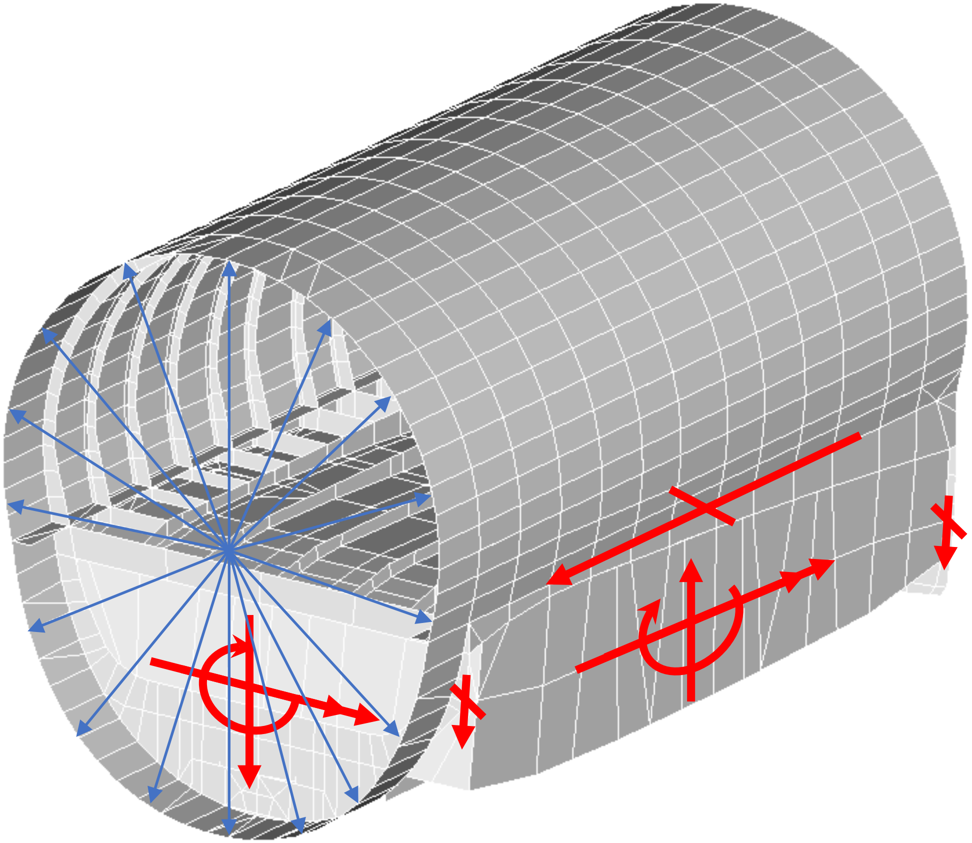
Spectrum Development for Complex Loading in Aircraft Structures

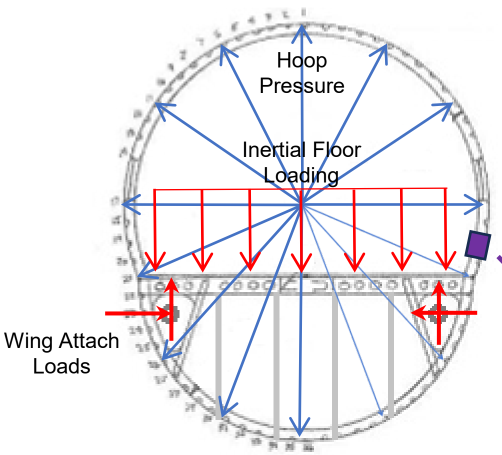


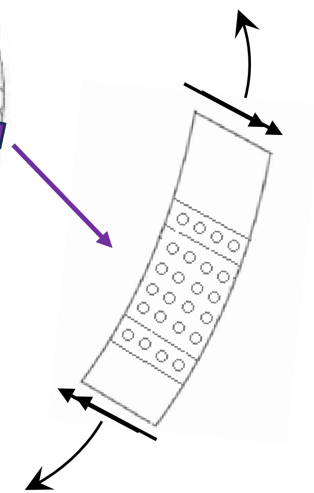
James Burd
Aeronautica
AFGROW Users Workshop 2023

Complex Spectrum Analysis

Structural Details Affected by Complex Loading:

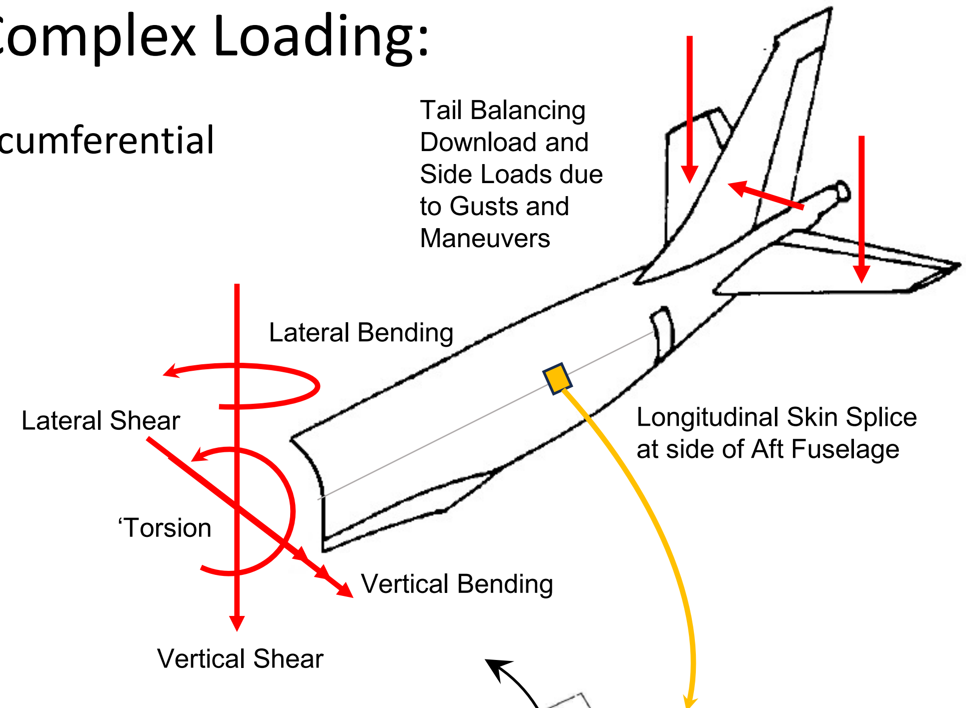
- Fuselage Skin Joints – Longitudinal and Circumferential
- Fuselage Bulkhead and Wing Attach Joints





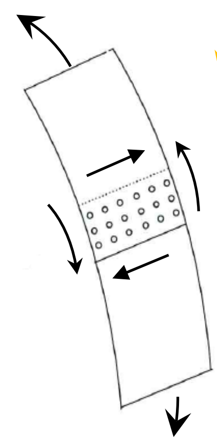
Frame Inner Cap Splice Joint experiences load transfer due to:

- Hoop Loading Tension due to Fuselage Pressure
- Inner Cap Tension due to Frame Bending from Wing Attach Loads and Floor Loading



Lap Joint experiences load transfer due to:

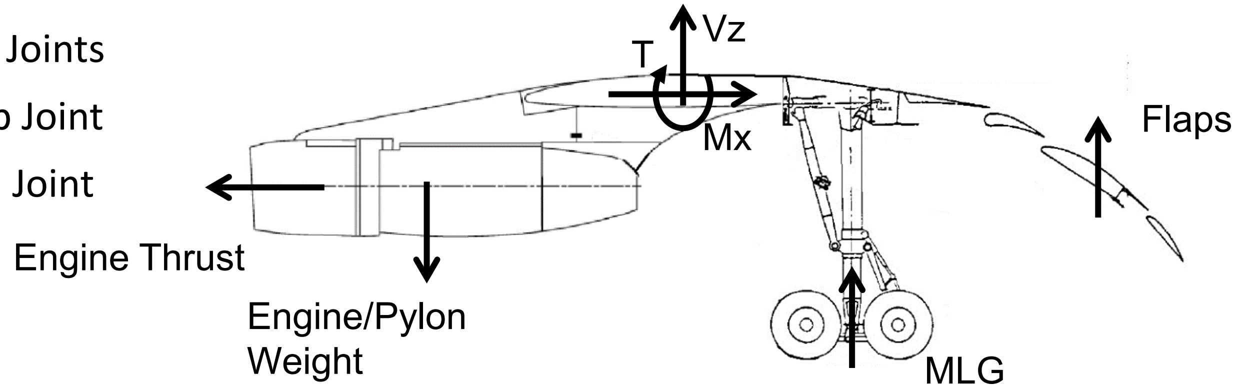
- Hoop Loading Tension due to Fuselage Pressure
- Fastener Loads due to Shear Flow in Skin Panel from Fuselage Bending



Complex Spectrum Analysis

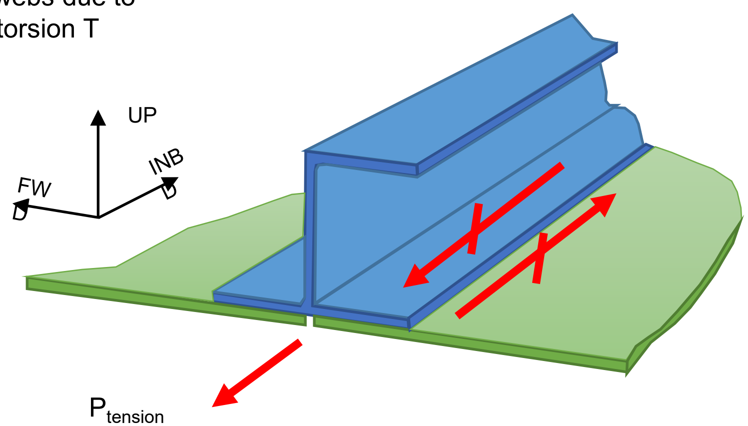
Typical Structural Details that are Affected by Complex Loading:

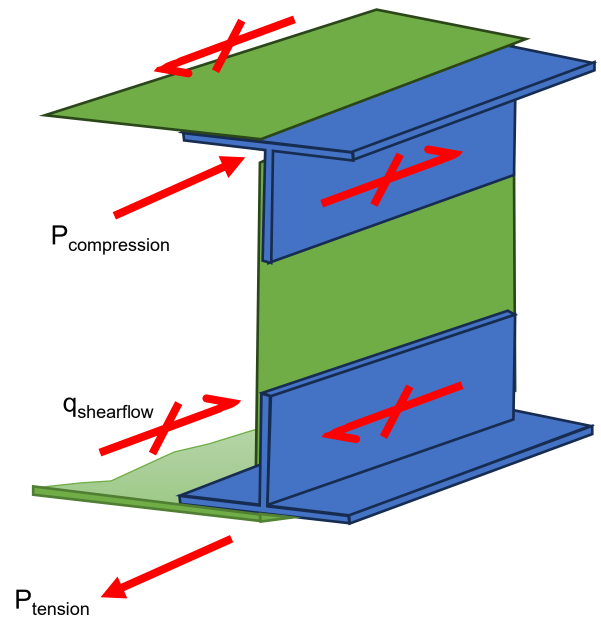
- Wing Spanwise Splice Joints
- Wing Spar Web to Cap Joint
- Wing Spar Cap to Skin Joint



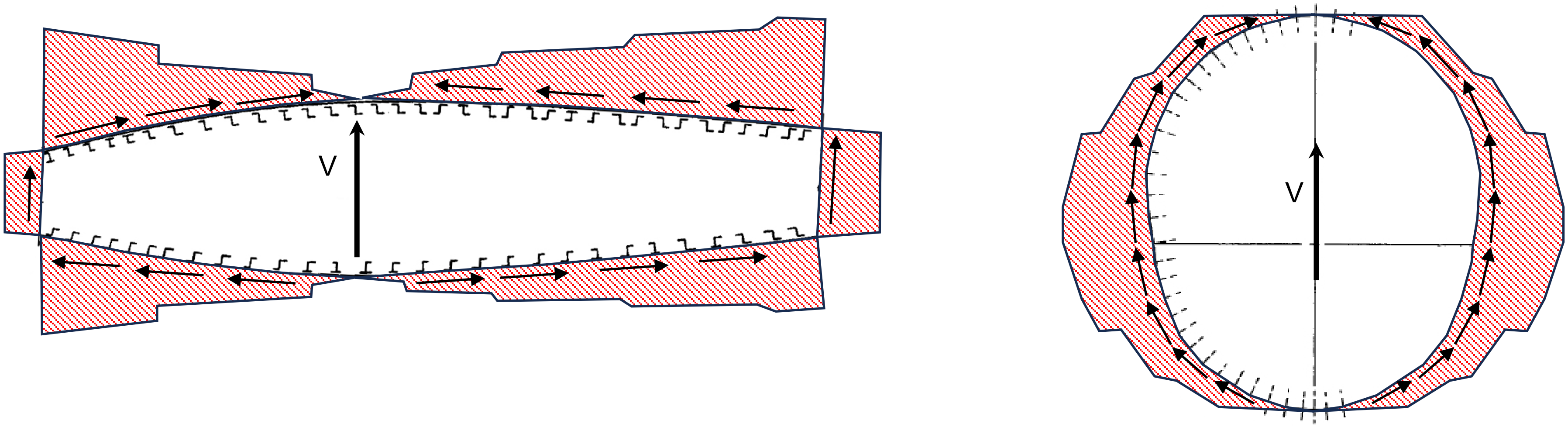
Joint experiences load transfer due to:

- Axial Loads due to wing bending Mx
- Shear Flow in skin panel and spar webs due to wing torsion T

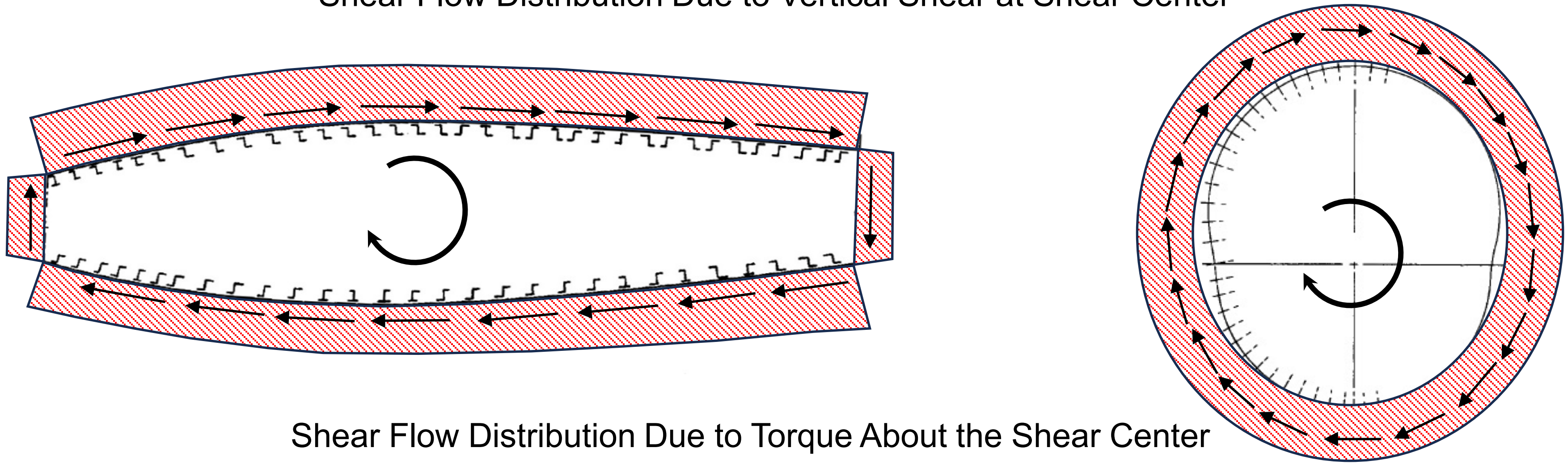




Complex Spectrum Analysis



Shear Flow Distribution Due to Vertical Shear at Shear Center

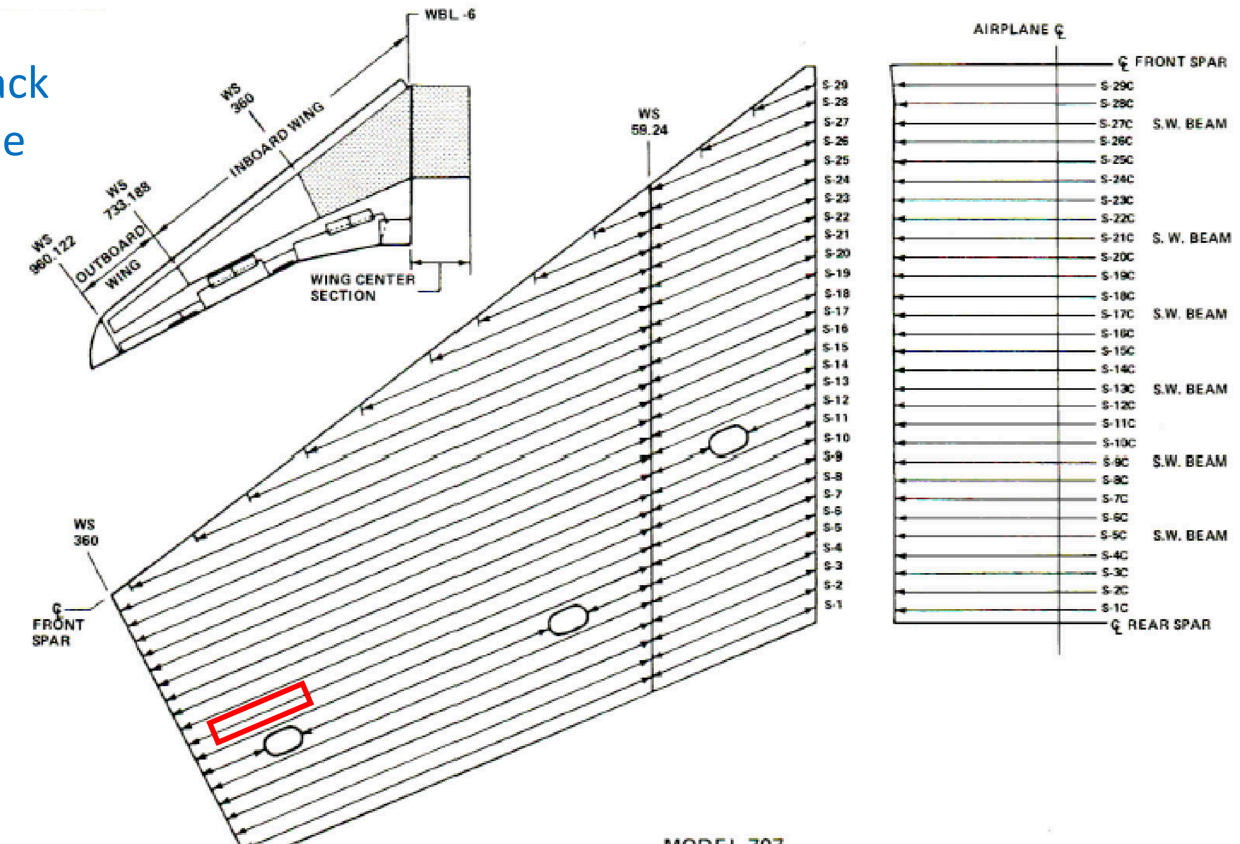


Shear Flow Distribution Due to Torque About the Shear Center

Sample Problem
Lower Wing Skin, Stringer 8, Spanwise Splice

Use multi-phase crack growth to determine

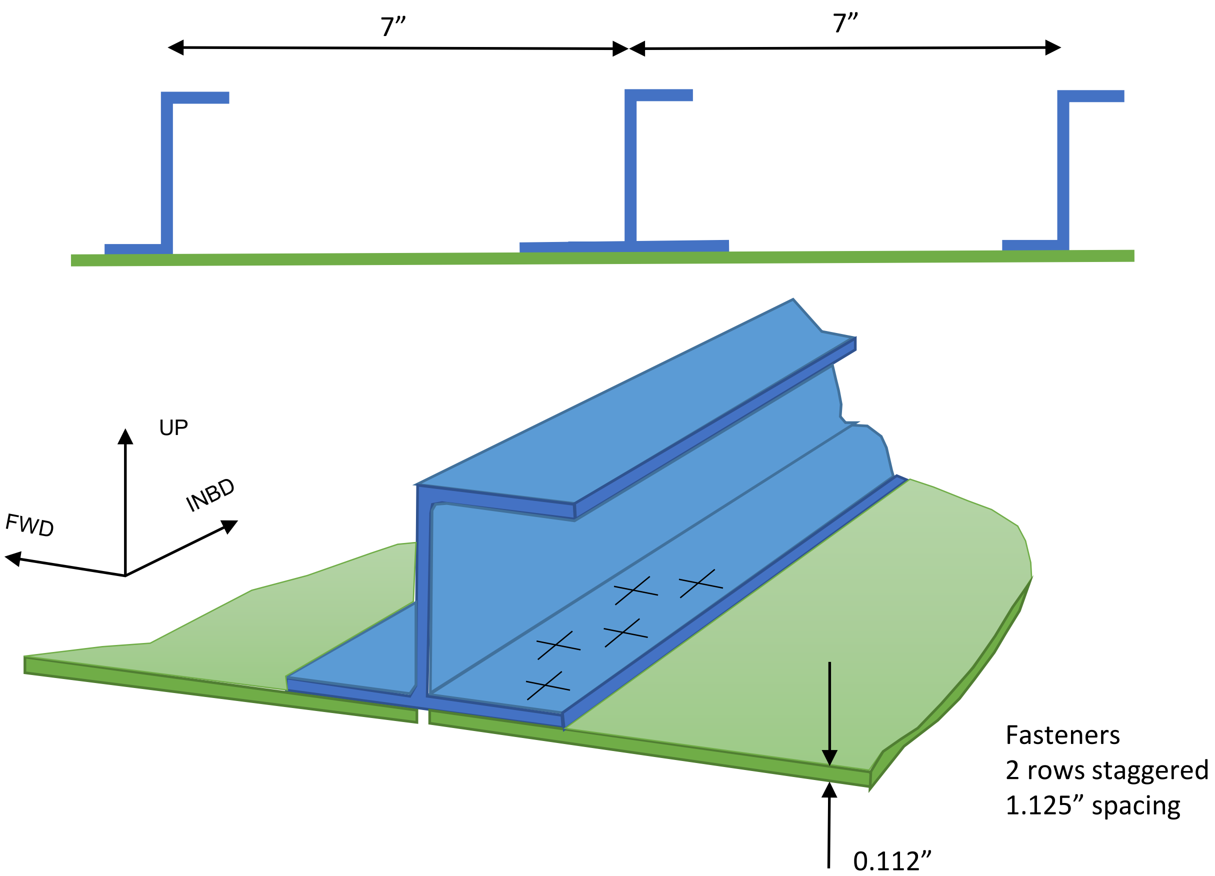
1. Multiple Load Path Capability
2. Inspection Requirements



MODEL 707

LOWER WING STIFFENERS WBL-6 TO WS 360

Structural Arrangement



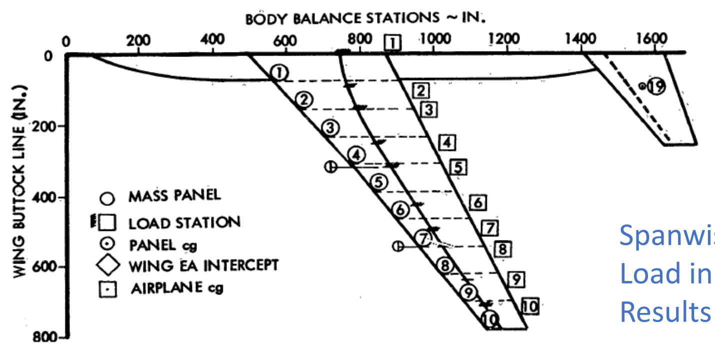
Fatigue Loads and Spectra

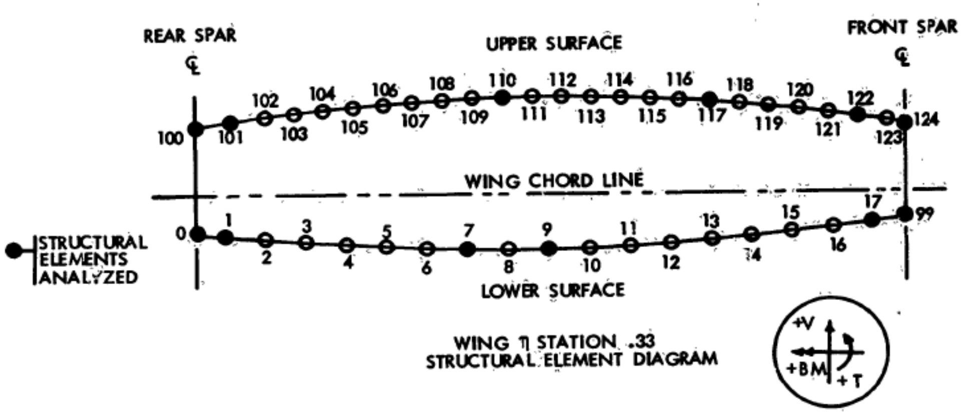
For the 720 model aircraft, FAA-ADS-54 provides the necessary wing 1G shear, moment and torsional loads for each of the flight segments in the mission profiles. For the example, a set of 3 mission profiles are chosen: short, medium and long.

720B 1G Wing Loads															
	Eta	Wing sta	1	2	3	4	5	6	7	8	9	10	11	12	13
Bending Moment	0	0	14900000	15700000	16900000	15300000	15400000	15000000	18100000	17200000	17200000	16100000	16600000	15000000	15400000
	0.12	94.4	12000000	12500000	13300000	11700000	12200000	11000000	13150000	13400000	13600000	12700000	13000000	11700000	11900000
	0.2	157.3	10400000	10600000	11800000	9300000	10300000	10400000	10700000	11200000	11400000	10900000	10900000	9800000	9900000
	0.33	259.6	7500000	7700000	8100000	6850000	7600000	7700000	7550000	7950000	8250000	8000000	7900000	6900000	7000000
	0.41	322.5	5800000	6000000	6250000	5150000	5850000	6200000	5450000	5900000	6200000	6300000	6000000	5000000	5000000
	0.55	432.7	3150000	3300000	3400000	2700000	3000000	3500000	3000000	3200000	3400000	3600000	3200000	2800000	2600000
	0.64	503.5	2150000	2200000	2250000	1800000	2000000	2400000	2000000	2200000	2400000	2400000	2450000	2000000	1800000
	0.7	550.7	1500000	1600000	1550000	1350000	1300000	1700000	1350000	1500000	1550000	1630000	1600000	1300000	1200000
	0.82	645.1	450000	500000	500000	400000	450000	550000	400000	400000	500000	500000	440000	400000	400000
	0.91	715.9	100000	100000	100000	100000	100000	200000	100000	200000	100000	100000	100000	200000	100000
Shear	0	0	48600	54500	58000	54400	53500	54000	63400	60300	56100	57300	57500	51500	54900
	0.12	94.4	37200	40100	43400	41700	38600	36400	48000	46400	44300	41300	43300	40400	42300
	0.2	157.3	31200	33400	36400	34400	32200	29400	39400	38400	37200	33600	35800	34100	35700
	0.33	259.6	22300	23000	25000	22700	24100	22400	25500	25500	25800	23500	24600	23500	24400
	0.41	322.5	26000	26000	27600	25800	27400	26000	27300	28000	28500	26400	27500	23700	24400
	0.55	432.7	16600	16600	17400	13800	16300	16300	14500	15800	16600	16500	16700	13100	13000
	0.64	503.5	9750	9800	10200	7400	9000	10900	7750	9000	10000	10800	9000	7000	9400
	0.7	550.7	12200	12000	13300	10400	10900	14200	11300	12300	13000	14300	11500	10000	10000
	0.82	645.1	6000	6000	6000	4950	5400	6700	5000	5600	6000	6900	5500	5000	4600
	0.91	715.9	2700	2500	2500	2100	2450	3000	2000	2200	2450	3000	2500	2500	2000
Torsion	0	0	-2600000	-2900000	-3270000	-3000000	-2600000	-2430000	-3530000	-3700000	-3880000	-2760000	-3180000	-3750000	-3720000
	0.12	94.4	-1530000	-1900000	-2100000	-1830000	-1690000	-1650000	-2490000	-2450000	-2350000	-1880000	-2170000	-2500000	-2550000
	0.2	157.3	-900000	-1300000	-1470000	-1290000	-1200000	-1240000	-1900000	-1740000	-1680000	-1490000	-1560000	-1850000	-1980000
	0.33	259.6	-550000	-940000	-1100000	-980000	-850000	-800000	-1580000	-1360000	-1160000	-1140000	-1250000	-1500000	-1600000
	0.41	322.5	-250000	-550000	-650000	-550000	-450000	-420000	-940000	-750000	-560000	-580000	-640000	-700000	-800000
	0.55	432.7	-380000	-630000	-700000	-620000	-550000	-540000	-940000	-800000	-670000	-700000	-730000	-790000	-850000
	0.64	503.5	-400000	-600000	-690000	-600000	-550000	-550000	-900000	-750000	-700000	-700000	-720000	-800000	-850000
	0.7	550.7	-50000	-100000	-150000	-140000	-110000	-100000	-410000	-120000	-90000	-90000	-100000	-70000	-100000
	0.82	645.1	-30000	-50000	-80000	-70000	-60000	-50000	-100000	-80000	-40000	-50000	-50000	-40000	-50000
	0.91	715.9	-10000	-10000	-50000	-40000	-40000	-20000	-50000	-40000	-10000	-40000	-40000	-10000	-10000

Fatigue Loads and Spectra

Wing Internal Loads:





Wing Internal loads are developed at the spanwise splice wing station using 1G loads

Spanwise Splice Stringer Load in Lower Cover Results

Px	Py	Pz	Rxy	Ryz	Rxz
853	33168	6376	33179	33775	6432
1027	40759	6874	40772	41334	6950
1147	46616	6542	46630	47073	6642
1172	48533	5779	48547	48876	5897
1794	75545	7632	75566	75929	7840
1924	82416	6803	82439	82697	7069
1007	43777	2940	43788	43875	3108
1960	86465	4538	86487	86584	4943
1605	71801	2782	71819	71855	3212
944	42837	1091	42848	42851	1443
936	43026	549	43037	43030	1085
809	37738	7	37747	37738	809
788	37327	-480	37336	37330	923
739	35671	-967	35679	35684	1217
1012	49739	-2089	49750	49783	2321
656	32962	-1940	32968	33019	2048
715	36832	-2855	36839	36943	2943
602	31695	-2958	31700	31832	3018
674	36371	-4021	36377	36592	4077

Fatigue Loads and Spectra

Wing Spectrum Input:

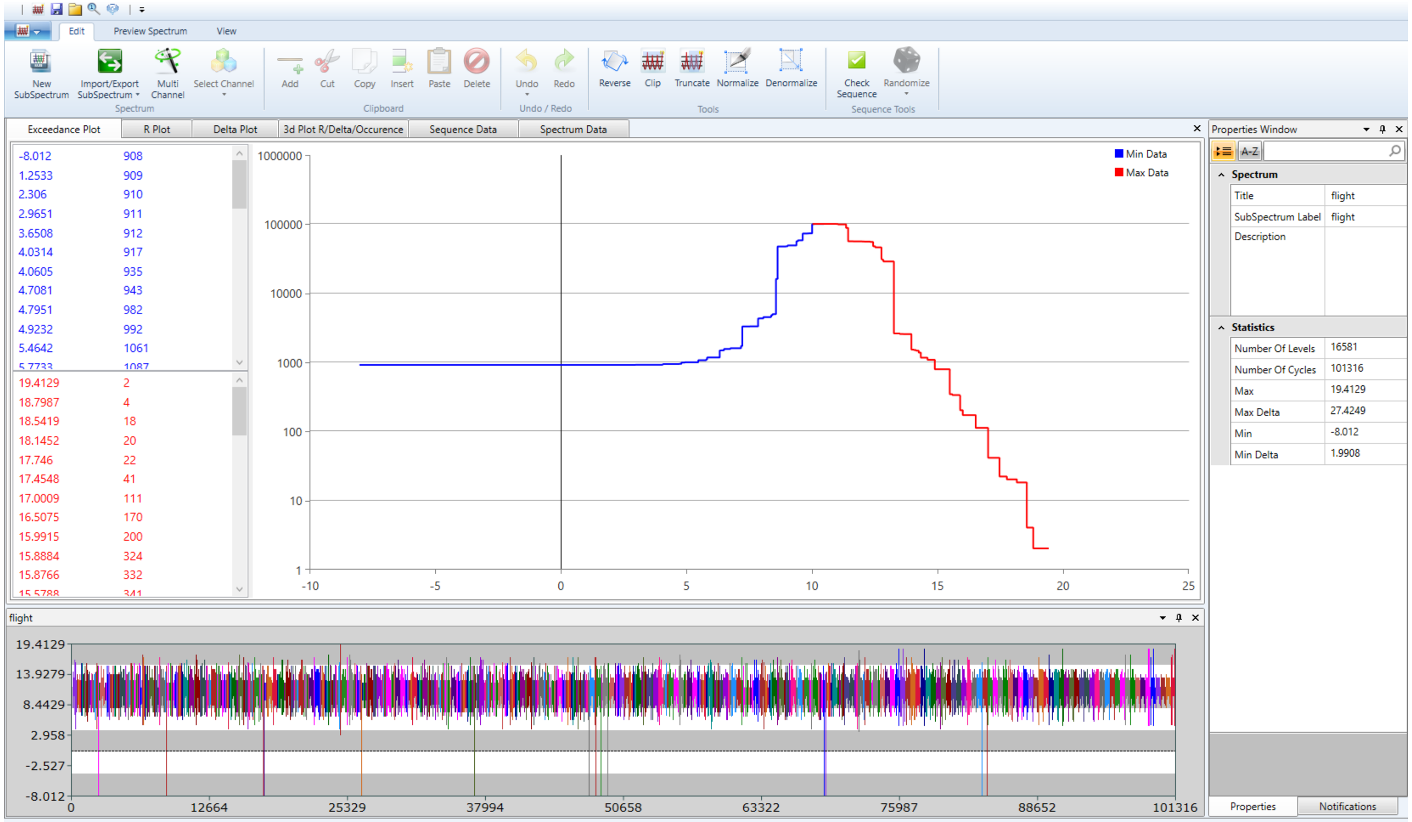
	Aeronautica ASPEC Analysis			
	Analysis	720 Analysis 8-23-21 Rev H		
	Aircraft	Boeing 720		
	Mission Mix	Medium 48%		
	Segment	Constant Load Stress 1G (ksi)	Alternating Load Stress (ksi)	Pressure Load Stress (ksi)
Damage Code	Long 28%			
1001	Taxi-Out	-9.071	-11.7923	--
1011	Take-Off Man	10.898	10.898	0
1021	Take-Off Gust	10.898	15.2572	0
1011	Departure Man	10.898	10.898	0
1021	Departure Gust	10.898	15.2572	0
1012	Climb Man	11.189	11.189	0
1022	Climb Gust	11.189	15.6646	0
1013	Cruise Man	11.625	11.625	0
1023	Cruise Gust	11.625	16.275	0
1014	Descent Man	10.026	10.026	0
1024	Descent Gust	10.026	14.0364	0
1015	Approach Man	10.026	10.026	0
1025	Approach Gust	10.026	14.0364	0
1002	Landing	-8.012	-9.6144	--
1001	Taxi-in	-8.012	-10.4156	--

Damage Code	Medium 48%			
2001	Taxi-Out	-8.529	-11.0877	--
2011	Take-Off Man	10.898	10.898	0
2021	Take-Off Gust	10.898	15.2572	0
2011	Departure Man	10.898	10.898	0
2021	Departure Gust	10.898	15.2572	0
2012	Climb Man	11.189	11.189	0
2022	Climb Gust	11.189	15.6646	0
2013	Cruise Man	9.954	9.954	0
2023	Cruise Gust	9.954	13.9356	0
2014	Descent Man	10.026	10.026	0
2024	Descent Gust	10.026	14.0364	0
2015	Approach Man	10.026	10.026	0
2025	Approach Gust	10.026	14.0364	0
2002	Landing	-8.012	-9.6144	--
2001	Taxi-in	-8.012	-10.4156	--

Damage Code	Short 24%			
3001	Taxi-Out	-8.327	-10.8251	--
3011	Take-Off Man	10.898	10.898	0
3021	Take-Off Gust	10.898	15.2572	0
3011	Departure Man	10.898	10.898	0
3021	Departure Gust	10.898	15.2572	0
3012	Climb Man	11.189	11.189	0
3022	Climb Gust	11.189	15.6646	0
3013	Cruise Man	10.971	10.971	0
3023	Cruise Gust	10.971	15.3594	0
3014	Descent Man	10.026	10.026	0
3024	Descent Gust	10.026	14.0364	0
3015	Approach Man	10.026	10.026	0
3025	Approach Gust	10.026	14.0364	0
3002	Landing	-8.012	-9.6144	--
3001	Taxi-in	-8.012	-10.4156	--

Fatigue Loads and Spectra

Spectrum Wizard Summary:



Fatigue Loads and Spectra

Spectrum Summary:

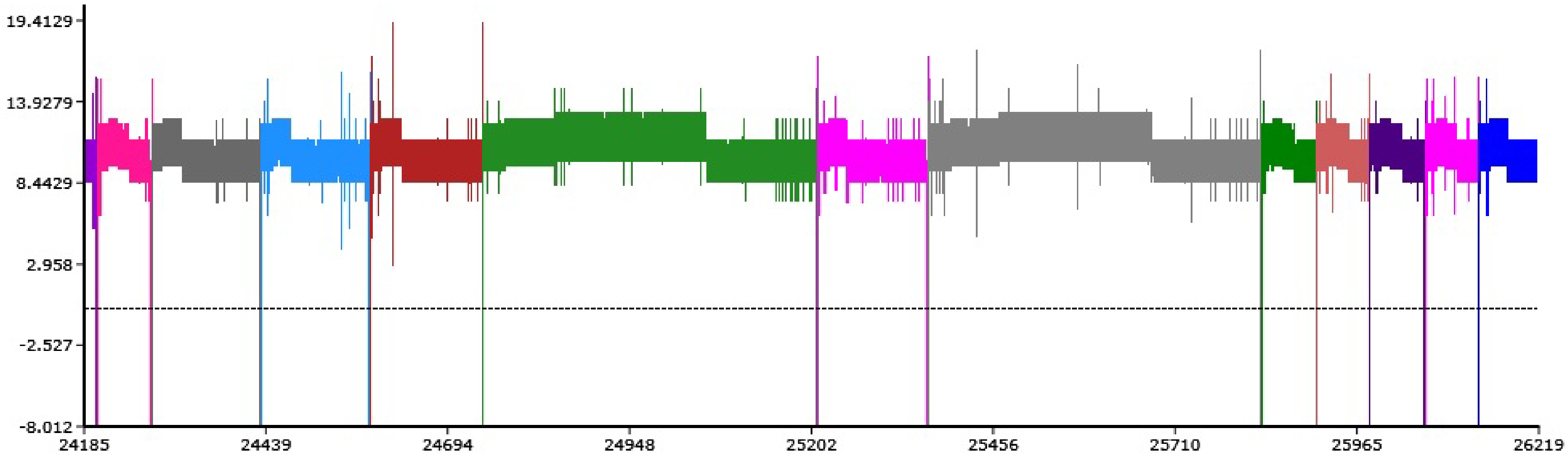
M I S S I O N   B R E A K D O W N

MISSION	SEGMENTS	MISSION TIME	FLIGHTS	TOTAL RUN TIME
1	16	332.00	127	42164.000 MINS.
2	16	93.00	218	20274.000 MINS.
3	16	37.00	109	4033.000 MINS.

TOTAL LOAD SPECTRUM TIME IN MINUTES: 66471.000

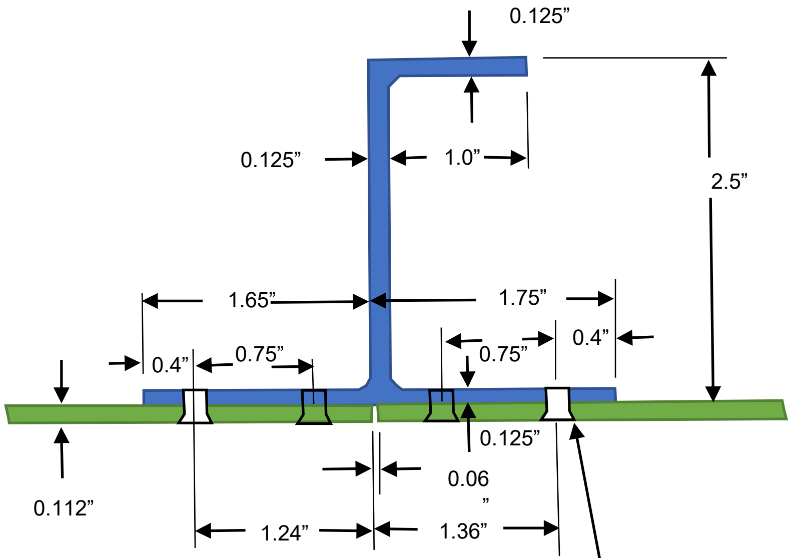
P R O G R A M   I N T E R N A L   S T A T I S T I C S

NUMBER OF FLIGHTS OUTPUT: 454
OUTPUT FLIGHTS RATIO: 99.6%
NUMBER OF LOADS OUTPUT: 203156
MAX LOAD STRESS: 19.4129
MIN LOAD STRESS: -8.0120



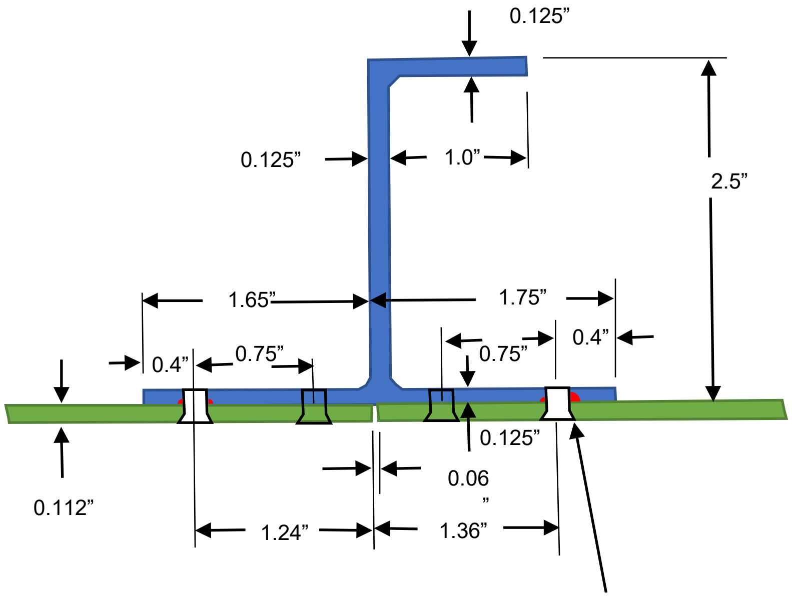
Materials and Geometry

- J Stringer
  - 7075-T6511 Extrusion
- Skin
  - 2024-T351 Plate
- $A_{eff} = 1.63\ in^2$
  - J stringer + full bay of skin
- 3 Phases of Analysis
- Phase I and II in stringer, Phase III in skin



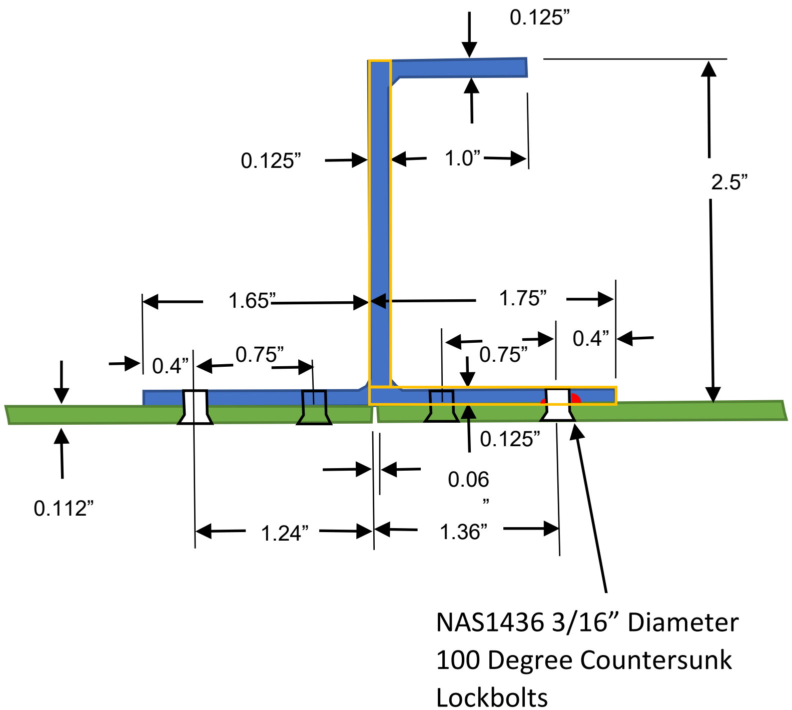
Phase I – Stringer

- Independent Structure
- Corner Cracks
  - $a_{DTA} = c_{DTA} = 0.05\ in$
  - $a_{CD} = c_{CD} = 0.005\ in$
- Superposition
  - Axial (no bypass)
  - Bearing
- Compounding
  - Filled Hole
  - Cracks growing toward a riser

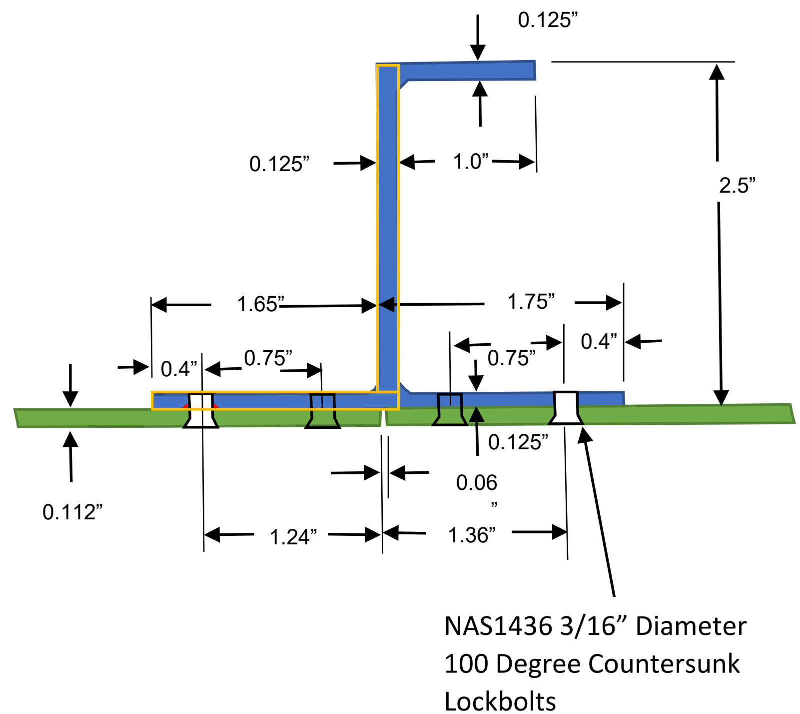


Phase I – Stringer Idealization

Phase Ia



Phase Ib



Limit Stress

- Axial, not bypass, no load transfer

$$\sigma_{Ax} = \frac{P_L}{A_{eff}} = \frac{49{,}739\ lbs}{1.63\ in^2} = 30.52\ \text{ksi}$$

- Bearing

$$q_{total} = \frac{\Delta P}{L} = \frac{49{,}739\ lbs - 32{,}962 lbs}{7\ in} = 2{,}396.7\ {}^{lbs}/_{in}$$
$$\cong 2{,}400\ {}^{lbs}/_{in}$$

$$q = \frac{q_{total}}{2} = \frac{2{,}400\ {}^{lbs}/_{in}}{2} = 1{,}200\ {}^{lbs}/_{in}$$

$$\sigma_{Brg} = \frac{q \cdot Pitch}{nDt} = \frac{1{,}200\ \ lbs/in \cdot 1.125\ in}{2 \cdot 0.188\ in \cdot 0.125\ in} = 28.7\ ksi$$

Stress - Reference

- $\sigma_{ref} = \sigma_{Ax} + \frac{P}{W_{eff} t}$
  - $W_{eff} \equiv Width\ bearing\ load\ acts\ over^1$
  - $W_{eff} = flange\ length = 1.75\ in$
- $\sigma_{ref} = 30.52\ ksi + \frac{675\ lbs}{1.75\ in \cdot 0.125\ in}$
- $\sigma_{ref} = 30.52\ ksi + 3.086\ ksi$
- $\sigma_{ref} = \underline{33.6\ ksi}$

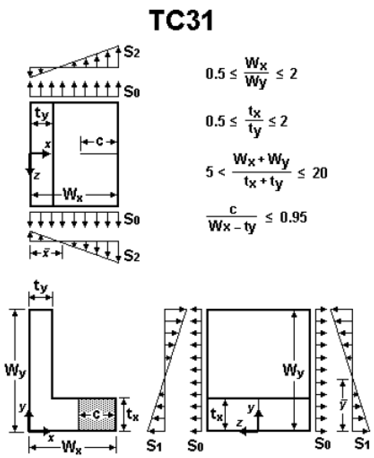
[1] Harter, J. A. and A. V. Litvinov (2016). "Modeling Bearing Load in Wide Panels Using AFGROW". AFGROW European Training, Winterthur, Switzerland.

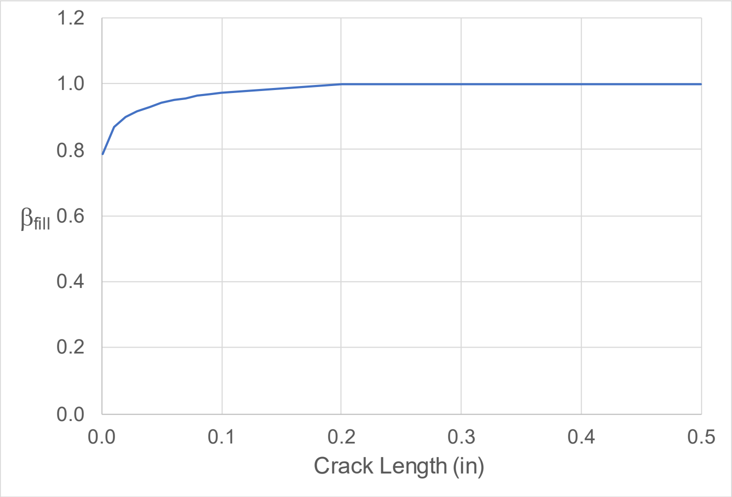
AFGROW Stress Ratios

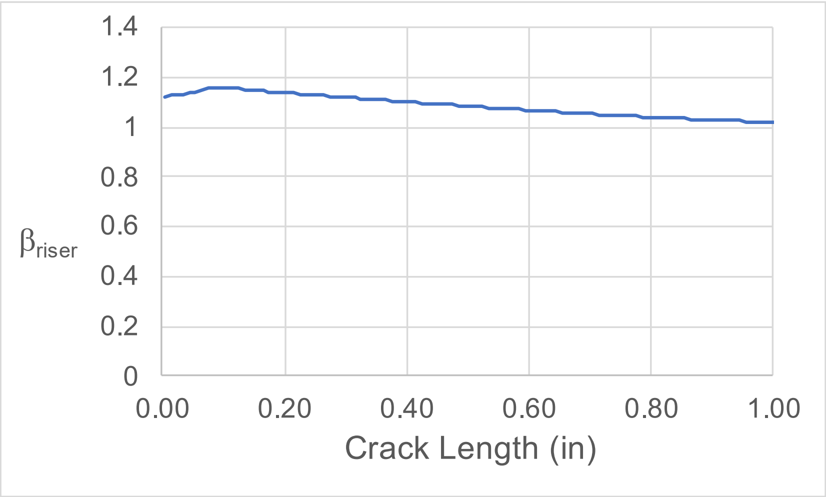
- Axial Stress Ratio
  - $ASR = \frac{\sigma_{Ax}}{\sigma_{ref}} = \frac{30.52}{33.6} = 0.908$
- Bearing Stress Ratio
  - $\text{Brg}SR = \frac{\sigma_{Brg}}{\sigma_{ref}} = \frac{28.7}{33.6} = 0.854$

Stress Intensity Factor

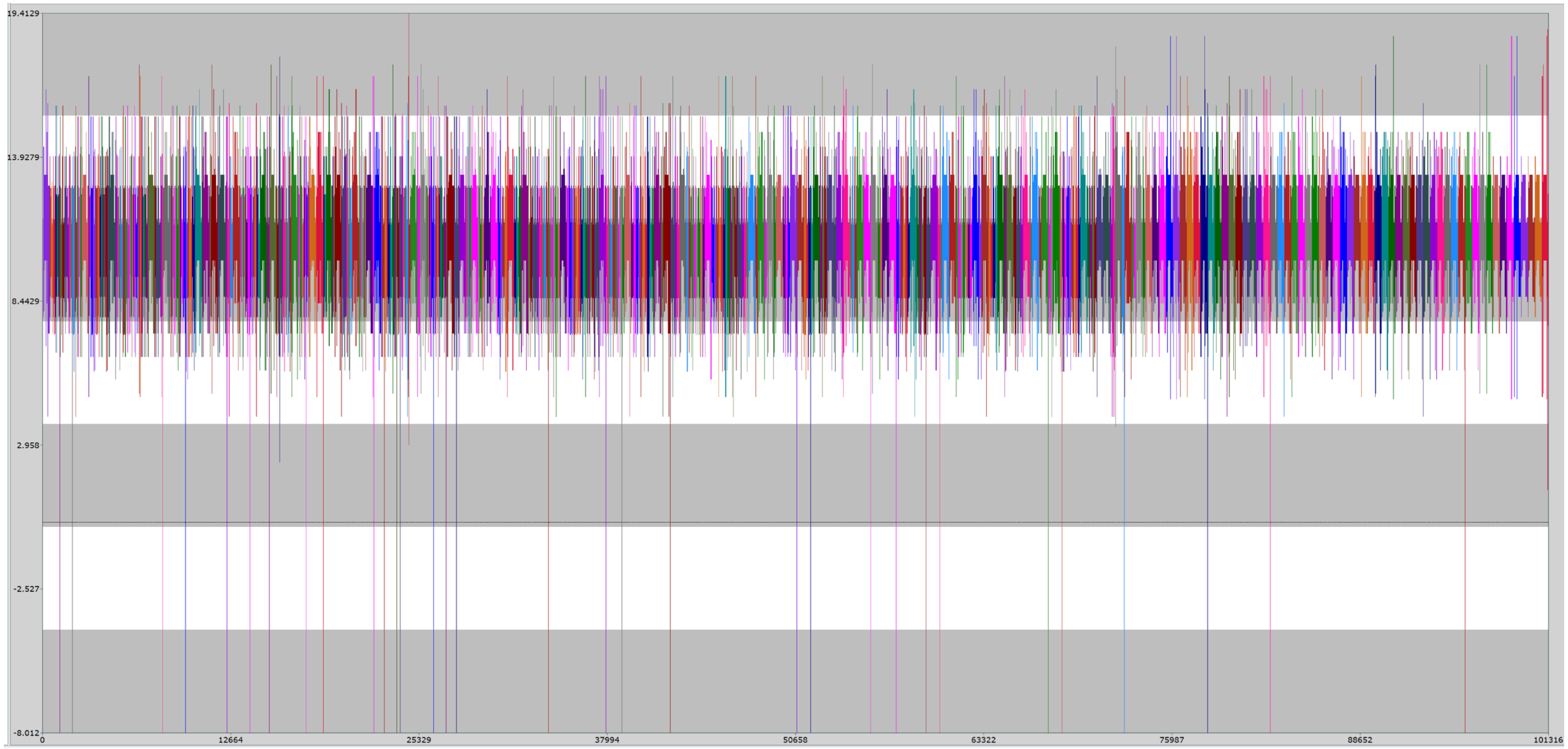
- $K_{SS} = \left[\sigma_{Ax}\beta_{Ax} + \sigma_{Brg}\beta_{Brg}\right]\sqrt{\pi a}\,\beta_{fill}\beta_{riser}$
  - β_{Ax}, β_{Brg} built into AFGROW
  - $\beta_{fill}, \beta_{riser}$





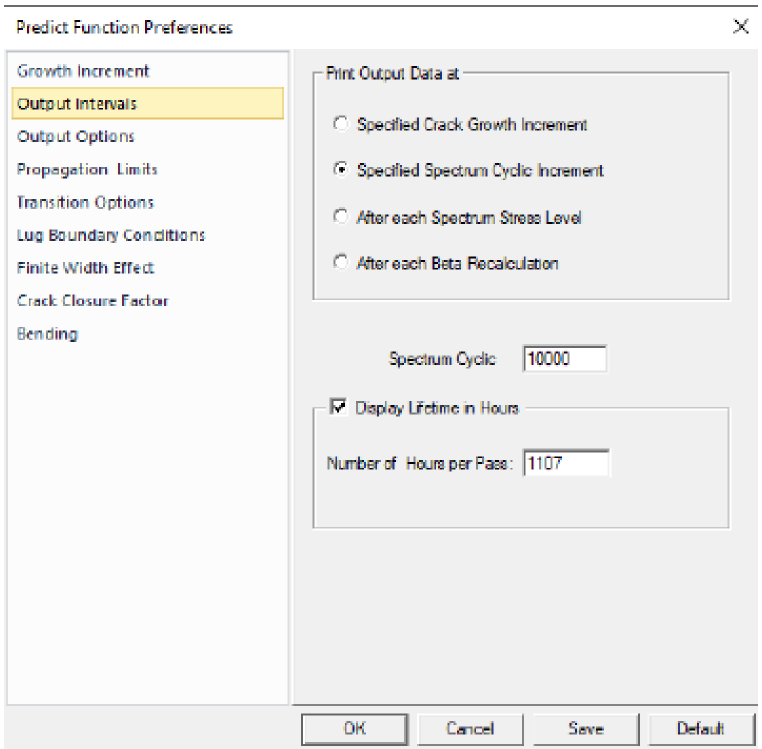


Fatigue Spectrum



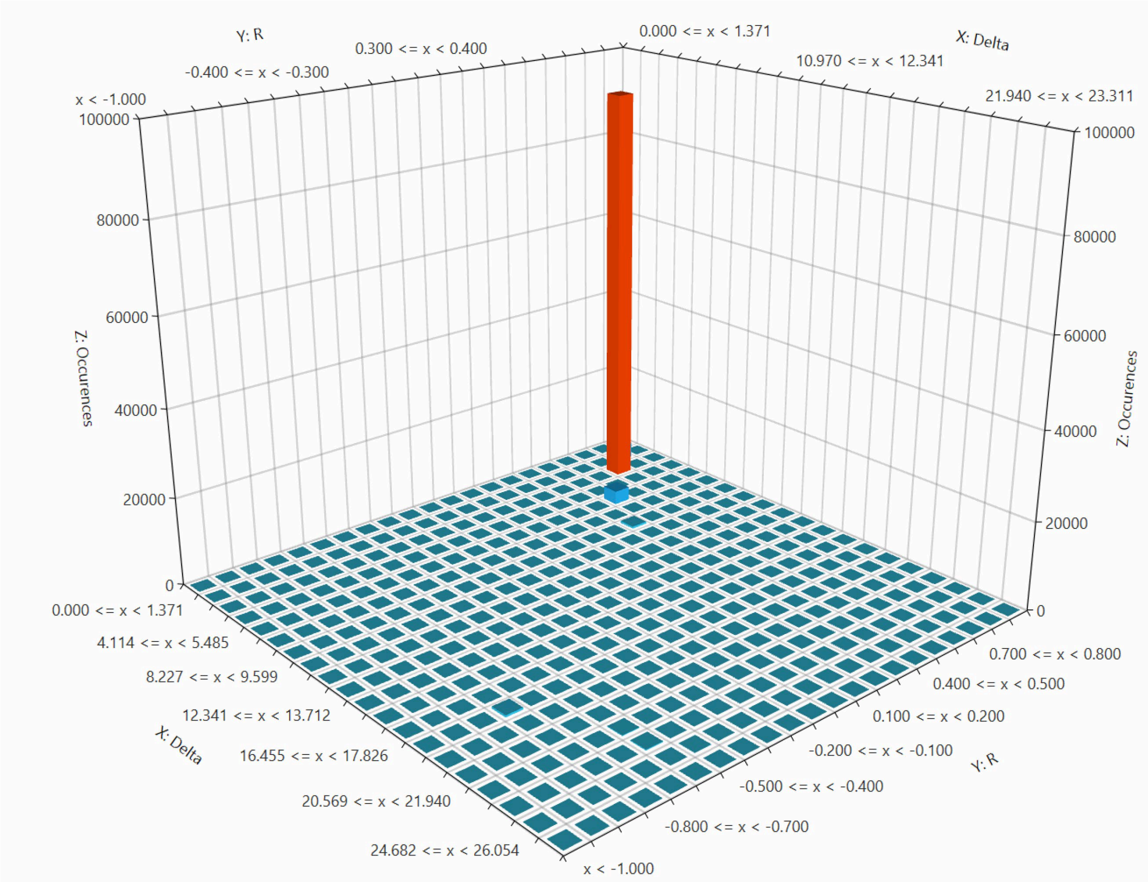
Spectrum Cycles to FC, Hours

Hours

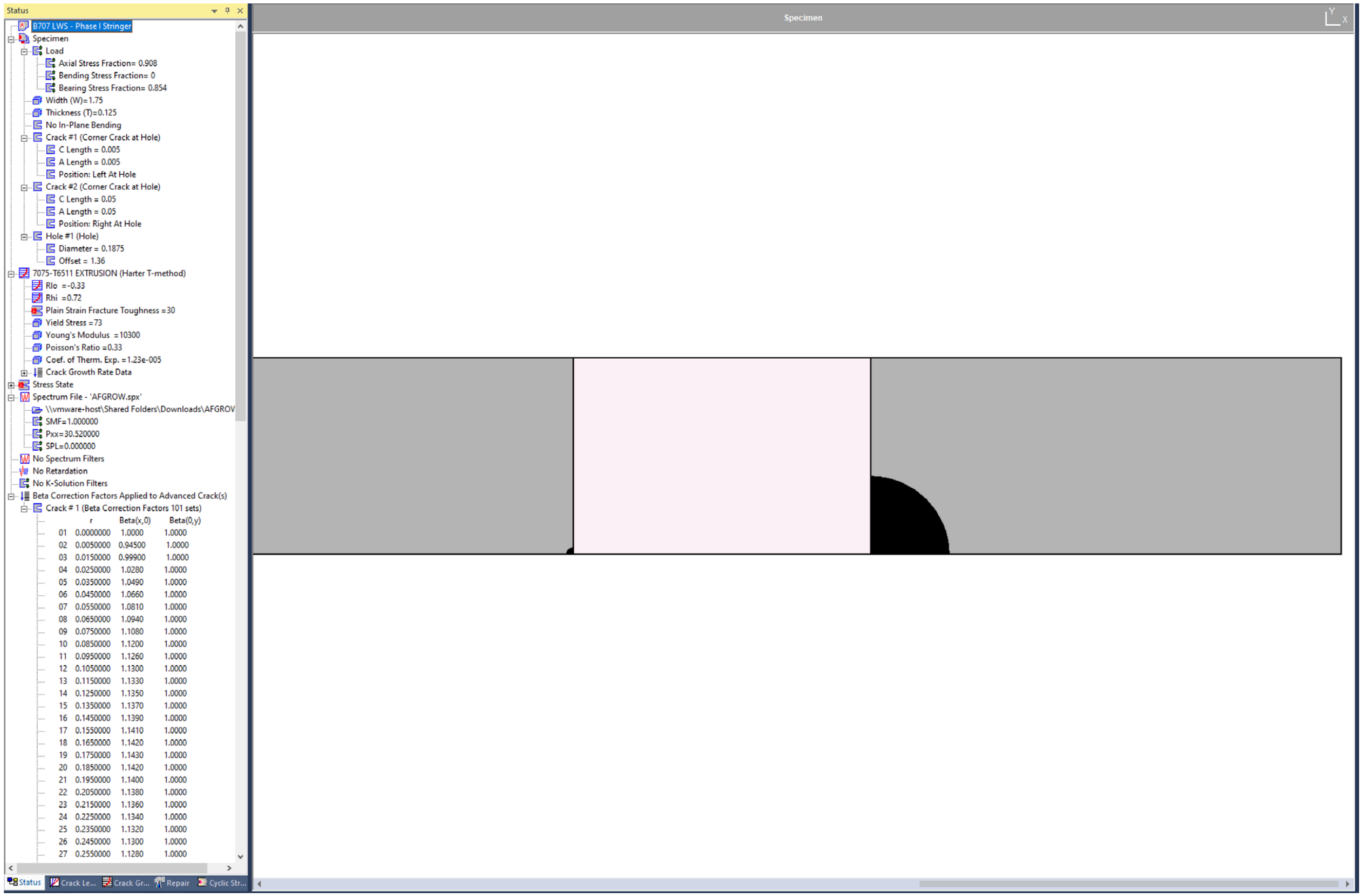


- Flight Cycles
  - ASPEC.OUT
    - 454 flights in 1,000 hour repeatable pass
    - Actual was 1,107 hrs
  - SpectrumManager
    - 101,578 cycles in spectrum
  - AFGROW.PL2
    - Import into Excel
    - Multiply “Cycles” column by
      - $N = \frac{454\ flights}{101{,}578\ cycles}$

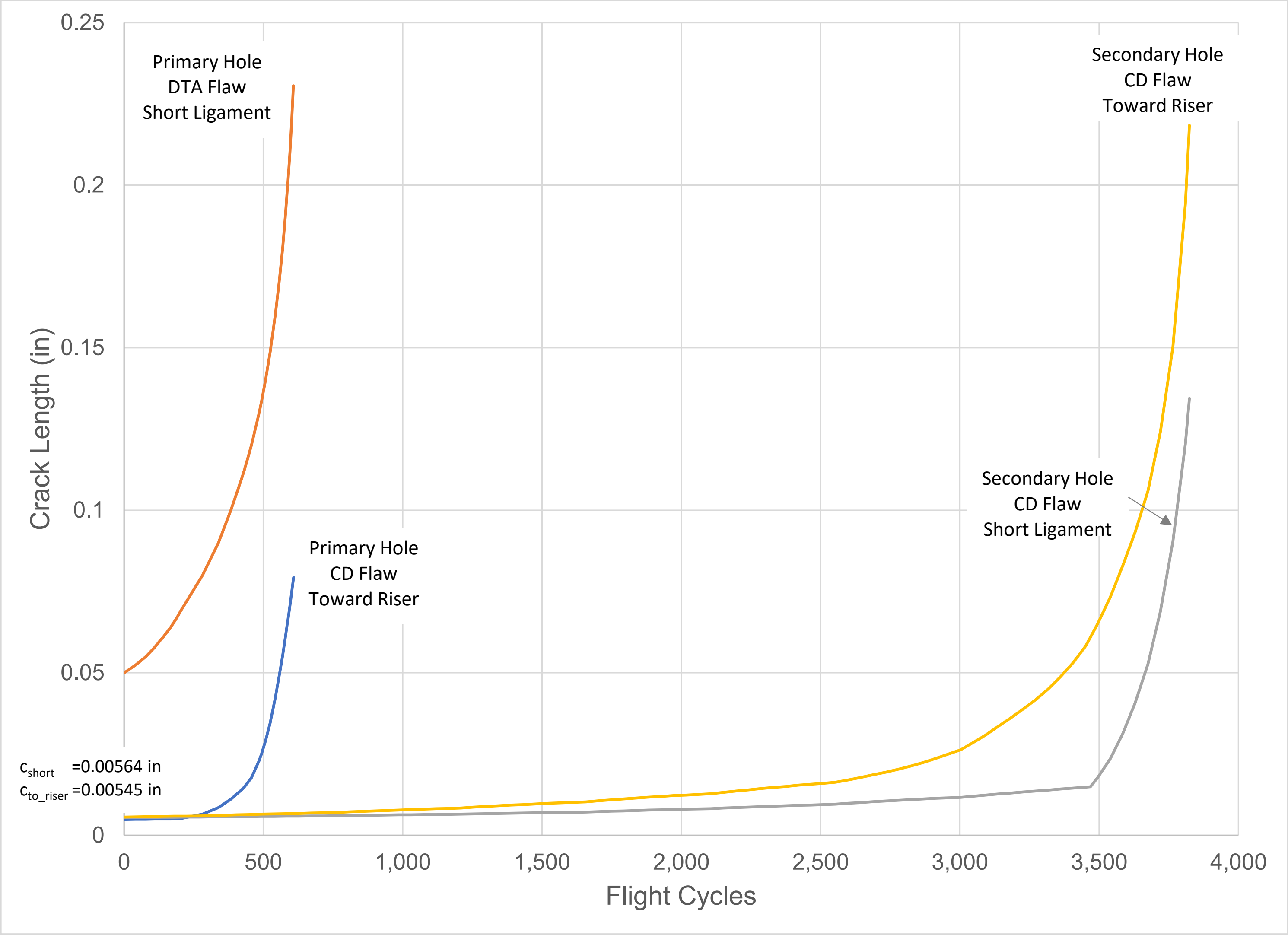
Fatigue Spectrum



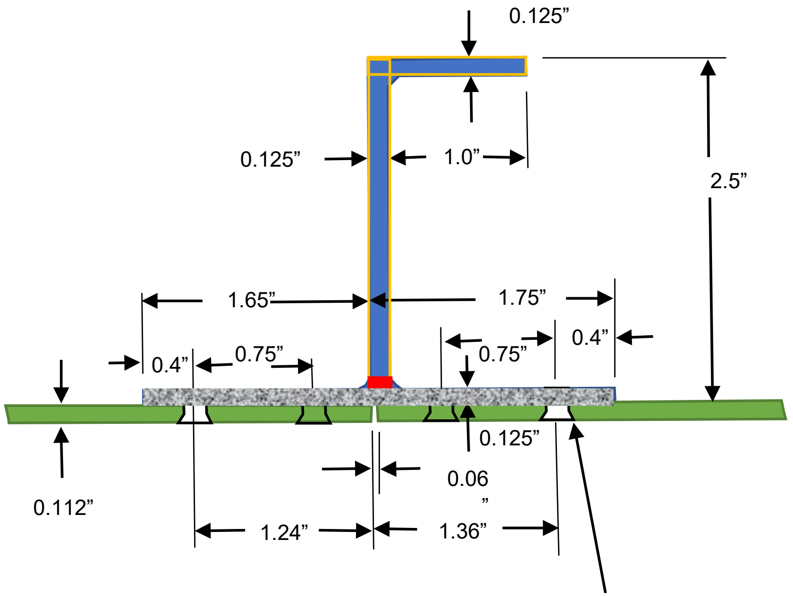
AFGROW Input – Phase I Stringer



Phase Ia & Ib Stringer Results



Phase II – Stringer Idealization



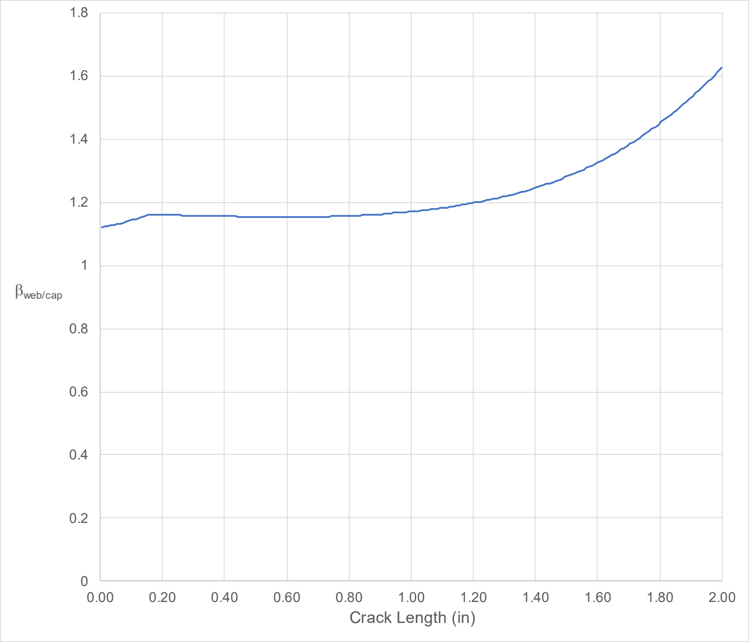
NAS1436 3/16” Diameter
100 Degree Countersunk
Lockbolts

AFGROW Stress Ratios

- Axial Stress Ratio
  - $ASR = 1.0$
- Stress Multiplication Factor, SMF
  - Use to account for cracked area in stringer flange
  - $SMF = \frac{A_{eff}}{A_{eff} - A_{cracked}} = \frac{1.63\ in^2}{1.63\ in^2 - 3.4\ in \cdot 0.125\ in} = 1.35$

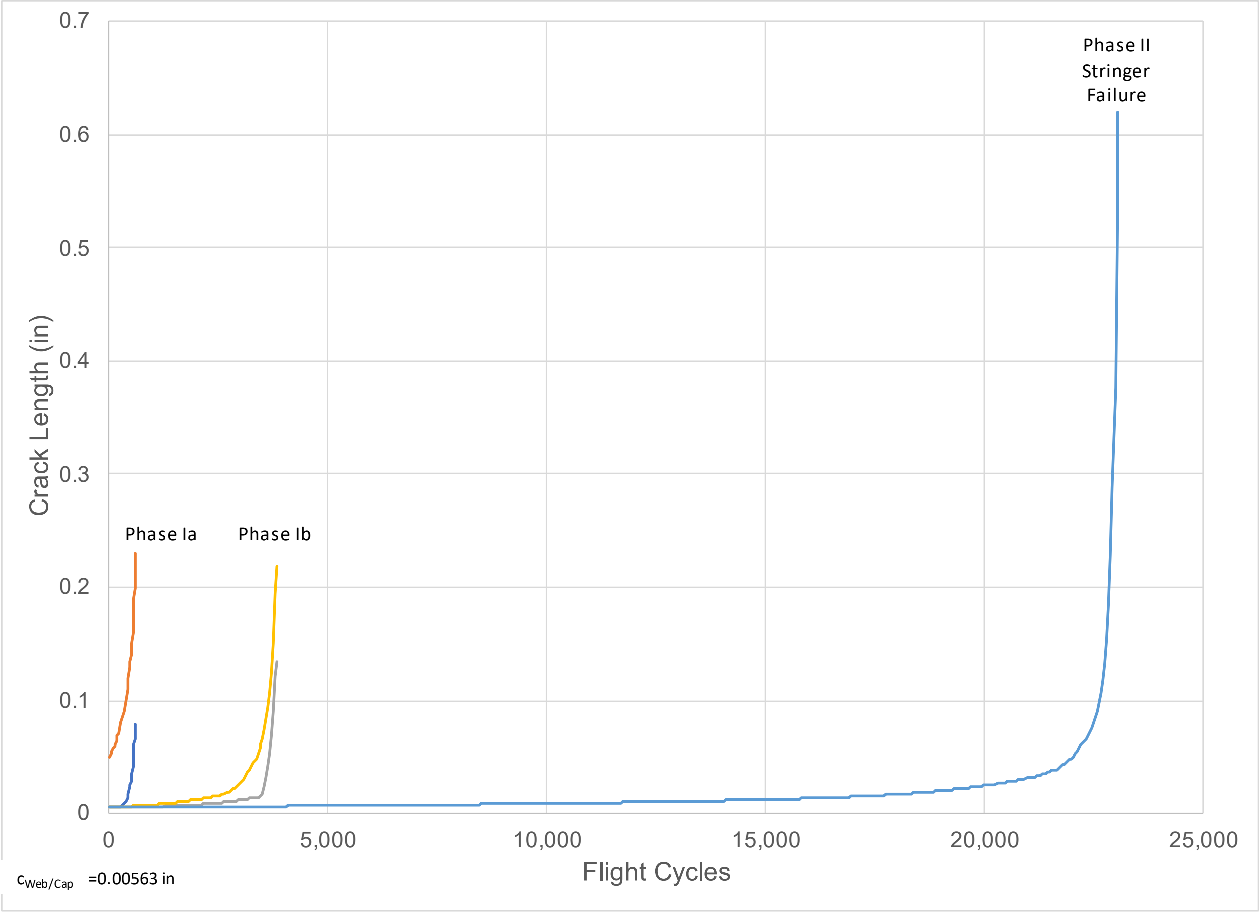
Stress Intensity Factor

- $K_{SS} = \beta_{Ax}\sqrt{\pi a}\beta_{Web/Cap}$
  - β_{Ax} built into AFGROW
  - $\beta_{Web/Cap}$



AFGROW Input – Phase II Stringer

Phase II Stringer Results



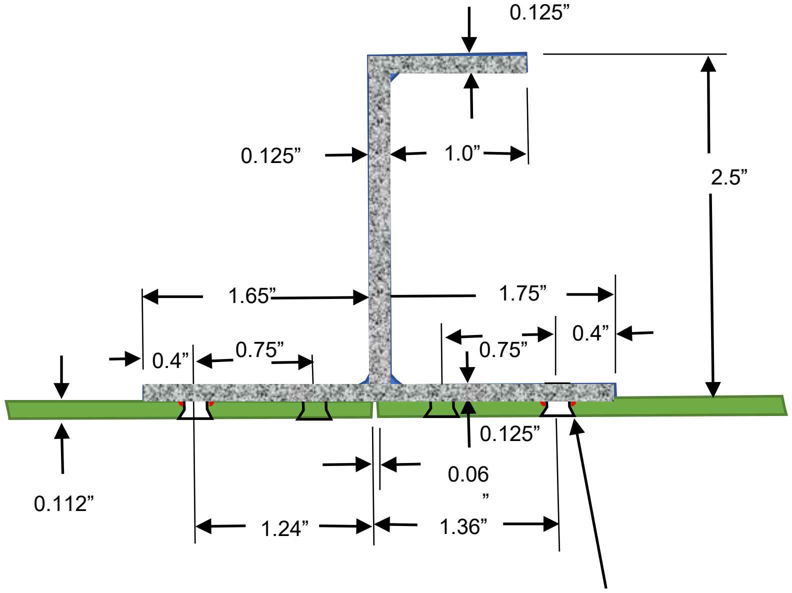
Phase III – Skin Idealization

- Corner Cracks – Both Holes
  - $a_{CD} = c_{CD} = 0.005\ in$
- Superposition
  - Axial (no bypass)
  - Bearing – no bearing since stringer is cracked
- Compounding
  - Filled Hole
  - Countersunk Hole (in AFGROW)
  - Crack growing to next hole at Z-stringer not used

    2" crack increases β by 1% which is negligible
  - Crack growing to Z-stringer

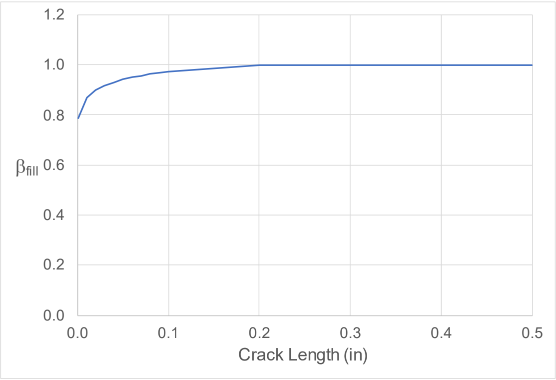
    R&C Figure 124, s = 1.0
  - Cracked Stringer

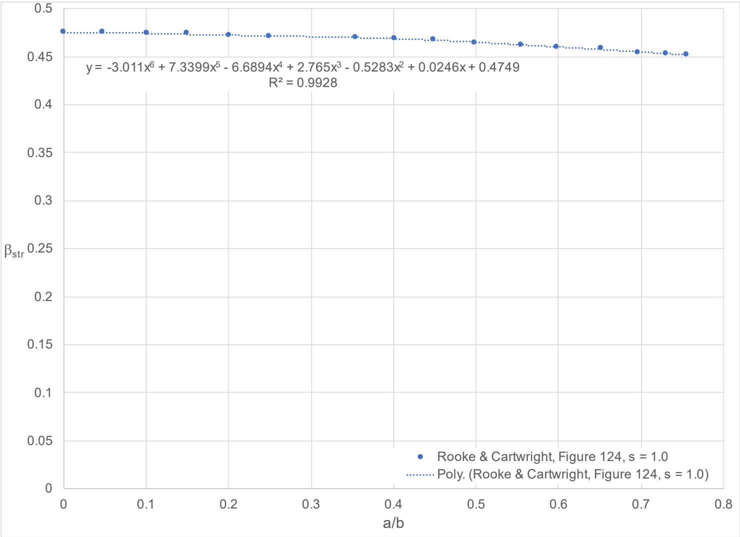
    R&C Report 75072, Figure 7, s = 1.0

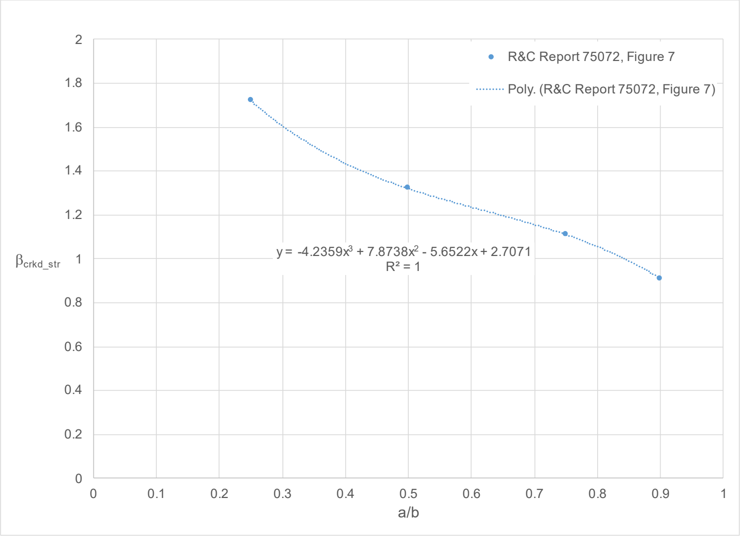


Stress Intensity Factor

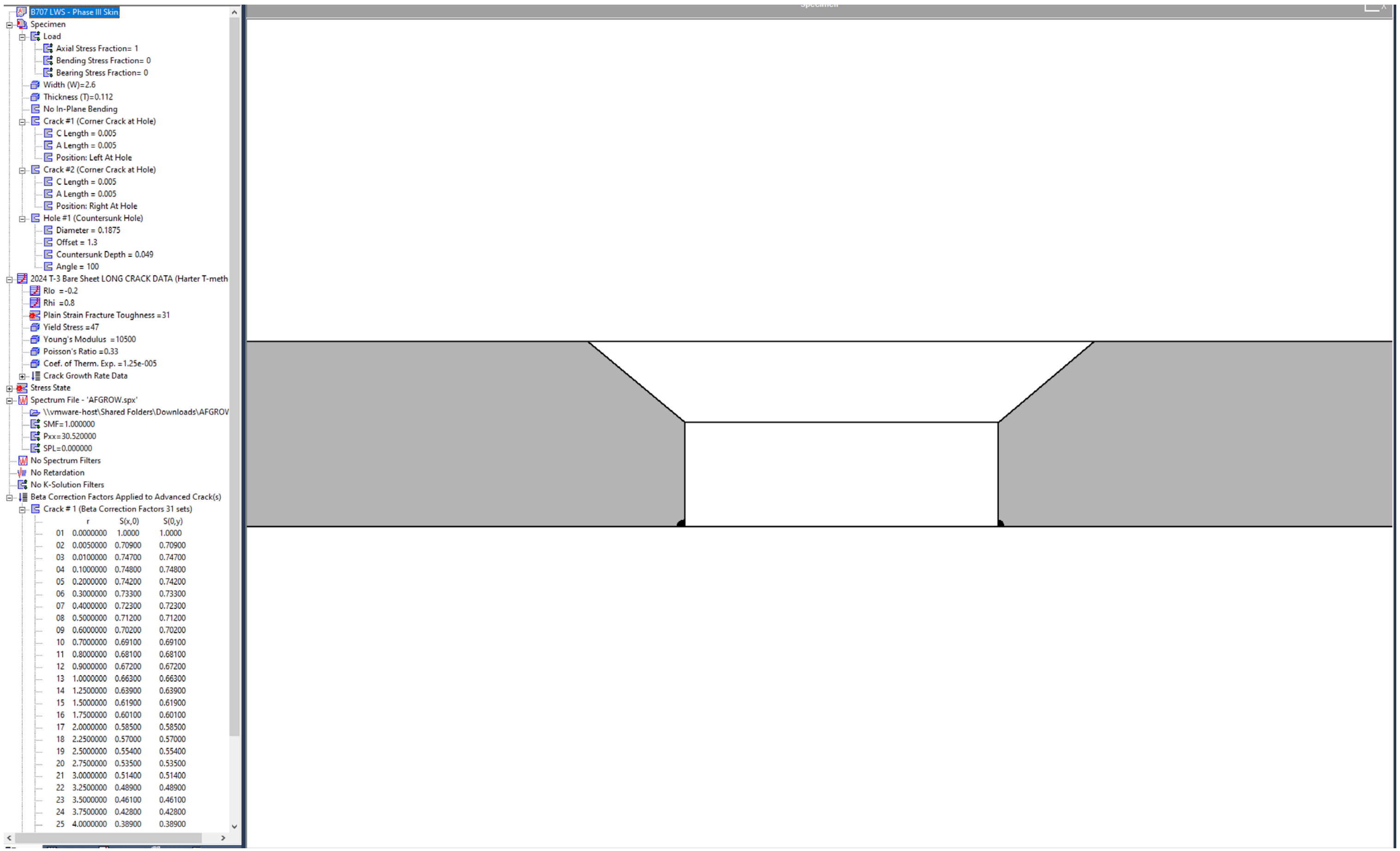
- $K_{SS} = \sigma_{Ax}\beta_{Ax}\sqrt{\pi a}\beta_{fill}\beta_{str}\beta_{crkd\_str}$
  - β_{Ax} built into AFGROW
  - $\beta_{fill}, \beta_{str}, \beta_{crkd\_str}$



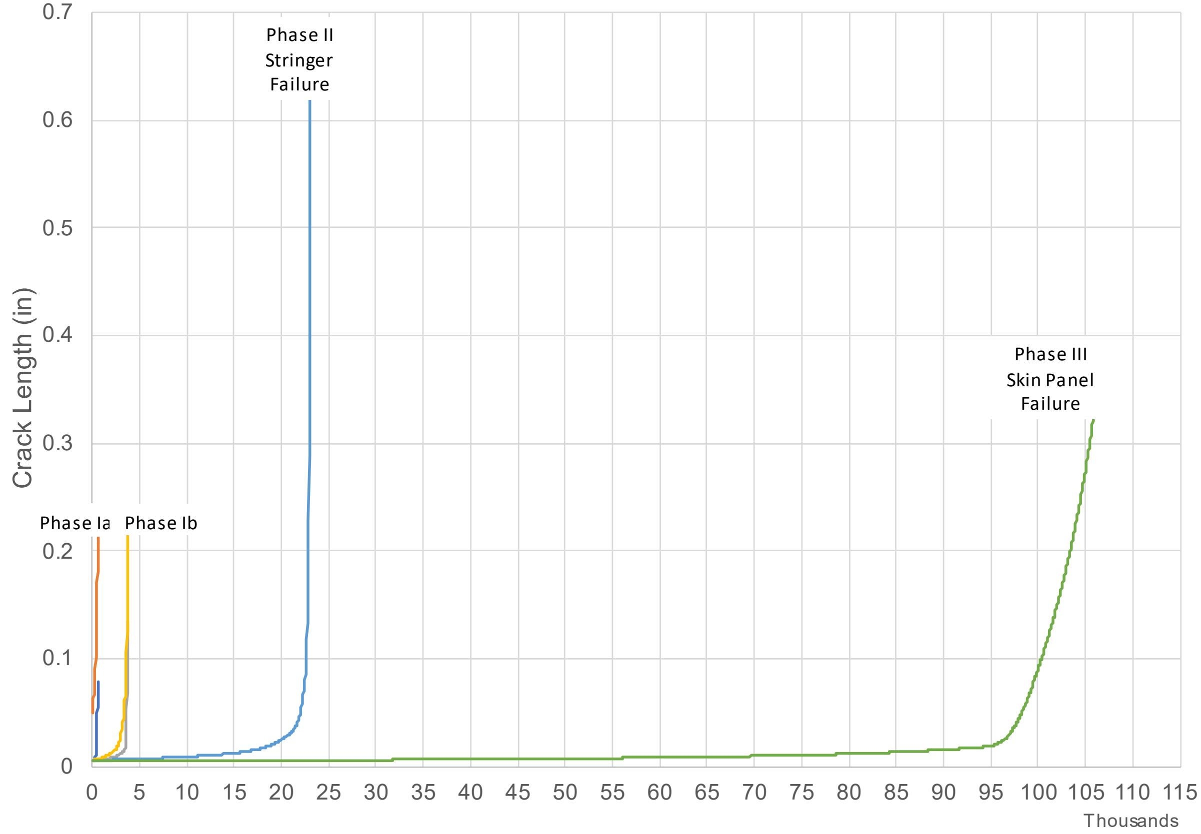




AFGROW Input – Phase III Skin



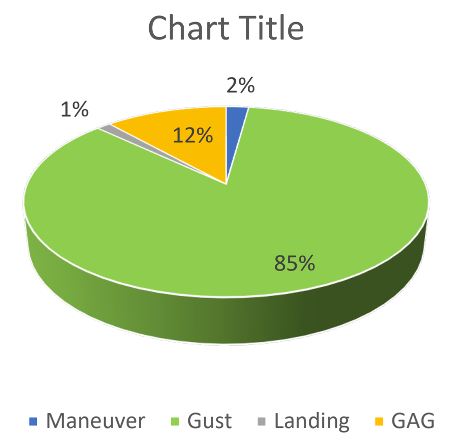
Phase III 1st Skin Panel Results



c_{skin} =0.00514 in

Phase III 1st Skin Panel Results

						Damage Code	% Damage	Damage Summary	
Percent	of	total	damage	due	to	'1011':	0.1	1.31	Maneuver
Percent	of	total	damage	due	to	'1012':	0.26		
Percent	of	total	damage	due	to	'1013':	0.55		
Percent	of	total	damage	due	to	'1014':	0.2		
Percent	of	total	damage	due	to	'1015':	0.2		
Percent	of	total	damage	due	to	'1021':	4.51	52.36	Gust
Percent	of	total	damage	due	to	'1022':	7.67		
Percent	of	total	damage	due	to	'1023':	26.47		
Percent	of	total	damage	due	to	'1024':	5.2		
Percent	of	total	damage	due	to	'1025':	8.51		
Percent	of	total	damage	due	to	'1090':	0.38	0.38	Lndg
Percent	of	total	damage	due	to	'1100':	3.83	3.83	GAG
Percent	of	total	damage	due	to	'2011':	0.09	0.67	Maneuver
Percent	of	total	damage	due	to	'2012':	0.17		
Percent	of	total	damage	due	to	'2013':	0.16		
Percent	of	total	damage	due	to	'2014':	0.12		
Percent	of	total	damage	due	to	'2015':	0.13		
Percent	of	total	damage	due	to	'2021':	3.96	25.45	Gust
Percent	of	total	damage	due	to	'2022':	5.08		
Percent	of	total	damage	due	to	'2023':	7.65		
Percent	of	total	damage	due	to	'2024':	2.53		
Percent	of	total	damage	due	to	'2025':	6.23		
Percent	of	total	damage	due	to	'2090':	0.63	0.63	Lndg
Percent	of	total	damage	due	to	'2100':	5.19	5.19	GAG
Percent	of	total	damage	due	to	'3011':	0.04	0.17	Maneuver
Percent	of	total	damage	due	to	'3012':	0.04		
Percent	of	total	damage	due	to	'3013':	0.03		
Percent	of	total	damage	due	to	'3014':	0.03		
Percent	of	total	damage	due	to	'3015':	0.03		
Percent	of	total	damage	due	to	'3021':	1.98	7.09	Gust
Percent	of	total	damage	due	to	'3022':	1.3		
Percent	of	total	damage	due	to	'3023':	1.52		
Percent	of	total	damage	due	to	'3024':	0.43		
Percent	of	total	damage	due	to	'3025':	1.86		
Percent	of	total	damage	due	to	'3090':	0.33	0.33	Lndg
Percent	of	total	damage	due	to	'3100':	2.6	2.60	GAG



Inspections

- Detectable flaw size is 0.05 in using BHEC
  - Using less robust methods gives unacceptable inspection program

Detail	Phase Ia	Phase Ib	Phase II	Phase III	N_{DTA}	N_{NDI}	N_{Detect}	$N_{Threshold}$	$N_{Interval}$
Stringer	608	3,823	N/A[1]	N/A	4,431	3,674	757	2,216	379
Skin	N/A	N/A	N/A	105,947	105,947	98,313	7,634	52,974	3,817

1 Can't inspect stringer during Phase II as the cracking is in the web and cap

(green) Inspections if Single Load Path

(yellow) Inspections if Multiple Load Path

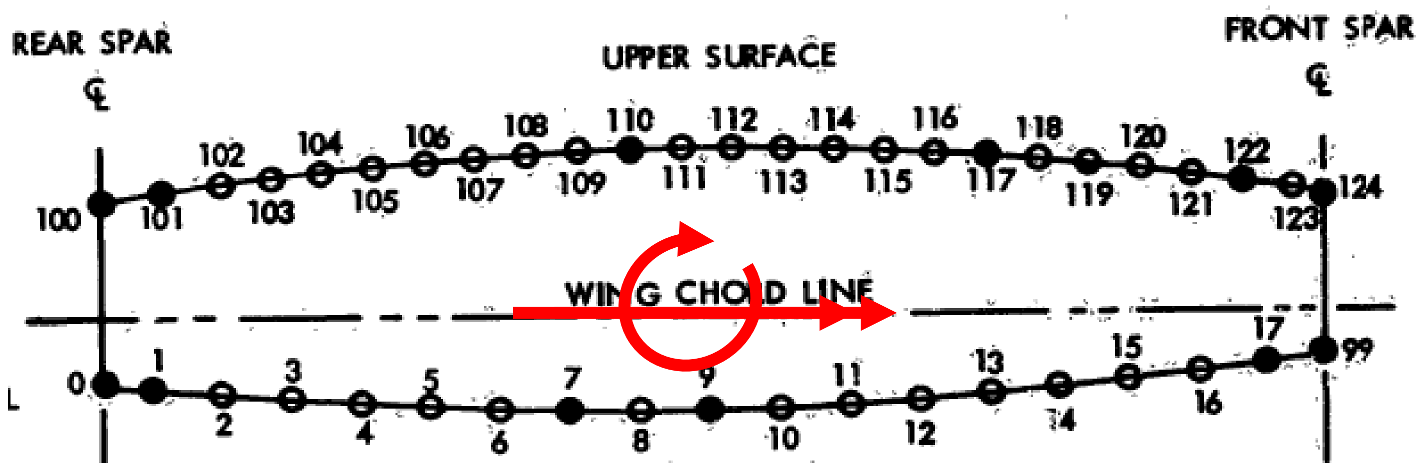
- Structure is MLP since the skin adequately carries the load once the stringer fails
- Inspections could include visual for a failed stringer if life of skin is long enough as in this case.

Complex Spectrum Analysis

- Certain Structures Have Complex Loading
  - Wing Spanwise Splice – Axial Stringer Loads + Wing Skin Shear Flow
  - Wing Spar – Spar Cap Axial Load + Web Shear Flow
  - Fuselage Attachment – Axial + Shear + Bending due to Fuselage Bending and Wing Bending and Torsion
- Complex Spectra Loads are **NOT always in phase**
- As a Result, Constant Linear Factors such as Bearing to Bypass or Bending to Bypass are NOT Accurate
- If Complex Loading is Present, Need to Utilize a Multi Channel Spectrum Approach

Internal Loads

- Wing Spanwise Splice:
  - J Stringer Axial Load driven by Wing Bending Moment
  - Wing Skin Shear Flow driven by Wing Torsion



Fastener Loads due Shear Flow

- To Accurately Represent this, 2 Spectra are developed:
  - J Stringer Axial Stress Spectrum Driven by Wing Bending Moment
  - Fastener Bearing Stress due to Shear Flow Driven by Torsion

Flt Cond	Ref. Axial Load	Ref. Axial stress	Shear Load	# fast	skin thic	fast diam	fast pitch	fast load	brg stress	brg/ref axial
10001	19348	10285	-518	2	0.16	0.1875	0.75	194	6477	63%
10002	19864	10560	-612	2	0.16	0.1875	0.75	229	7645	72%
10003	20895	11108	-467	2	0.16	0.1875	0.75	175	5842	53%
10004	17671	9395	-594	2	0.16	0.1875	0.75	223	7429	79%
10005	19605	10423	-600	2	0.16	0.1875	0.75	225	7501	72%
10006	19864	10560	-577	2	0.16	0.1875	0.75	216	7212	68%
10007	19476	10355	-764	2	0.16	0.1875	0.75	286	9549	92%
10008	20509	10903	-728	2	0.16	0.1875	0.75	273	9102	83%
10009	21282	11314	-697	2	0.16	0.1875	0.75	261	8713	77%
10010	20637	10971	-666	2	0.16	0.1875	0.75	250	8323	76%
10011	20379	10835	-696	2	0.16	0.1875	0.75	261	8698	80%
10012	17799	9463	-711	2	0.16	0.1875	0.75	267	8886	94%
10013	13619	8035	-898	2	0.16	0.1875	0.75	337	11231	140%
10040	-14783	-7859	-107	3	0.16	0.1875	0.75	27	894	-11%
10041	-14224	-7562	-100	4	0.16	0.1875	0.75	19	627	-8%
10042	-15140	-8049	-112	5	0.16	0.1875	0.75	17	560	-7%
10043	-15522	-8252	-117	6	0.16	0.1875	0.75	15	486	-6%
10044	-16104	-8561	-125	7	0.16	0.1875	0.75	13	445	-5%

- Note: Ratio of bearing to axial stress is NOT constant across load conditions.
- Bearing is due to skin shear flow which is dependent on wing torsion
- Wing Torsion and Wing Bending Moments are not linearly related

Complex Spectra - Axial

- First, Axial Spectrum is developed in Aspec:
  - 1g stress from Internal Load Cases
  - Delta g stress
  - Dynamic factors

		AXIAL STRESS SPECTRUM INPUT				
		Segment	DMF Factor	Constant Load	Alternating Load	Pressure
Load Case	Damage Code	Long 28%				
10044	1001	Taxi-Out	1.3	-8.561	-11.130	--
10001	1011	Take-Off Man	1	10.285	10.285	0
10001	1021	Take-Off Gust	1.4	10.285	14.400	0
10001	1011	Departure Man	1	10.285	10.285	0
10001	1021	Departure Gust	1.4	10.285	14.400	0
10002	1012	Climb Man	1	10.560	10.560	0
10002	1022	Climb Gust	1.4	10.560	14.784	0
10010	1013	Cruise Man	1	10.971	10.971	0
10010	1023	Cruise Gust	1.4	10.971	15.359	0
10013	1014	Descent Man	1	8.035	8.035	0
10013	1024	Descent Gust	1.4	8.035	11.249	0
10013	1015	Approach Man	1	8.035	8.035	0
10013	1025	Approach Gust	1.4	8.035	11.249	0
10041	1002	Landing	1.2	-7.562	-9.074	--
10041	1001	Taxi-in	1.3	-7.562	-9.831	--
Load Case	Damage Code	Medium 48%				
10042	2001	Taxi-Out	1.3	-8.049	-10.464	--
10001	2011	Take-Off Man	1	10.285	10.285	0
10001	2021	Take-Off Gust	1.4	10.285	14.400	0
10001	2011	Departure Man	1	10.285	10.285	0
10001	2021	Departure Gust	1.4	10.285	14.400	0
10002	2012	Climb Man	1	10.560	10.560	0
10002	2022	Climb Gust	1.4	10.560	14.784	0
10004	2013	Cruise Man	1	9.395	9.395	0
10004	2023	Cruise Gust	1.4	9.395	13.152	0
10013	2014	Descent Man	1	8.035	8.035	0
10013	2024	Descent Gust	1.4	8.035	11.249	0
10013	2015	Approach Man	1	8.035	8.035	0
10013	2025	Approach Gust	1.4	8.035	11.249	0
10041	2002	Landing	1.2	-7.562	-9.074	--
10041	2001	Taxi-in	1.3	-7.562	-9.831	--
Load Case	Damage Code	Short 24%				
10040	3001	Taxi-Out	1.3	-7.859	-10.216	--
10001	3011	Take-Off Man	1	10.285	10.285	0
10001	3021	Take-Off Gust	1.4	10.285	14.400	0
10001	3011	Departure Man	1	10.285	10.285	0
10001	3021	Departure Gust	1.4	10.285	14.400	0
10002	3012	Climb Man	1	10.560	10.560	0
10002	3022	Climb Gust	1.4	10.560	14.784	0
10007	3013	Cruise Man	1	10.355	10.355	0
10007	3023	Cruise Gust	1.4	10.355	14.497	0
10013	3014	Descent Man	1	8.035	8.035	0
10013	3024	Descent Gust	1.4	8.035	11.249	0
10013	3015	Approach Man	1	8.035	8.035	0
10013	3025	Approach Gust	1.4	8.035	11.249	0
10041	3002	Landing	1.2	-7.562	-9.074	--
10041	3001	Taxi-in	1.3	-7.562	-9.831	--

Complex Spectra - Bearing

- Second, Bearing Spectrum is developed in Aspec:
  - 1g stress
  - Delta g stress
  - Dynamic factors

		BEARING STRESS SPECTRUM INPUT				
		Segment	DMF Factor	Constant Load	Alternating Load	Pressure
Load Case	**Damage Code**	**Long 28%**				
10044	1001	Taxi-Out	1.3	0.445	0.579	--
10001	1011	Take-Off Man	1	6.477	6.477	0
10001	1021	Take-Off Gust	1.4	6.477	9.067	0
10001	1011	Departure Man	1	6.477	6.477	0
10001	1021	Departure Gust	1.4	6.477	9.067	0
10002	1012	Climb Man	1	7.645	7.645	0
10002	1022	Climb Gust	1.4	7.645	10.703	0
10010	1013	Cruise Man	1	8.323	8.323	0
10010	1023	Cruise Gust	1.4	8.323	11.652	0
10013	1014	Descent Man	1	11.231	11.231	0
10013	1024	Descent Gust	1.4	11.231	15.723	0
10013	1015	Approach Man	1	11.231	11.231	0
10013	1025	Approach Gust	1.4	11.231	15.723	0
10041	1002	Landing	1.2	0.627	0.753	--
10041	1001	Taxi-in	1.3	0.627	0.816	--
Load Case	**Damage Code**	**Medium 48%**				
10042	2001	Taxi-Out	1.3	0.560	0.728	--
10001	2011	Take-Off Man	1	6.477	6.477	0
10001	2021	Take-Off Gust	1.4	6.477	9.067	0
10001	2011	Departure Man	1	6.477	6.477	0
10001	2021	Departure Gust	1.4	6.477	9.067	0
10002	2012	Climb Man	1	7.645	7.645	0
10002	2022	Climb Gust	1.4	7.645	10.703	0
10004	2013	Cruise Man	1	7.429	7.429	0
10004	2023	Cruise Gust	1.4	7.429	10.400	0
10013	2014	Descent Man	1	11.231	11.231	0
10013	2024	Descent Gust	1.4	11.231	15.723	0
10013	2015	Approach Man	1	11.231	11.231	0
10013	2025	Approach Gust	1.4	11.231	15.723	0
10041	2002	Landing	1.2	0.627	0.753	--
10041	2001	Taxi-in	1.3	0.627	0.816	--
Load Case	**Damage Code**	**Short 24%**				
10040	3001	Taxi-Out	1.3	0.894	1.163	--
10001	3011	Take-Off Man	1	6.477	6.477	0
10001	3021	Take-Off Gust	1.4	6.477	9.067	0
10001	3011	Departure Man	1	6.477	6.477	0
10001	3021	Departure Gust	1.4	6.477	9.067	0
10002	3012	Climb Man	1	7.645	7.645	0
10002	3022	Climb Gust	1.4	7.645	10.703	0
10007	3013	Cruise Man	1	9.549	9.549	0
10007	3023	Cruise Gust	1.4	9.549	13.369	0
10013	3014	Descent Man	1	11.231	11.231	0
10013	3024	Descent Gust	1.4	11.231	15.723	0
10013	3015	Approach Man	1	11.231	11.231	0
10013	3025	Approach Gust	1.4	11.231	15.723	0
10041	3002	Landing	1.2	0.627	0.753	--
10041	3001	Taxi-in	1.3	0.627	0.816	--

Combining Spectra

- Third, combine axial and bearing spectra in spectrum manager or Excel to Nasgro Multi Channel Format:
- Cycles, Max/Min S0, S1, S2, S3 S0 = Axial S3 = Bearing

707axialbrg.prn - Notepad

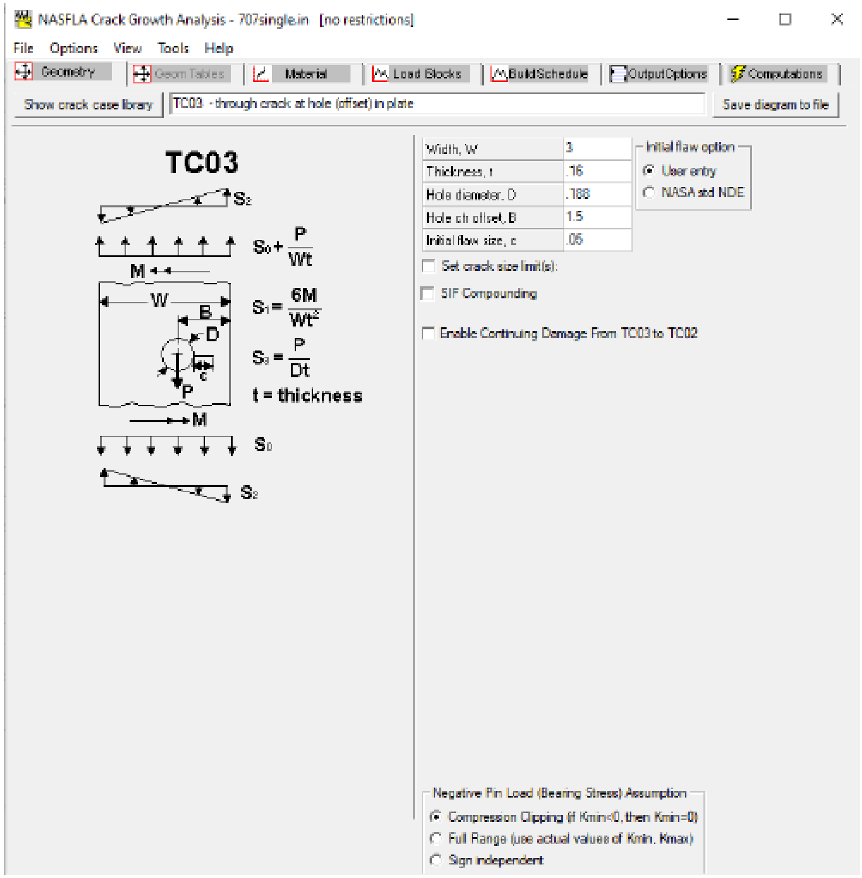
File Edit Format View Help

```
707 multi channel
       18  11.725   8.845        0        0        0        0   7.383   5.569
        1  11.314   9.257        0        0        0        0   7.124   5.828
        9  11.725   8.845        0        0        0        0   7.383   5.569
        1  13.165   7.405        0        0        0        0   8.289   4.663
        1  11.725   8.845        0        0        0        0   7.383   5.569
        1  13.517   7.603        0        0        0        0   9.786   5.504
       32  12.038   9.082        0        0        0        0   8.715   6.575
        1  11.616   9.504        0        0        0        0    8.41   6.881
        3  12.038   9.082        0        0        0        0   8.715   6.575
        1  13.517   7.603        0        0        0        0   9.786   5.504
        9  12.038   9.082        0        0        0        0   8.715   6.575
        1  11.616   9.504        0        0        0        0    8.41   6.881
       10  12.038   9.082        0        0        0        0   8.715   6.575
        1  11.616   9.504        0        0        0        0    8.41   6.881
        8  12.038   9.082        0        0        0        0   8.715   6.575
        1  12.067   9.873        0        0        0        0   9.155   7.491
       77  12.506   9.434        0        0        0        0   9.488   7.158
        1  12.067   9.873        0        0        0        0   9.155   7.491
       20  12.506   9.434        0        0        0        0   9.488   7.158
        1  15.578   6.362        0        0        0        0  11.819   4.827
        5  12.506   9.434        0        0        0        0   9.488   7.158
        1  14.042   7.898        0        0        0        0  10.653   5.993
       20  12.506   9.434        0        0        0        0   9.488   7.158
        1  12.067   9.873        0        0        0        0   9.155   7.491
       17  12.506   9.434        0        0        0        0   9.488   7.158
        1  14.042   7.898        0        0        0        0  10.653   5.993
       23  12.506   9.434        0        0        0        0   9.488   7.158
        1  12.067   9.873        0        0        0        0   9.155   7.491
       22  12.506   9.434        0        0        0        0   9.488   7.158
        1  12.067   9.873        0        0        0        0   9.155   7.491
        5  12.506   9.434        0        0        0        0   9.488   7.158
        1  12.067   9.873        0        0        0        0   9.155   7.491
        1  12.506   9.434        0        0        0        0   9.488   7.158
        1  14.042   7.898        0        0        0        0  10.653   5.993
```

Multi Channel Crack Growth

- Perform Nasgro Analysis using Multi Channel Spectrum with Variable Bearing to Reference Stress Ratio:

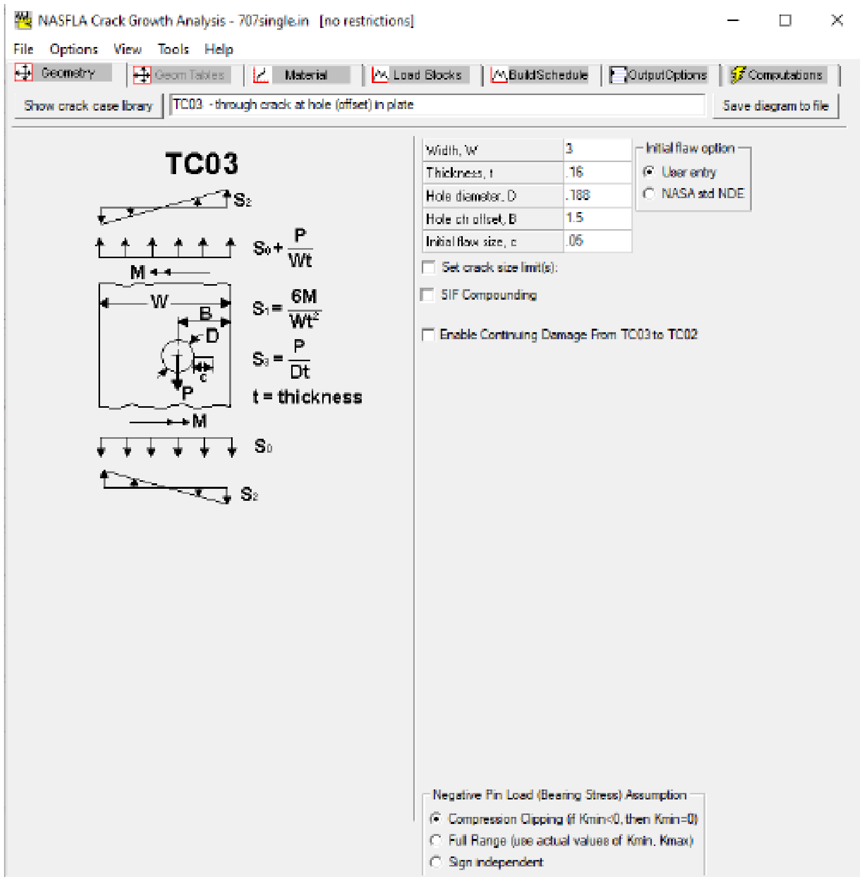
```
GEOMETRY
--------
MODEL: TC03-Through crack from hole in plate.
Pin Load DeltaK is based on compression clipping, Kmin = Max[0,Kmin]

Continuing damage from TC03 to TC02 is not allowed.

Plate Thickness,  t =   0.1600
Plate Width,      W =    3.000
Hole Diameter,    D =   0.1880
Edge to Hole Ctr, B =    1.500


INITIAL FLAW SIZE (user specified)
------------------------------------------

   c (init.) =  0.5000E-01


MATERIAL
--------
Material File Name: NASMF.XMLZ
Material File Description: NASA data/NASGRO eqn (single temp)

MATL 1:  1000-9000 SERIES AL
         2000 series
Material  1,  Data ID: M2EA11AB1
Alloy Description: 2024-T3 Al

Alloy Cond/HT:Plt & Sht; L-T; LA; Room temp

FATIGUE SPECTRUM
----------------
              [schedule title]

[Note: Stress = Input Value * Scale Factor]

Stress Scale Factors for Block Case:  1

Scale Factor for Stress S0:     1.0000
Scale Factor for Stress S1:     0.0000
Scale Factor for Stress S2:     0.0000
Scale Factor for Stress S3:     1.0000
```



Single Channel Crack Growth

- Perform Nasgro Analysis using Multi Channel Spectrum with Constant Linear Bearing to Reference Ratio:

```
GEOMETRY
--------
MODEL: TC03-Through crack from hole in plate.
Pin Load DeltaK is based on compression clipping, Kmin = Max[0,Kmin]

Continuing damage from TC03 to TC02 is not allowed.

Plate Thickness,  t =   0.1600
Plate Width,      W =    3.000
Hole Diameter,    D =   0.1880
Edge to Hole Ctr, B =    1.500


INITIAL FLAW SIZE (user specified)
-------------------------------------------

   c (init.) =  0.5000E-01


MATERIAL
--------
Material File Name: NASMF.XMLZ
Material File Description: NASA data/NASGRO eqn (single temp)

MATL 1:  1000-9000 SERIES AL
         2000 series
Material  1,  Data ID: M2EA11AB1
Alloy Description: 2024-T3 Al

Alloy Cond/HT:Plt & Sht; L-T; LA; Room temp

FATIGUE SPECTRUM
----------------
              [schedule title]

[Note: Stress = Input Value * Scale Factor]

Stress Scale Factors for Block Case:  1

Scale Factor for Stress S0:     1.0000
Scale Factor for Stress S1:     0.0000
Scale Factor for Stress S2:     0.0000
Scale Factor for Stress S3:    0.53000
```



Crack Growth Results

- Comparison of Multi Channel Spectra Using Either Variable or Constant Load Ratio:
- Variable Brg/Ref Ratio
  - Critical Crack Length = 1.1655
  - Total Cycles = 2234194
  - Total Flight Hours = **22150**
- Constant Brg/Ref Ratio @0.53
  - Critical Crack Length = 1.1285
  - Total Cycles = 2545998
  - Total Flight Hours = **25242**

Life is 12% Lower Using Multi Channel Spectrum

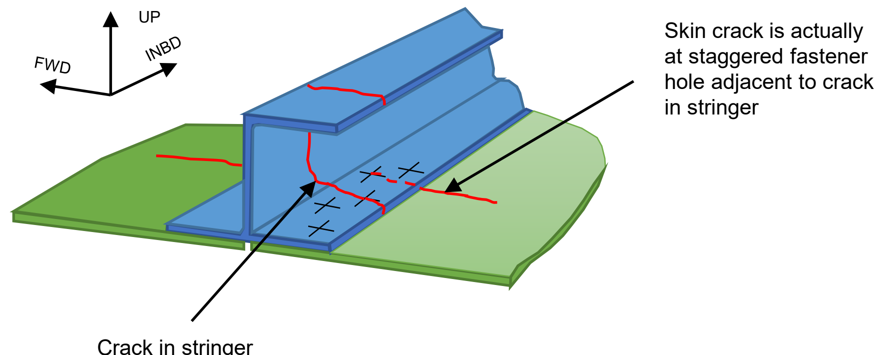
- Constant Brg/Ref Ratio @1.40
  - Total Flight Hours = **18530**

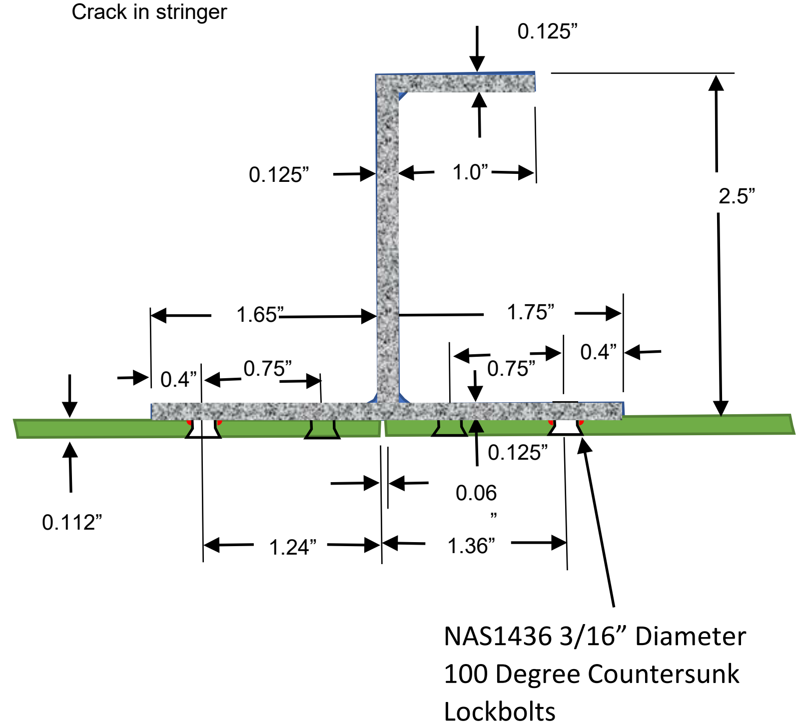
Life is 17% Higher Using Multi Channel Spectrum

- When bearing stress is driven by a secondary load that is not linearly related to primary load, large errors in results can be encountered
- In theses cases, a multi channel variable spectrum must be developed for each independent load source.

Phase III – Skin - Revised

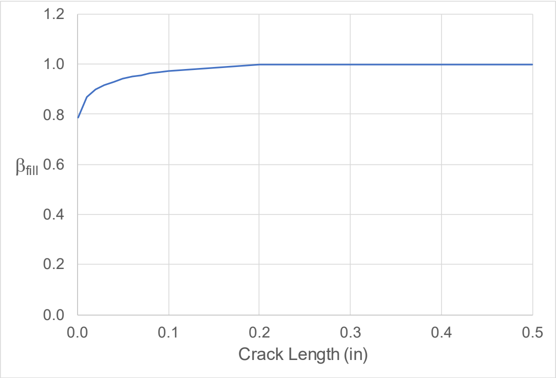
- Revise Phase III in Skin to Adjacent Fastener Hole and Include Fastener Load due to loads from highest damage segment in spectrum
- Corner Cracks – Both Holes
  - $a_{CD} = c_{CD} = 0.005\ in$
- Superposition
  - Axial (no bypass, see Session 12)
  - Bearing – due to shear flow
- Compounding
  - Filled Hole
  - Regular Hole (in AFGROW)
  - Crack growing to Z-stringer
    R&C Figure 124, s = 1.0
  - Cracked Stringer
    R&C Report 75072, Figure 7, s = 1.0





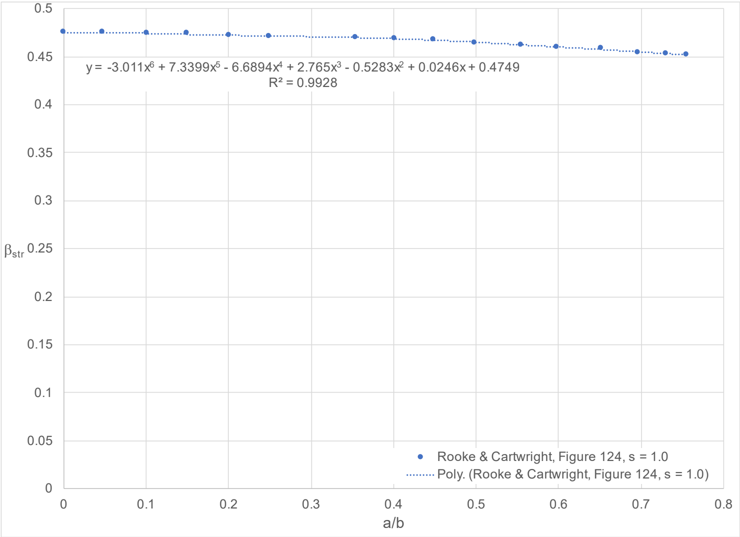
Stress Intensity Factor

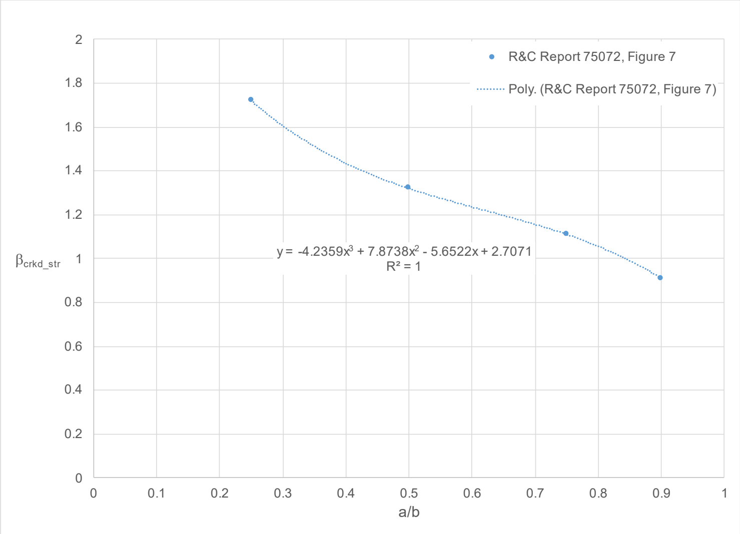
- $K_{SS} = [\sigma_{Ax}\beta_{Ax} + \sigma_{Brg}\beta_{Brg}]\sqrt{\pi a}\beta_{fill}\beta_{str}\beta_{crkd\_str}$
  - β_{Ax}, β_{Brg} built into AFGROW
  - $\beta_{fill}, \beta_{str}, \beta_{crkd\_str}$



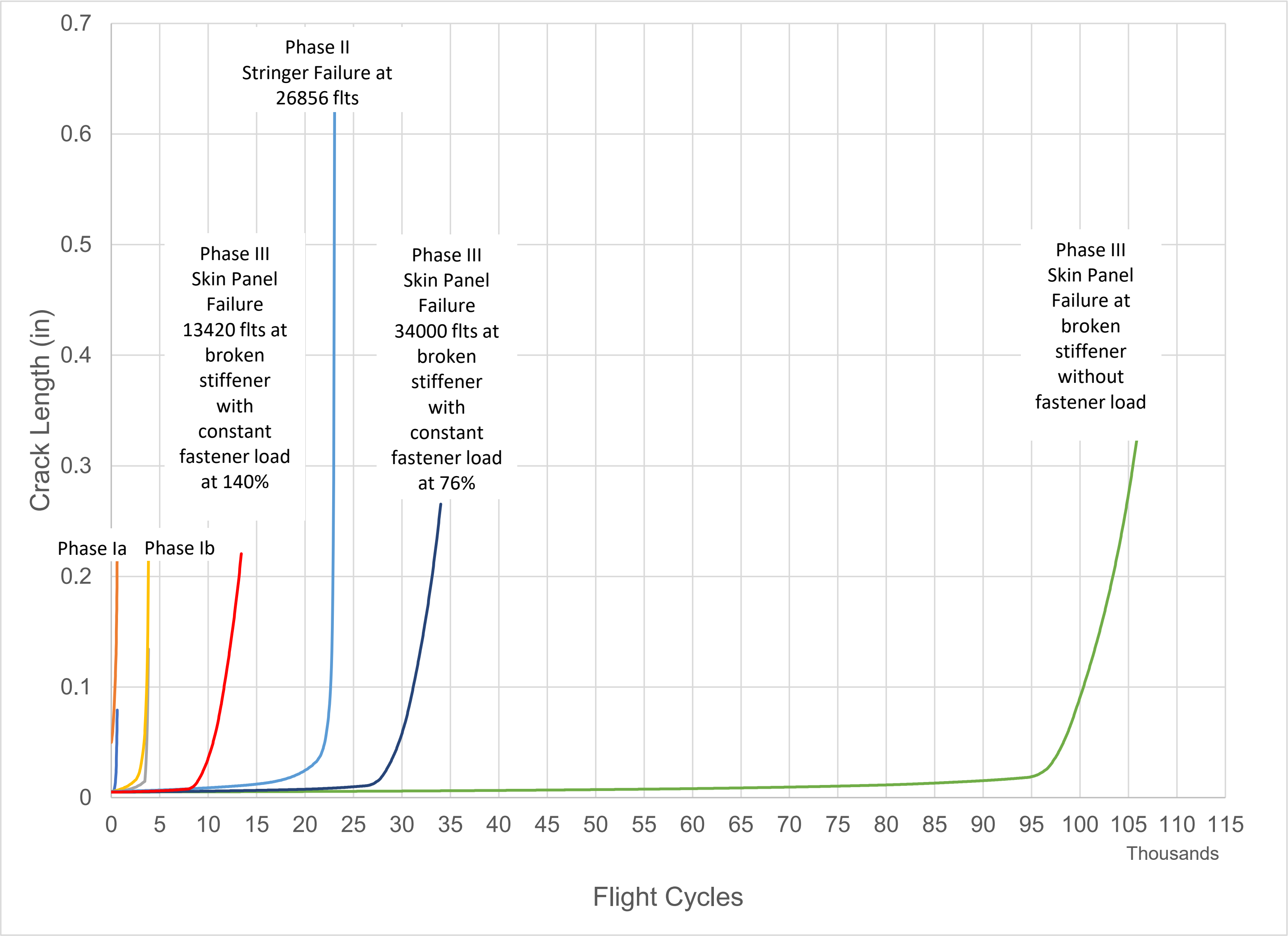
- Bearing Stress Ratio
  - $BrgSR = \frac{\sigma_{Brg}}{\sigma_{ref}} = 0.76$

Based on highest damage coming from segment 1023 which uses loads from condition 10010 with a 76% SR. Next highest is 1025 for condition 10013 with a 140% SR.





Phase III – Skin Revised Results



Updated Inspections

- Approximate analysis of the skin at the adjacent fastener hole results in a much shorter life using 76% constant SR for bearing but still supports a MLP inspectable for load path failure approach.

Inspection = Visual for Broken Stringer

- Approximate analysis using 140% constant SR for bearing does not support MLP. Skin fails prior to stringer.

Inspection = NDT for Cracks in Stringer

Complex Spectra Impact

- Structure being analyzed may have stresses driven from multiple load sources which require a multi channel spectra
- Its imperative for complex spectra to be able to identify damage sources so that contributing load sources can be determined
- Assuming a constant linear relationship between load sources may or may not be conservative depending on structural detail
- Example illustrates impact of load transfer can be driving factor in determining if structure is Multiple Load Path Inspectable for Load Path Failure or Not Inspectable. This has large impact on inspection requirements.
- Recommend that analytical tools should be capable of handling multi channel spectra.

SAVE THE DATE

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  - FAA REQUIREMENTS & GUIDANCE
  - FATIGUE VERSUS DESIGN ENVIRONMENT
  - MISSION PROFILES AND USAGE
  - AIRCRAFT PARAMETERS
  - EXTERNAL LOADS
  - INTERNAL LOADS
  - LOAD HISTORIES
  - DYNAMIC EFFECTS
  - SPECTRUM DEVELOPMENT
- DAMAGE TOLERANCE EVALUATION OF STRUCTURE
  - SELECT DETAILS OF INTEREST
  - STRESS ANALYSIS
  - INITIAL FLAW SIZES
  - STRESS INTENSITY FACTORS
  - MATERIALS
  - DETECTABLE CRACK LENGTHS
  - FATIGUE CRACK GROWTH MODELS
  - INSPECTIONS
  - DTA METHODS AND EXAMPLES
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NOVEMBER 27 - Aircraft Structural Integrity Program Conference, Denver, CO, USA

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