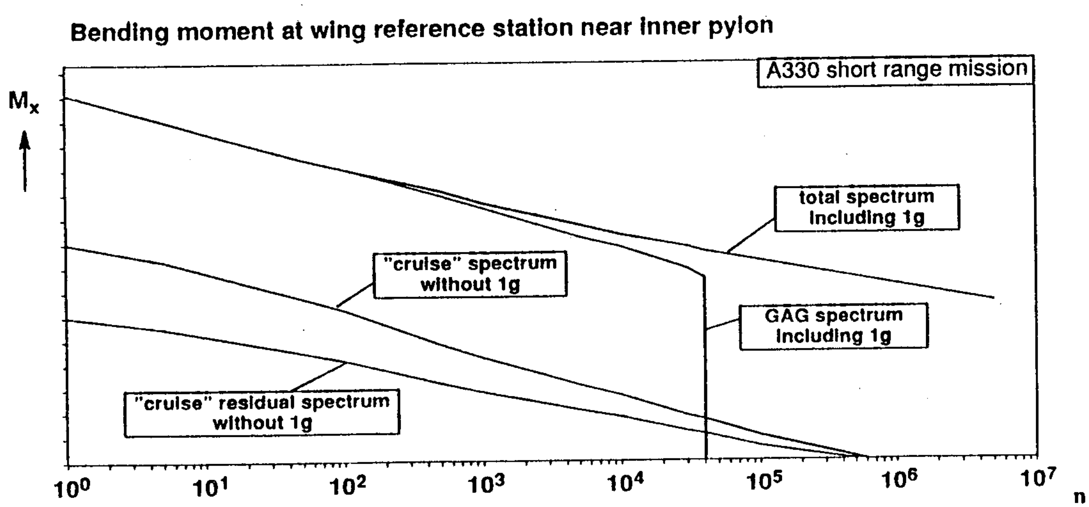


Fig. 9 "Cruise" residual spectrum.

The matrix of Fig. 10 shows the simulation of the GAG spectrum and the load cycles for the residual spectrum. This procedure of stepping and representation has been applied to all segments for the three mission profiles.

Summary of load step frequencies A330 (short range): "cruise"													
flight type	frequency of flight type per block	step I	step II	step III	step IV	step V	step VI	step VII	step VIII	step IX	load cycles per flight	load cycles per block	load cycles per life
A	5	+1			1	2	4	5	7	22	41	205 +5	2 050 +50
B	7		+1			1	2	4	6	21	34	238 +7	2.380 +70
C	22			+1			1	3	5	15	24	528 +22	5.280 +220
D	56				+1			2	4	10	16	896 +56	8 960 +560
E	130					+1			3	8	11	1.430 +130	14.300 +1.300
F	380						+1		2	6	8	3 040 +380	30.400 +3.800
G	1.000							+1		3	3	3 000 +1 000	30 000 +10.000
H	2.400								+1	1	1	2.400 +2.400	24.000 +24.000
gust load cycles per block		+5	+7	+22	5 +56	17 +130	56 +380	231 +1 000	1561 +2.400	9 867		Σ	117.370 +40 000
gust load cycles per life		+50	+70	+220	50 +560	170 +1.300	560 +3 800	2 310 +10.000	15 610 +24 000	98.670			
cumulative no. of cycles per life		+50	+120	+340	50 +900	220 +2.200	780 +6.000	3.090 +16.000	18 700 +40.000	117.370			

Fig. 10 Loads matrix, ground air ground spectrum (GAG) (example for A330 short range mission).

3.2 Definition of Truncation and Omission

The test spectrum definition includes the consideration of truncation (high load clipping) and omission (low load clipping), see Fig. 11. The truncation level has a significant impact on fatigue crack initiation and on crack growth. Different methods exist for definition of the truncation level which lead to different test results especially for wing structure. The method applied to the EF2 spectra is a statistical approach. The defined truncation level will be reached or exceeded by 99 percent of the in–service aircraft within an inspection interval, i.e. from a statistical point of view only one percent of the in–service aircraft may crack earlier than the test specimen and show a faster crack growth. According to this procedure the maximum test load is 79 percent of the load occurring once per inspection interval.

- level is set to 79 percent of the incremental loads level, which occurs once per an inspection interval:
  -> A330: 8.000 flights,
  -> A340: 4.500 flights,
- value represents the 99 percent confidence level that this load will be exceeded by the aircraft fleet within the interval.

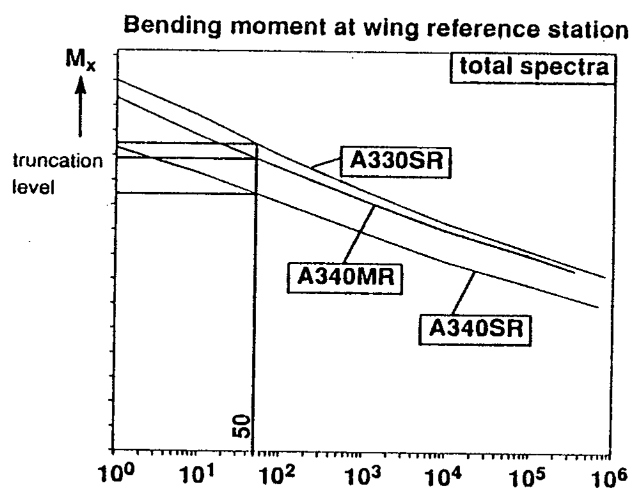


Fig. 11 Truncation level.

The determination of the omission level is described in Fig. 12. Many investigations have shown the importance of a low omission level to achieve representative crack growth results. Since this is important for both, natural and artificial damages, this aspect has been considered from the beginning of the test. Based on the comparative coupon tests for the A320 (Ref. /1/) the omission was set to 11 to 12 MPa for a representative bottom wing station which results in 26 to 33 gust cycles per flight depending on the aircraft type and mission.

- determination of the omission level to realize gust distribution by steps but with a minimum error in fatigue life and crack propagation:
  - test phase I with A340 loads and in average 26 gust cycles + 1 GAG cycle per flight,
  - test phase II with A330 loads and in average 25 gust cycles + 1 GAG cycle per flight,
- stress level of about 11 MPa in wing panels.

A340MR:

32+1 gust cycles/flight: (32+1) x 10.000 = 330.000 cycles

A340SR:

20+1 gust cycles/flight: (20+1) x 10.000 = 210.000 cycles

A330SR:

25+1 gust cycles/flight: (25+1) x 40.000 = 1.040.000 cycles

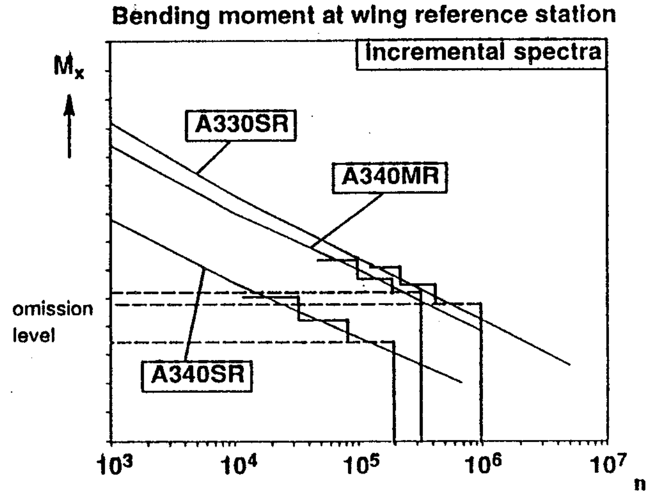


Fig. 12 Omission level.

3.3 Ground Load Spectra Representation

The full scale fatigue test considers a total of seven different 1g conditions on ground, i.e. four before and three after the airborne time. The basic 1g loads are superimposed by incremental loads due to taxi, turning, rotation, braking and touch down, where the load distribution for taxi and turning are based on the ESDU data sheets 75008.

Fig. 13 contains the load spectrum for touch down which was already used for all previous Airbus full scale fatigue tests. The touch down loads are simulated by three loading steps representing sinking speeds of 2.0, 3.5 and 6.0 ft/s. The three step spectrum is based on an equivalent damage approach. Fig. 13 also shows the braking spectrum which is based on earlier Airbus A300 measurements and simulated by a two step spectrum with decelerations of 0.2 g and 0.3 g.

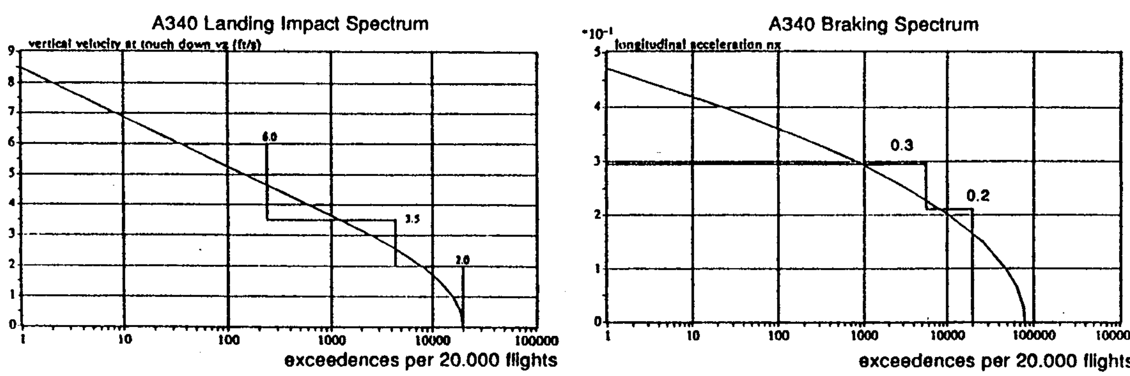


Fig. 13 Landing and braking spectrum.

The combination of the basic flight types A to H with the ground loads which are different in the flight types, i.e. touch down, taxi and braking, is given in Fig. 14. As a result of this combination 21 flight types are defined for each mission profile, i.e. in test phase I (two missions) 42 different flight types are simulated and 21 flight types in test phase II (one mission).

- simulation of rough and smooth flights by 8 basic flight types A to H to represent severity of weather and landing conditions,
  - severity: rough <——————> smooth
  - flight type: A—B—C—D—E—F—G—H
- combination with additional three ground cases to consider typical runway configurations (X, Y and Z),
- in total 21 flight types

aircraft mission	flight type	total number of flights	number of taxi cases			number of landing cases			number of braking cases	
			step X	step Y	step Z	6.0 ft/s	3.5 ft/s	2.0 ft/s	−0.3g (x,y)	−0.2g (z)
A330 SR	A – H	4.000	160	960	2.880	50	830	3.120	1.120	2.880
A340 SR	A – H	1.000	40	240	720	12	208	780	280	720
A340 MR	A – H	1.000	40	240	720	12	208	780	280	720

Fig. 14 Combination of ground and flight load cases.

3.4 Definition of Loading Sequence

Besides the ground and flight loads described above, the cabin differential pressure is simulated during application of flight loads. The cabin differential pressure distribution is in accordance with the mission profile and simplified by a linear variation between defined fix–points and a maximum of 574 hPa at cruise; see Fig.15.

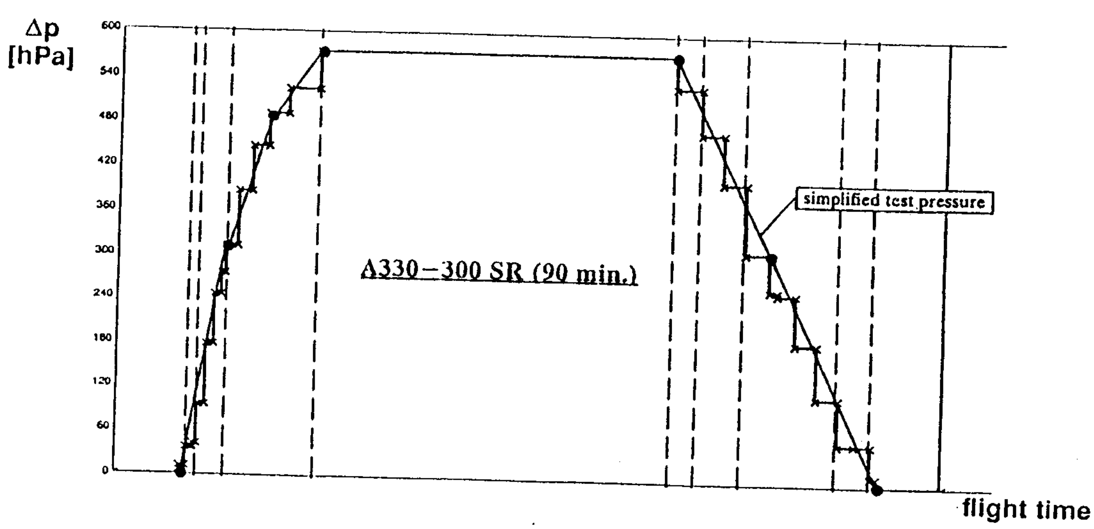


Fig. 15 Cabin pressure differential.

The definition of the loading sequence contains three aspects, i.e. definition of flight types, definition of the sequence of the flight types in a given block and the sequence of the blocks.

Fig. 16 contains the load time histories for the most severe flight type AZ and the smoothest flight type HZ for the A340 medium range. The main distribution of loads is pre–defined by the load spectra for the representative segments and the described combination between flight and ground loads. The load distribution within the segments is randomized with some limitations as no half cycle representation; an upgust is followed by a downgust, an upward taxi bump is followed by a downward taxi bump.

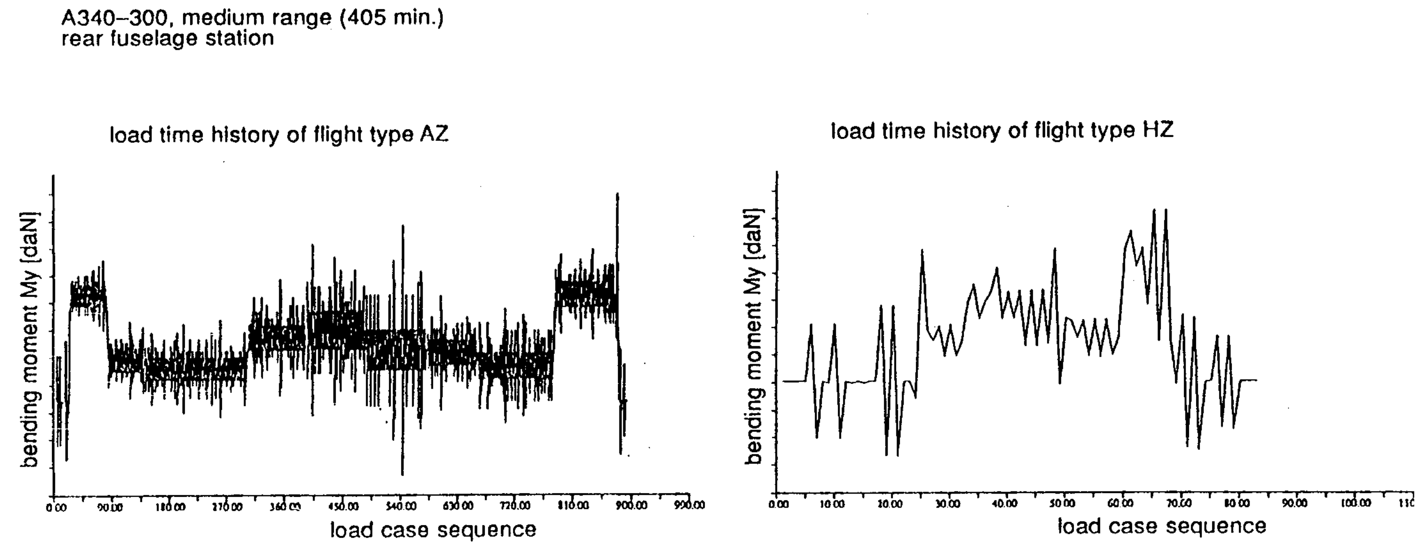


Fig. 16 Load sequence in test flights.

Fig. 17 contains the distribution of the A330 short range flight types within a block of 4.000 flights which is repeated 10 times within test phase II. The more severe flight types AZ to DZ are positioned by an equal space distribution whereby the other flight types are randomly distributed. During test phase I 20 blocks will be applied containing A340 loads and afterwards during test phase II 10 blocks of A330 loads.

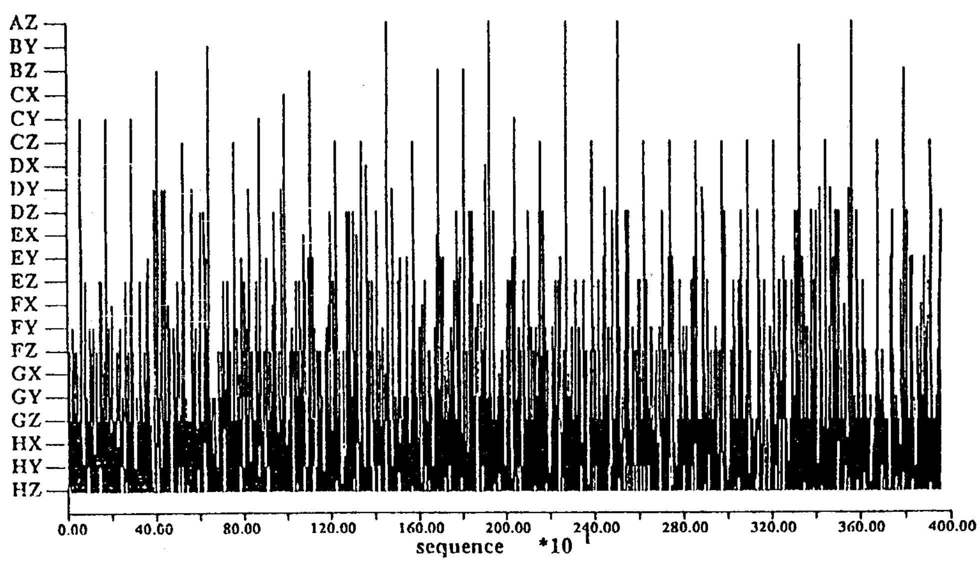


Fig. 17 Block sequence.

3.5 Interpretation of Test Results

Due to the fact that one specimen is used to justify the A340 and A330 and all test loads are increased by 10 percent, all test results have to be evaluated carefully. The test results have to be recalculated to define the relevant fatigue crack initiation and the crack growth periods for the three aircraft types certified up to now, i.e. A340–200, A340–300 and A330–300. The re–evaluation of the fatigue crack initiation is normally carried out by a Miner calculation and the periods between damage detection and repair by crack growth calculations or Miner calculation (risk analysis for parts not inspectable for less than load path failure).

The effect of the load increase can be determined by using the relevant SN curve for the structural detail. The slope of the SN curve $\varkappa$ is dependent on the loading environment (load level, spectrum shape etc.) and geometry (stress concentration, eccentricity, pre–stresses etc.). In general $\varkappa$ for constant amplitude tests and TWIST spectra is greater than 3; therefore a load increase of 10 percent results in a justified fatigue life of at least 1.25 times of the test life. For most of the structural details $\varkappa$ or the exponent n of the Forman equation is significantly greater than 3, so that an individual re–evaluation leads to more than 1.25 times of the test life. The accuracy of the relevant $\varkappa$ or the n to be applied needs not to be very high, since a variation of the exponent of ± 0.5 results in approximately ± 5 percent on life for a 10 percent load increase.

4. Development of Load Spectra for Rear Fuselage Test

The rear fuselage specimen EF3 contains 21 m of the rear fuselage structure up to the attachment of the rear spar of the horizontal tailplane; see Fig. 18. The horizontal tailplane and the APU compartment are replaced by steel constructions for load introduction purposes. The vertical tailplane loads are applied to the fuselage attach fittings by hydraulic jacks, because the CFRP vertical tailplane is tested separately. The specimen is supported by a steel construction at the forward end.

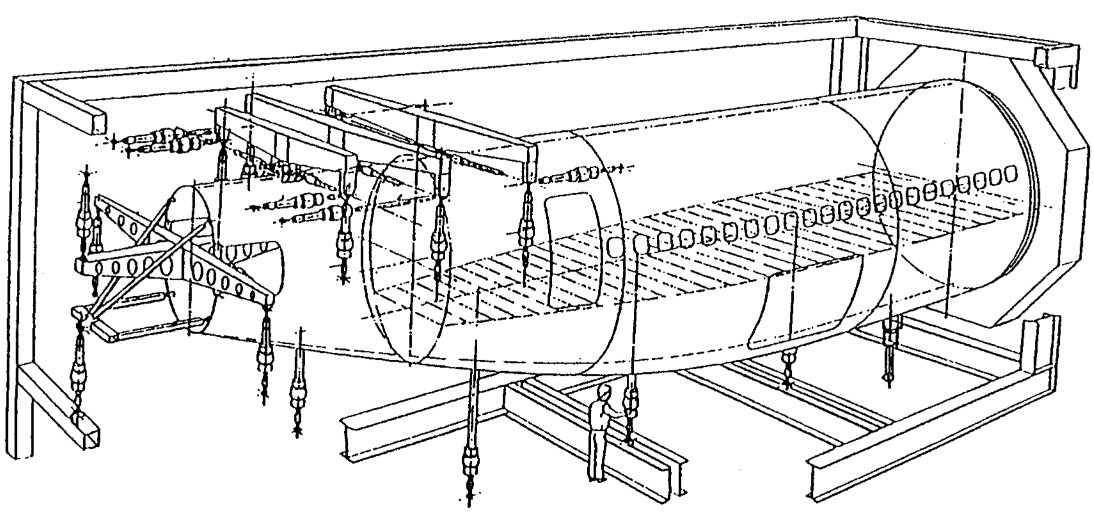


Fig. 18 Full scale fatigue test EF3 "rear fuselage".

In contrast to the EF2 specimen the goal of the EF3 test is > 100 000 flights, since no load increase factor of 10 percent is applied and at least 2.5 lifetimes should be justified. The application of a load increase was considered not to be necessary, since the test speed is similar to previous Airbus tests.

In general the test execution is very common to the EF2 test; i.e. A340 loads will be applied during phase I (50 000 flights) and A330 loads during phase II (> 50 000 flights). The following sub–chapters contain the major differences between EF2 and EF3 tests. Similar details are not addressed again.

4.1 Test Loading

Fig. 19 includes an overview about the EF3 test loading. This table shows that the EF3 is loaded additionally by lateral gusts and lateral and vertical manoeuvre as well as by temperature loads at the fuselage pick–up points to the CFRP vertical tailplane.

	basic loads (1G)	incremental loads	internal pressure	temperature effects
ground	standing on ground, taxi–out, take off run, rotation	taxi bumps (low speed) rolling bumps (high speed)		
flight	climb . cruise . approach (up to eleven different flight cases)	vertical gust lateral gust vertical manoeuvre lateral manoeuvre	according to altitude given in mission profile	according to altitude and defined temperature profile
ground	touch down, landing roll–out, taxi in	landing (2.0–6.0ft/s) rolling bumps (high speed) taxi bumps (low speed)		

Fig. 19 Test loading.

The lateral gust spectra which are important for the fuselage attachment area to vertical tailplane are based on the same statistics as the vertical gusts as described in chapter 3.1. The difference between vertical and lateral frequencies is considered by the factor K_0. Fig. 20 shows an example of a lateral gust spectrum for cruise.

The GAG spectrum is included due to the definition of the different flight types. The application of the definition according to ESDU 79024 is not considered, since this information is mainly valid for the wing.

The vertical and lateral manoeuvres are important for the unpressurized fuselage and the fuselage attachment areas to horizontal and vertical tailplanes. The manoeuvre spectra are calculated using the following equation:

$$\log N_{(y)} = \log P_L / L \times Y + \log (M_F \times D_F \times N_F)$$

where $N_{(Y)}$: load frequency exceeding load Y, sum of load cycles with a loading higher than value Y

P_L: probability of occurrence of limit load per load cycle

	normal flights	crew training flights
vertical manoeuvre	1.0×10^{-12}	7.0×10^{-6}
lateral manoeuvre	1.0×10^{-5}	7.0×10^{-3}

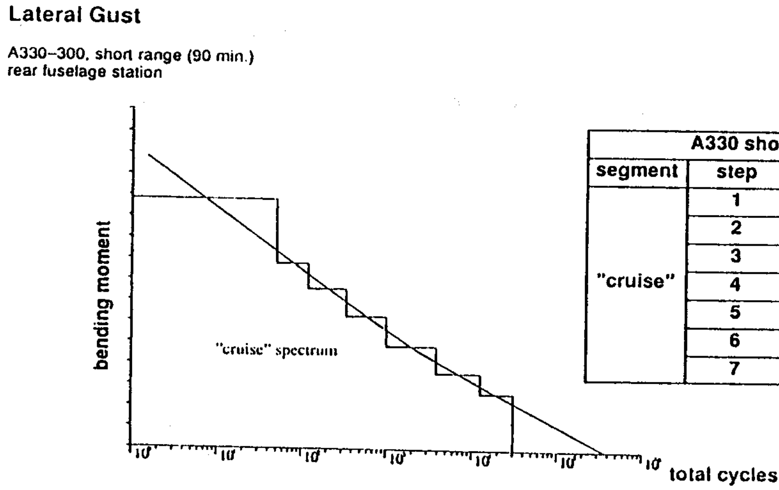
L : limit load

Y : loading

M_F : manoeuvre frequency in relation to flight distance (for normal and crew training flights)

D_F : flight distance

N_F : number of normal of crew training flights in one aircraft design goal.



A330 short range		
segment	step	lateral gust [ft/s]
"cruise"	1	29.90
	2	22.30
	3	19.20
	4	15.90
	5	12.30
	6	9.11
	7	6.70

Fig. 20 Lateral gust.

The ratio between crew training and normal flights is set to 1:50. Fig. 21 shows examples of the lateral and vertical manoeuvre spectra.

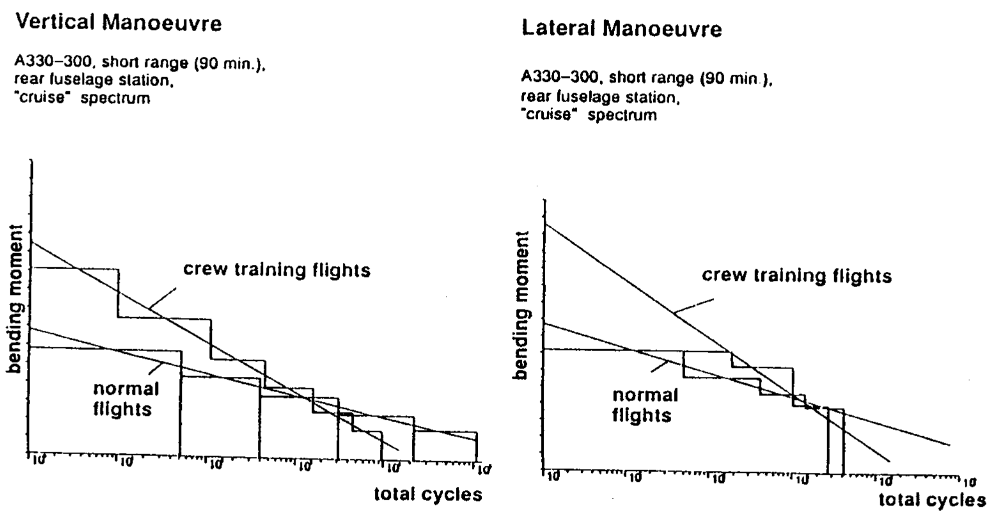
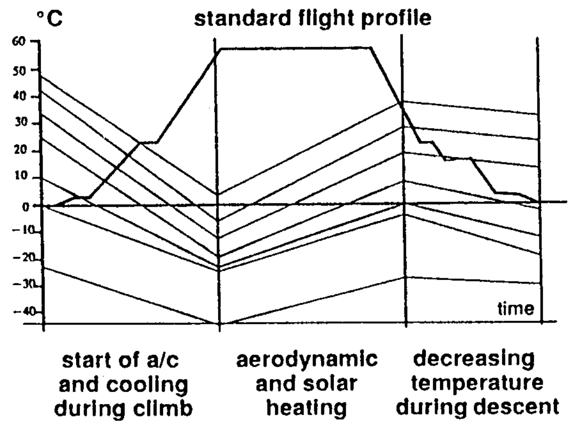


Fig. 21 Vertical and lateral manoeuvre.

The application of the ground loads at the EF3 is similar to the EF2 except turning and braking which are deleted due to their insignificance for the rear fuselage.

Due to the existence of a CFRP vertical tailplane temperature x–loads result from the different thermal expansions of the Al–fuselage and the CFRP tailplane. Therefore it is not possible to test the fuselage and the vertical tailplane structure in one specimen. Seven different temperature profiles are defined to consider the various missions as shown in Fig. 22.



	number of flights	
	A330	A340
T7	1.500	540
T6	9.400	4.680
T5	8.340	4.160
T4	15.220	7.700
T3	4.800	2.400
T2	360	180
T1	300	140
Σ	40.000	20.000

Fig. 22 Temperature loads.

4.2 Definition of Flight Types and Loading Sequence

For each of the three mission profiles 12 different basic flight types are defined, i.e. eight for normal operation and four for crew training flights. These basic flight types are combined with the different ground load types similar to EF2 and temperature load profiles. In addition the airbrakes extension is simulated in 50 percent of the flights with 50 percent full and 50 percent half angle airbrake extension. Fig. 23 shows the combination of basic flight types with taxi and touch down loading types resulting in 29 flight types for A330 and 27 flight types for A340 which are combined further with the seven temperature profiles and the different airbrakes conditions.

The methods for definition of the loading sequence within the flights and the sequence of the flight types within a block are similar to the EF2 test program.

flight type	number of taxi steps per block							
	A330 SR				A340 MR / SR each			
	X	Y	Z	Σ	X	Y	Z	Σ
A	–	–	5	5	–	–	5	5
B	–	2	5	7	–	2	4	6
C	1	5	16	22	1	3	7	11
D	2	14	40	56	1	6	18	25
E	5	31	94	130	2	13	38	53
F	16	92	272	380	4	26	80	110
G	39	234	707	980	9	57	169	235
H	92	552	1.696	2.340	21	130	384	535
I	–	–	1	1	–	–	1	1
J	–	–	4	4	–	–	4	4
K	1	5	13	19	–	1	4	5
L	3	23	30	56	–	2	8	10
total	159	958	2.883	4.000	38	240	722	1.000

Fig. 23 Definition of flight types

5. Conclusion

The tests and test programs described are examples of the test philosophy and load spectra development for large transport aircraft investigated by multi–section testing.

Two aircraft types with mostly similar structure can be covered by one set of specimens as demonstrated. This is an important economical benefit which is reached without unacceptable technical constraints. The envisaged changes of regulations and advisory circulars should allow similar procedures in the future.

The applied increase of spectrum loading by 10 percent leads to a significant economical benefit regarding test execution and earlier information about necessary actions for in–service and production aircraft. However, the implications of this procedure regarding technical and economical advantages and disadvantages should be carefully assessed before application, especially for other aircraft types. The increased engineering effort for re–evaluation and interpretation of test results necessary to cover the above mentioned aspects is small compared with the advantages.

6. References

/1/ Fatigue Crack Propagation Programme for the A320 Wing
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