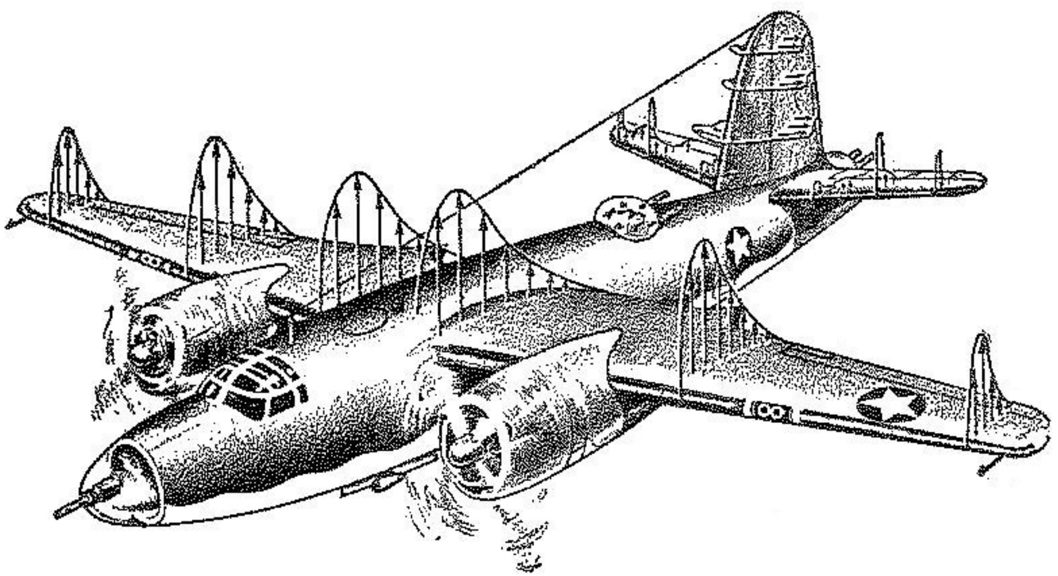
Fatigue Loads and Spectra Development
A Brief Overview

AFGROW User Workshop 2022



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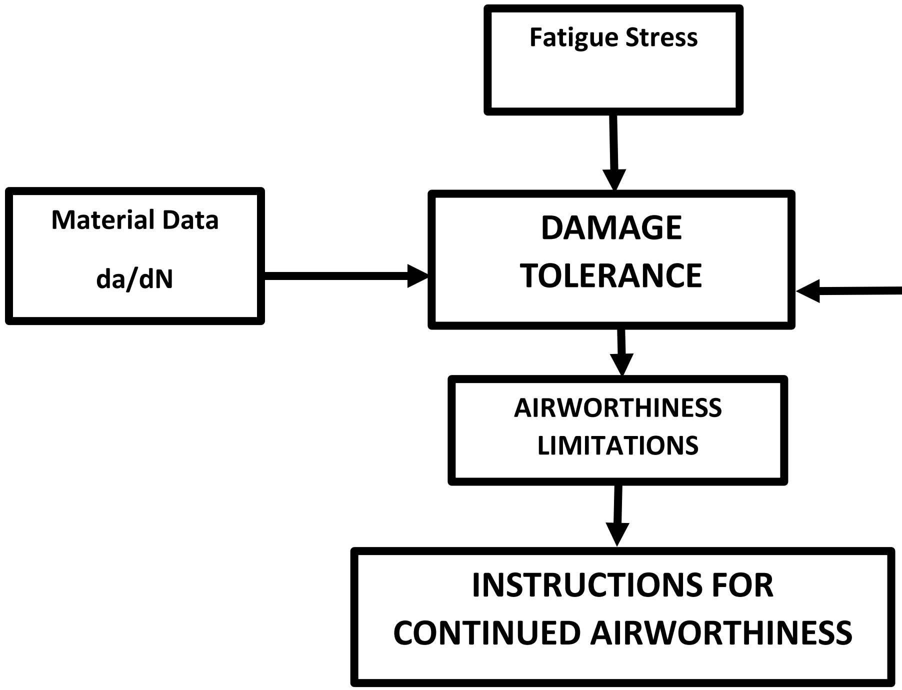
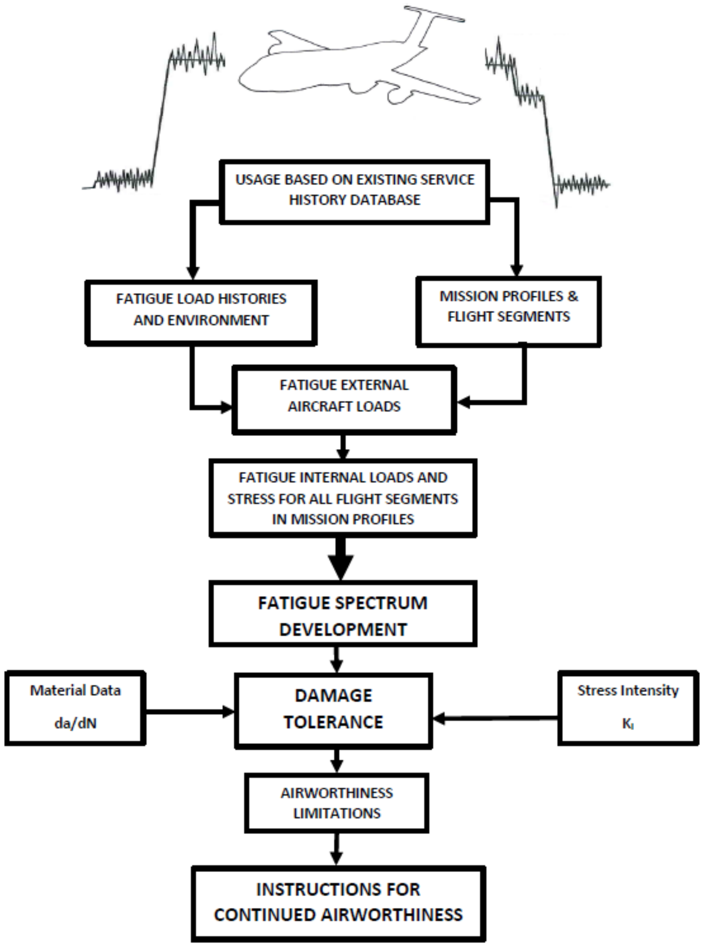
1. Spectrum Requirements

The current general perception of what is meant by Damage Tolerance has a fairly narrow focus at times. Much of this can be attributed to the general tendency to relate Damage Tolerance purely with fracture mechanics while not fully understanding the impact that service usage and the resulting fatigue loads and spectra can have on the outcome.



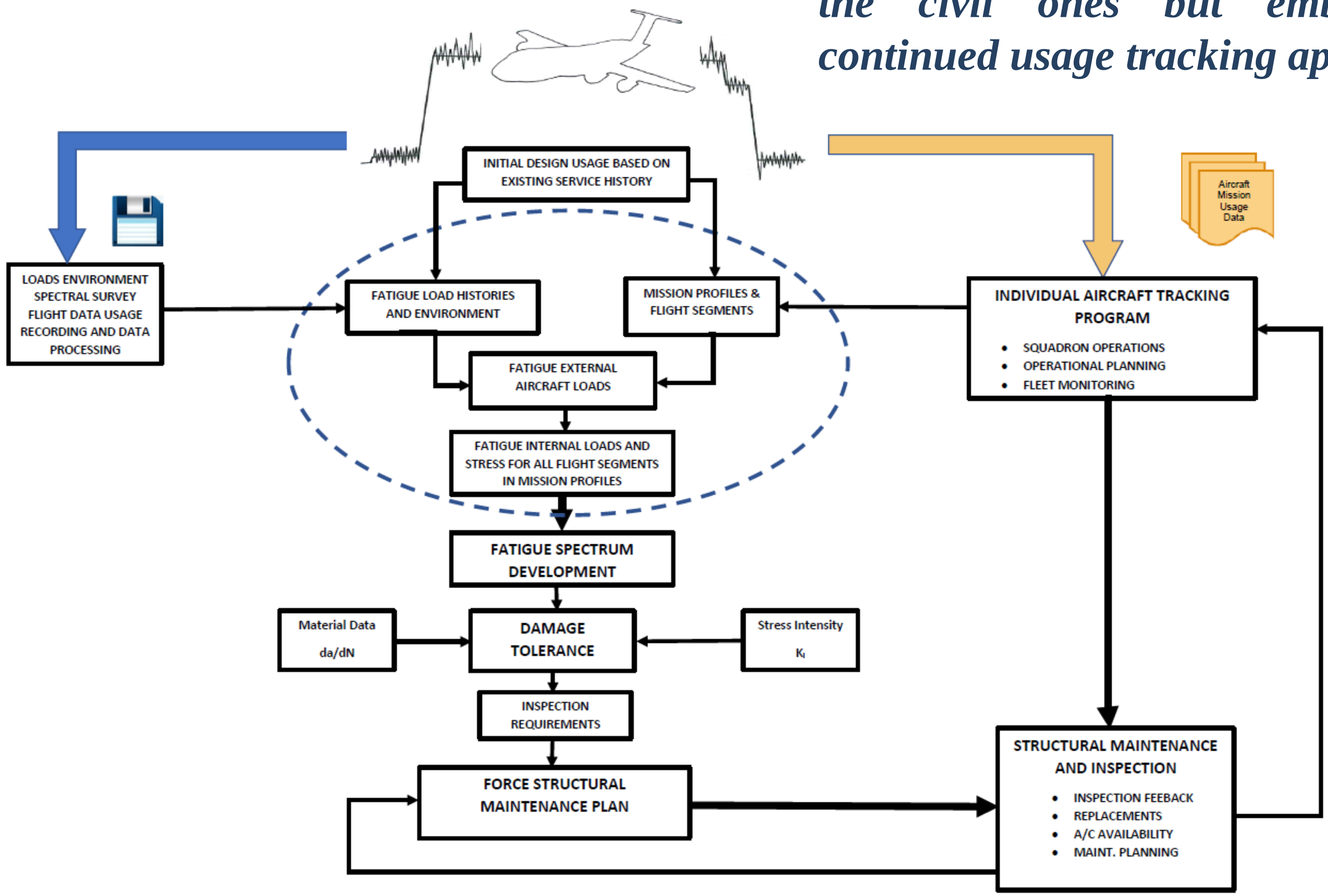
1. Civil Requirements



The following flowchart is a detailed process flow for the requirements associated with performing Damage Tolerance evaluations according to Civil Airworthiness regulations. One primary item to note is that there is no requirement for continued evaluation of service usage.

1. Military Requirements

Military requirements are similar to the civil ones but embody a continued usage tracking approach



2. Usage Data: Large Transport

Usage data consists of several different data sets and parameters and are obtained in different ways. The typical usage data needed first is some definition of the type and length of missions or flights planned. This type of data can be obtained or found from different sources.

I. Commercial Airline Flight Data
- ***i. Can be obtained directly from airlines or operator***
- ***ii. Can be obtained from FAA/DOT database***
- ***iii. Can be estimated based on planned routes (typical for new aircraft design)***
- ***iv. Established by owner/operator specification (for example armed forces)***

II. Flight Segment Definition
- ***i. Can be established based on normal flight manual operations***
- ***ii. Can be established based on recorded data***
- ***iii. Established by owner/operator***

III. Fatigue Load Histories
- ***i. Existing database of load histories for similar aircraft***
- ***ii. Newly recorded data if in statistically adequate amount***

2. Usage Data: Large Transport

One source of flight duration type usage data for US and Foreign air carries is available thru the Bureau of Transportation Statistics. The Bureau manages a database of all air carrier flights from 1990 to present. Data from December 2005 to present is available directly from the website. The website can be accessed at:

https://www.bts.gov/browse-statistical-products-and-data/bts-publications/data-bank-28ds-t-100-domestic-segment-data
https://www.bts.gov/topics/airlines-and-airports/data-bank-28is-t-100-and-t-100f-international-segment-data-us-and

The database provides a listing of all routes flown daily by each carrier with the type of aircraft and number of passengers carried. In order to use the database, the codes for each parameter are necessary but these can be obtained from the website. Data provided includes:

- Airline
- Point of Departure & Arrival
- Payload
- Ramp Time
- Flight Time
- Distance Flown
- # of Passengers Carried
- Weight of Freight Carried
- Aircraft Type

Major benefit of database is that is provides a source for establishing usage data in terms of types of missions flown and flight lengths. Since the usage data spans over 30 years, it provides a very comprehensive look at the operational usage of each aircraft type which includes over 400 types.

2. Usage Data: Large Transport

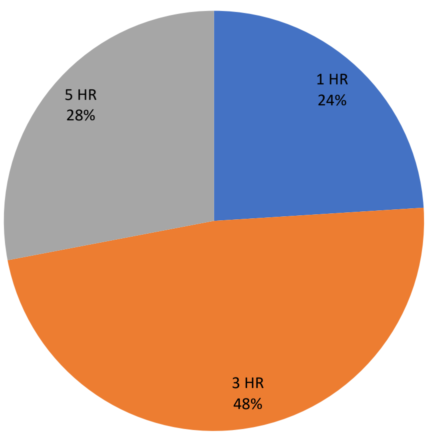
By focusing on some of the more relevant data items, it is easier to see the usefulness of the database. The following shows a abbreviated subset of the data focusing on flight distance, payload, passengers and ramp time and flight time.

1	6	7	10	14	17	21	22	23	24	26	27
	Origin	Dest	Destination		Aircraft	Payload	Available	Pax	Freight	Ramp	Airborne
Year	City Name	Airport	City Name	Distance	Type	in Pounds	Seats	Carried	Transp	in Minutes	in Minutes
2018	ALBUQUERQUE,NEW MEXICO,USA	DEN	DENVER,COLORADO,USA	349	27	101567	364	346	1	97	52
2018	ANCHORAGE,ALASKA,USA	DFW	DALLAS/FORT WORTH,TEXAS,USA	3043	27	103900	273	253	15148	343	323
2018	ANCHORAGE,ALASKA,USA	DFW	DALLAS/FORT WORTH,TEXAS,USA	3043	27	103900	273	209	17216	349	316
2018	ATLANTA,GEORGIA,USA	ANC	ANCHORAGE,ALASKA,USA	3417	27	102190	291	267	25365	706	690
2018	ATLANTA,GEORGIA,USA	DFW	DALLAS/FORT WORTH,TEXAS,USA	731	27	103900	273	186	0	137	112
2018	ATLANTA,GEORGIA,USA	DFW	DALLAS/FORT WORTH,TEXAS,USA	731	27	102190	291	0	0	147	118
2018	ATLANTA,GEORGIA,USA	DTW	DETROIT,MICHIGAN,USA	594	27	102190	291	254	0	110	86
2019	ATLANTA,GEORGIA,USA	DTW	DETROIT,MICHIGAN,USA	594	27	102190	296	269	0	107	85
2018	ATLANTA,GEORGIA,USA	DTW	DETROIT,MICHIGAN,USA	594	27	102190	291	159	0	106	84
2018	ATLANTA,GEORGIA,USA	DTW	DETROIT,MICHIGAN,USA	594	27	204380	582	404	21380	289	210
2018	ATLANTA,GEORGIA,USA	DTW	DETROIT,MICHIGAN,USA	594	27	102190	291	167	15380	110	87
2018	ATLANTA,GEORGIA,USA	GSP	GREER,SOUTH CAROLINA,USA	153	27	102190	291	0	0	55	34

2. Usage Data: Large Transport

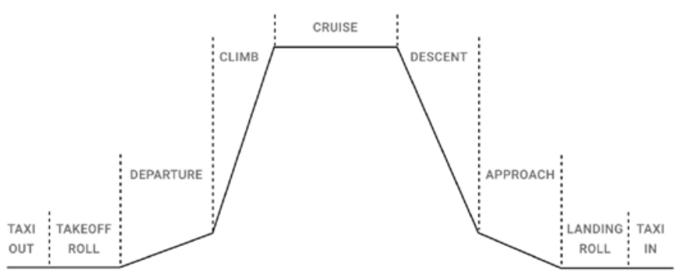
The following are a couple of mission length utilization rates based on the airline usage data. The first is for the 737-800 while the second is for the 777-200.

Boeing 737-800/-8 Airline Usage Statistics from January thru December 2019



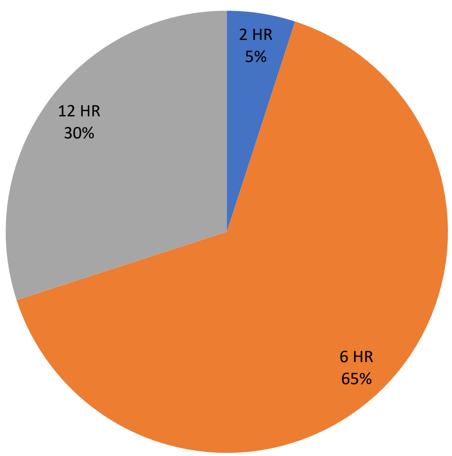
Typical Missions:
- ***Short Flight ~ 1 hour***
- ***Medium Flight ~ 2 to 5 hours***
- ***Long Flight > 5 hours***

Note: Missions Vary between Narrow and Wide Body and Regional Jets



Operational Air Carrier Usage Data

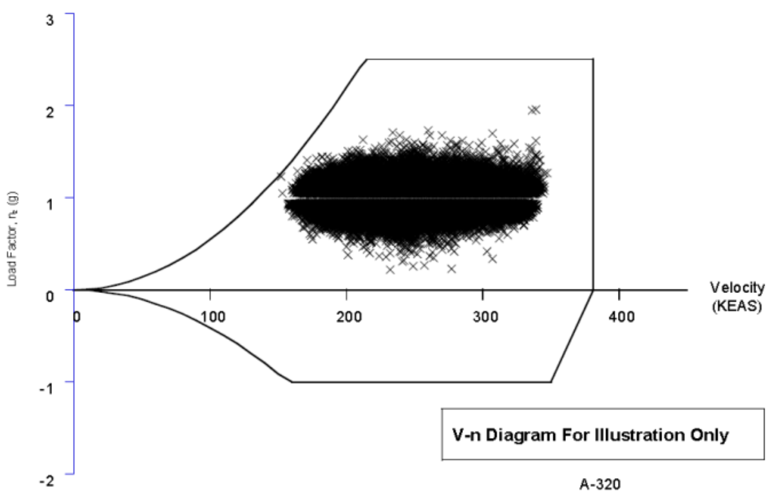
Boeing 777 Airline Usage Statistics from January thru December 2019

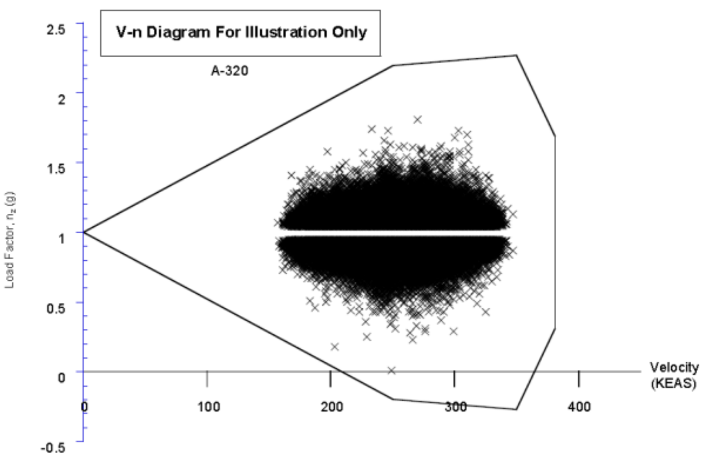


Typical Missions:
- ***Short Flight ~ 2 hour***
- ***Medium Flight ~ 6 hours***
- ***Long Flight > 12 hours***

2. Usage Data: Large Transport

Airframe fatigue in terms of loading is simply characterized by stating that it is the endurance of the airframe under the effects of repeated loads. Repeated loads on an aircraft are those encountered during normal operational services rather than those extreme loads to which an airframe is designed.

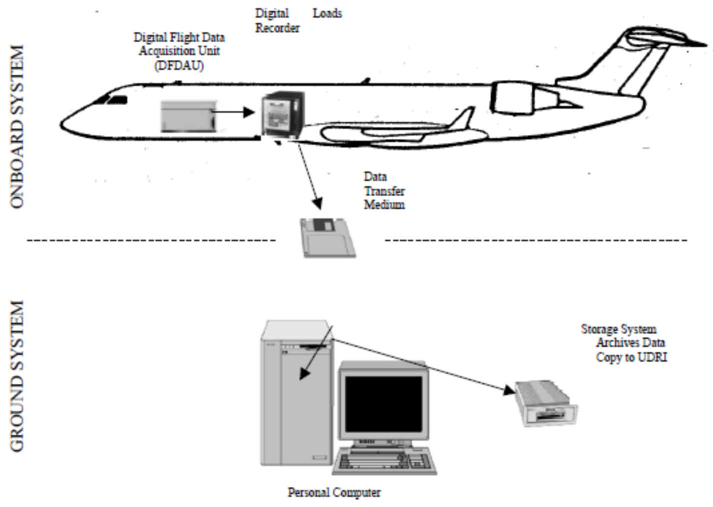


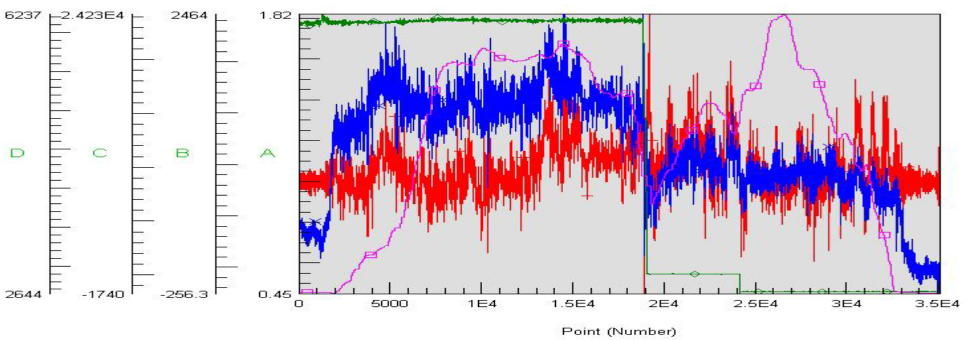


Design Vn Diagrams for Maneuver and Gust Compared to Service Loads

2. Usage Data: Large Transport

The typical method for collecting usage data is thru the use of digital flight data recorders. These systems are designed to collect aircraft accelerations and the corresponding flight parameters.





Legend

Marker	Axis	Title	Y Max	Y Min	Y Mean	Y Units
	A	ADAPT_000112_20070713_2007071…	1.82	0.45	1.06	g's
	B	ADAPT_000112_20070713_2007071…	2464	-256.3	1154	microstrain
	C	ADAPT_000112_20070713_2007071…	2.423E4	-1740	1.226E4	pounds
	D	ADAPT_000112_20070713_2007071…	6237	2644	4578	feet

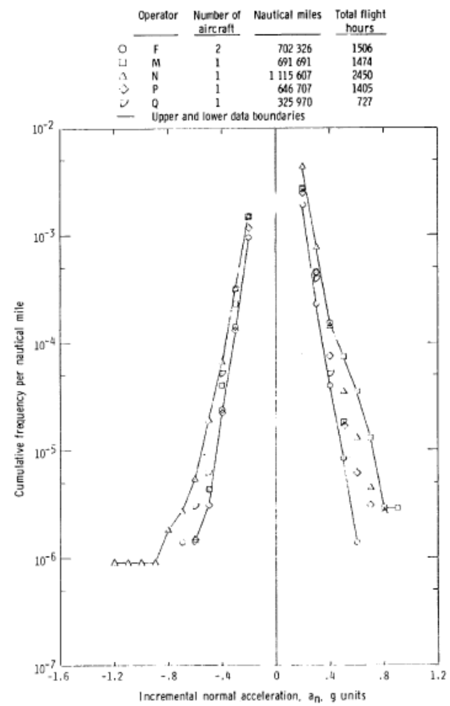
Typical VG/VGH Flight Usage Recording Approach

2. Usage Data: Large Transport

The resulting accelerations, in particular Nz, are screened, filtered and then plotted in statistical distributions. The following is an example for a wide body transport (747) from NASA-TN-D-8481.

(a) Wide-body transports

	Operation					Total all operations
	FXVII	MXVII	NXVIIA	PXVII	QXVII	
Recording period	Aug. 1970 to Feb. 1972	Aug. 1970 to June 1971	Nov. 1971 to Oct. 1972	Jan. 1971 to Oct. 1971	Mar. 1971 to June 1972	
Number of aircraft	2	1	1	1	1	6
Route	Circumglobal	Transpacific	Circumglobal	U.S. and Pacific	U.S. and transpacific	
Operational flights						
Number of flights	282	232	565	390	180	1649
Flight hours	1506.2	1455.0	2381.0	1391.4	715.0	7438
Distance flown, n. mi.	702 272	687 391	1 103 140	643 895	322 895	3 459 593
Check flights						
Number of flights	0	32	85	51	18	186
Flight hours	0	18.9	69.0	13.5	12.2	113.6
Distance flown, n. mi.	0	4296	12 473	2827	3030	22 626



(d) Total in-flight accelerations.

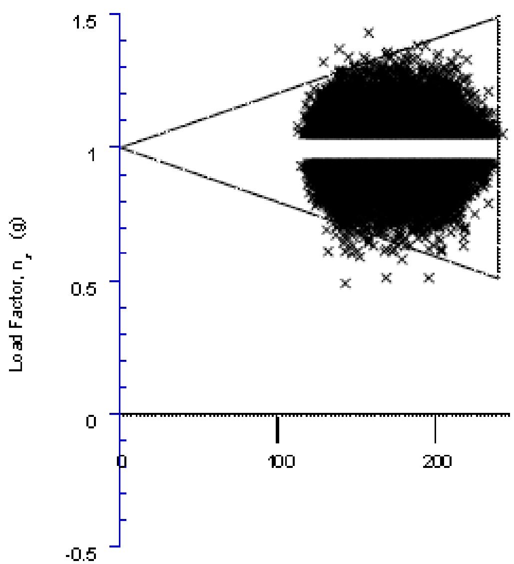
TABLE 5.- FREQUENCY DISTRIBUTION OF INCREMENTAL NORMAL ACCELERATIONS DUE TO OPERATIONAL FLIGHT MANEUVERS FOR WIDE-BODY TRANSPORTS

Acceleration interval, a_n, g units	Frequency for –				
	FXVII	MXVII	NXVIIA	PXVII	QXVII
-0.7 to -0.6			1		
-.6 to -.5	2		3	1	1
-.5 to -.4	2	4	13	7	3
-.4 to -.3	31	28	99	33	26
-.3 to -.2	218	229	471	344	175
.2 to .3	757	717	2401	866	405
.3 to .4	89	89	288	180	44
.4 to .5	16	16	43	22	4
.5 to .6	4	5	6	2	1
.6 to .7			5	2	2
.7 to .8				1	

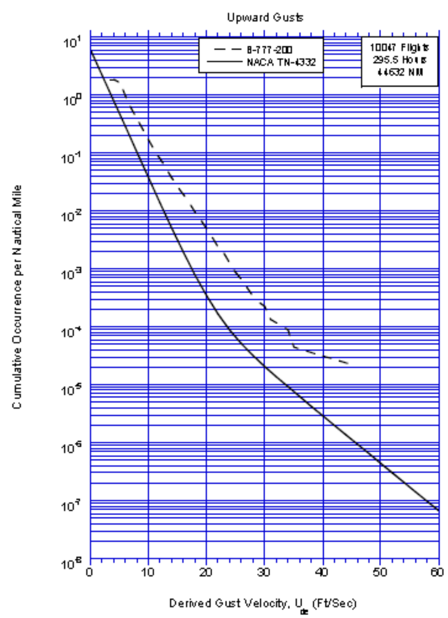
Typical Processing of Flight Usage Data

2. Usage Data: Large Transport

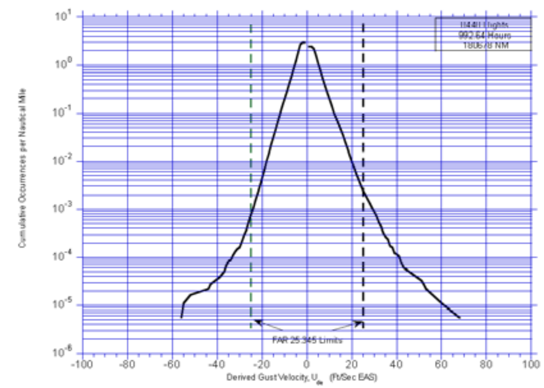
The FARs and guidance make specific reference to service history and measured statistical data because in many cases the operation usage can deviate significantly from design values derived using theoretical methods.



767-200ER Recorded Loads for Gust with Flaps Extended



777-200ER Recorded Loads for Gust at 500 to 1500 feet



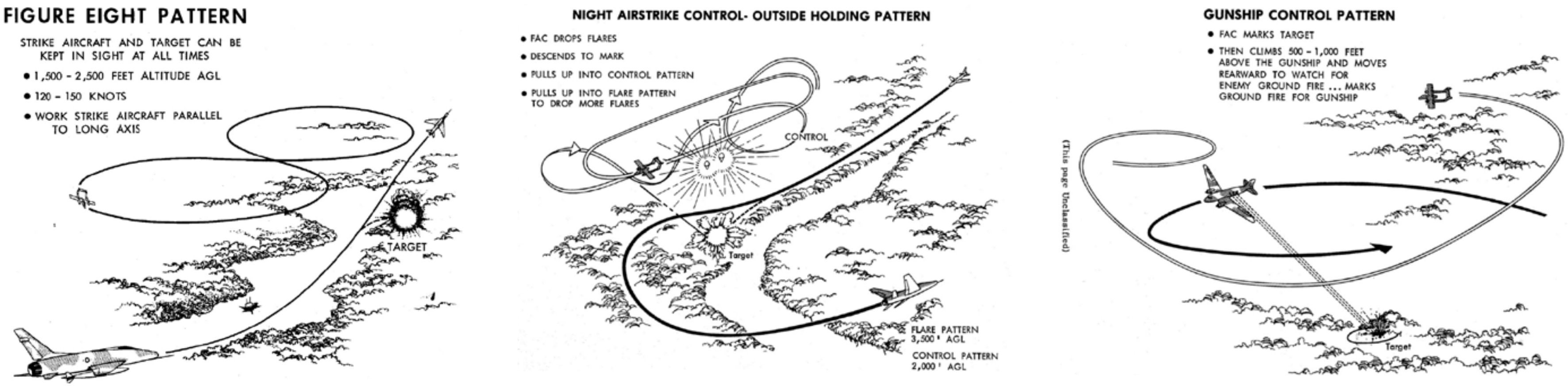
737-400 Recorded Loads for Gust with Flaps Extended

Comparison of Operational Flight Usage Data versus Design Data (various DOT/FAA reports)

3. Usage Data: Special Ops/Military Usage

The general usage definition for these type of operations can be more straight forward as typically they are dictated by the operator specifications. For example, for the US armed services, this is usually specified in the tailored JSSG 2006 specification provided during contract award for a new aircraft design development. Subsequent to this, usage surveys are performed regularly to capture any changes in operation or environment.

For example, the USAF OV-10 was used as a forward air controller and close support aircraft. As such, the missions performed were quite varied and of very different lengths and altitudes.

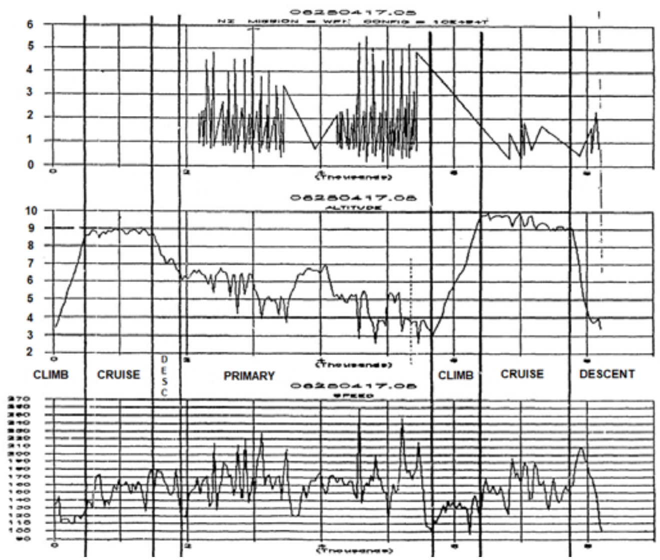


Examples of OV-10 Military Flight Operational Usage

3. Usage Data: Special Ops/Military Usage

In the 1980's, as part of the ASIP Force Management Plan, the USAF undertook a comprehensive tracking program, and as part of this, the fleet was instrumented to establish updated usage data.

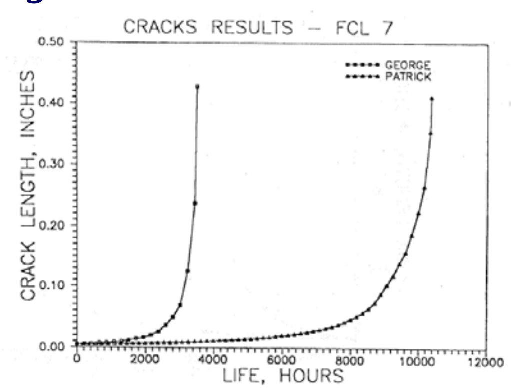
For the OV-10, a total of 4 mission profiles or flights were identified which included both operational missions and training. These were further broken down into 2 severity levels based on operations.



- ***Pilot Proficiency/Navigation Training***
- ***Surface Rocket/Strafe Attack***
- ***Forward Air Control/Target Identification***
- ***Maintenance Test Flight***

Example: OV-10 Rear Spar

Life is reduced by a factor of 3 or more due to severity of the George AFB operated aircraft versus those of Patrick AFB.



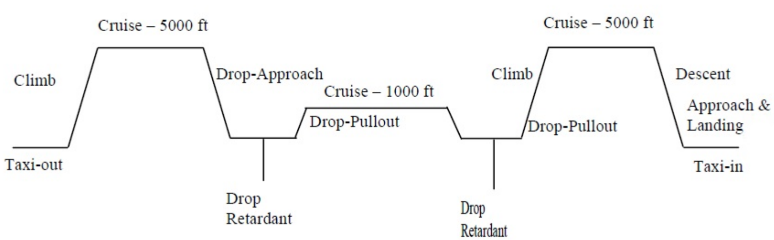
Impact of Variations in Operational Usage

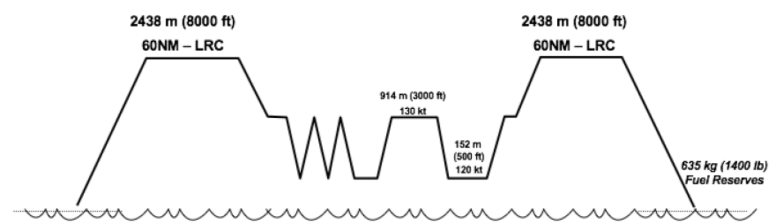
3. Usage Data: Special Ops/Military Usage

Special operations are not limited to only aircraft of the armed forces, many private companies and government agencies operate aircraft in more austere environments. Some of these include Coast Guard and Maritime Patrol, Firefighting, Oil Pipeline Surveillance. Many of these aircraft are commercial models that are pressed into service under these environments.

Firefighting:
- Low Level
- Severe Maneuvers
- Large Weight Changes
- Speed Variations
- Flight Controls

Maritime Patrol:
- Low Level
- Long Duration
- Flight Controls

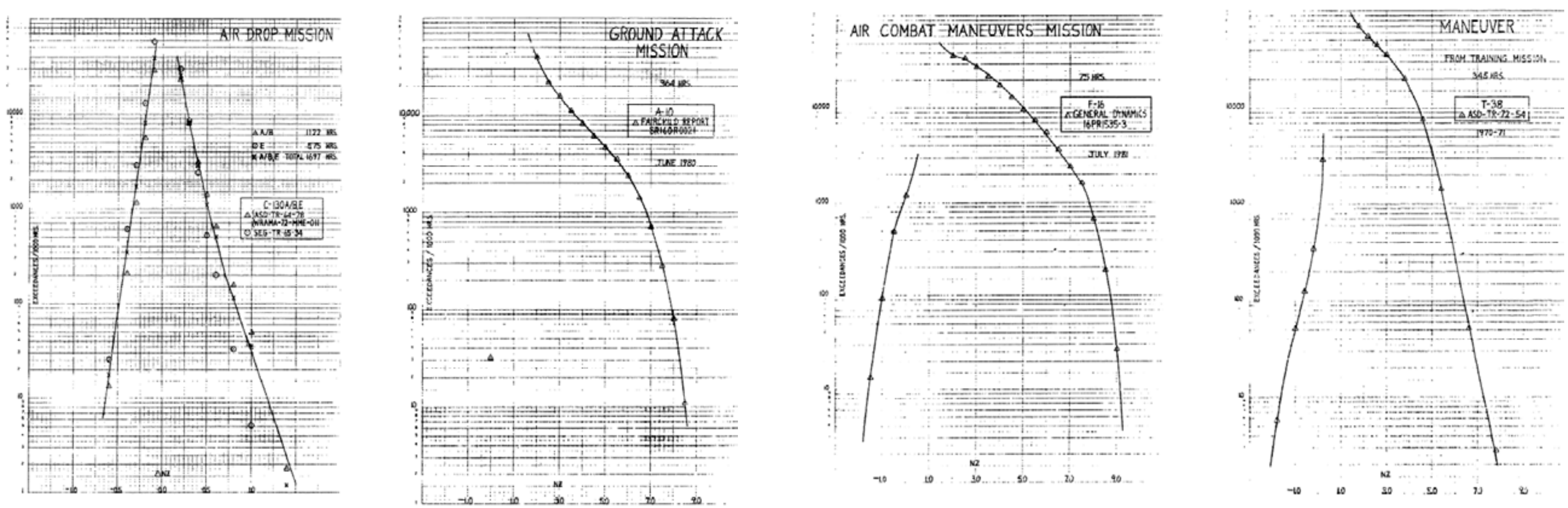




Examples of Special Mission Operations for Firefighting and Maritime Patrol

3. Usage Data: Special Ops/Military Usage

The operational usage data for military and special operations can be quite different than those normally encountered in air carrier operations.
For instance, maneuvers are more drastic and occur more frequently. As such, their statistical occurrence can be very different that those for air carriers. Additionally, with respect to gust or turbulence, military and special mission aircraft tend to have a large portion of their operational flights at much lower altitudes where the gust environment is significantly more severe.



Maneuver Usage Examples for C-130, A-10, F-16 and T-38 (ASD-TR-82-5010)

3. Usage Data: Special Ops/Military Usage

There are similar examples of more severe usage in the special mission category such as firefighting operations, agricultural use and coastal patrol use.

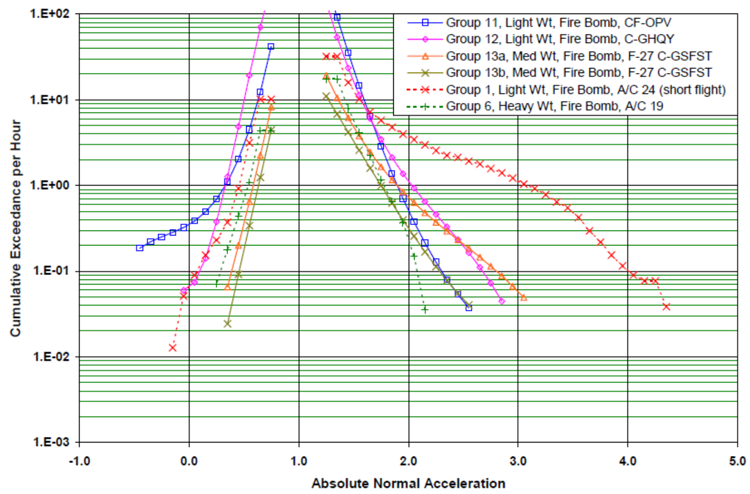


FIGURE 4-7. EXCEEDANCE PLOT FOR OTHER FIREBOMBERS [3], FIREBOMBER DATA

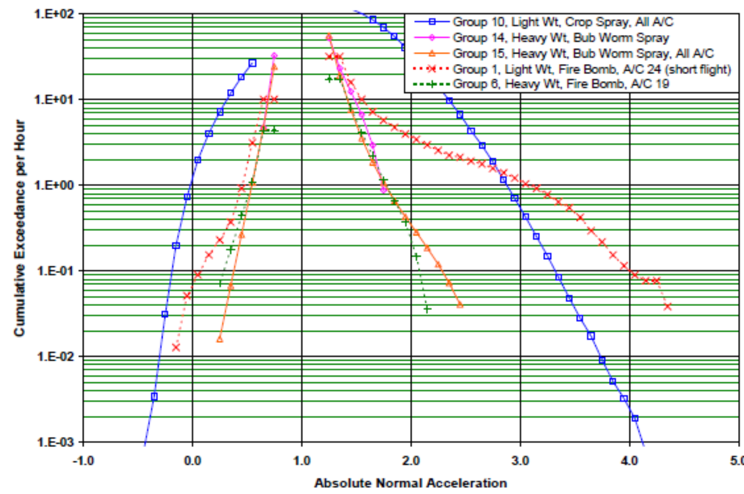
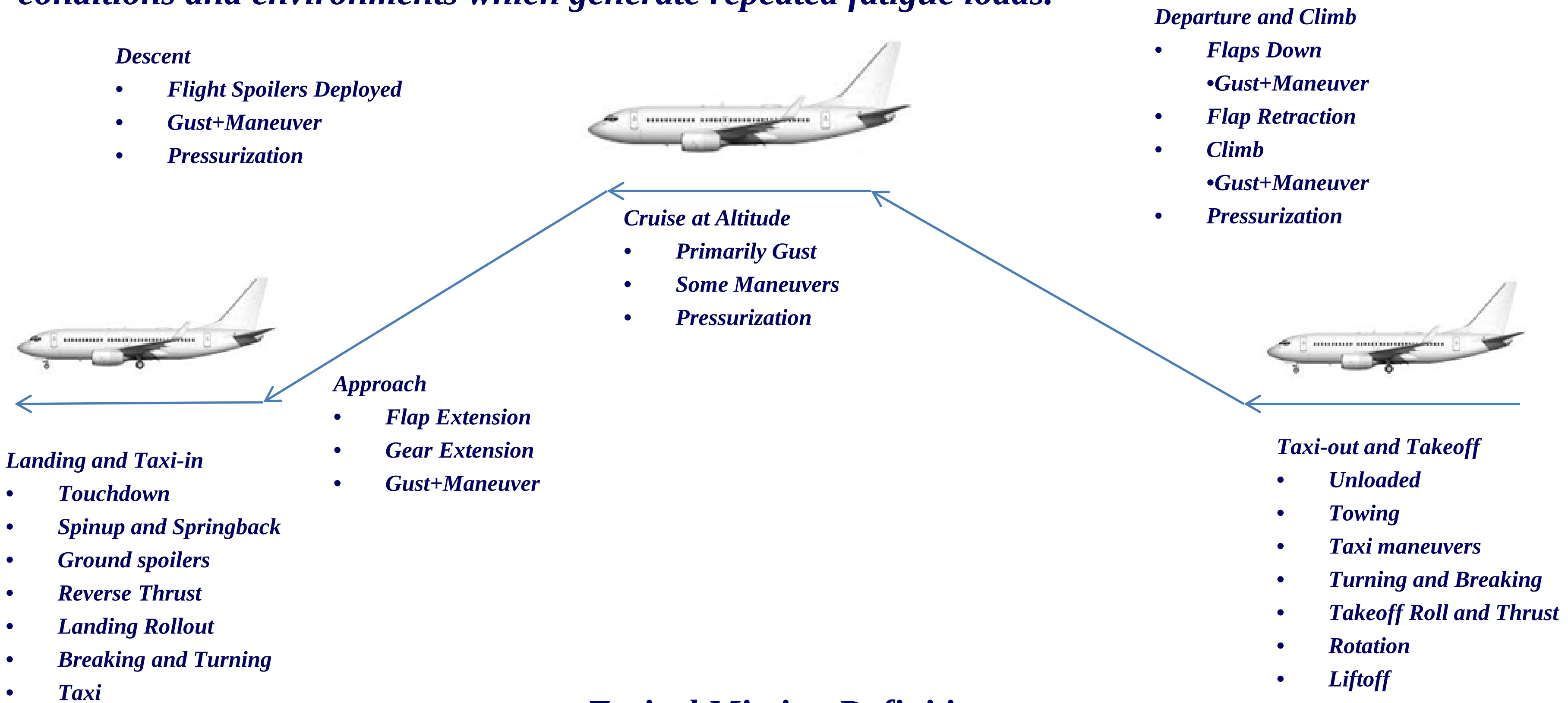


FIGURE 4-9. EXCEEDANCE PLOT, AGRICULTURAL AIRCRAFT DATA

Examples of Severe Maneuver Usage for Firebombers and Ag Use (DOT/FAA reports)

4. Mission Profiles and Usage:

The mission profile of the aircraft is subdivided into each of the flight phases and is subject to various conditions and environments which generate repeated fatigue loads.



Typical Mission Definitions

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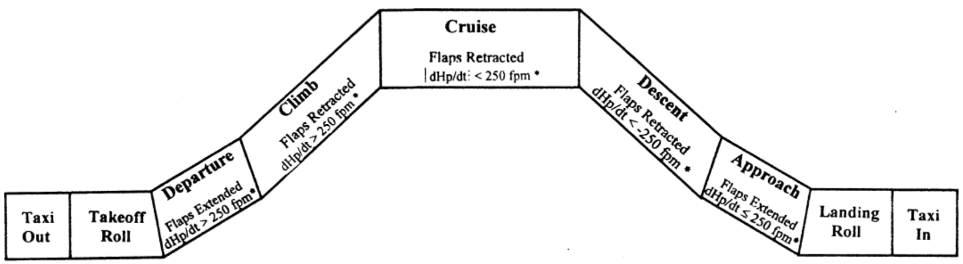
4. Mission Profiles and Usage:

The following is a typical mission profile description with the corresponding parameters identified. These parameters are used to develop the aircraft balanced external loads for each of the flight segments:

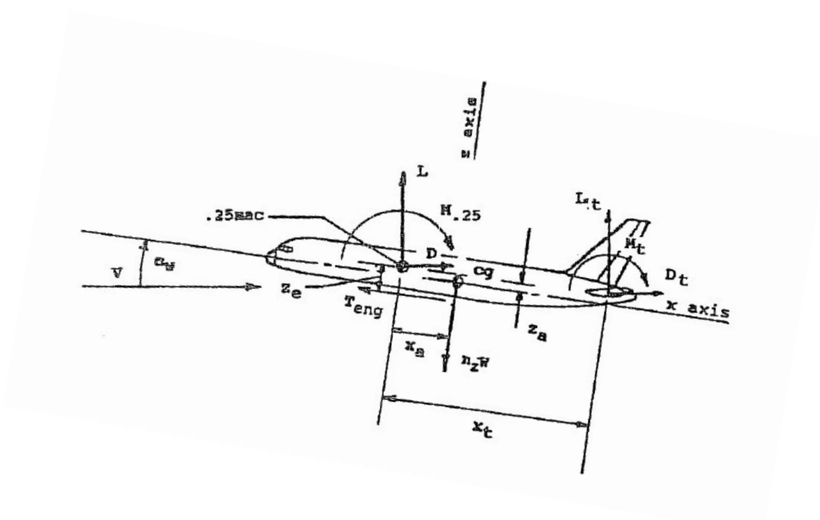


Mission 1		Time (min.)	Speed (knots)	Speed (mph)	Miles	Fuel Consumed	Weight	Altitude
1	Taxi-out	5	15	17	1	29	116000	0
2	Takeoff/Climb	15	180	207	52	523	115477	5000
3	Enroute-Cruise	90	210	242	363	3626	111851	10000
4	Descent	5	180	207	16	161	111690	5000
5	Approach	5	180	207	16	161	111528	1000
6	Taxi-in	5	15	17	1	29	111500	0
	Total Time	2.07						

Parameters Affecting a Flight Segment

4. External Fatigue Loads:

In order to develop fatigue loads, several key parameters are required. These are the basic geometric, aerodynamic and inertia properties which characterize the basic airplane. These parameters are used in the development of the basic aircraft wing lift, drag and tail balancing loads development for each of the flight conditions being investigated. The following are an example of some of the parameters to be considered.

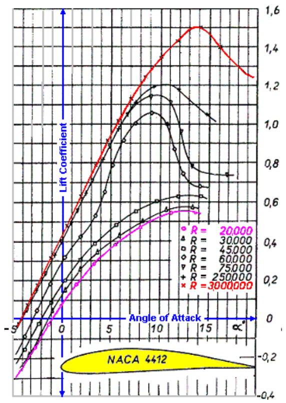


- ***Gross Weight***
- ***Airspeed***
- ***Angle of Attack***
- ***Wing Airfoil***
- ***Tail Airfoils***
- ***Surface Area***
- ***MAC***
- ***Aircraft Lift Coeff***
- ***Engine Thrust***
- ***Thrust line***
- ***Tail location***
- ***Weight Distribution***

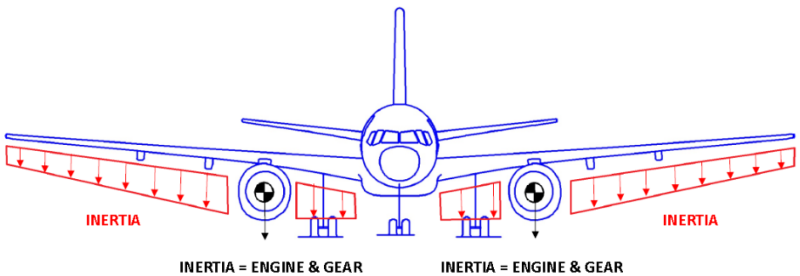
Typical Aircraft Parameters

4. External Fatigue Loads:

The previous parameters may include pertinent characteristic data which may need to be developed or obtained either thru analysis or thru instrumentation.

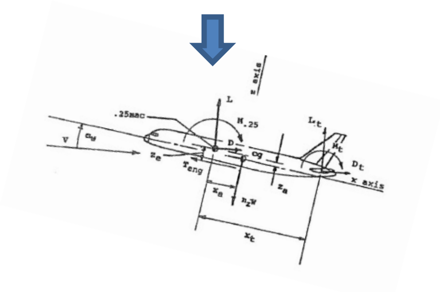


- ***Lift Slope Curve***



- ***Mass Distribution***

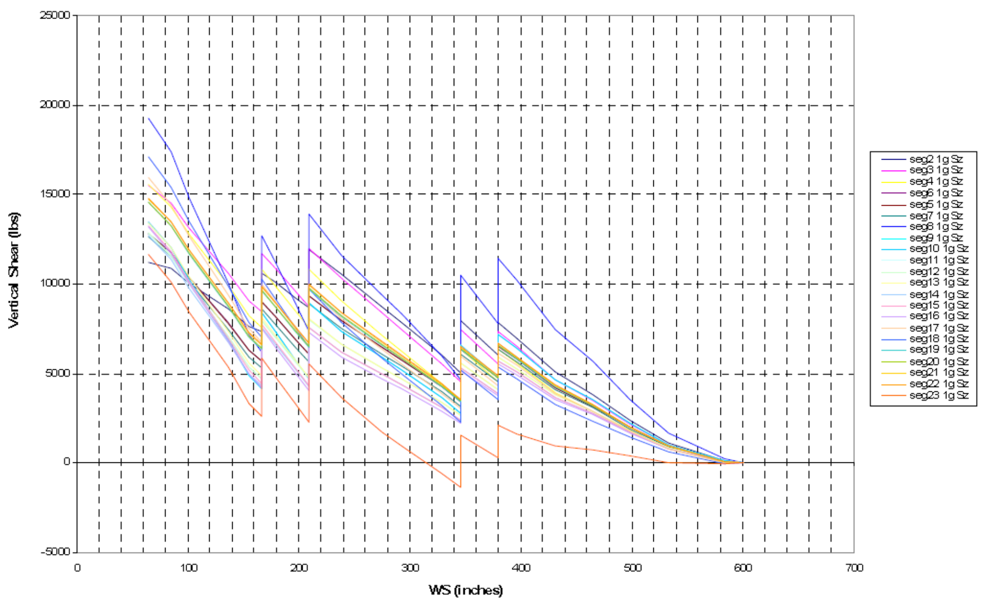
- ***Fuel Distribution***



Major Contributions to External Loads

4. External Fatigue Loads - Wing:

Utilizing the inertia and aerodynamic equations for shear, moment and torsion in combination with the aircraft parameters specific to each flight segment, external loads can be developed for each complete mission. These are obtained for both unit 1g conditions as well as delta g conditions in order to develop the spectra.



Typical Wing 1g Shear Loads for all Segments in a Typical Mission

4. External Fatigue Loads - Fuselage:

The same principles are used in developing the external loads for the fuselage although they are less involved. To better understand the primary fatigue loads acting on the fuselage, they are separated into the forward, center and aft fuselage:

Forward Fuselage Load Sources:

- ***Inertia Loads = Structural Weight plus Payload***
- ***Aerodynamic Loading = Highest in Nose Section***
- ***Discrete Loads = Nose Gear Reactions***

Aft Fuselage Fatigue Load Sources:

- ***Inertial Loads = Structural Weight plus Payload plus Fuel***
- ***Aerodynamic Loading***
- ***Discrete Loads = Balancing Tail Load***

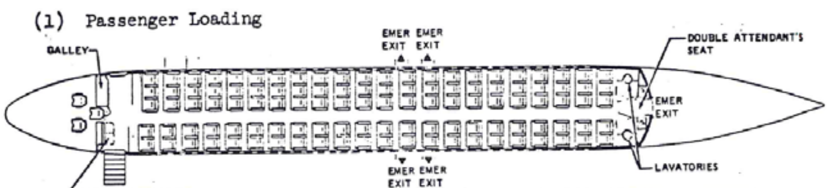
Center Fuselage Load Sources:

- ***Fwd and Aft Fuselage Reactions***
- ***Wing Reactions***
- ***Center Tank Fuel***

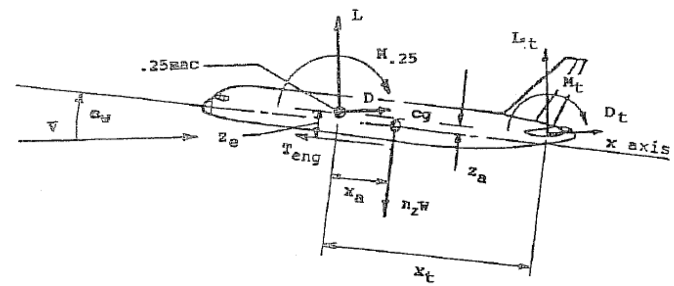
4. External Fatigue Loads - Fuselage:

The following illustrates the necessary calculations for calculating the tension loads in the aft fuselage crown as an example. Note that the basic inputs are the inertia loading and balancing tail load and the aerodynamic loading is conservatively ignored as it is relieving for this example.

(1) Passenger Loading

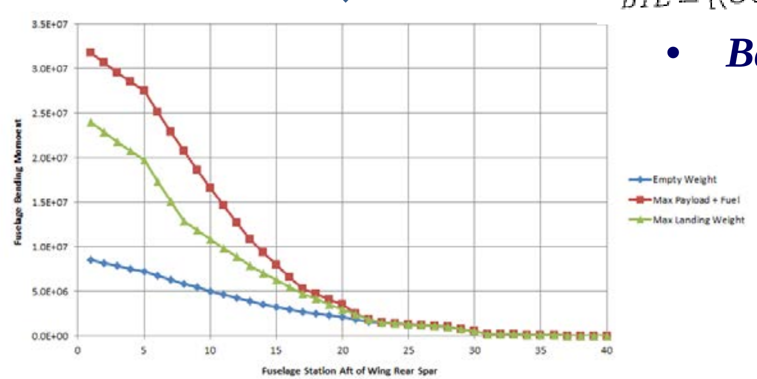


WEIGHT, POUNDS PER ROW AT 170 LBS PER PASSENGER				
1-PASS.	2-PASS.	3-PASS.	4-PASS.	5-PASS.
170	340	510	680	850



$$BTL = [(CG - 0.25)C_{La} + C_{M0.25}]qS_wc_w/x_t$$

- ***Mass Distribution***
- ***Balancing Tail Load***



Typical Aft Fuselage 1g Bending Moments

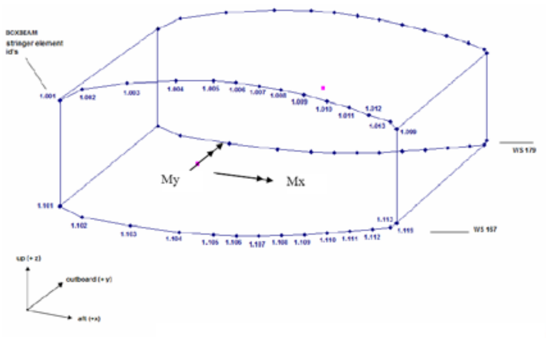
Effects which could impact loads:

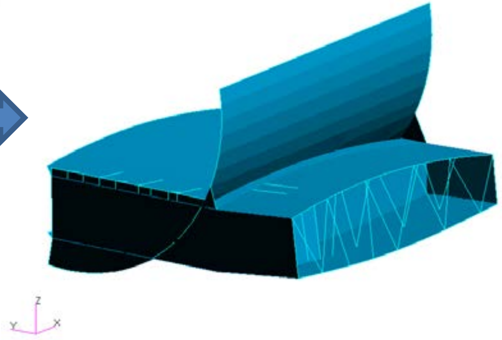
- Structural inertia distribution
- Payload and passengers
- Fuselage fuel cells
- Balancing Tail Loads

5. Internal Fatigue Loads:

Depending on the type of project being supported, a combination of methods for developing internal loads can be utilized. The following describes typical industry methods that can be employed for each airframe component which include both classical and FEA approaches.

- ***Wing Box***
  - ***Cozzone's Unit Beam Method***
  - ***Finite Element Analysis***
- ***Nacelle's***
  - ***Equations of Static Equilibrium***
  - ***Finite Element Analysis***
- ***Fuselage Structure***
  - ***Fuselage Bending Modified Beam Theory - Bruhn***
  - ***Frame Ring Analysis NACA TN 1310***
  - ***Finite Element Analysis***
- ***Aileron and Flap Tracks***
  - ***Equations of Static Equilibrium***

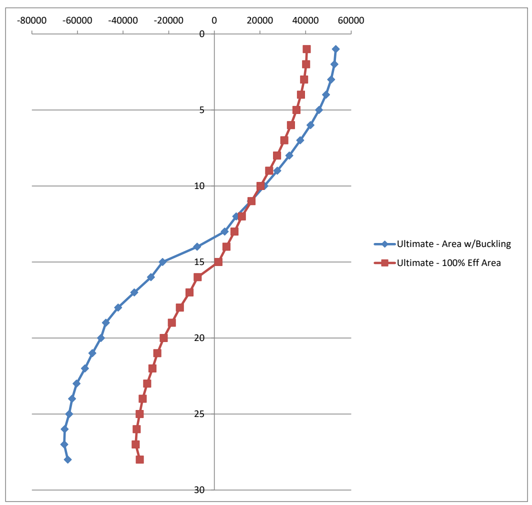




Typical Methods Employed for Internal Loads

5. Internal Fatigue Loads: Example

To develop internal fatigue loads and the resulting stresses for an aft fuselage upper crown, the external fatigue shear and moments can be applied to a fuselage cross section. Note, ensure method used can account for buckling. Lower fuselage typically buckle below limit load and affect stresses.

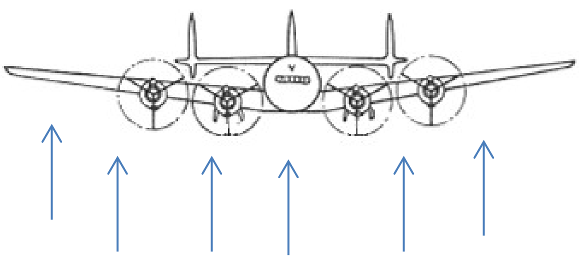


FATIGUE SPECTRUM STRESS CALCULATOR AT ANALYSIS POINT						
FS Station =	1616					
Stringer # =	4					
Ycg of FS Sta =	233.17					
Ixc of FS Sta =	622236					
Analysis Pt Waterline =	340.01					
Analysis Pt Buttline =	27.44					
MISSION 1 - SHORT	Damage Code	Seg Name	Seg #	Vz	My	Stress
	1001	Taxi-Out	1	74264	35159453	6.037
	1002	Take-Off	2	74264	35159453	6.037
	1011	Dep Man	3A	83695	42218153	7.249
	1021	Dep Gust	3B	83695	42218153	7.249
	1012	Climb Man	4A	83181	41958813	7.205
	1022	Climb Gust	4B	83181	41958813	7.205
	1013	Cruise Man	5A	80601	40657582	6.982
	1023	Cruise Gust	5B	80601	40657582	6.982
	1014	Desc Man	6A	76727	38703509	6.646
	1022	Desc Gust	6B	76727	38703509	6.646
	1015	App Man	7A	76084	38379325	6.590
	1021	App Gust	7B	76084	38379325	6.590
	1003	Landing Roll	8	67077	31756925	5.453
	1001	Taxi-In	9	67077	31756925	5.453
	1100	GAG				

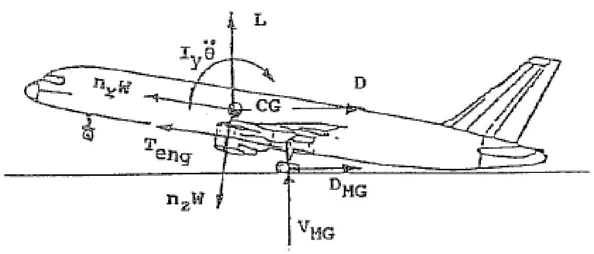
Typical Methods Employed for Internal Loads

6. Environmental Effects :

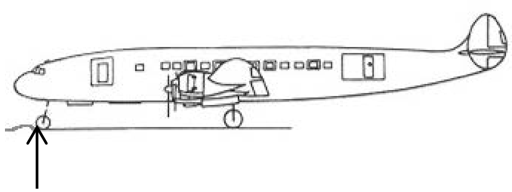
1. ***Environmental Effects – Ground Conditions***
2. ***Environmental Effects – Flight Conditions***
3. ***Discrete Events***



Gust



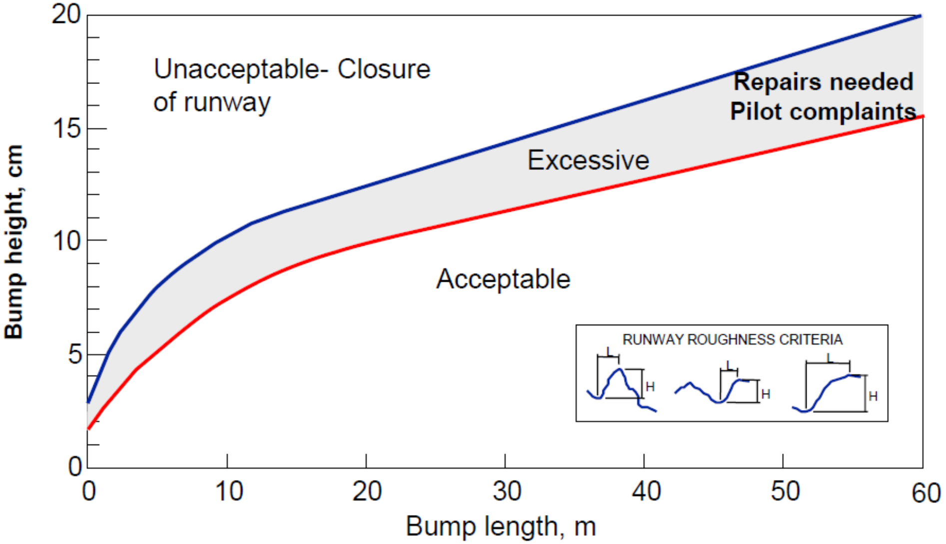
Landing Impact



Taxi

6. Environmental Effects : Ground Conditions

The primary runway environmental condition which affects the ground fatigue loads on the airframe is termed as "Runway Roughness". This terminology is meant as a way to describe the degree of surface unevenness of a particular runway. This roughness can typically be a result of uneven settlement, frost and also due to repairs. If the roughness is severe enough, it can have a severe impact on both static and fatigue loads. For static conditions, see FAA guidance in AC 25.491-1.



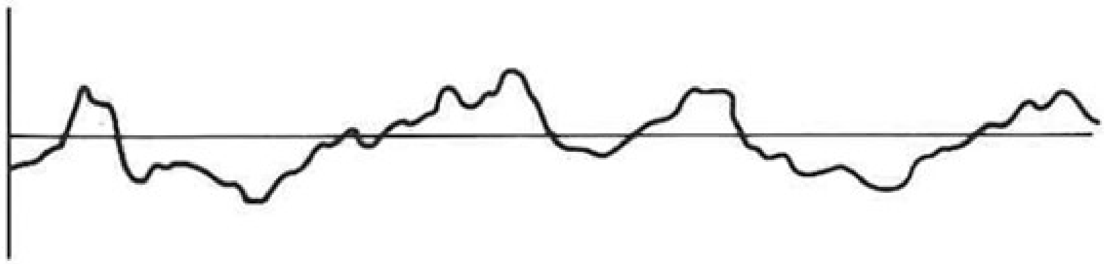
Evaluation of the Runway Roughness in terms of an Equivalent Bump Height & Length

(Ref. Runway Roughness Evaluation – Boeing Bump Methodology – Michael Roginski)

6. Environmental Effects : Flight Conditions

Generally, gust is considered an environmental effect and typically, gust profiles tend to be continuous and irregular and essentially represent a gust velocity time history when the distance scale is divided by the airplane forward speed thereby becoming a time scale. Numerous methods have been investigated and developed by industry in order to develop the resulting loads due to this gust profile.

Typical Gust Profile

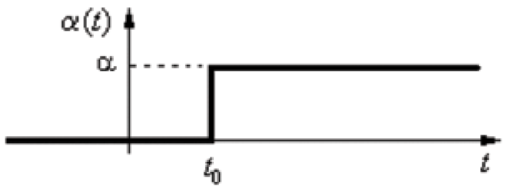


6. Environmental Effects : Flight Conditions

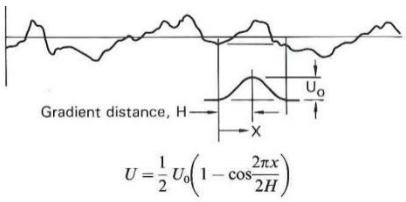
The following basic approaches for developing loads due to the gust profiles will be reviewed:

- ***Discrete Gust Loads***
- ***Power Spectral Density (PSD) Loads***

<u>Discrete Gust Loads</u> – idealizes the gust profile into a discrete representation of load. Earlier approaches used a sharp edge gust which gave no consideration to the effects of motion. Later, these effects were account for by using a "one-minus-cosine" pulse.



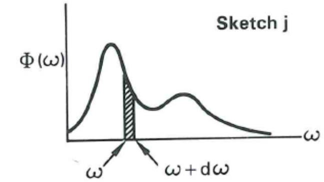
Sharp Step/Edge Gust



Gust Pulse of one-minus-cosine

<u>PSD Loads</u> – this method employ's a continuous gust criteria which assumes a random distribution in time.

$$\Phi(\Omega) = \frac{L}{\pi} \frac{1 + \frac{8}{3}(1.339\Omega L)^2}{\left[1 + (1.339\Omega L)^2\right]^{11/6}}$$



PSD Gust

Power = mean square of variable   Spectral = frequency   Density   = continuous frequency

6. Environmental Effects : Flight Conditions

Although very appropriate for design loads, the basic potential problem with trying to use the analytical PSD method is that the parameters are not based on current usage data. The basic equation is made up non-storm and storm turbulence components. The parameters P1 and P2 describe the amount of time spent in the environment while b1 and b2 prescribe the intensity. The published parameters are meant for use as design values but are not appropriate for fatigue. The original coefficients were based on usage data recorded in the 1960's (Ref. AIAA Hoblit & FAA-ADS-53/54) for much older aircraft (DC-6, DC-7, etc.) and without being adjusted for recorded data may not be applicable to all aircraft models.

$$\frac{N(y)}{N_0} = P_1 \exp\left(-\frac{y/\bar{A}}{b_1}\right) + P_2 \exp\left(-\frac{y/\bar{A}}{b_2}\right)$$

- Parameters may no longer be representative of usage
- If used, ASIP requires update of P's and b's based on recorded data
- No requirement for commercial aircraft to update usage over time

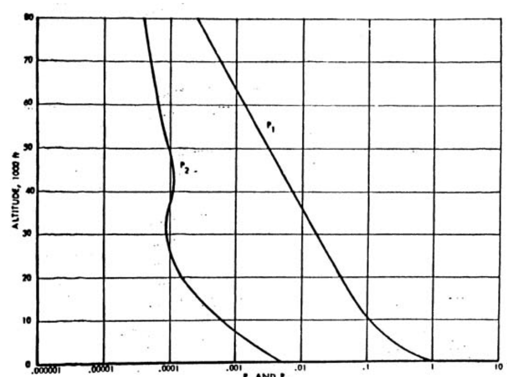


FIGURE 1 P_1 AND P_2 VALUES

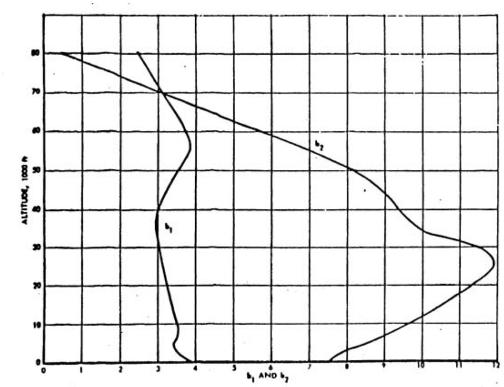
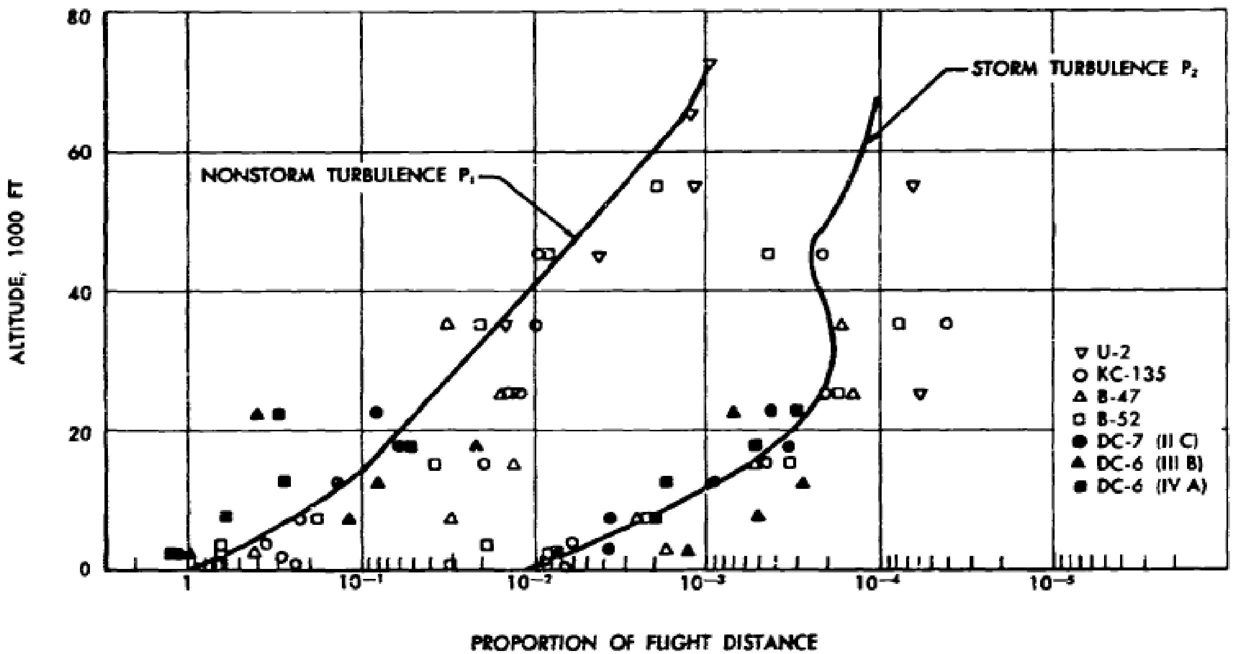


FIGURE 2 b_1 AND b_2 VALUES

PSD Gust Exceedance Equation (AIAA Gust Loads – Hoblit)

6. *Environmental Effects : Flight Conditions*

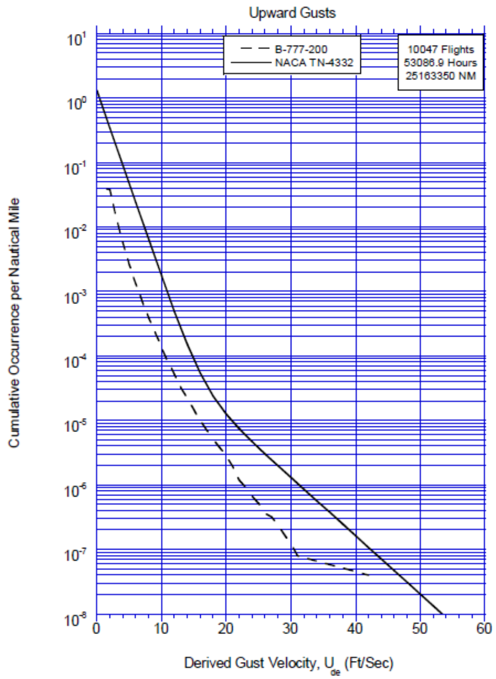
To illustrate the variation of the non-storm and storm turbulence parameters, the following plot illustrates the comparison of the derived parameters to the source usage data in FAA-ADS-54. As a result, this is why DoD ASIP programs require usage updates and why the PSD equation should not be used without correlation and adjustment to actual recorded data.



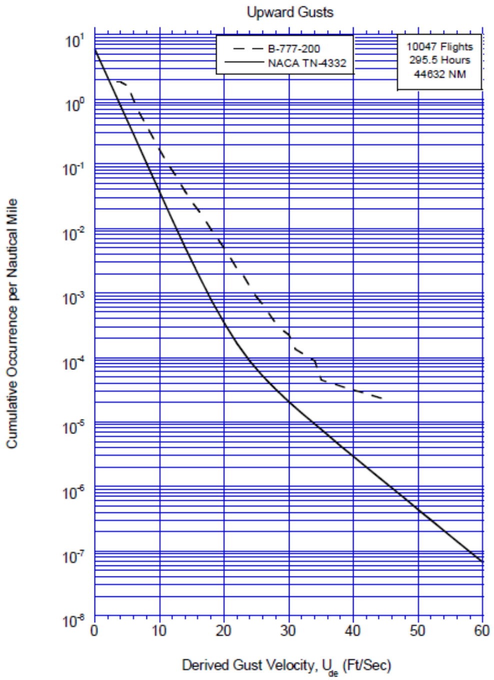
Comparison of PSD Gust parameters to Recorded Usage (ASD-TR-61-235)

6. Environmental Effects : Flight Conditions

For recorded loads, power spectral gust velocities are not always conservative. DOT/FAA compares discrete gust velocities to those calculated in NACA-TN4332 using the power spectral gust method:



Upward Gust at 29500 ft to 39500 ft - Conservative



Upward Gust at 500 ft to 1500 ft – Not Conservative

Representativeness of Actual versus Analytical PSD Gust Velocities

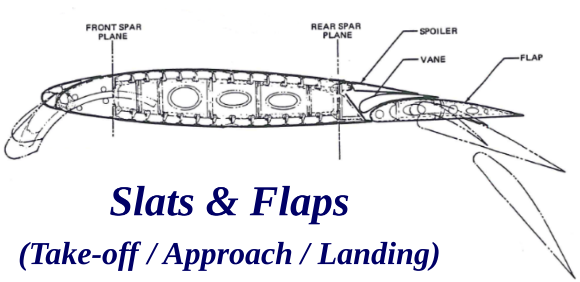
6. Environmental Effects : Flight Conditions

Key Takeaways from Recorded Data versus Gust Methodologies:

1. ***Actual Recorded Usage Data should be used for all evaluations***
2. ***Pure analytical methods should only be used if deemed representative***
3. ***Recorded Nz Accelerations are the source data for all fatigue spectra***
4. ***Gust Velocities, either Discrete or Continuous, are not a requirement but may be used.***
5. ***Discrete or Continuous Gust Velocities should only be used if based on recorded data***
6. ***Fatigue spectra exceedances should not be developed based on the PSD equation without adjustments made based on actual usage data***
7. ***Regardless of the method, dynamic effects must be accounted for***
8. ***PSD Gust may be required for Residual Strength depending on FAR Amdt. Level***

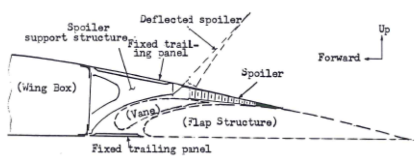
7. Discrete Events:

Service load histories also include loads which are considered discrete. By this it is meant that they occur at a specific instance within the mission profile and either as a single cycle or limited number of cycles. For this reason, they are not considered entirely random.



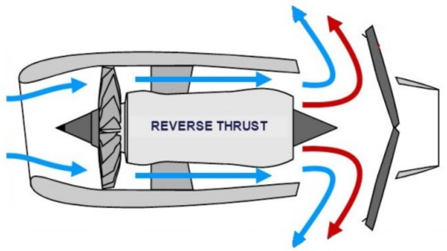
Slats & Flaps

(Take-off / Approach / Landing)

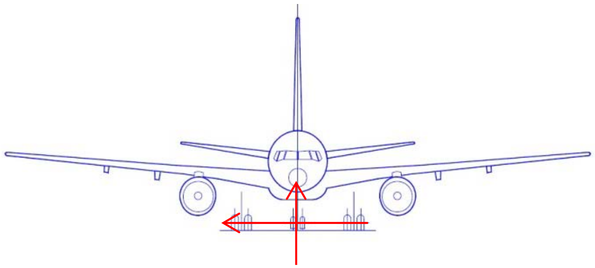


Flight & Ground Spoilers

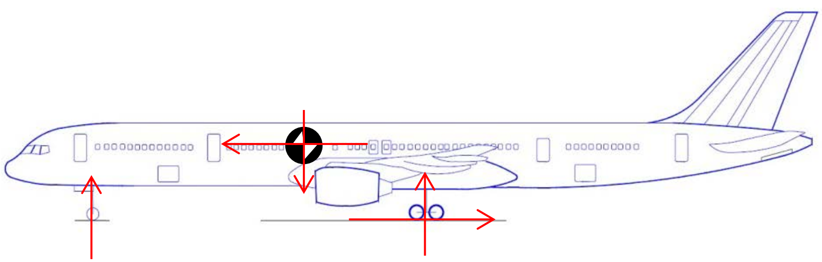
(Descent / Landing Roll)



Reverse Thrust



Ground Turnoffs



3 Point Braked Roll

Discrete Event Conditions

8. Spectrum Development – Example

Having completed a review of most of the major contributors, it is now possible to assemble a complete airframe fatigue load spectrum. The spectrum is an assembly of the repeated cycles in an entire mission due to all load sources accounting for any dynamic effects. This is normally accomplished thru a spectrum generation software program. There are several industry methods including FALSTAFF, TWIST and SPECF. At Aeronautica we utilize a flight by flight code named ASpec.

Typical input requirements are as follows:

- ***Mission distribution***
- ***Load Histories***
- ***Mission Definition***
- ***Flight Segment Definition***
- ***Load Factor Coefficients***

The following example demonstrates the general process of generating a flight by flight fuselage bending spectrum for a modification to the upper fuselage crown. Note, the data in this example is purely for training purposes only and not to be construed as actual aircraft data.

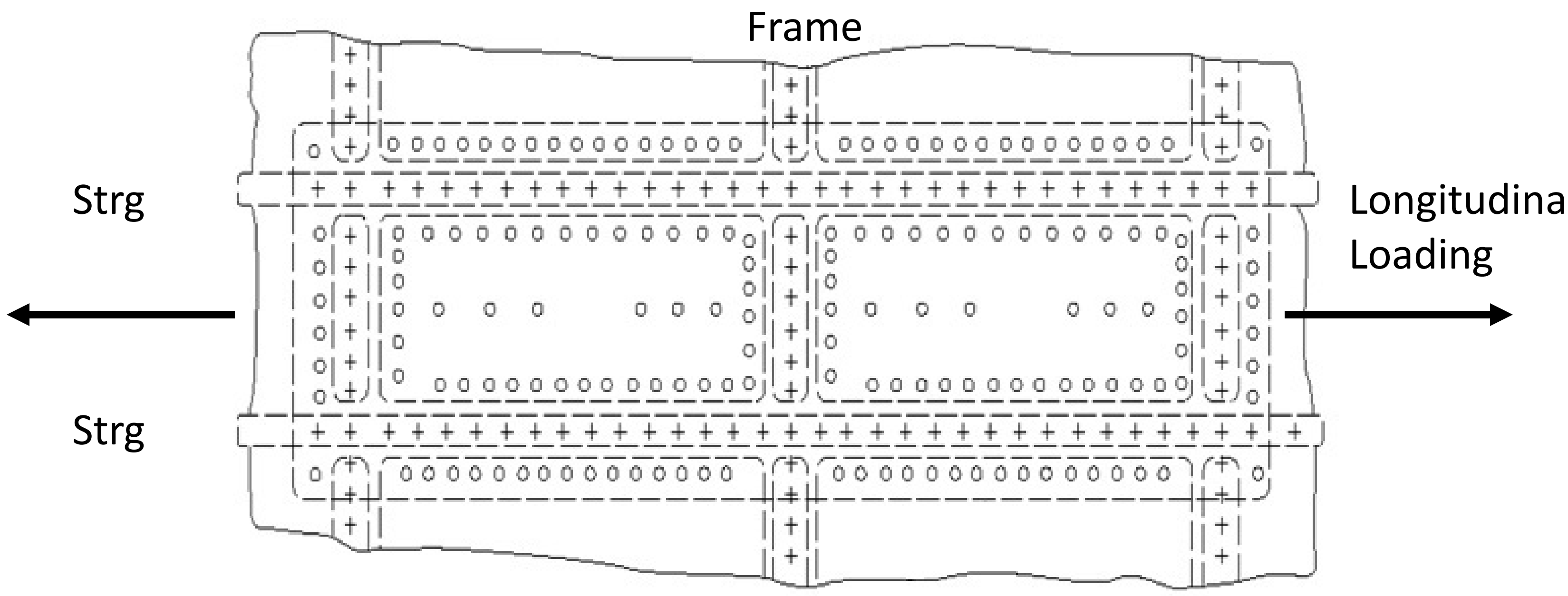
8. Spectrum Development Example:

Aft Upper Crown at Stringer 1 for a 122" Fuselage Radius

2024-T3 Clad 0.07" Sheet Skin with 7075-T6 Sheet Stringers

Modification Consists of a 3 Frame Bay x 2 Stringer Bay Doubler

Example 1: 6 inch wide 0.07" sheet with 0.188" centered countersunk hole



Example 1 –Fuselage Crown (Ref. FAA AC 120-104 Fig. 5-13)

8. Spectrum Development Example

The following presentation details and compares a DTA/WFD evaluation using the FAA Service Load Histories versus that of a pseudo equivalent single cycle (SEC) per flight:

Flight by Flight Method (FBF):

- ***FAA Recorded Load Histories in a Flight by Flight Sequenced Program utilizing the data contained in DOT/FAA/AR-06/11***

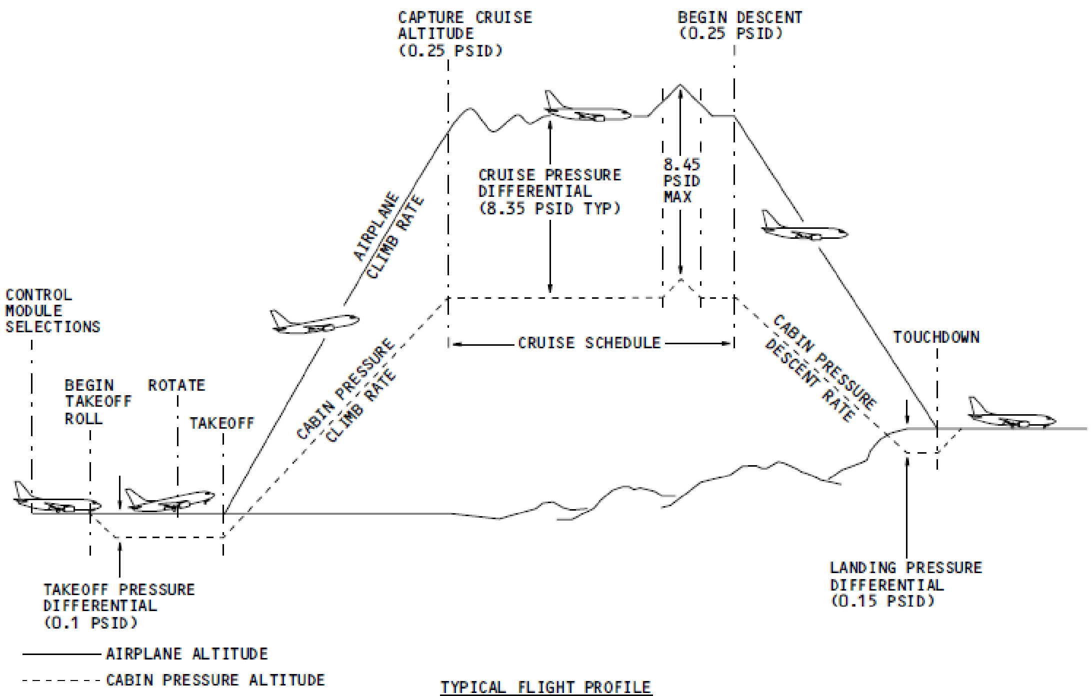
Single Equivalent Cycle (SEC) based on Material Data Only assuming 1 cycle / flight or hour and does not account for aircraft configuration or usage:

- ***TC-12/17 Development and Assessment of Simplified Stress Sequences***

8. Spectrum Development Example

FBF Spectrum Process begins with Mission Profile definition and flight segment description:

- ***FAA and Industry Data is Utilized to Establish Missions and Flight Segments (DOT/FAA/AR-06/11, Bureau of Transportation Usage Statistics, FAA SDR database)***



Definition of Mission Profile

8. Spectrum Development Example

Next step is to establish the average durations for each of the missions. To accomplish this, the data from the Bureau of Transportation previously cited in Session 4 is most useful:

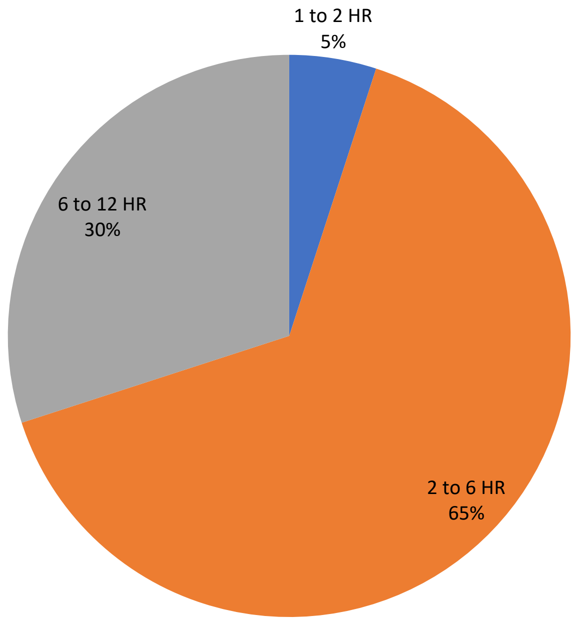
Average Daily Aircraft Utilization

Copy Table

Aircraft	Carrier	Ops	BHs	RPMs	ASMs	Load Factor
Widebodies		*1.5*	*12.0*	*1,221,393*	*1,474,788*	*82.8%*
767-200/ER	American	2.0	10.9	699,968	795,185	88.0%
767-300/ER	United	1.3	10.7	770,918	995,834	77.4%
767-300/ER	North American	0.8	5.3	288,666	490,387	58.9%
767-200/ER	US Airways	2.2	13.3	972,619	1,223,707	79.5%
767-300/ER	American	1.6	10.6	881,274	1,054,949	83.5%
787-800	United	1.4	10.4	966,588	1,130,503	85.5%
767-300/ER	Delta	1.8	12.2	1,044,748	1,249,756	83.6%
A330-200	Delta	1.4	11.8	1,208,528	1,368,813	88.3%
767-400	United	1.5	11.7	1,120,433	1,344,849	83.3%
767-400	Delta	1.5	13.2	1,278,768	1,530,640	83.5%
777-200	American	1.2	11.9	1,184,305	1,452,882	81.5%
767-300/ER	Hawaiian	1.6	10.4	978,936	1,261,068	77.6%
777-200	Delta	1.3	14.0	1,671,443	1,894,972	88.2%
777-200	United	1.4	12.6	1,399,752	1,704,284	82.1%
A330-200	US Airways	2.1	15.8	1,597,632	2,012,832	79.4%
A330-200	Hawaiian	1.9	13.4	1,568,341	1,882,493	83.3%
A330-300	Delta	1.6	13.5	1,682,727	1,922,845	87.5%
777-300	American	1.3	12.1	1,424,881	1,840,495	77.4%
747-400	United	1.1	10.9	1,727,545	2,089,995	82.7%
747-400	Delta	1.4	11.9	1,957,006	2,242,093	87.3%

www.PlaneStats.com

US DOT Form 41 Data via PlaneStats.com.



Development of Mission Utilization from DOT Data

8. Spectrum Development Example

Recorded Statistical Fatigue Loads are Obtained for each relevant flight segment from FAA/Industry Data:

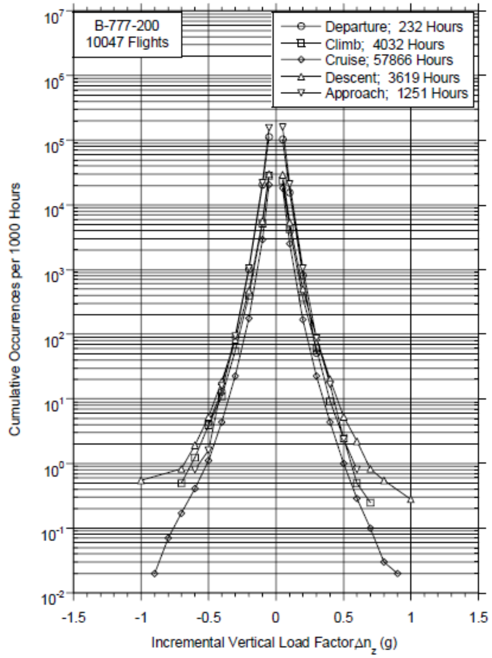


Figure C-41. Cumulative Occurrences of Incremental Vertical Gust Load Factor per 1000 Hours by Flight Phase

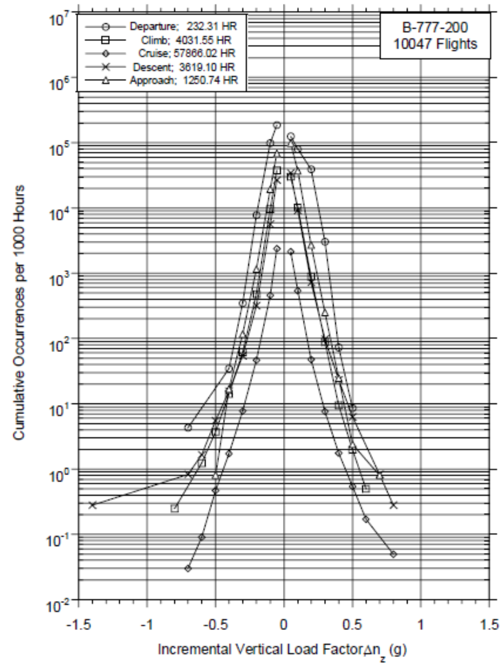
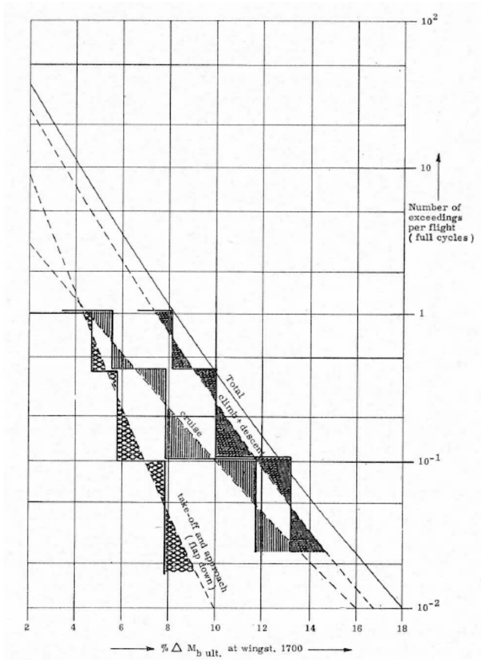


Figure C-69. Cumulative Occurrences of Incremental Vertical Maneuver Load Factor per 1000 Hours by Flight Phase

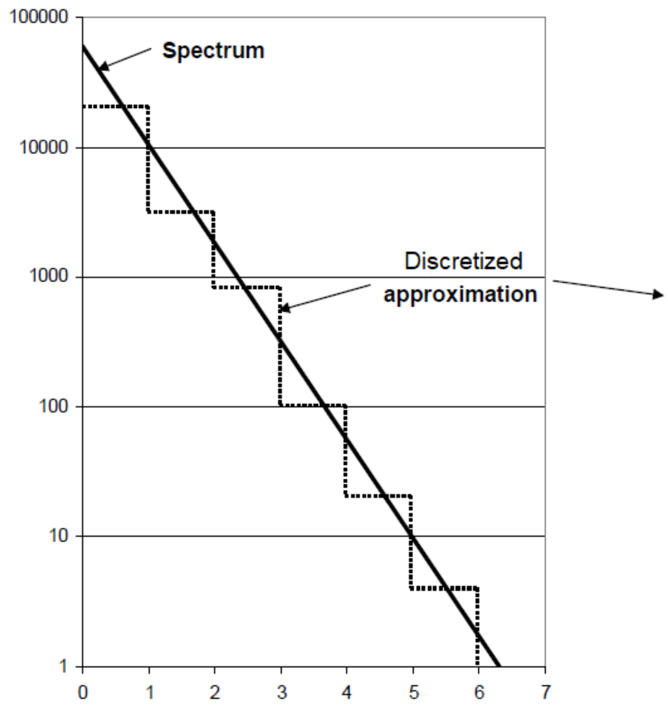


Sample F28 Discretized Gust Load Histories (ICAF 1967)

Selected Load Histories for Discretization

8. Spectrum Development Example

Load History exceedance data is obtained for the relevant load sources such as gust, maneuver, taxi, landing, etc. for each flight segment from industry data. This data must then be discretized into load levels. Typical data is organized in 1000 flight hour blocks.



Level	Exceedances/Year
1	20000
2	3000
3	800
4	100
5	20
6	4

Sample Discretized Load History Block

8. Spectrum Development Example

Block spectra can be utilized directly however there are significant impacts of utilizing this type of spectrum.

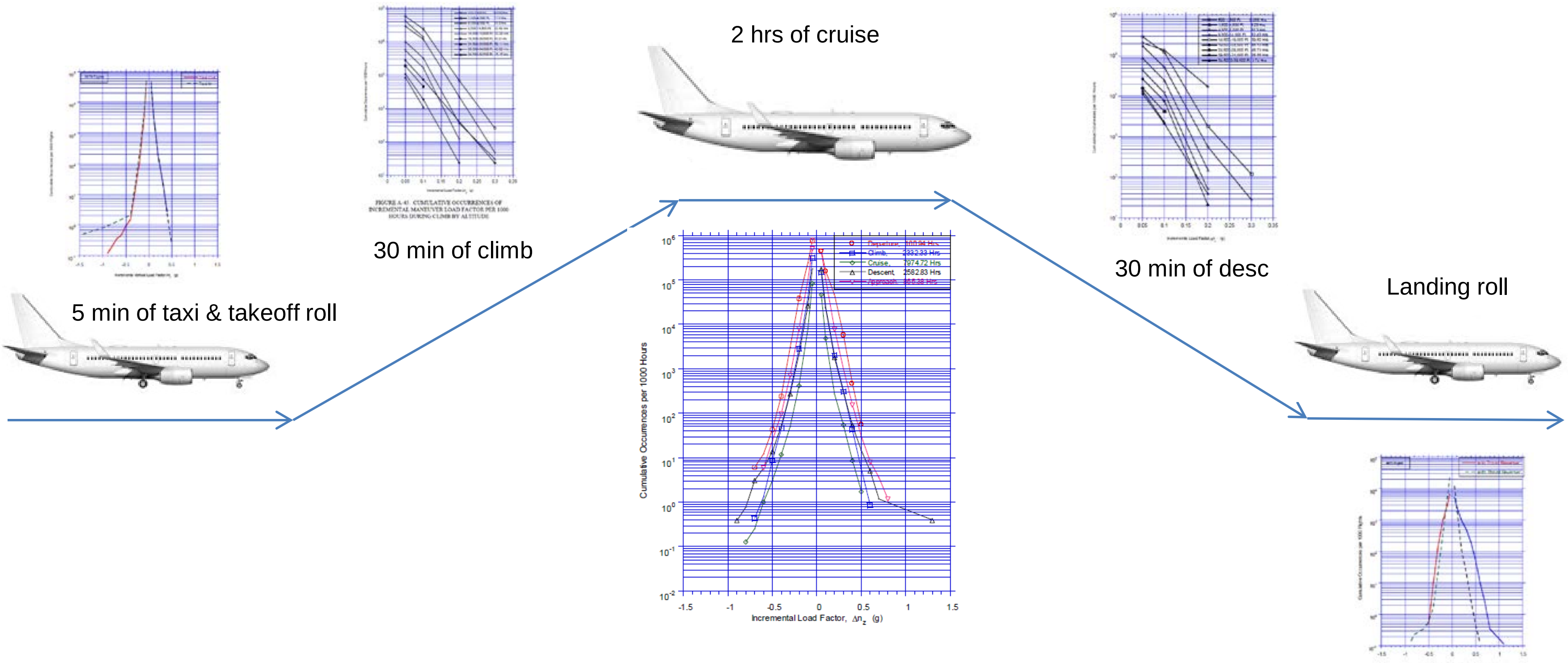
- ***Block Spectra are presented typically in 1000 hour blocks***
- ***Crack growth failure within a block negates use of that block***
- ***Cannot represent usage or damage severity impacts***
- ***Cannot account for retardation effects***

Flight by flight spectra are the most representative spectra that can be developed and complies with commercial and government requirements.

- ***Best reflects actual utilization***
- ***Permits usage severity and damage source identification***
- ***Supports crack growth on a flight by flight basis***

8. Spectrum Development Example

All pertinent load histories must be discretized first. Then a probability distribution can be assigned to each. This permits a random selection of loads during each segment of the flight based on the duration of the event.

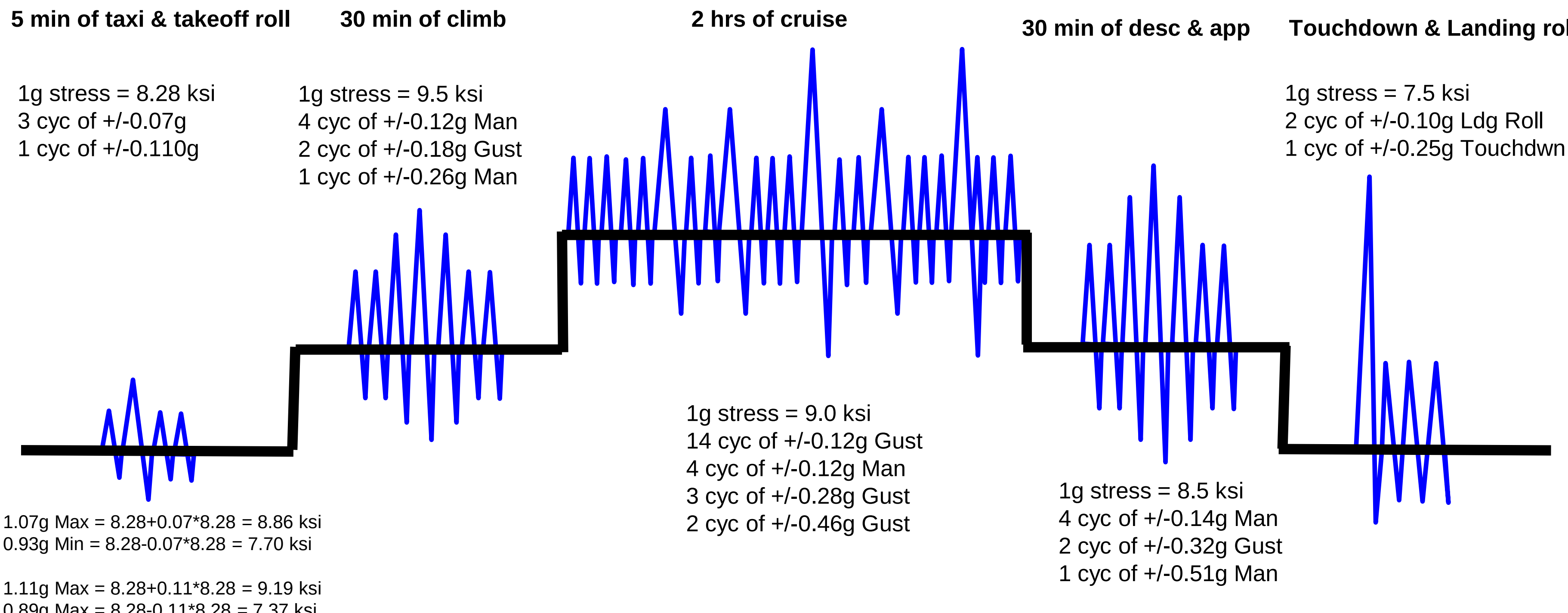


Sample Flight by Flight Load Compilation

8. Spectrum Development Example

All pertinent load histories must be discretized first. Then a probability distribution can be assigned to each. This permits a random selection of loads during each segment of the flight based on the duration of the event using the general equation for max and minimum stress.

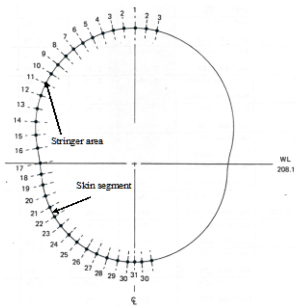
$$\sigma_{max/min} = \sigma_{1g} +/- [(\Delta\sigma / \Delta N_{xyz}) * \Delta N_{xyz} * DMF]$$



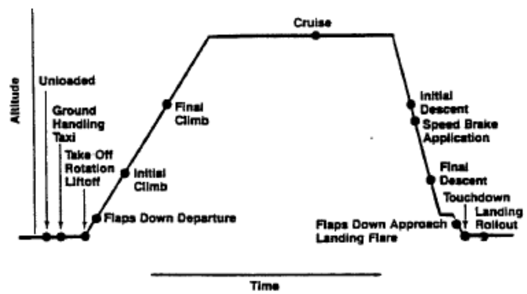
Sample Flight by Flight Spectrum Assembly

8. Spectrum Development Example

Compilation of Internal Loads and Stresses, Mission Definition and Load Histories as well as Dynamic Effects into FBF Spectrum Software to Produce Spectrum



Unit Beam Model Internal Stresses



Mission Profiles

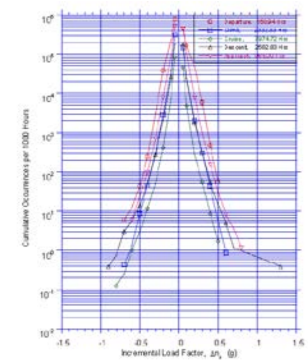
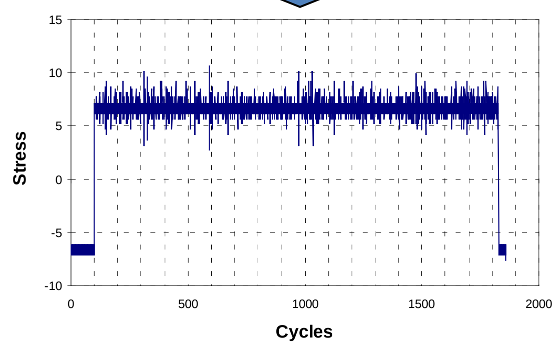


FIGURE A-29. CUMULATIVE OCCURRENCES OF VERTICAL GUST LOAD FACTOR PER 1000 HOURS BY FLIGHT PHASE

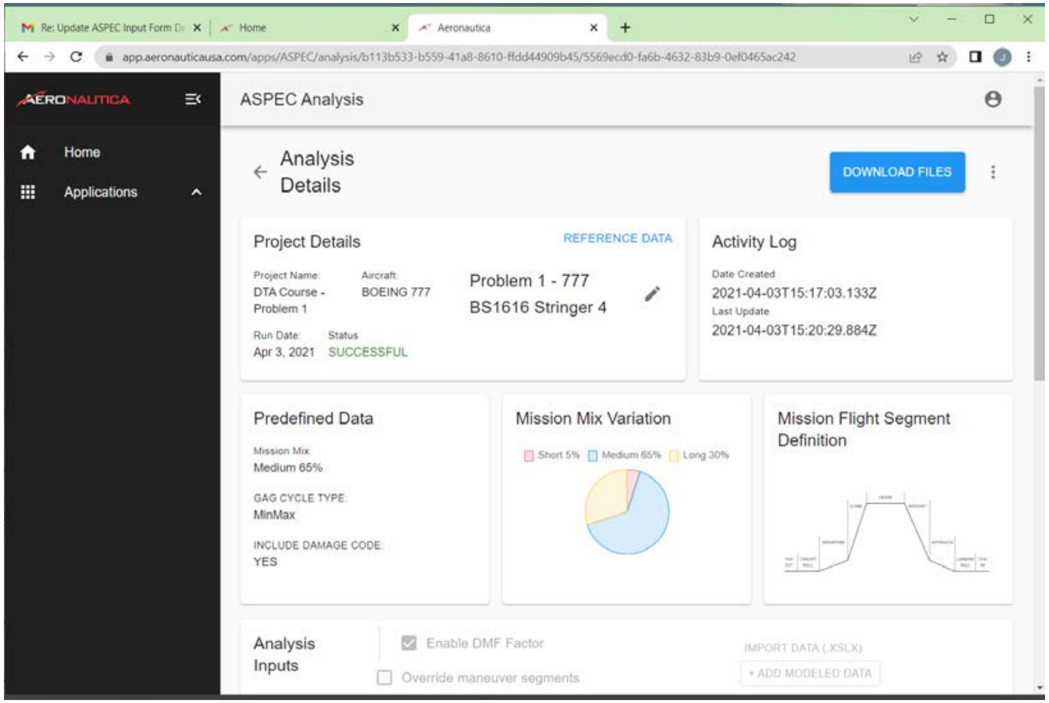
Load Histories & Dynamic Effects



Input of All Data and Development of Flight by Flight Spectrum

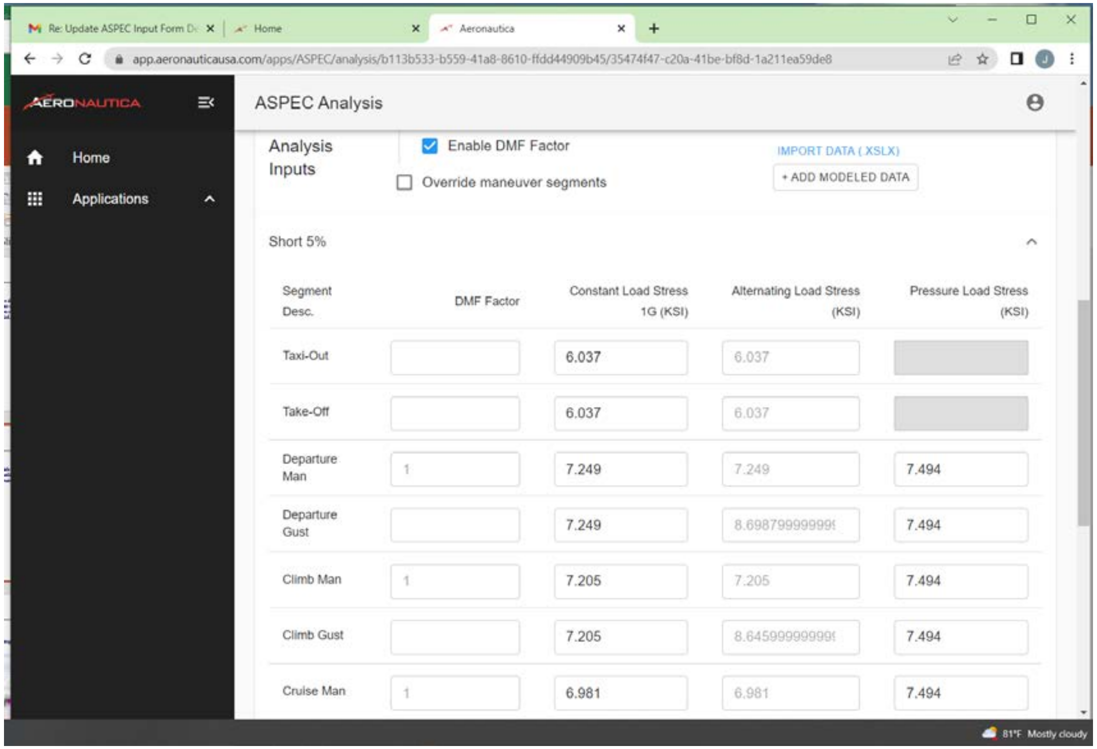
8. Spectrum Development Example

Having developed both external and internal fatigue loads, fatigue stresses are determined for each of the flight segments for 1g and delta g values. Additionally, any dynamic magnification factors (DMF) are also included. These stresses are then input into a spectrum code to develop a flight by flight randomized spectrum. Code developed by Aeronautica is called ASpec and is a web based tool.



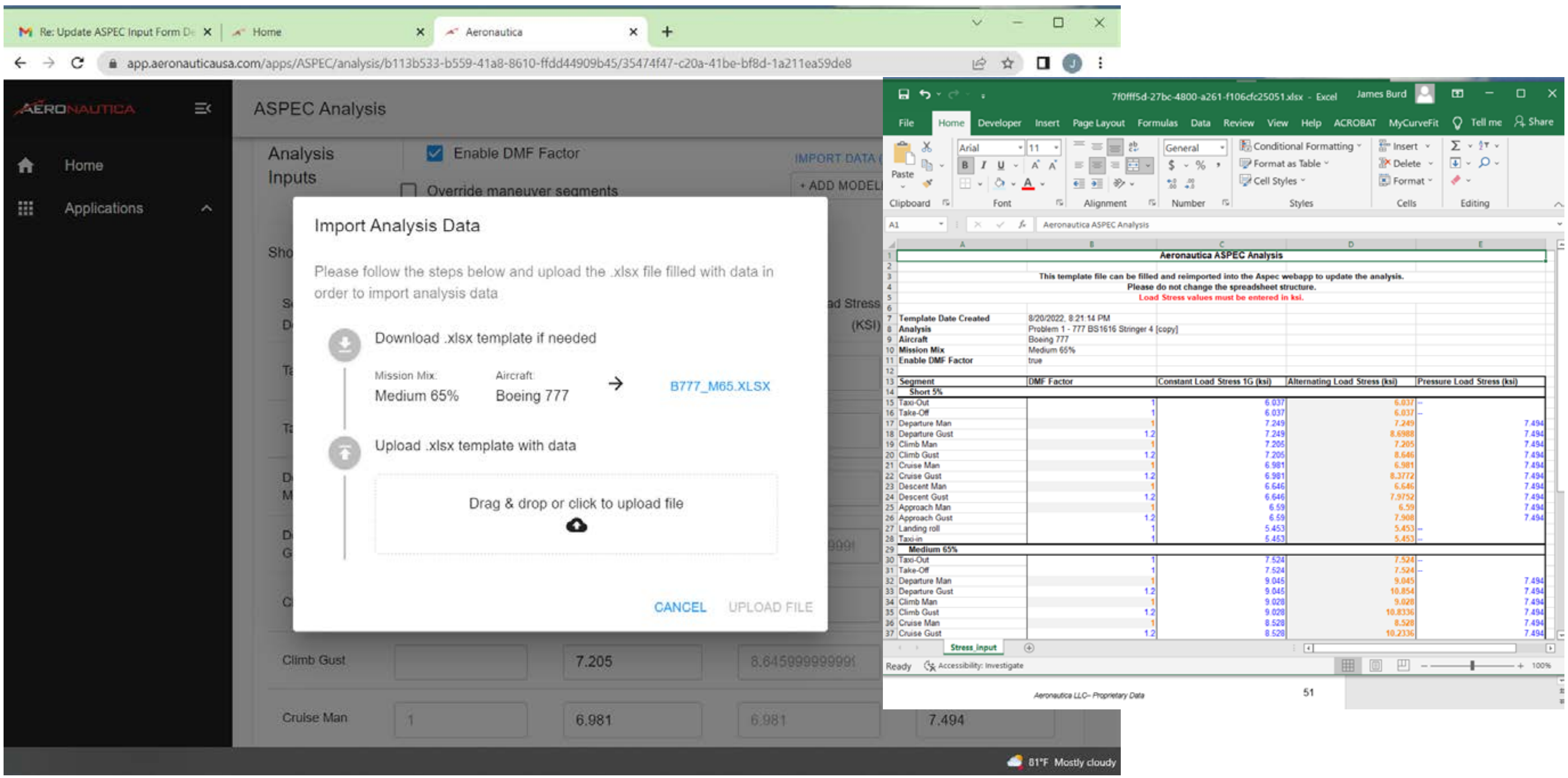
8. Spectrum Development Example

ASpec utilizes the FAA database of load histories for a variety of aircraft models and also the DOT mission utilizations. Once an aircraft model is selected, then a specific utilization is chosen along with the various types of output data formats. Fatigue stress inputs can be made manually into the web tool or uploaded via an excel template.



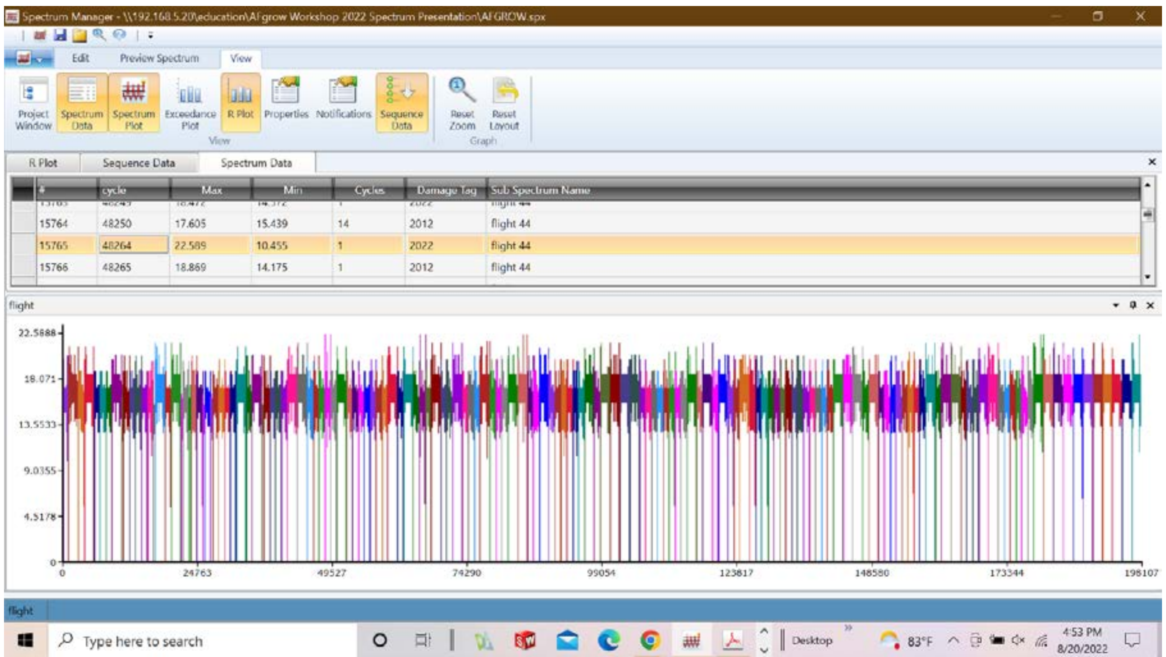
Aeronautica LLC– Proprietary Data

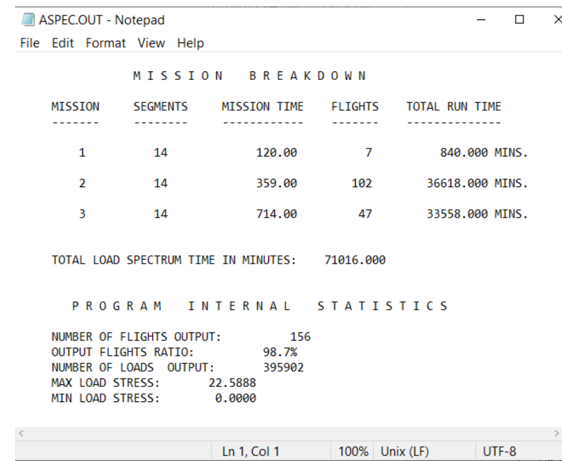
8. Spectrum Development Example

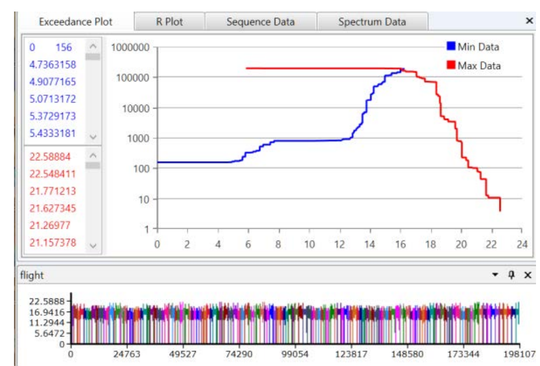


8. Spectrum Development Example

Based on the data entered for the aft upper fuselage crown, a spectrum consisting of 1000 flight hours representing 156 flights was developed.

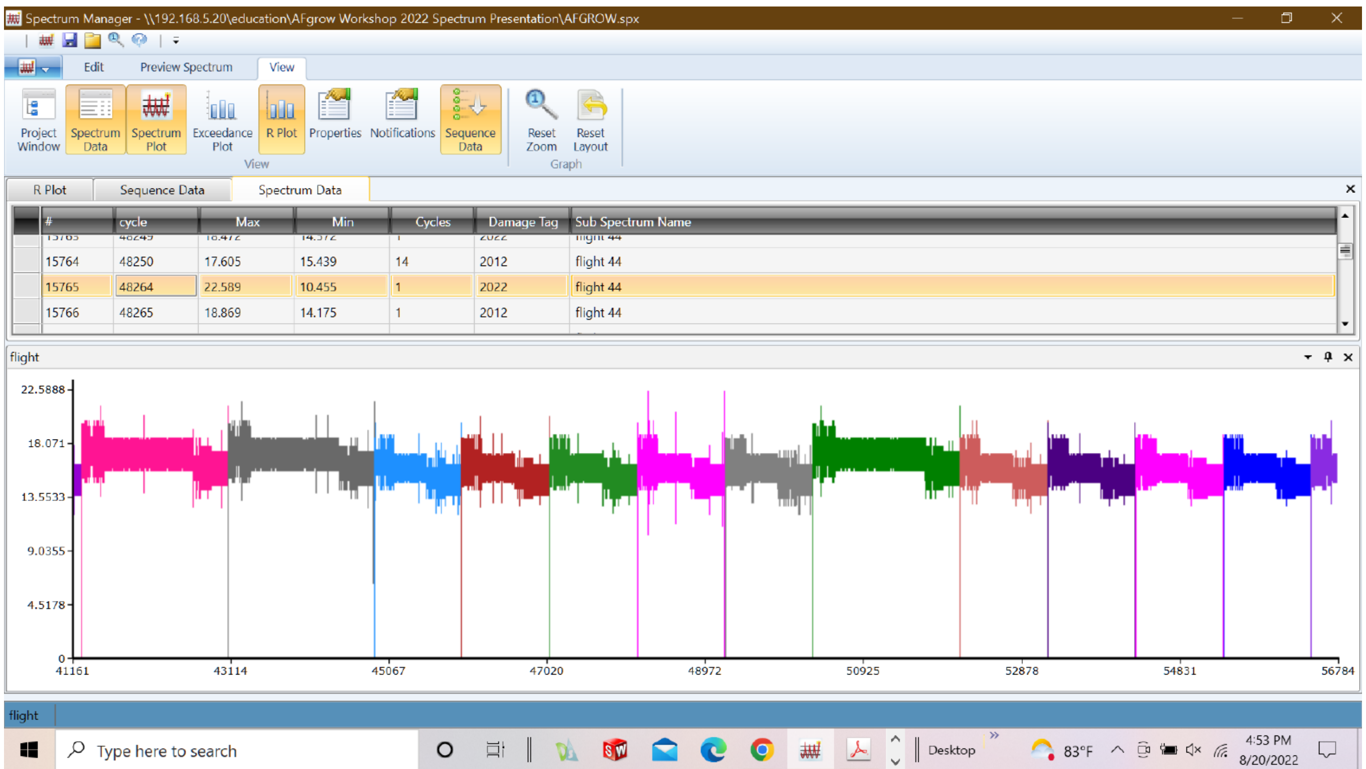






8. Spectrum Development Example

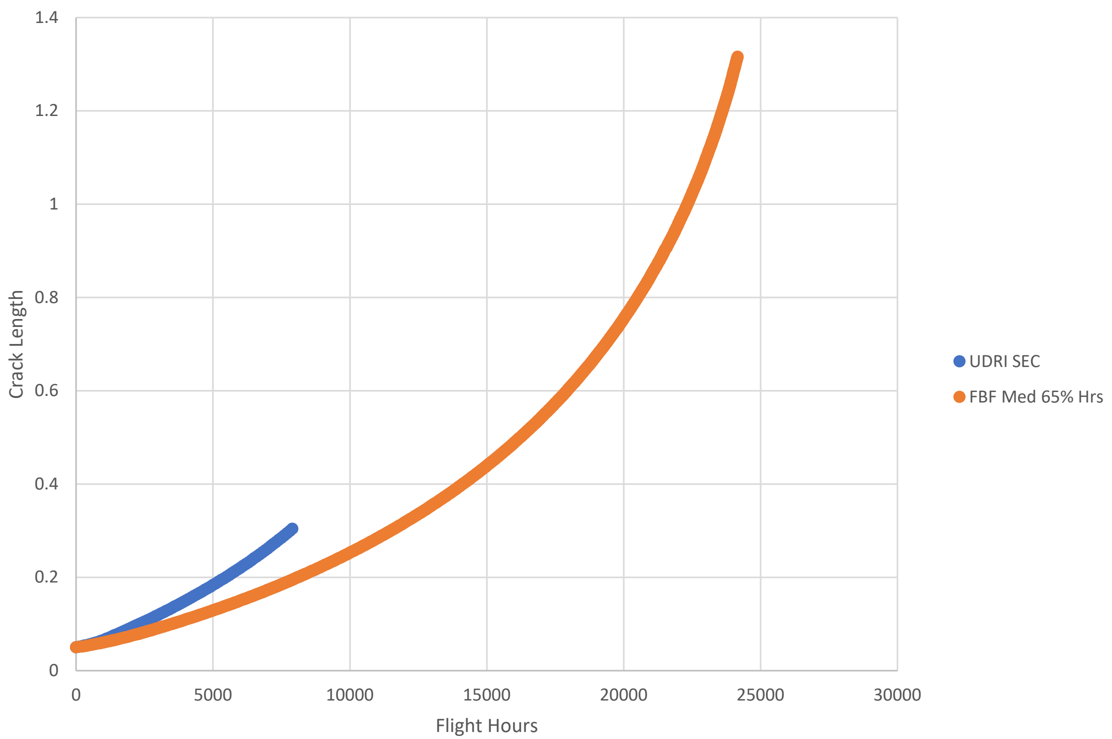
Based on the data entered for the aft upper fuselage crown, a spectrum consisting of 1000 flight hours representing 156 flights was developed. A plot of the flight with the maximum stress is shown below:



Sample Flight 44 from Example Spectrum

8. Spectrum Development Example

Crackgrowth comparison is made for a 6” wide 2024-T3 plate 0.07” thick with a centered 3/16” diameter countersunk fastener hole with no load transfer and a single 0.05” corner.



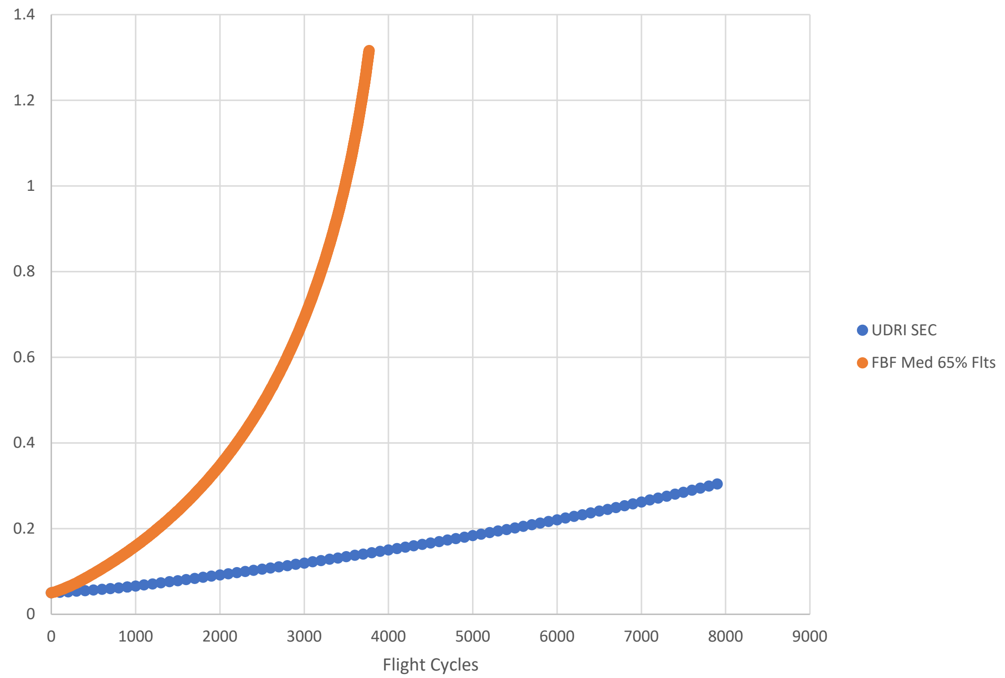
<u>FBF:</u>
N = 24164 Hours
Ccrit = 1.316”

<u>SEC:</u>
N = 7900 Hours
Ccrit = 0.30”

Comparison of Crack Growth Life in terms of Flight Hours

8. Spectrum Development Example

Converting the crack growth results into flight cycles instead of the flight hours, the following comparison is also made. Note that the SEC method produces a longer life than the FBF. This is predominantly due to the fact that the SEC assumes that the GAG fatigue loads is the most damaging source and also it can only really predict flight cycles.



FBF:
N = 3770 Flights
Ccrit = 1.316”

SEC:
N = 7900 Flights
Ccrit = 0.30”

Summary:
SEC approach is NOT conservative for this type of mission utilization & spectra

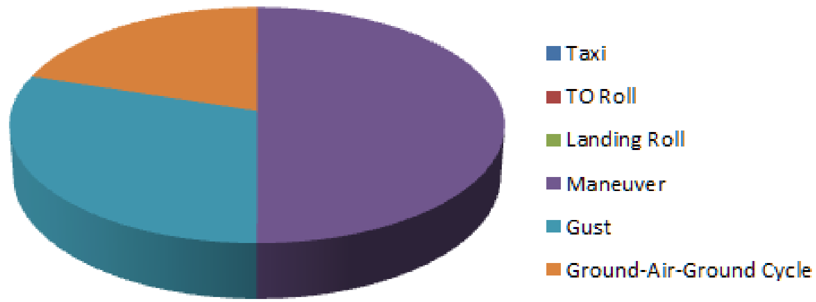
Comparison of Crack Growth Life in terms of Flight Cycles

8. Spectrum Development Example

FAA FAR 25.571 clearly requires that the utilization of the aircraft be accounted for. As previously shown, this cannot be accomplished with a Single Equivalent Cycle for all aircraft. In particular, aircraft usage which includes longer flights will have their crack growth damage source from several portions of the flight segment depending on the mission profile. Below is an AFGROW output summary for the damage source from the previous example:

1st Digit	Mission #	ie 1 = Missin type 1
2nd Digit	GAG Type	ie 1 = Max-min
3d Digit	Load Source	ie 23 = Gust Cruise

```
Damage Summary (By Source)
Percent of total damage due to '1001':     0.00%
Percent of total damage due to '1002':     0.00%
Percent of total damage due to '1011':     0.15%
Percent of total damage due to '1012':     0.09%
Percent of total damage due to '1013':     0.09%
Percent of total damage due to '1014':     0.07%
Percent of total damage due to '1015':     0.10%
Percent of total damage due to '1021':     0.17%
Percent of total damage due to '1022':     0.09%
Percent of total damage due to '1023':     0.03%
Percent of total damage due to '1100':     0.45%
Percent of total damage due to '2001':     0.00%
Percent of total damage due to '2002':     0.01%
Percent of total damage due to '2011':     2.52%
Percent of total damage due to '2012':     8.30%
Percent of total damage due to '2013':     7.49%
Percent of total damage due to '2014':     4.58%
Percent of total damage due to '2015':     3.31%
Percent of total damage due to '2021':     5.41%
Percent of total damage due to '2022':     7.58%
Percent of total damage due to '2023':     2.78%
Percent of total damage due to '2100':    10.26%
Percent of total damage due to '3001':     0.00%
Percent of total damage due to '3002':     0.02%
Percent of total damage due to '3011':     3.55%
Percent of total damage due to '3012':     5.66%
Percent of total damage due to '3013':    12.68%
Percent of total damage due to '3014':     3.00%
Percent of total damage due to '3015':     1.73%
Percent of total damage due to '3021':     3.41%
Percent of total damage due to '3022':     5.23%
Percent of total damage due to '3023':     4.84%
Percent of total damage due to '3100':     6.38%
```



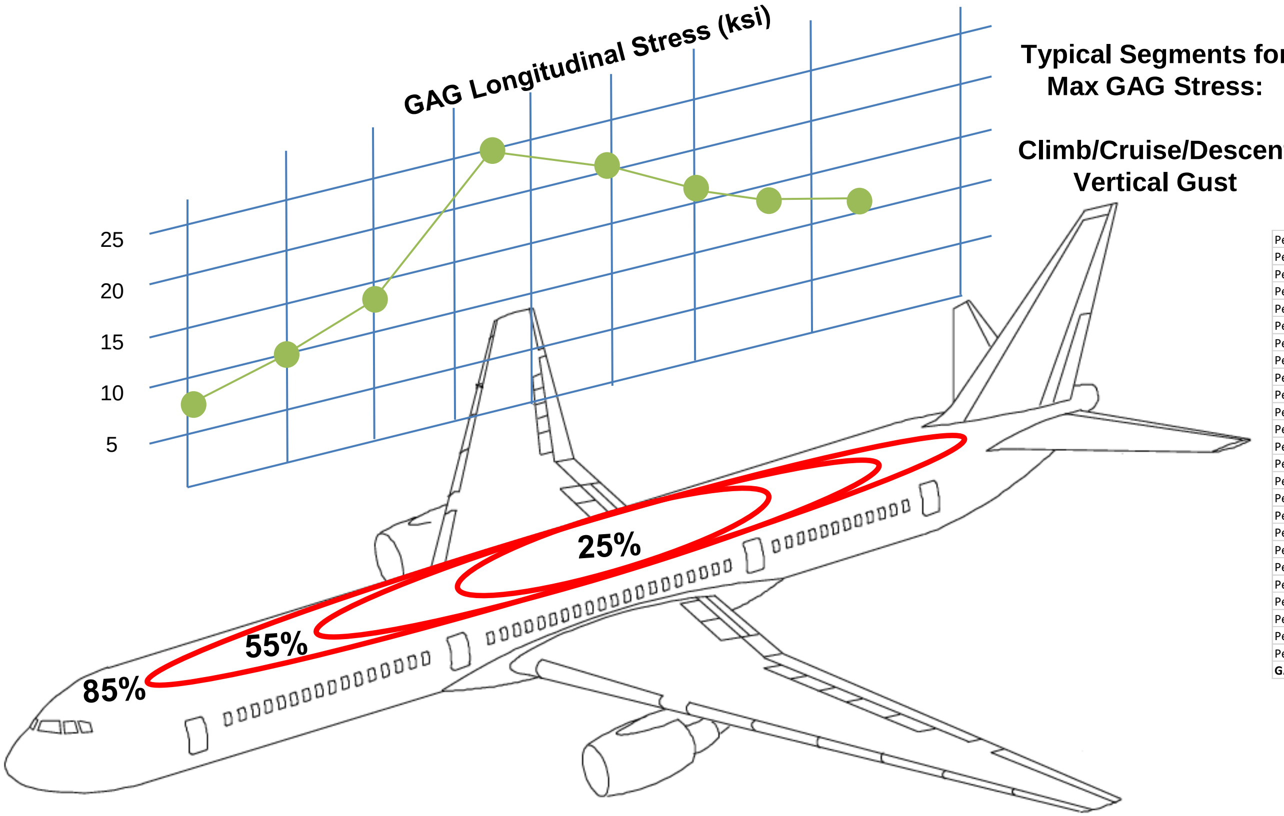
Note: Military aircraft can likewise be affected:

LOCATION	PERCENT OF TOTAL DAMAGE		
	GAG	GUST	MANEUVER
B-47			
BL 45 LOWER	11	44	45
WS354 LOWER	12	72	16

Benefit of Damage Source Summary – Determination of Hours versus Cycles Criticality

8. Spectrum Development Example

The ASpec spectrum file in AFGROW format also includes a damage code which is very useful in the crack growth analysis to identify mission usage severity and damage sources.



Percent of total damage due to 'Mission 1 Departure Maneuver':	0.74%
Percent of total damage due to 'Mission 1 Climb Maneuver':	0.28%
Percent of total damage due to 'Mission 1 Cruise Maneuver':	0.19%
Percent of total damage due to 'Mission 1 Descent Maneuver':	0.19%
Percent of total damage due to 'Mission 1 Descent Maneuver':	0.11%
Percent of total damage due to 'Mission 1 Departure/Approach Gust':	0.00%
Percent of total damage due to 'Mission 1 GAG':	0.74%
Percent of total damage due to 'Mission 2 Departure Maneuver':	6.13%
Percent of total damage due to 'Mission 2 Climb Maneuver':	15.03%
Percent of total damage due to 'Mission 2 Cruise Maneuver':	10.06%
Percent of total damage due to 'Mission 2 Descent Maneuver':	9.45%
Percent of total damage due to 'Mission 2 Descent Maneuver':	4.20%
Percent of total damage due to 'Mission 2 Departure/Approach Gust':	0.03%
Percent of total damage due to 'Mission 2 Climb/Descent Gust':	0.02%
Percent of total damage due to 'Mission 2 Cruise Gust':	0.00%
Percent of total damage due to 'Mission 2 GAG':	13.89%
Percent of total damage due to 'Mission 3 Departure Maneuver':	5.64%
Percent of total damage due to 'Mission 3 Climb Maneuver':	7.69%
Percent of total damage due to 'Mission 3 Cruise Maneuver':	12.89%
Percent of total damage due to 'Mission 3 Descent Maneuver':	4.57%
Percent of total damage due to 'Mission 3 Descent Maneuver':	1.28%
Percent of total damage due to 'Mission 3 Departure/Approach Gust':	0.01%
Percent of total damage due to 'Mission 3 Climb/Descent Gust':	0.03%
Percent of total damage due to 'Mission 3 Cruise Gust':	0.00%
Percent of total damage due to 'Mission 3 GAG':	6.82%
GAG Damage:	**21.45%**

Example Wide-body GAG Contour Plot

9. Summary of DTA Course

The preceding was a brief summary of the topics and content that are presented in the full 40 hour Damage Tolerance Course offered. The following is a listing of the topics and subjects which are addressed in much more depth during the course:

A. ***Development of Mission Utilization from DOT data***
B. ***Development and Implementation of Load Histories***
C. ***External and Internal Fatigue Loads Development***
D. ***Spectrum Development Methods***
E. ***Detailed Examples Worked Thru to Illustrate Methods***
F. ***Comparisons of Results***
G. ***Full Bibliography of References***

Next DTA Course offering: ***26 thru 30 October in Colorado Springs***

https://aeronauticausa.com/courses/