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CENTER OF EXCELLENCE

Investigation of Static Strength Variability between Composite and Metallic with respect to Overload Factors

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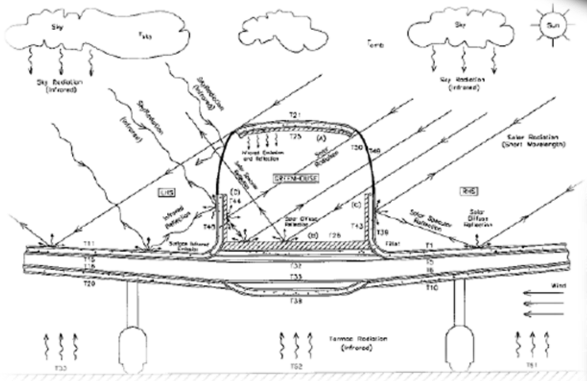
Background & Motivation

- During service, composite structures absorb atmospheric moisture and rate of moisture absorption is accelerated by the elevated temperature.
- It was demonstrated that static strength behavior is affected by the environmental conditions; however, the fatigue behavior is relatively insensitive.
- In addition to the environmental factors, scatter factors or material variability are also acute factors.
- Therefore, during the substantiation process of static test articles, DUL are increased in a manner similar to the load enhancement factor (LEF) approach to compensate for the environmental effects and material scatter; However, this procedure varies from company to company.
- Despite the many advantages, composite structural certification becomes challenging due to the lack of experience in large-scale structures, complex interactive failure mechanisms, sensitivity to temperature and moisture, and scatter in the data.
- Static overload factor for composite structural substantial assumes that the strength variability in composites is significantly higher than that for metals, and the effects of humidity and temperature on metals is insignificant.
- Therefore, overly conservative overload factors applied during composite static strength substantiation.



The overall objective of this research is to investigate static strength variability between composites and metallic with respect to overload factors that are applied during static strength substantiation of composite structures and develop guidelines.

- *Task 1: Literature Survey*
  - *Composite Data*
  - *Metallic Data*
  - *Industry Standards*
- *Task 2: Analysis and Comparison*
- *Task 3: Guidelines for Development and Application of Static Overload Factor*
- *Task 4: Validation*

Roadmap of Project – Technical Approach

Task 1
Literature Survey

- Conduct literature survey on static strength variability under extreme environmental conditions for each level of building block testing:
    1. **Composite Data**
    2. Metallic Data
- Collect available various industry standards for full scale substantiation

Task 2
Data Analysis and Comparison

- Environmental Compensation Factor (ECF)

$$ECF = \frac{\sigma_{RTA}}{\sigma_{Min\ (Critical\ Env.condition)}}$$

- Scatter Factor (SF)

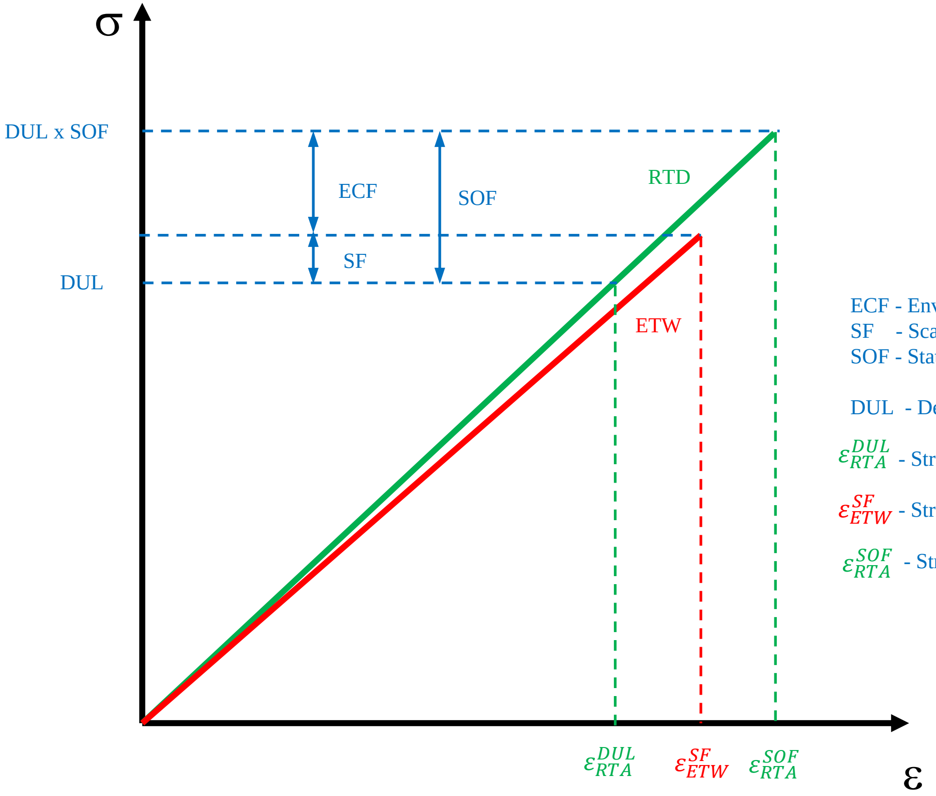
$$SF = \frac{\sigma_{Mean\ (Env)}}{\sigma_{B-Basis\ (Env)}}$$

- Static Overload Factors (SOF)

Task 3
Guidelines for Development and Application of Static Overload Factor

- Analyzed data and industry standards are evaluated to develop:
    - Guidance for SOF calculations
    - Guidance for SOF applications

Full-Scale Static Test



ECF - Environmental Compensation Factor
SF - Scatter Factor
SOF - Static Overload Factor

DUL - Design Ultimate Load

ε_{RTA}^{DUL} - Strain at DUL x SF (RTA test)

ε_{ETW}^{SF} - Strain at DUL x SF (ETW test)

ε_{RTA}^{SOF} - Strain at DUL x SOF (RTA test)

Environmental degradation is accounted for

Option 1
RTA test to DUL x SOF

Option 2
RTA test to DUL x SF and strain correlation with ECF**

Option 3
ETW test to DUL x SF

For ETW full-scale static test:

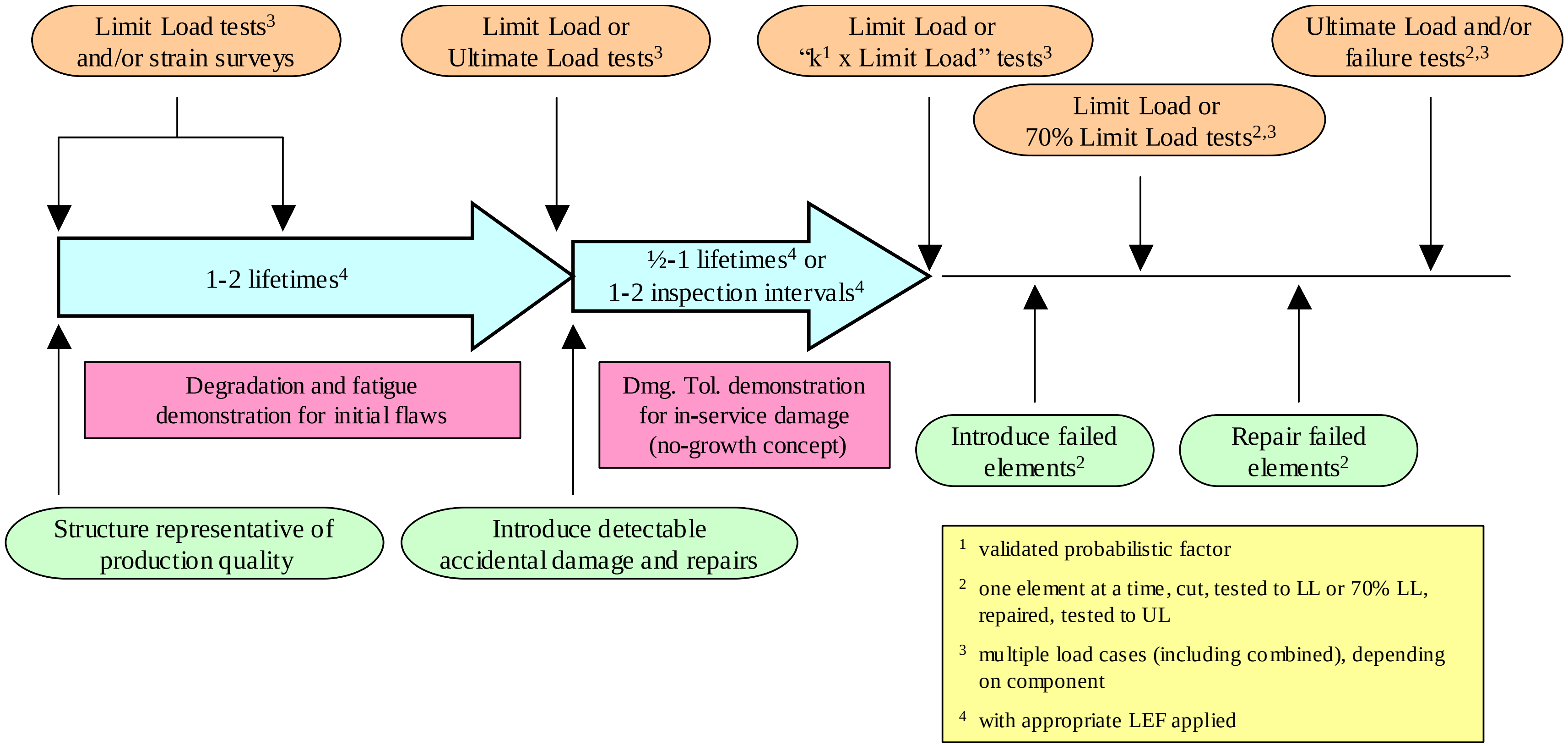
$$\varepsilon_{ETW}^{SF} < \varepsilon_{ETW}^{B}$$

For RTA full-scale test:

$$\varepsilon_{RTA}^{SOF} < \varepsilon_{ETW}^{B}$$

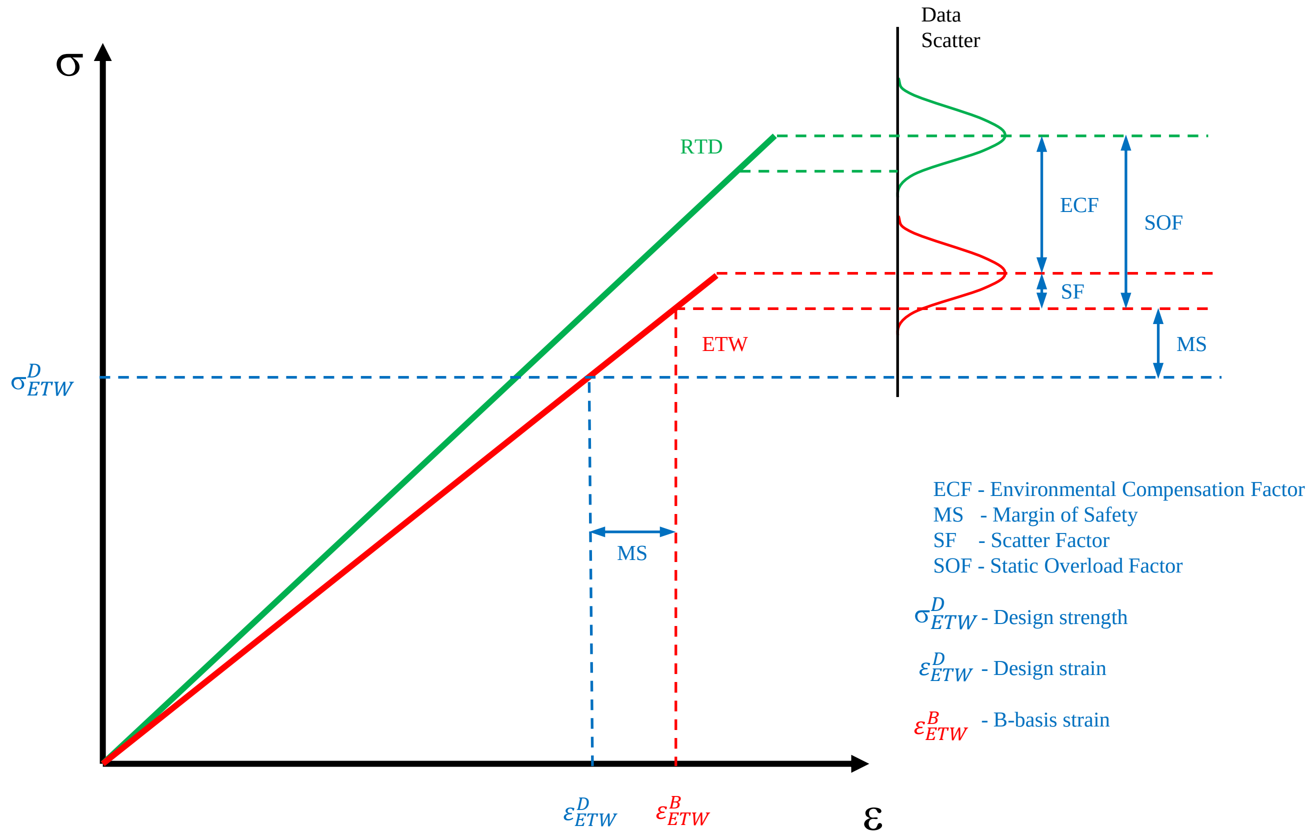
Note: **strain-based approach relies heavily on assumption that the FEM is so good that we could get one-to-one correlation coupled with all BB testing to go with all predicted failure modes regardless of whether we could duplicate such behavior at coupon/component level

Full-Scale Test Sequence



Composite Materials Handbook (CMH-17)

Development of Static Overload Factor (SOF)



Assume

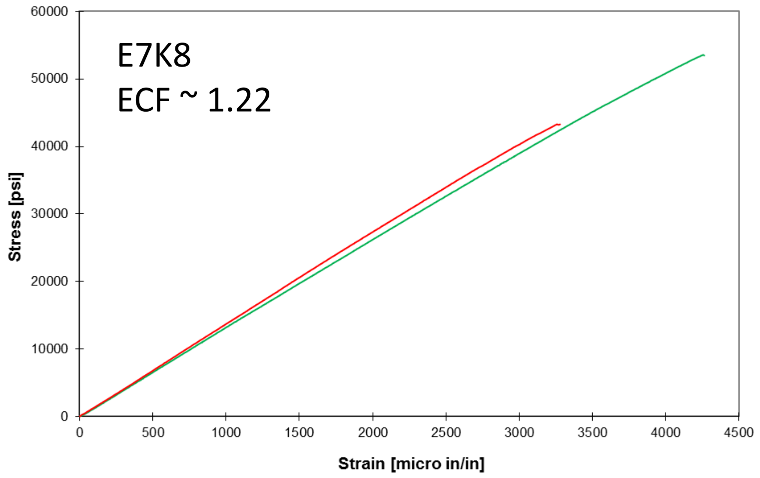
1. Composite strength variability is independent of environment.
2. Linear stress-strain response for RTA and critical environmental condition
3. Critical failure mode is independent of environment and can be predicted

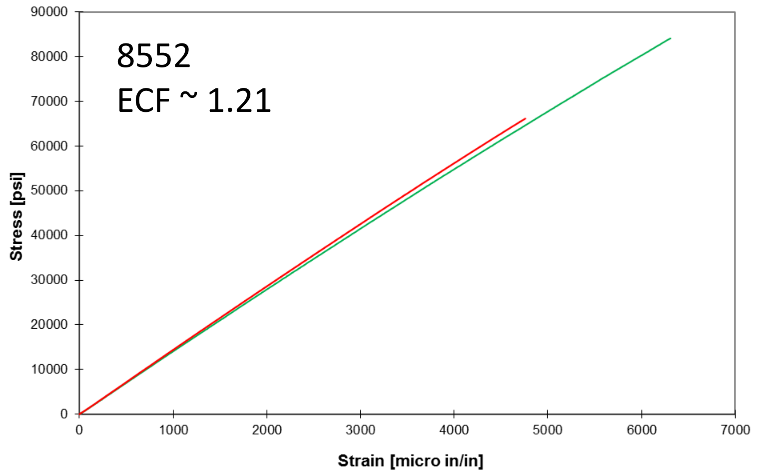
Static Overload Factor

SOF = ECF x SF

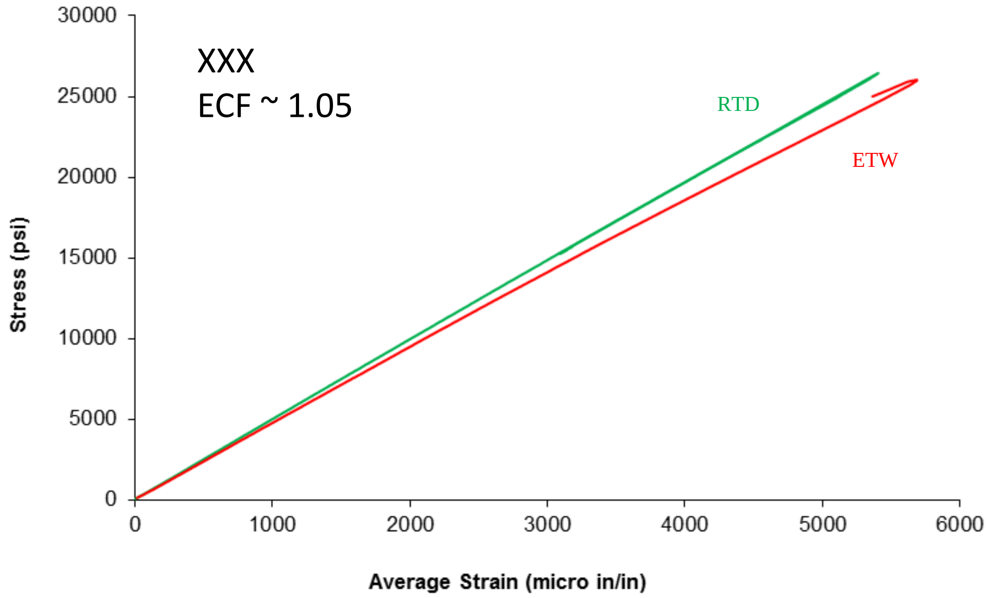
Compression After Impact

Example RTA & ETW Curves



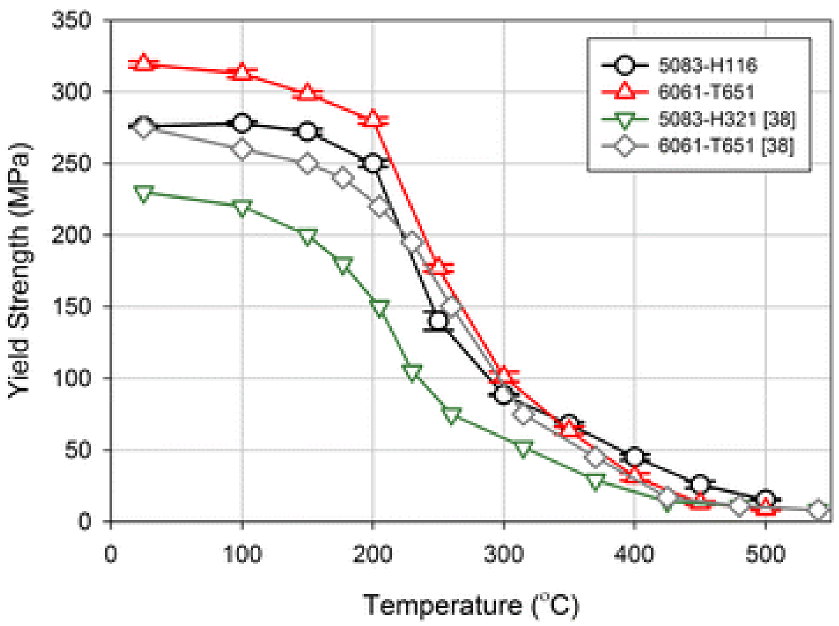


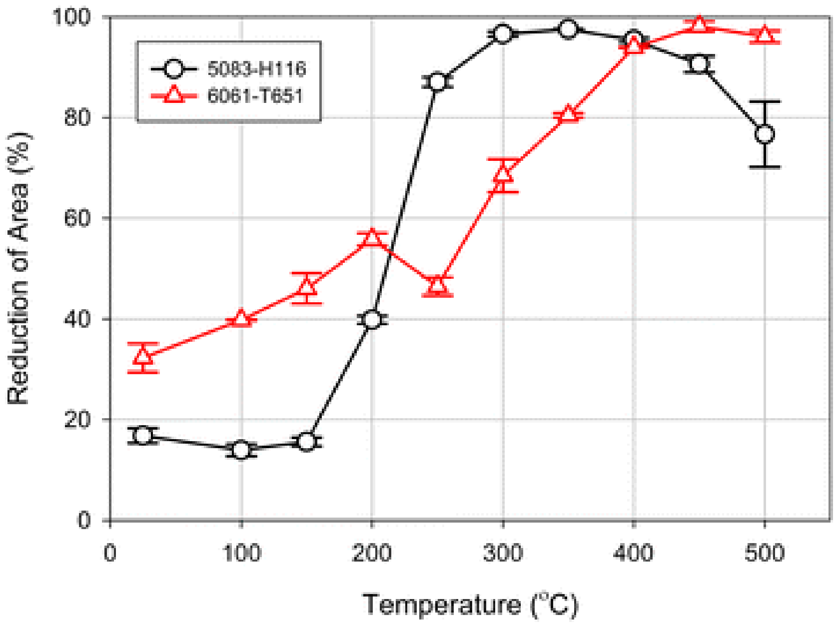
- Some new composite material systems have shown significantly low ECFs



- For certain failure modes and design details, ETW may not be the critical environmental condition
- Other failure modes must also be interrogated

ECF for Metals

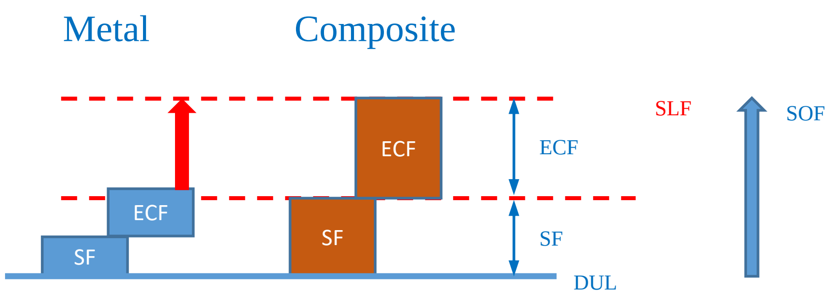




Ref: Kaufman JG (ed) (2000) Introduction to aluminum alloys and tempers. ASM International, Metals Park, OH

Allen B (2012) Thermomechanical behavior and creep response of marine-grade aluminum alloys. Thesis, Virginia Polytechnic Institute & State University

SOF for Hybrid Structures



- Data scatter in composite is higher than metals
  ➔ $SF_{Metals} < SF_{Composites}$
- ECF_{Metals} only includes temperature effects and $ECF_{Metals} < ECF_{Composites}$

- If Option 2 is employed, hybrid test must be conducted to DUL x $SF_{Composites}$
- When employing Option 2, strain correlation for both metals and composites must be conducted separately.
- Option 3 may be employed at component or subcomponent levels to address critical environmental effects for composites

- Static Load Factor

$$SLF = \frac{C_{\substack{composite\\variability}} \cdot C_{\substack{composite\\temperature}} \cdot C_{\substack{composite\\moisture}}}{F_{\substack{metals\\variability}} \cdot F_{\substack{metals\\temperature}} \cdot F_{\substack{metals\\moisture}}}$$

$C_{\substack{composite\\variability}}$ - Composite material variability

$F_{\substack{metals\\variability}}$ - Metal material variability

$C_{\substack{composite\\temperature}}$ - Composite temperature effects

$F_{\substack{metals\\temperature}}$ - Metal temperature effects

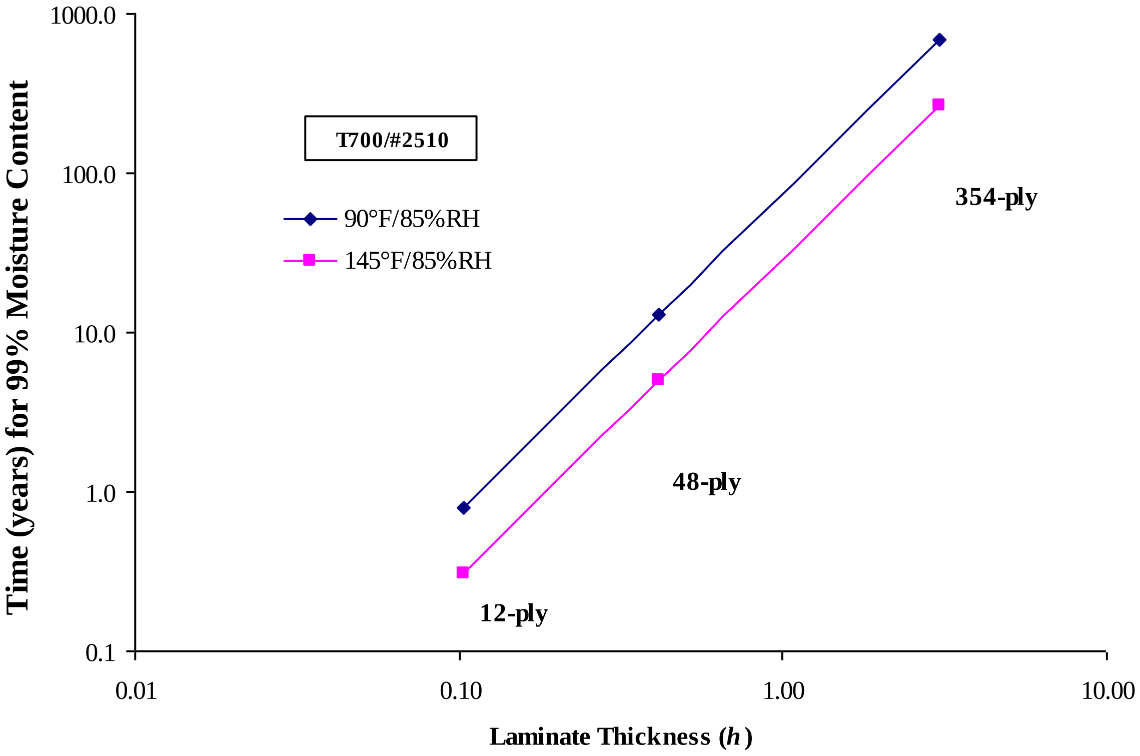
$C_{\substack{composite\\moisture}}$ - Composite moisture effects

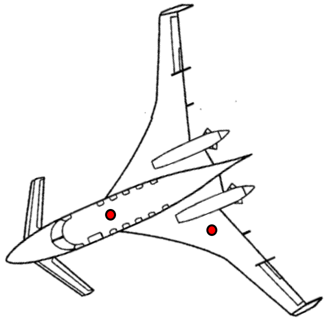
$F_{\substack{metals\\moisture}}$ - Metal moisture effects

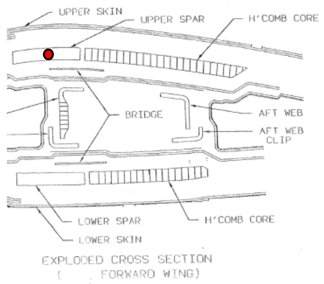
Thick Composite Structures

- What is realistic?

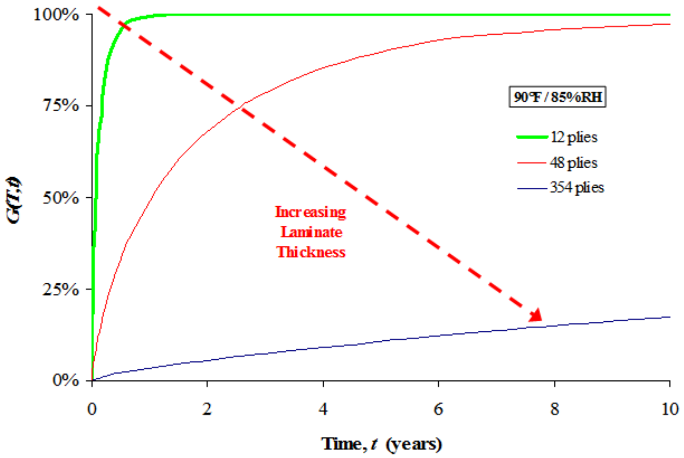
Laminate Thickness (in)	Years for 99% Saturation 0.1032	0.4128	3.0444
90°F/85%RH	0.8	12.8	696.6
145°F/85%RH	0.3	5.0	269.4



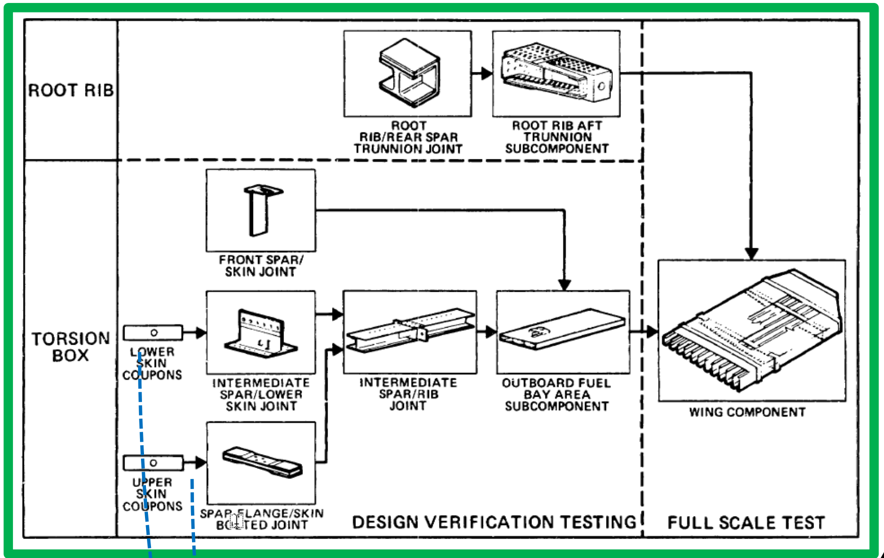


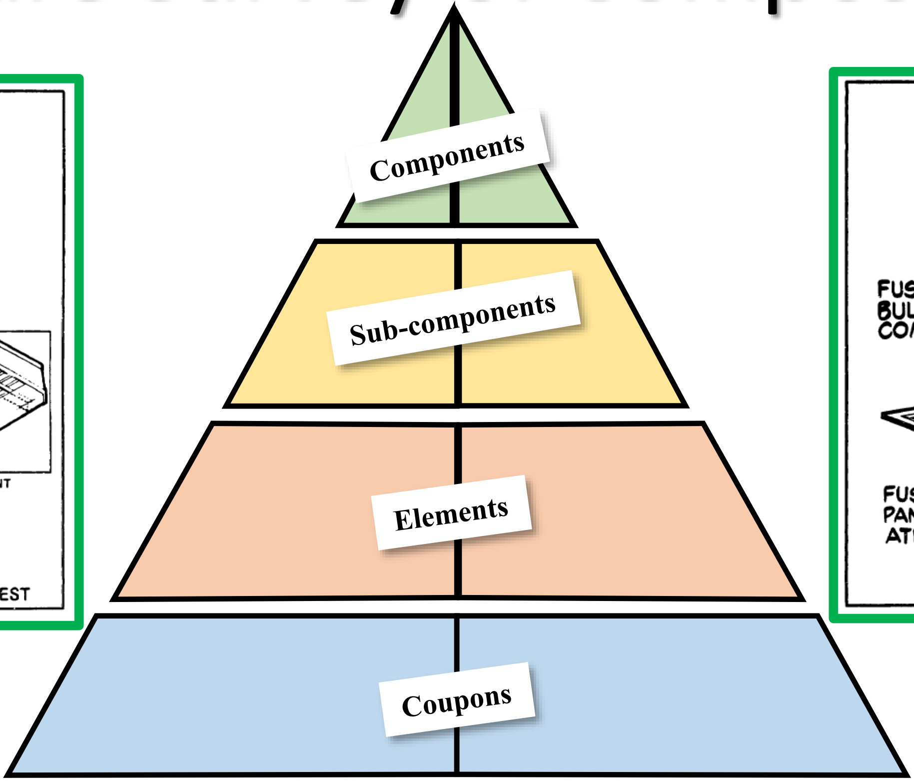


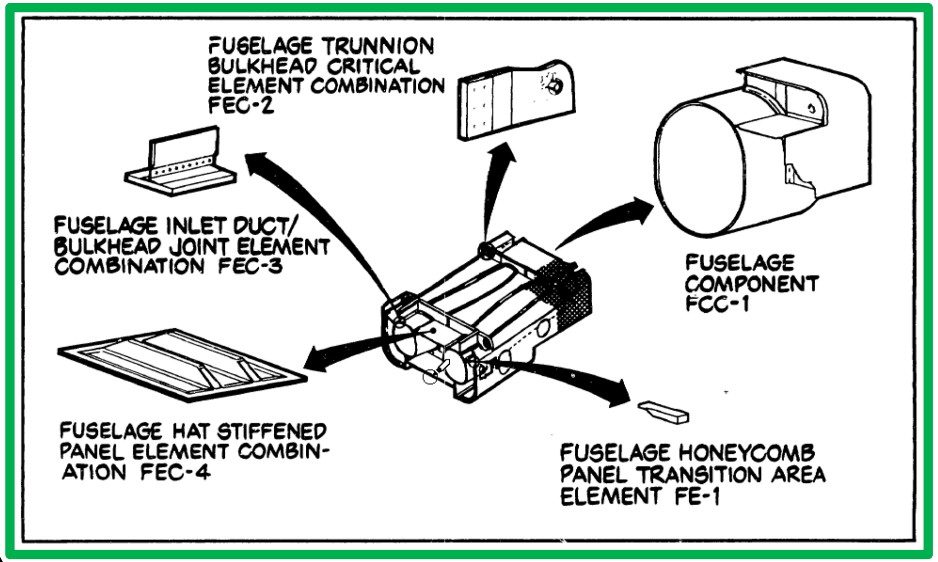
- Effects of thickness on the moisture equilibrium can be used to generate customized (lower) ECFs for thick structures



Literature Survey of Composite Data







Elements
Large Saw Cut Tension
Large Saw Cut Compression
Large 4pt Bend
Crippling
CAI (6X12)
Wing skin Elements
Fuselage Honeycomb Elements

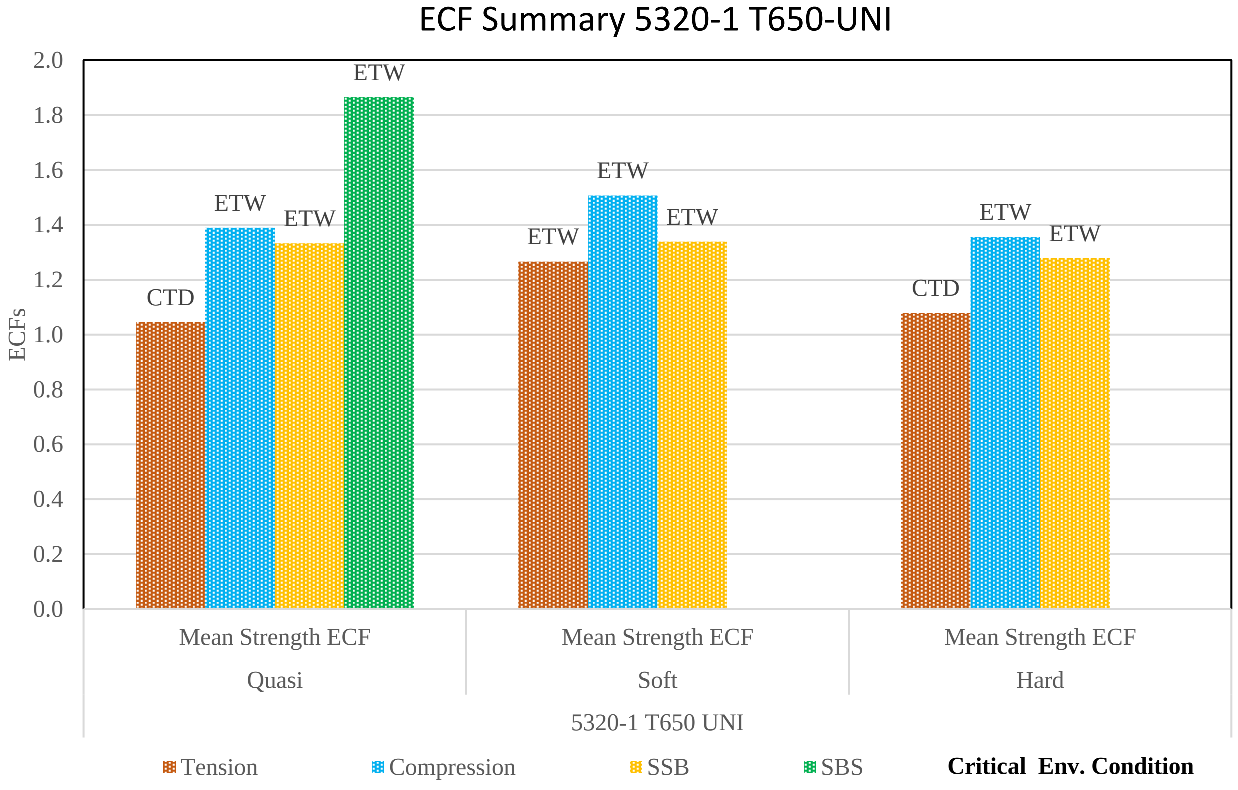
Coupon Level Testing

Materials	Layups	Test Methods	Dominant Failure Modes	Environmental Conditions
Toray TC1225 UNI	Soft	OHT	Tension	RTA
Solvay 5320-1 T650 UNI	Quasi-isotropic	FHT		ETW
Solvay 5320-1 T650 PW	Hard	UNT		CTD
Hexcel 8552 AS4 UNI		OHC	Compression	
Hexcel 8552 AS4 PW		FHC		
Hexcel 8552 IM7 UNI		UNC		
Wing Skin Coupons		SSB	Bearing	
		DNS	Shear	
		SBS		

Coupon Level ECF Analysis *(5320-1 T650-UNI)*

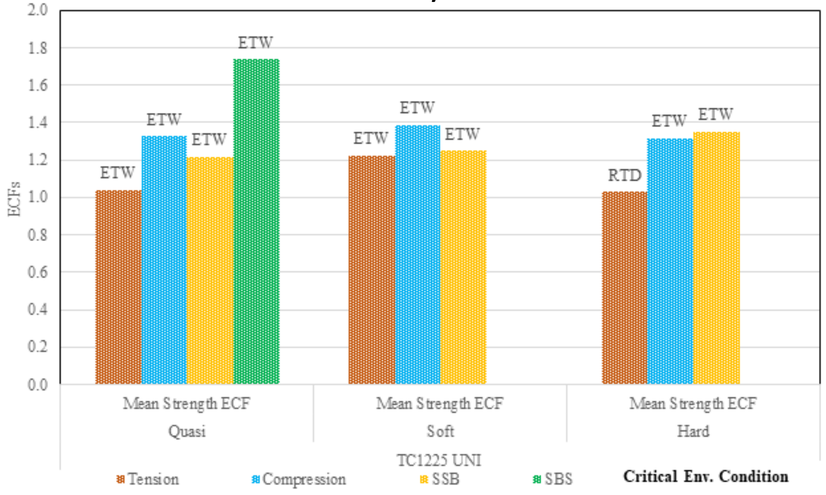
Material	Laminate	Test Method	Env. Conditions °F	Laminate (3 Batch) # of Specimens-Batches	Laminate (3 Batch) Mean [ksi]	Laminate (3 Batch) ASAP B-Basis	Laminate (3 Batch) 3-Batch CV	Critical Condition
5320-1 T650 UNI	25/50/25 [45/0/-45/90]2S	OHT	CTD (-65)	21 from 3	47.105		5.534	CTD
			RTD (70)	21 from 3	49.601		5.909	
			ETW (250)	21 from 3	53.675	47.505	6.032	
		OHC	RTD (70)	21 from 3	50.894	46.119	6	ETW
			ETW (250)	21 from 3	39.199	34.424	6	
		FHT	CTD (-65)	21 from 3	56.416	50.344	6	CTD
			RTD (70)	21 from 3	57.962	51.89	6.143	
			ETW (250)	21 from 3	60.048	53.976	6	
		FHC	RTD (70)	21 from 3	81.56	73.794	6.299	ETW
			ETW (250)	21 from 3	55.757	47.991	6.644	
		UNT	CTD (-65)	21 from 3	92.513	82.306	6	CTD
			RTD (70)	21 from 3	97.622	87.415	6	
			ETW (250)	21 from 3	103.351	93.145	6	
		UNC	RTD (70)	21 from 3	96.628	82.369	7.822	ETW
			ETW (250)	21 from 3	68.635	60.866	6	
		SSB 2%	RTD (70)	21 from 3	136.627	123.999	6	ETW
			ETW (250)	21 from 3	102.565	89.937	6	
		SSB Initial	RTD (70)	21 from 3	135.155	122.477	6.022	ETW
			ETW (250)	21 from 3	101.299	88.8	6.041	
		SSB Ultimate	RTD (70)	21 from 3	151.576	137.05	6.341	ETW
			ETW (250)	21 from 3	113.84	99.314	6	
		SBS	RTD (70)	21 from 3	13.71	10.649	6.205	ETW
			ETW (250)	21 from 3	7.356		5.199	
	10/80/10 [45/-45/0/45/-45/90/45/-45/45/-45]S	OHT	CTD (-65)	21 from 3	44.056	39.018	6	ETW
			RTD (70)	21 from 3	42.535		6	
			ETW (250)	21 from 3	35.238	31.209	6	
		OHC	RTD (70)	21 from 3	44.484	40.343	6	ETW
			ETW (250)	21 from 3	32.389	28.248	6	
		FHT	CTD (-65)	21 from 3	50.295	46.363	6	ETW
			RTD (70)	21 from 3	49.558	44.626	6	
			ETW (250)	21 from 3	39.898	34.966	6	
		FHC	RTD (70)	21 from 3	61.954	56.352	6	ETW
			ETW (250)	21 from 3	41.262	35.66	6	
		UNT	CTD (-65)	21 from 3	71.302	64.693	6	ETW
			RTD (70)	21 from 3	67.633	61.023	6	
			ETW (250)	21 from 3	50.13	43.52	6	
		UNC	RTD (70)	21 from 3	72.33	63.044	6.737	ETW
			ETW (250)	21 from 3	43.957	38.76	6.204	
		SSB 2%	RTD (70)	21 from 3	134.738	122.062	6	ETW
			ETW (250)	21 from 3	101.082	88.406	6	
		SSB Ultimate	RTD (70)	21 from 3	161.861	146.052	6.359	ETW
			ETW (250)	21 from 3	120.367	104.558	6.046	
	50/40/10 [0/45/90/0/-45/0/45/0/-45]S	OHT	CTD (-65)	21 from 3	65.202	56.773	7.373	CTD
			RTD (70)	21 from 3	70.597	62.169	6.51	
			ETW (250)	21 from 3	86.585	78.192	6	
		OHC	RTD (70)	21 from 3	66.016	59.676	6	ETW
			ETW (250)	21 from 3	52.759	46.394	6	
		FHT	CTD (-65)	21 from 3	70.552		5.417	CTD
			RTD (70)	21 from 3	77.031	68.396	6.188	
			ETW (250)	21 from 3	83.001	74.401	6	
		FHC	RTD (70)	21 from 3	94.14	85.188	6	ETW
			ETW (250)	21 from 3	71.163	62.21	6.133	
		UNT	CTD (-65)	21 from 3	144.363	127.579	6.344	CTD
			RTD (70)	21 from 3	153.345	136.561	6.547	
			ETW (250)	21 from 3	164.899	148.115	6	
		UNC	RTD (70)	21 from 3	129.217	117.435	6	ETW
			ETW (250)	21 from 3	86.522	74.689	6	
		SSB 2%	RTD (70)	21 from 3	137.336	124.107	6.084	ETW
			ETW (250)	21 from 3	102.704	89.422	6.315	
		SSB Initial	RTD (70)	21 from 3	129.575	116.805	6	ETW
			ETW (250)	21 from 3	100.496	87.46	6.049	
		SSB Ultimate	RTD (70)	21 from 3	145.805	131.62	6	ETW
			ETW (250)	21 from 3	120.521	106.279	6	

		Tension	Compression	Bearing	Shear
Quasi	Mean Strength ECF	1.045	1.390	1.333	1.864
	Critical Condition	CTD	ETW	ETW	ETW
Soft	Mean Strength ECF	1.266	1.507	1.339	-
	Critical Condition	ETW	ETW	ETW	-
Hard	Mean Strength ECF	1.079	1.356	1.279	-
	Critical Condition	CTD	ETW	ETW	-

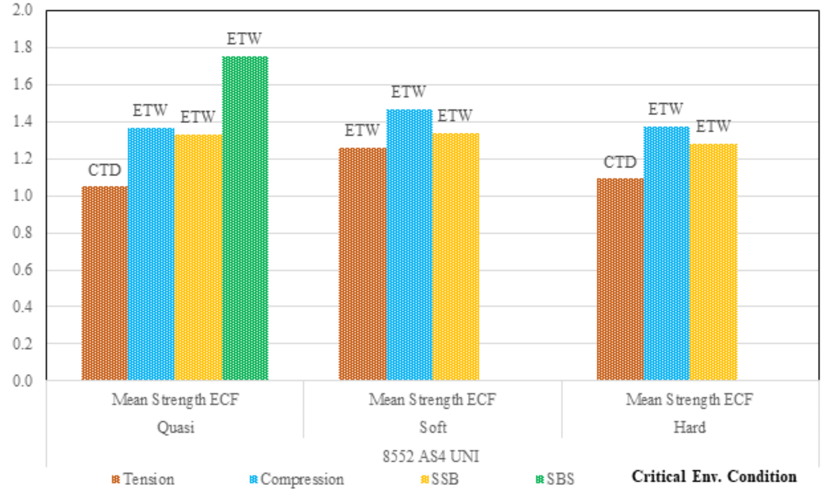


Coupon Level ECF Summaries

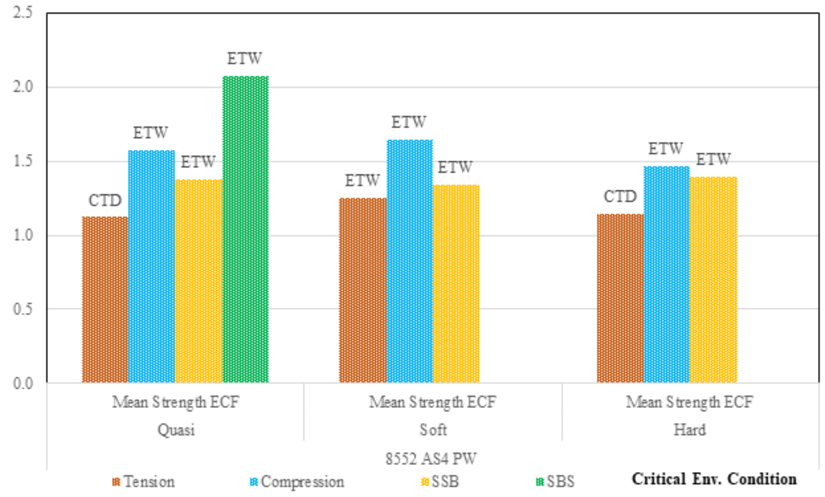
ECF Summary TC1225-UNI



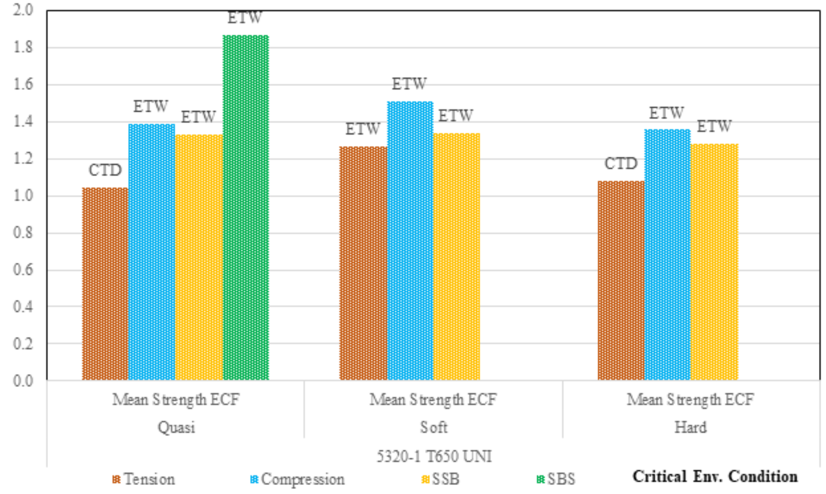
ECF Summary 8552 AS4-UNI



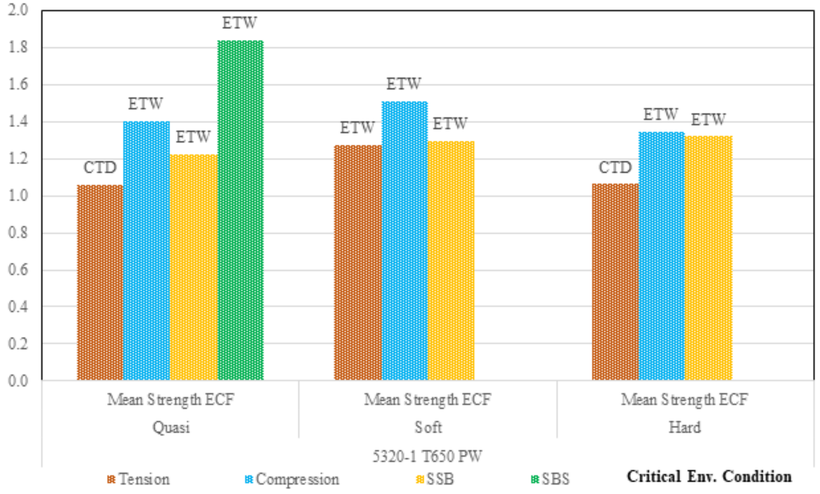
ECF Summary 8552 AS4-PW



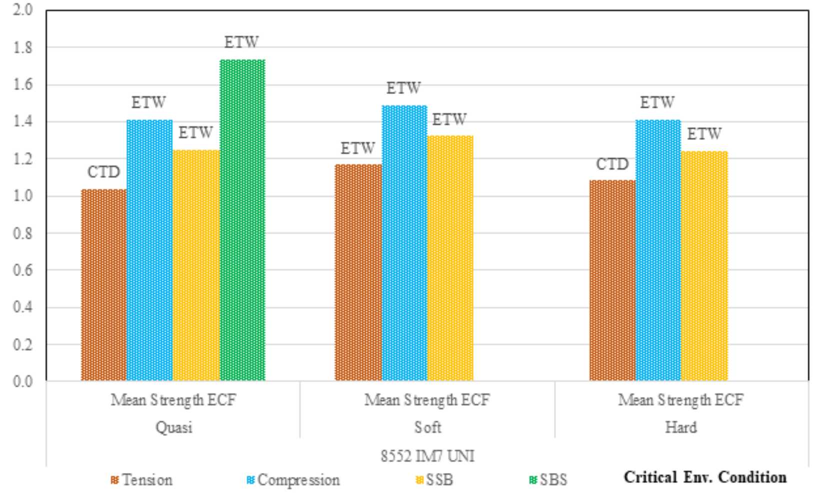
ECF Summary 5320-1 T650-UNI



ECF Summary 5320-1 T650-PW



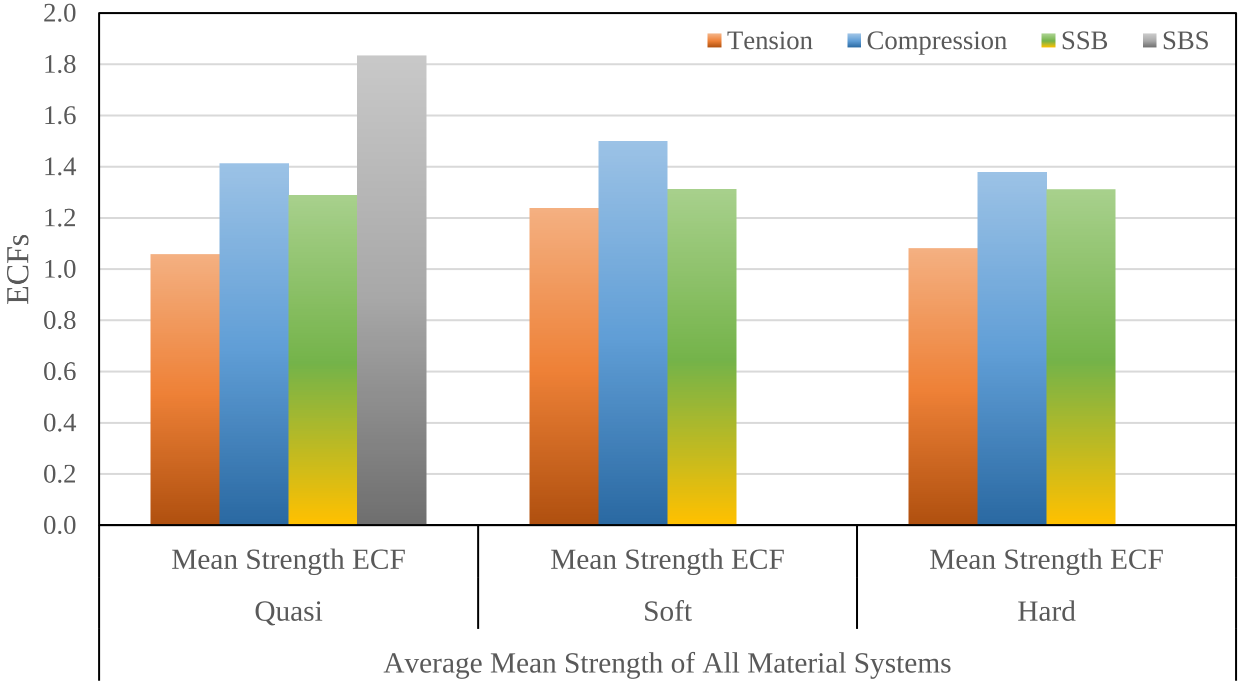
ECF Summary 8552 IM7-UNI

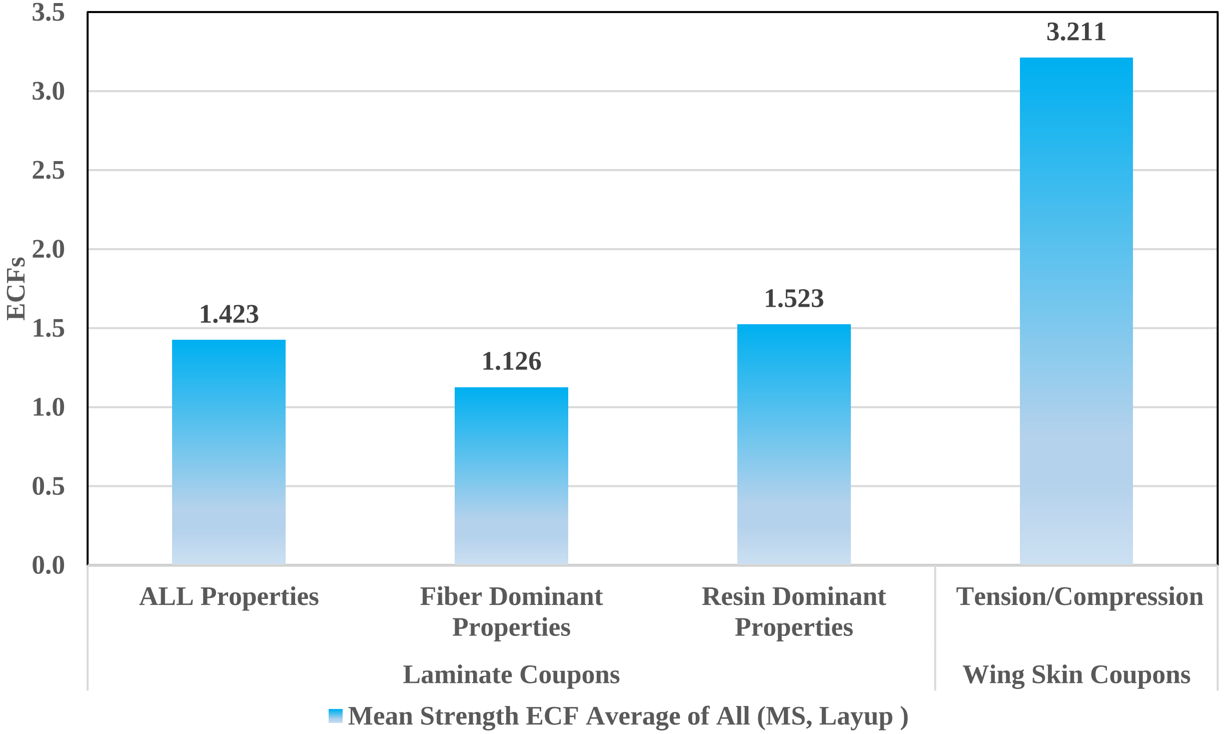


Overall Coupon Level ECF Summary and Comparison to Coupons Extracted from Wing Skin

		Tension	Compression	SSB	SBS
Quasi	Mean Strength ECF	1.057	1.403	1.224	1.840
Soft	Mean Strength ECF	1.273	1.510	1.292	-
Hard	Mean Strength ECF	1.063	1.344	1.319	-

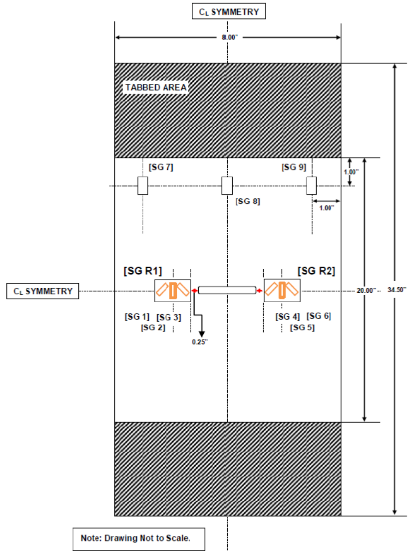
Test Method	Environmental Condition	Mean Load % DUL	ECF M/min(M)	Critical Condition
Wing Skin Tension/Compression	RTA	244	3.211	ETW
	ETW	76		

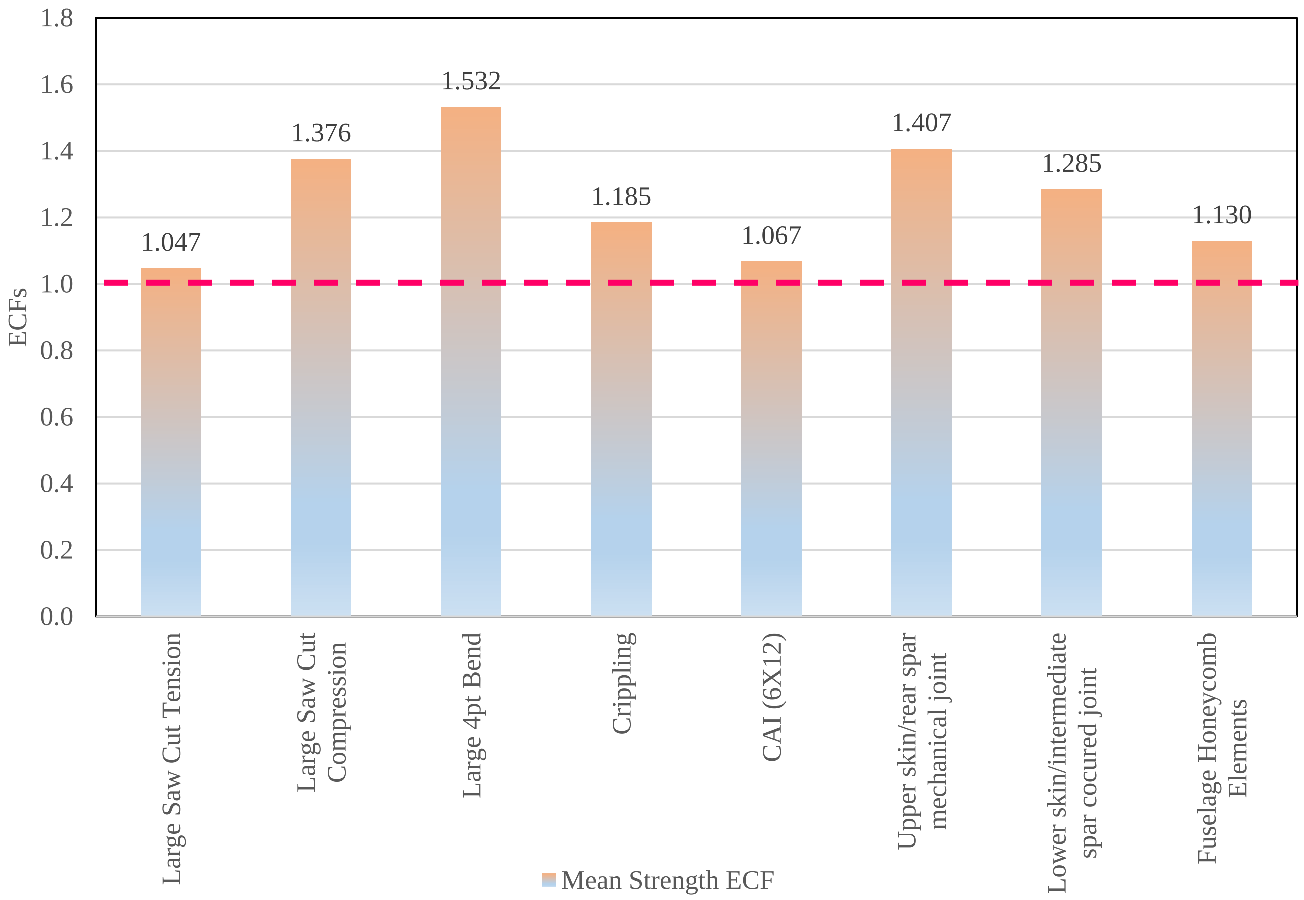


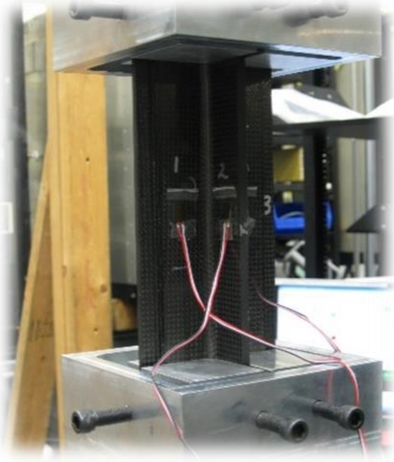


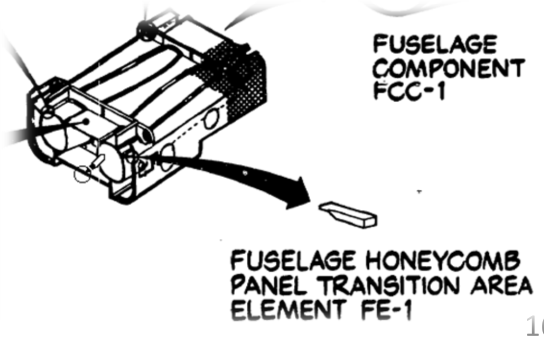
Element Level ECF Analysis

Test Method	Large Saw Cut Tension	Large Saw Cut Compression	Large 4pt Bend	Crippling	CAI (6X12)	Upper skin/rear spar mechanical joint	Lower skin/intermediate spar cocured joint	Fuselage Honeycomb Elements
ECF M/min(M)	1.047	1.376	1.532	1.185	1.067	**1.407**	**1.285**	**1.130**
							Overall Mean	**1.253**



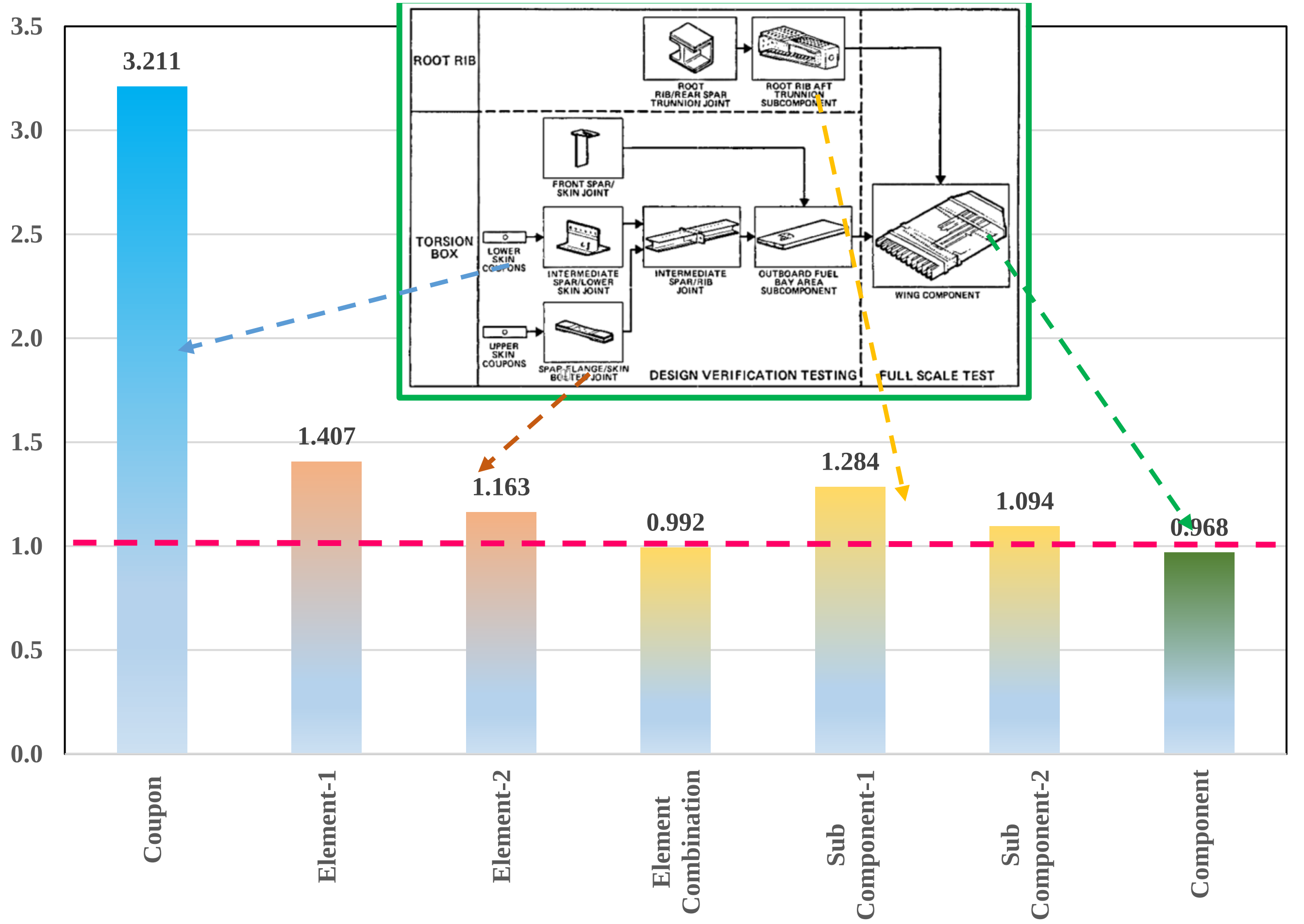




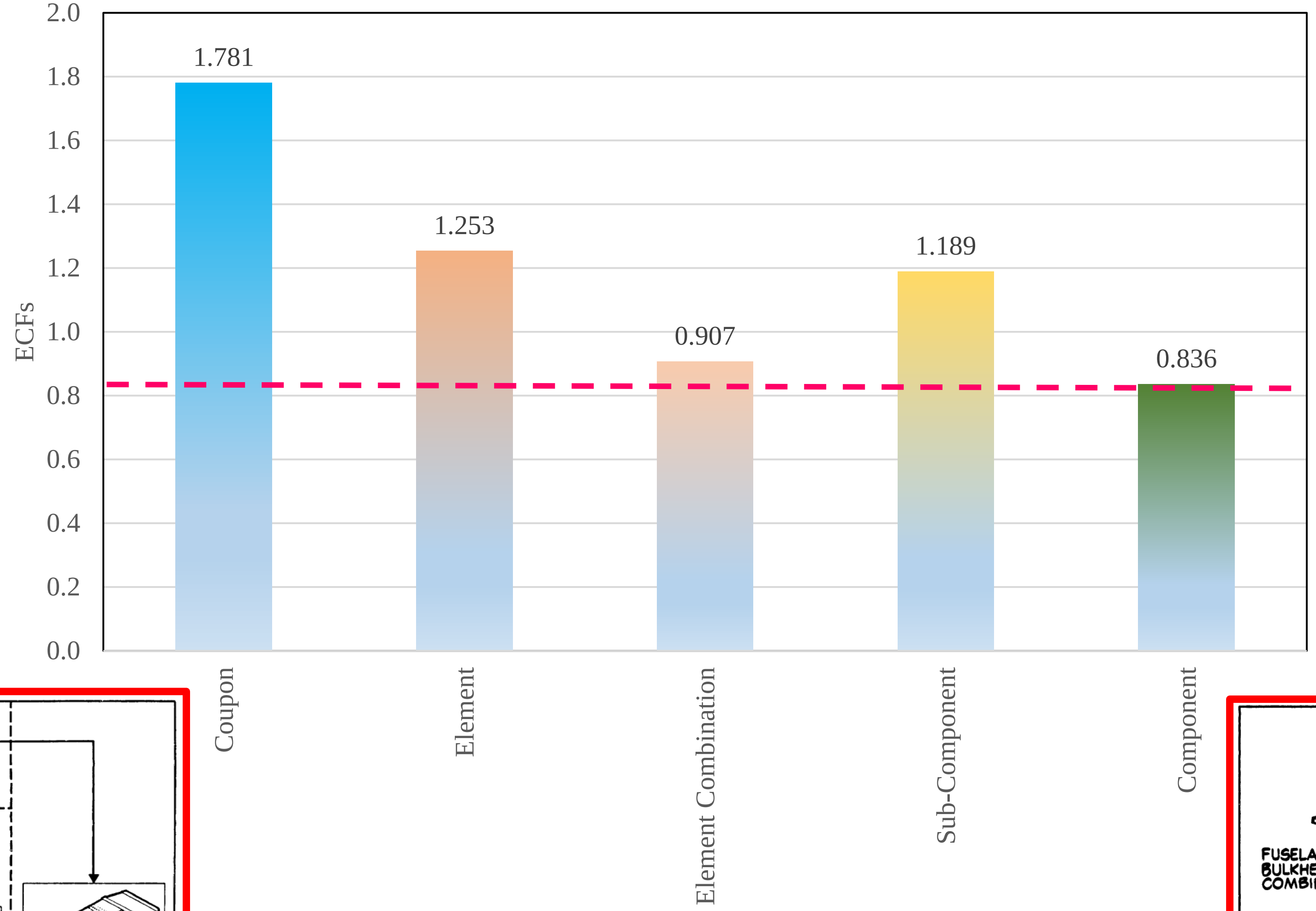


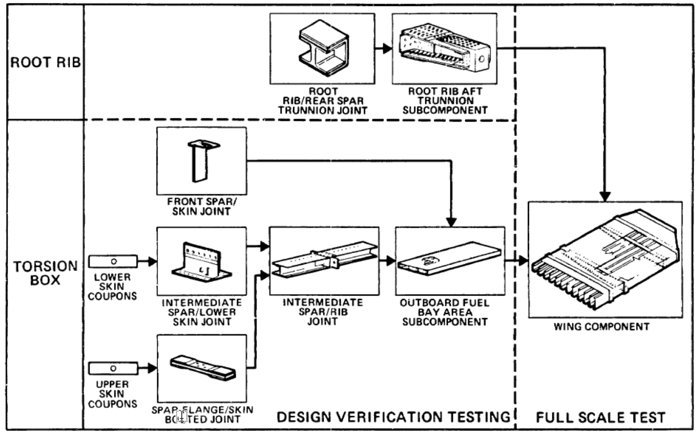
ECF Data Analysis for each Level of Building Block (Composite Wing Structure)

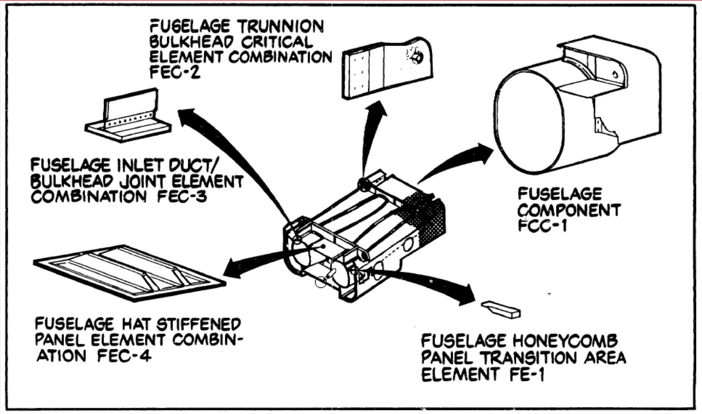
Complexity Level	Name	Description	Loading	Failure Modes	Failure Loads % DUL: RTA	Failure Loads % DUL: ETW	ECF
Coupon	Coupon	Wing skin coupon specimens	Tension/Compression	Net section at fastener hole	244	76	3.211
Element	Element-1	Upper skin/Rear spar mechanical joint	Compression load transfer	Fastener hole	173	123	1.407
	Element-2	Lower skin/Intermediate spar cocured joint	Combine shear/ Fuel pressure/ Chordwise loading	Spar web failure/ Fuel drain hole	186	160	1.163
Element Combination	Element Combination	Intermediate spar/Pylon rib transfer joint	Load transfer between spar and rib	Cocured joint/ Upper skin	128	129	0.992
Sub-Component	Sub Component-1	Three bay box beam	All the above	Upper skin/ Lower skin/ Cocured joint	131	102	1.284
	Sub Component-2	Highly loaded root rib/atf	All the above	Rib web	197	180	1.094
Component	Component	Wing component	all the above	Cocured joint/ Upper skin	122	126	0.968



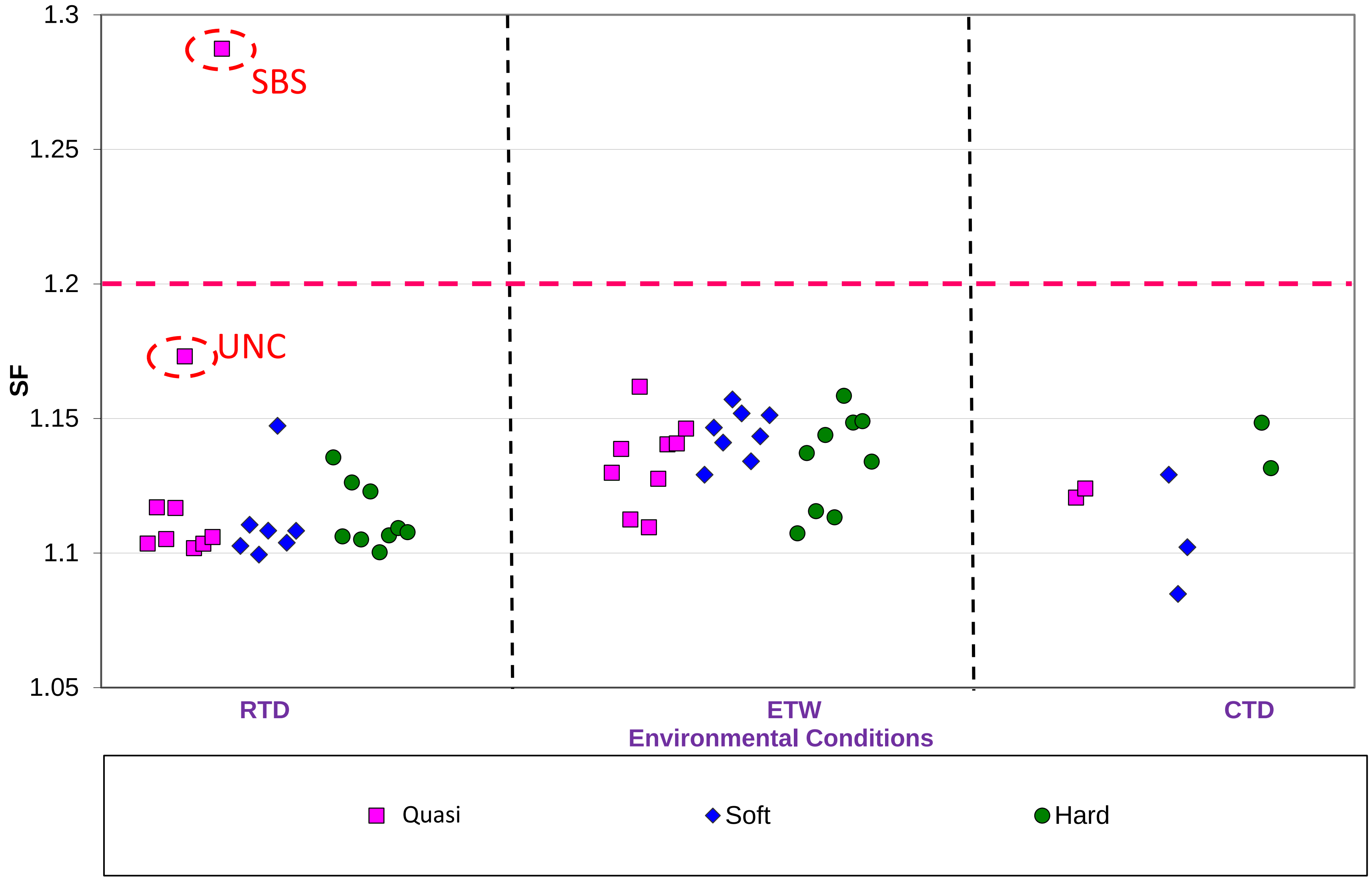
ECF Summary for each Level of Building Block





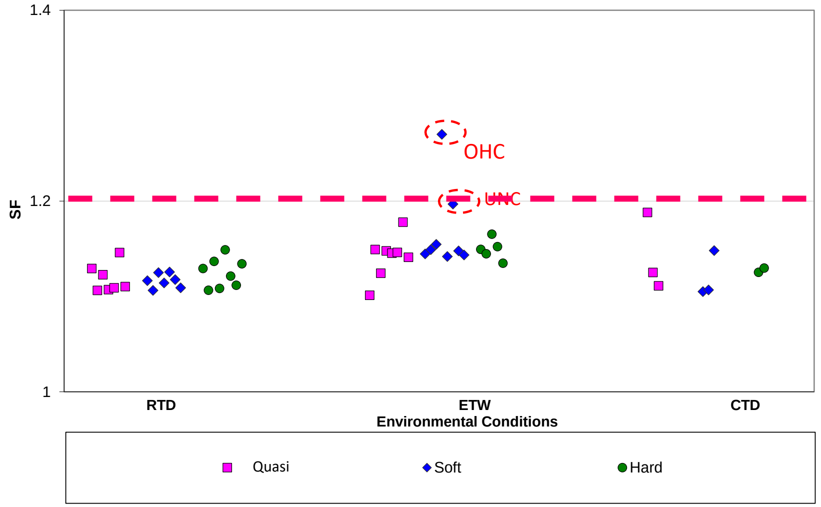


Coupon Level Scatter Factor Analysis *(5320-1 T650-UNI)*

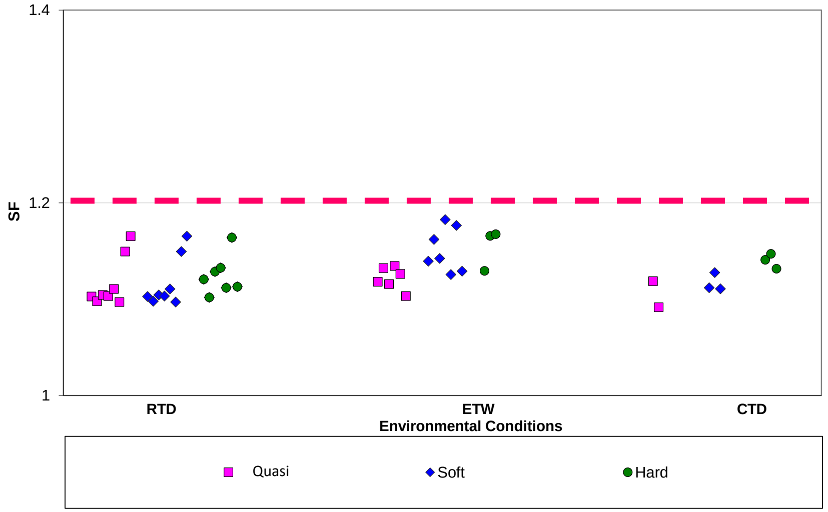


Coupon Level SF Summaries

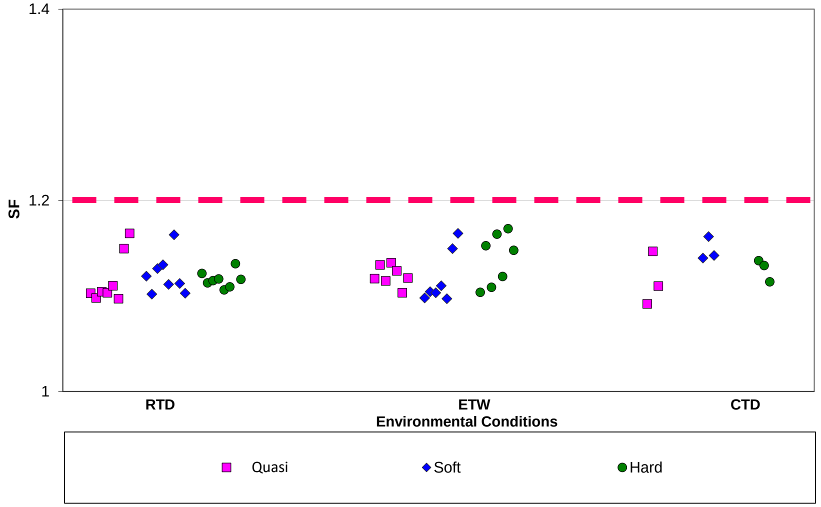
SF Summary TC1225-UNI



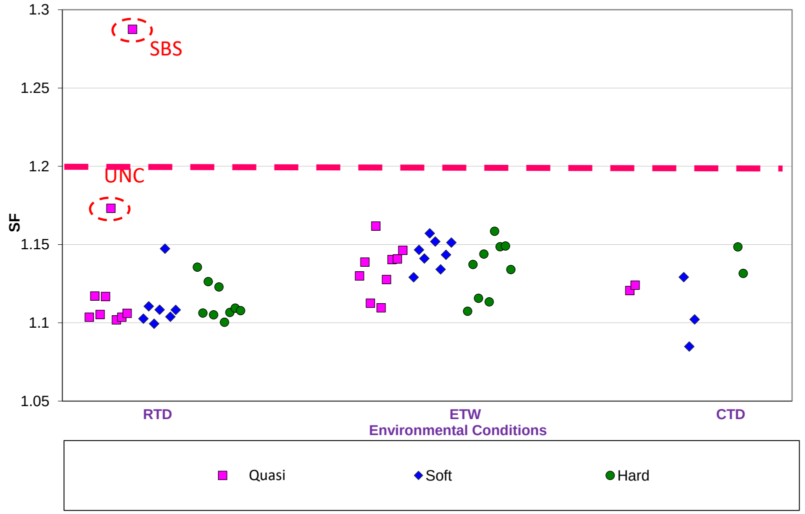
SF Summary 8552 AS4-UNI



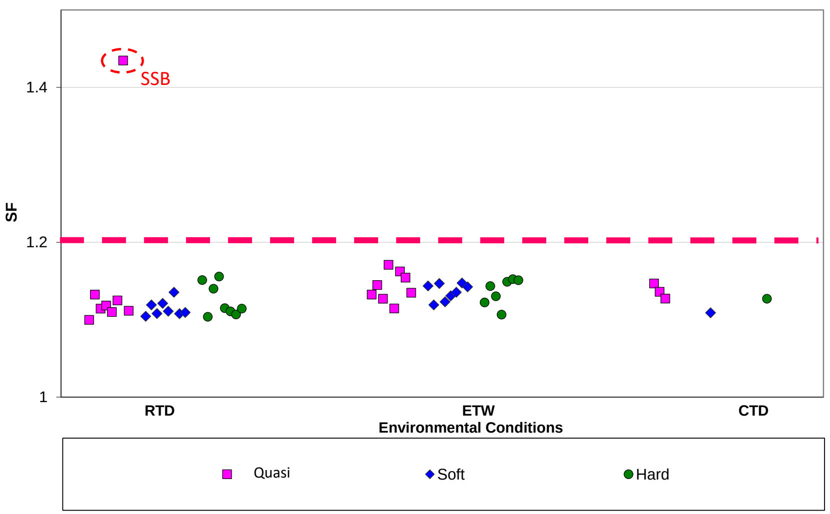
SF Summary 8552 AS4-PW



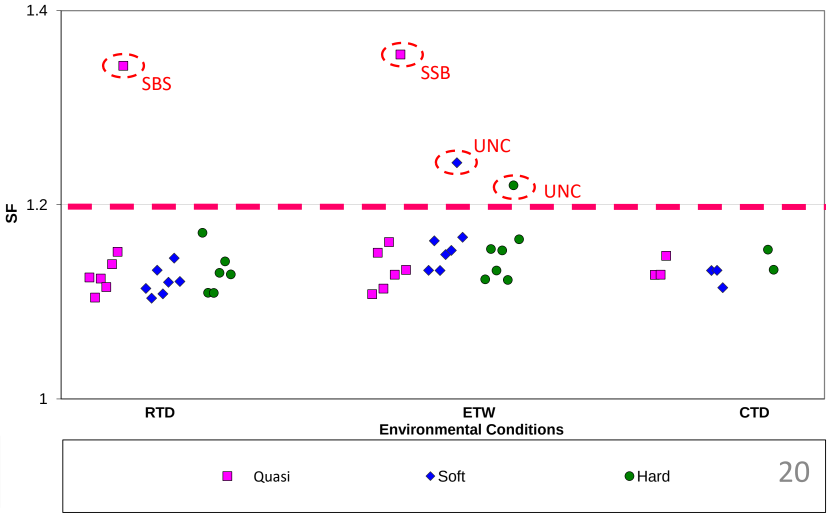
SF Summary 5320-1 T650-UNI



SF Summary 5320-1 T650-PW

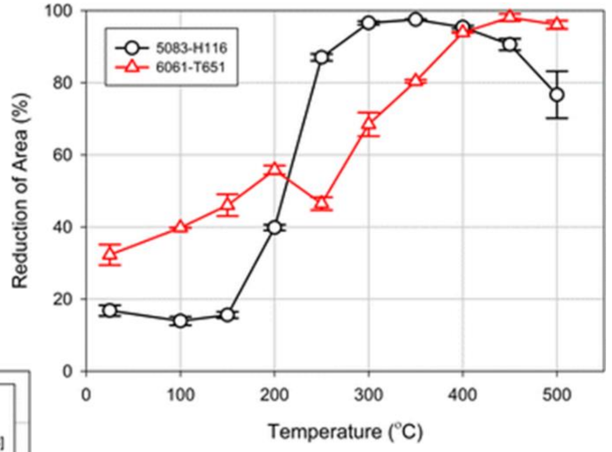


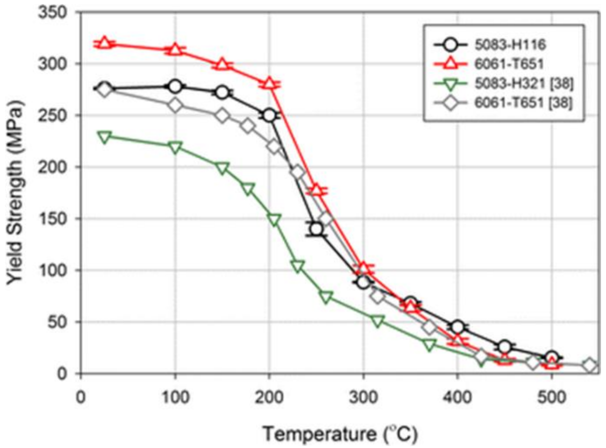
SF Summary 8552 IM7-UNI



Looking Forward / Future Work

- Benefit to Aviation
  - Generating guidance materials for development and application of Static Overload Factors
  - Better understanding of SOF is resulted in efficient composite structures
- Next Steps:
  - Continue literature survey on:
    - Metallic compensation factors used during substantiation process
    - Metallic and Composite industry standards
  - Guidance for SOF calculation and application





Contact & References

- Contact: Waruna Seneviratne (waruna@niar.wichita.edu)

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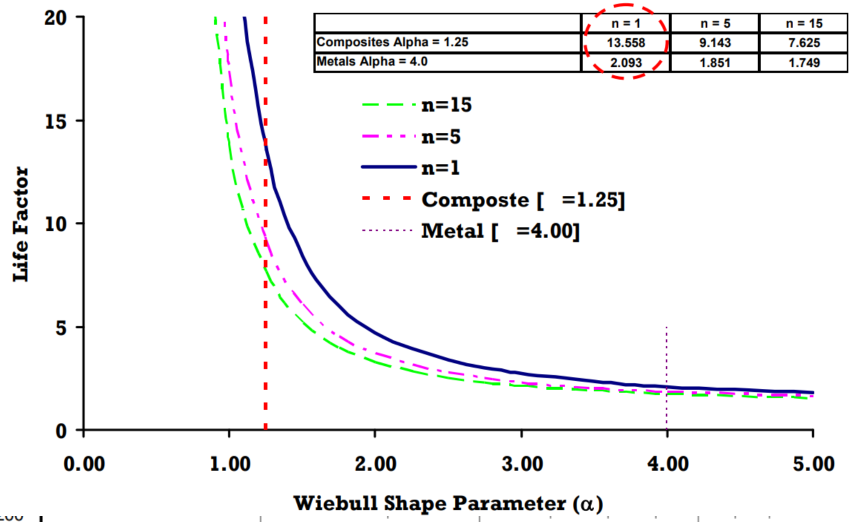
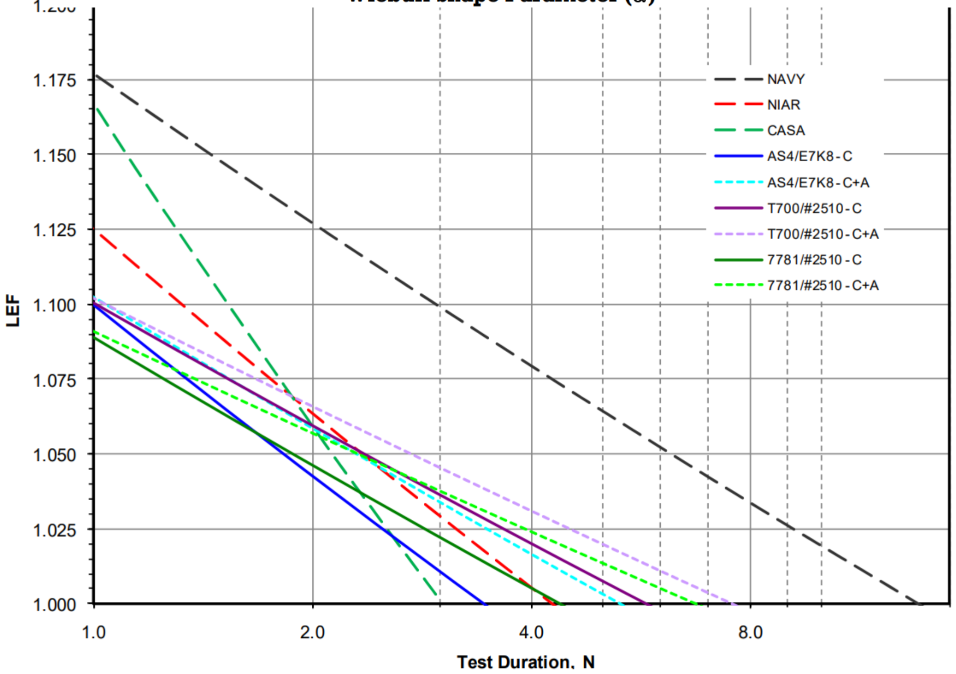
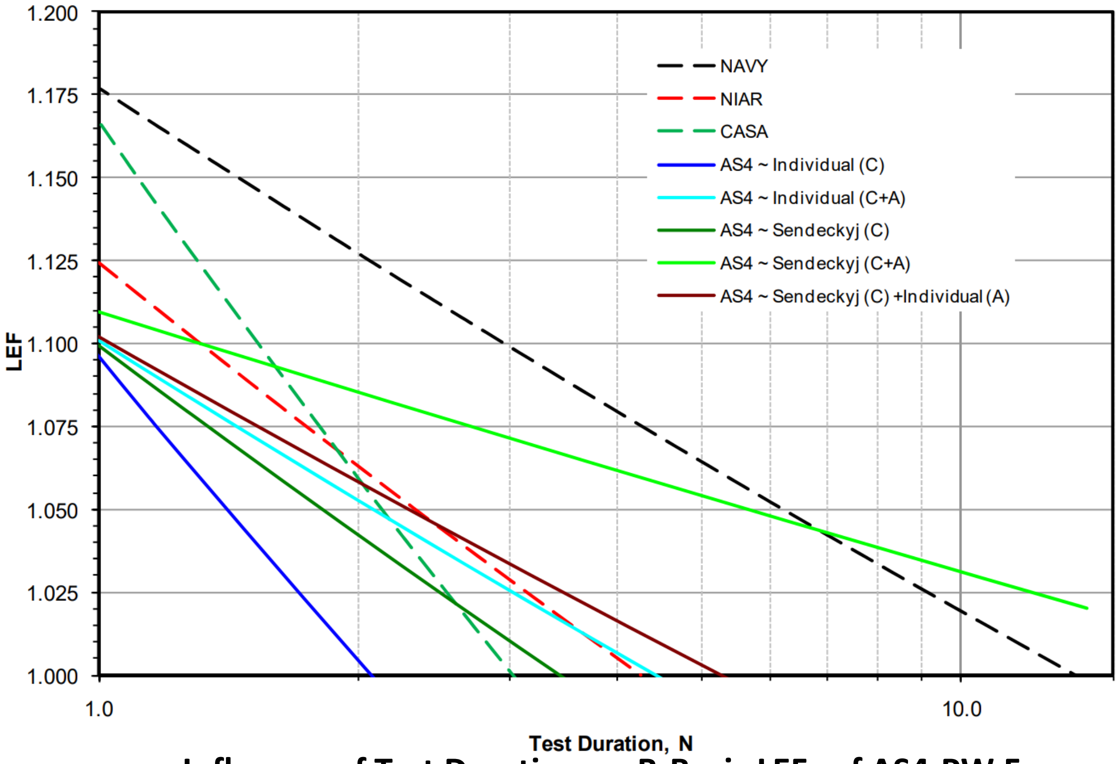
Fatigue LEF Approach Similar to SOF (FAA)



Analysis Method	α_L	N_F
Individual Weibull (C)	4.056	2.070
Individual Weibull (C+A)	2.082	4.418
Sendeckyj (C)	2.475	3.431
Sendeckyj (C+A)	1.021	26.296
Sendeckyj (C)+Individual Weibull (A)	1.880	5.267

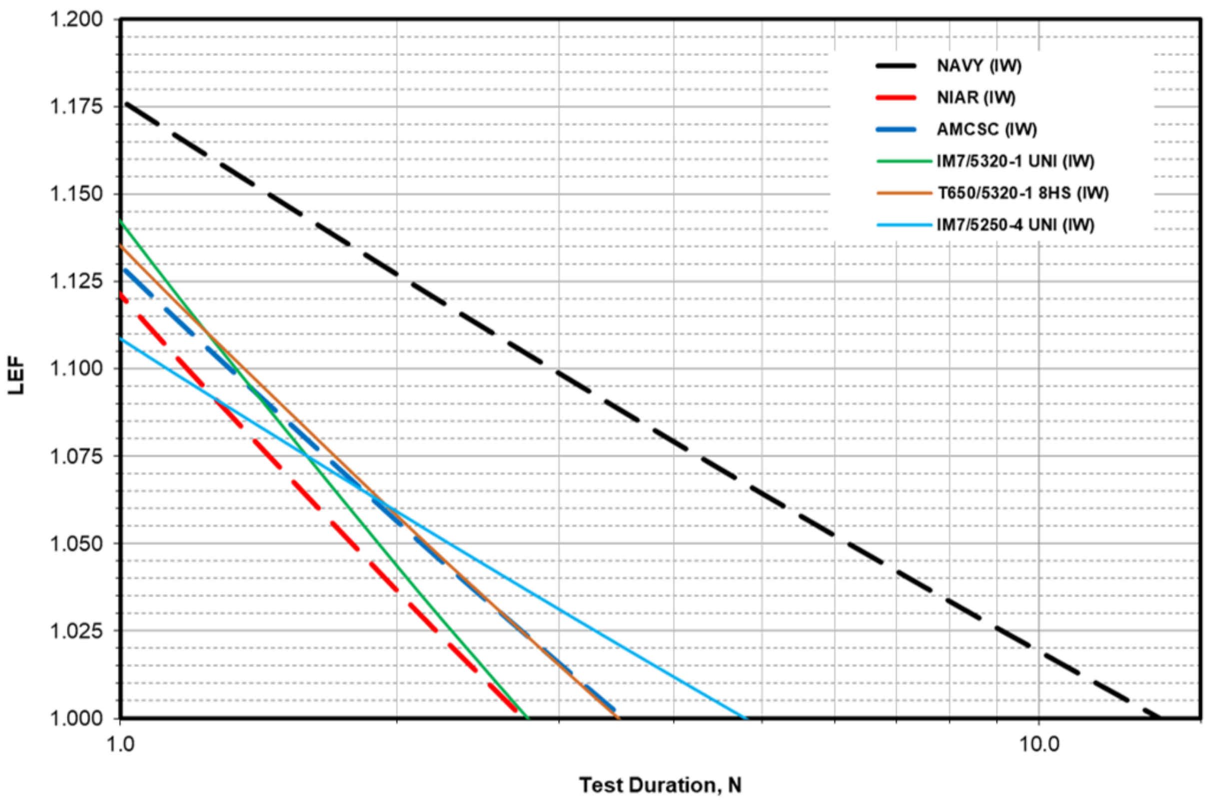


Influence of Test Duration on B-Basis LEFs for Different Materials

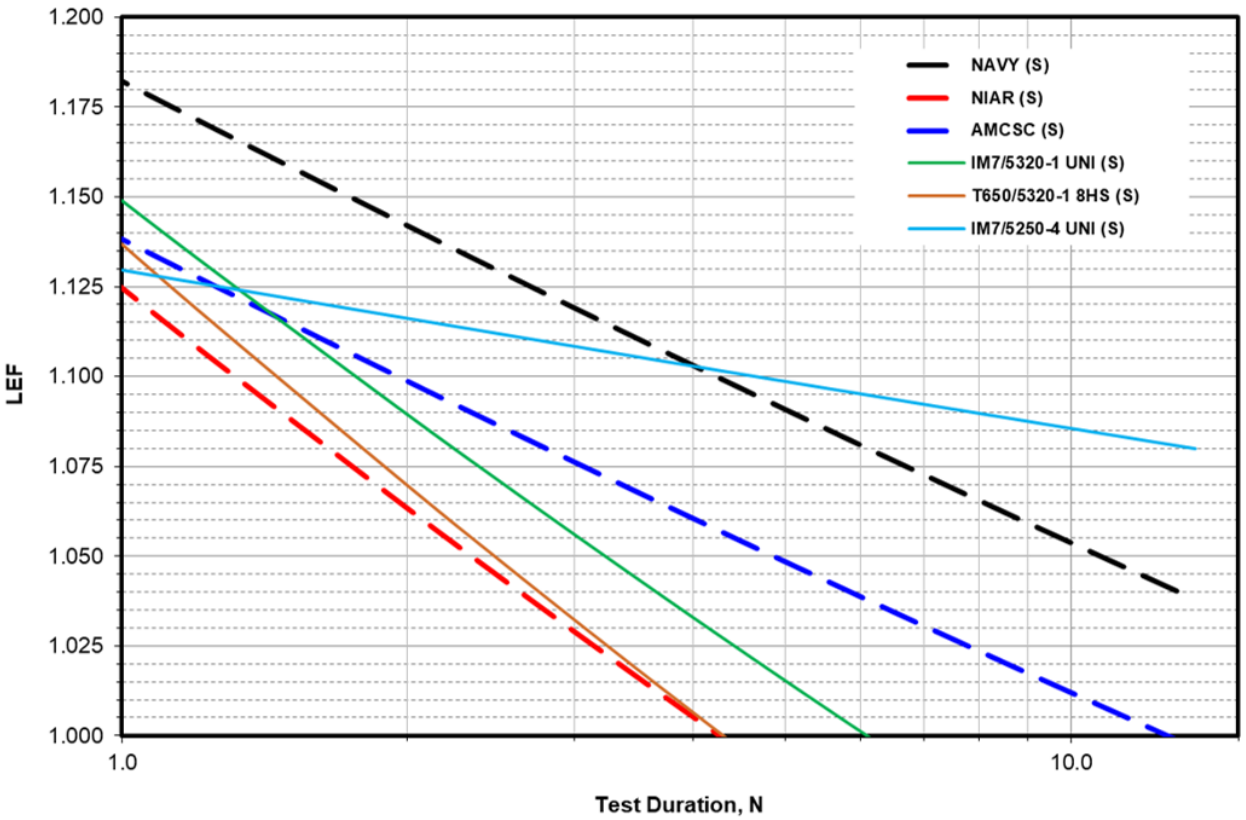


Influence of Test Duration on B-Basis LEFs of AS4-PW From Different Analytical Techniques

Fatigue LEF Approach Similar to SOF (MASC)



Individual Weibull (IW) analysis of SN data



Sendeckyj (S) analysis of SN data

Metallic Shape Parameters for Fatigue Data