Regulatory Considerations for RS, and ERSI' Scope and Charter

with excerpts from 2017 RS Summit Presentation

Presented at:

ERSI Workshop

April 3, 2024

San Antonio, TX

Presented by:

Michael Gorelik, PhD

FAA Chief Scientist and Technical Advisor

for Fatigue and Damage Tolerance

Disclaimer

The views presented in this talk are those of the author and should not be construed as official FAA position, rules interpretation or policy

System-Level View of F&DT Discipline
… *and related RS considerations*

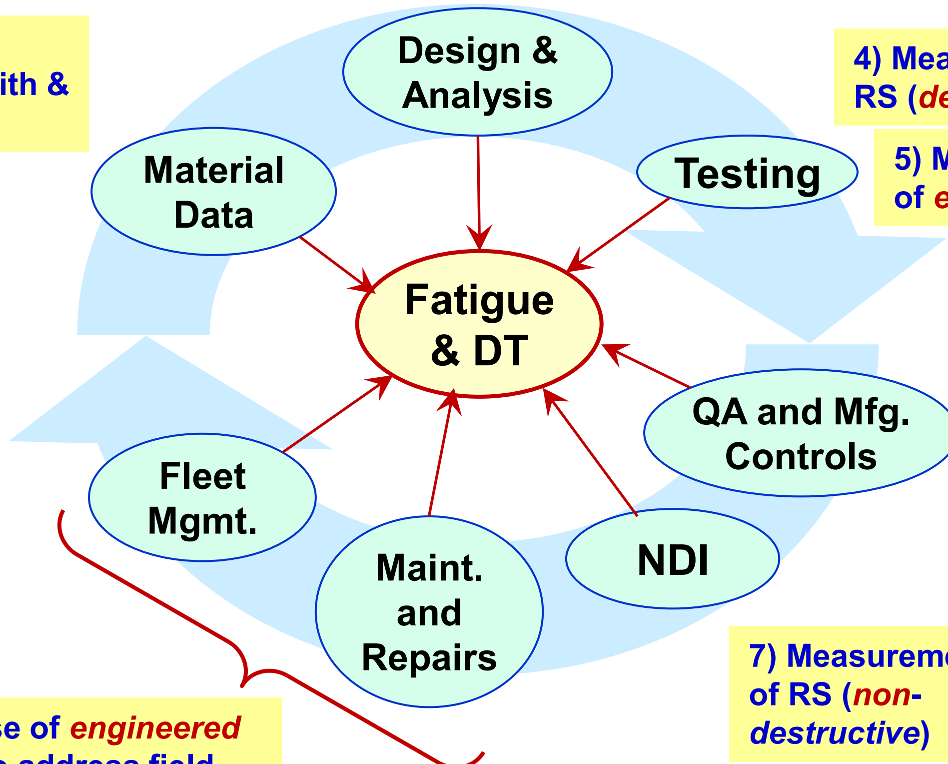
1) Material behavior with & without RS

2) Modeling of RS

3) Modeling of *effect* of RS

4) Measurement of RS (*destructive*)

5) Measurement of *effect* of RS



6a) Process Control – *Engineered RS*

6b) Process Control – *"Manufacturing" RS*

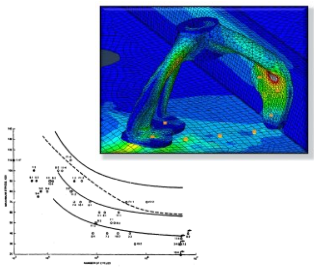
7) Measurement of RS (*non-destructive*)

8) Use of *engineered* RS to address field issues / life extension

All elements of the system are essential to ensure safety …

Life Predictions vs. Life Management

(a highly simplified view)



From Models to Airplanes

Crack Initiation Predictions → **Safe Life**

Crack Initiation Predictions ↔ ***Design Considerations***

Crack Propagation Predictions ↔ ***Design Considerations***

Crack Propagation Predictions → **Damage Tolerance**

- Manufacturing
- Airworthiness
- Design
- Testing
- Maintenance
- Repairs
- *Etc…*

Use of Fatigue and Fracture Models in Various Elements of LMS

(LMS - *Life Management System*)

Examples:

- **Damage tolerance (Part 25) – establishment of effective inspection / repair / modification plans**
- **Fatigue (Part 25) – reducing risk of design iterations and FSFT**
- **Fatigue (Part 33) – establishment of safe retirement limits**
- **Damage tolerance (Part 33) – supplemental design metric**
- **Flaw tolerance (Part 29) – a method to account for presence of flaws and damage**
- **Continued Operational Safety (COS) - total life assessment (*used as an input into risk assessment*)**
- **MRB (manufacturing review board) – disposition of manufacturing deviations**

Key Drivers

Refinement of Existing Lifing Methods

- **More accurate assessment**
- **Reduced level of conservatism**
- **Uncertainty reduction**

***Examples*:**

- Account of residual stresses
- More accurate fatigue and fracture prediction tools & methods (e.g. multiaxial fatigue, TMF, dwell fatigue, crack retardation, etc.)

"Lessons Learned" from Field Experience

- **New types of material or manufacturing defects *for existing materials***

***Examples*:**

- Undetectable near-surface machining damage
- New (or previously misunderstood) material anomalies
- Advanced failure mechanisms (e.g. cold dwell fatigue in Ti)
- SCC / EAC of high-strength *Al* alloys

Lifing Methods for New Materials or Manufacturing Processes

- **New types of material or manufacturing defects (failure modes) *for new materials***

***Examples*:**

- Additive Manufacturing
- Flow forming process
- LFW
- …

Excerpts from FAA Regulations *(relative to RS)*

Part 33 [*engine*]

- **Rules – *No references found***
- **AC 33.70-1 "Guidance Material for Aircraft Engine Life-Limited Parts Requirements"**
  - 8.b (7) (e) 2 [Damage Tolerance Assessment / surface damage monitoring] - Use beneficial *residual stresses* due to finishing processes, such as shot peening, if appropriate and if data supports the ability of the process to slow or suppress the growth of the damage.

Part 25 [*transport airplane*]

- **Rules / ACs - *No references found***
- **PS-ANM-25-22 "*Repair Deferral Limitations for Known Cracks*"**
  - 5.4.4 Preload and *residual stresses* in the structure should be well understood and accounted for in the analysis.

Part 29 [*transport rotorcraft*] – *No references found*

Part 23 [*general aviation*]

- **AC 23-13A "Fatigue, Fail-Safe, and Damage Tolerance Evaluation of Metallic Structure for Normal, Utility, Acrobatic, and Commuter Category Airplanes"**
  - This S-N data (*Appendix* 2) is applicable to conventional built-up aluminum structure with no fittings (other than continuous splice fittings), no parts with high *residual stresses*, …

Limited Guidance Relative to Residual Stress Considerations in Design and Fleet Management

Example of Legacy Practices

<u>Reference</u>: T. Swift, "*Fail-Safe Design Requirements and Features, Regulatory Requirements*", AIAA / ICAS International Air and Space Symposium and Exposition, Dayton, OH 2003 [https://arc.aiaa.org/doi/abs/10.2514/6.2003-2783].

"… If the fastener hole is cold expanded, the beneficial effects of *compressive residual stresses will retard the growth* of the standard 0.05" crack.

However, *accounting for the non-linear stress distributions in calculating stress intensity factors has been difficult*.

To avoid this complication an *equivalent initial crack size* of 0.005" has been used to conservatively account for the residual stress field.

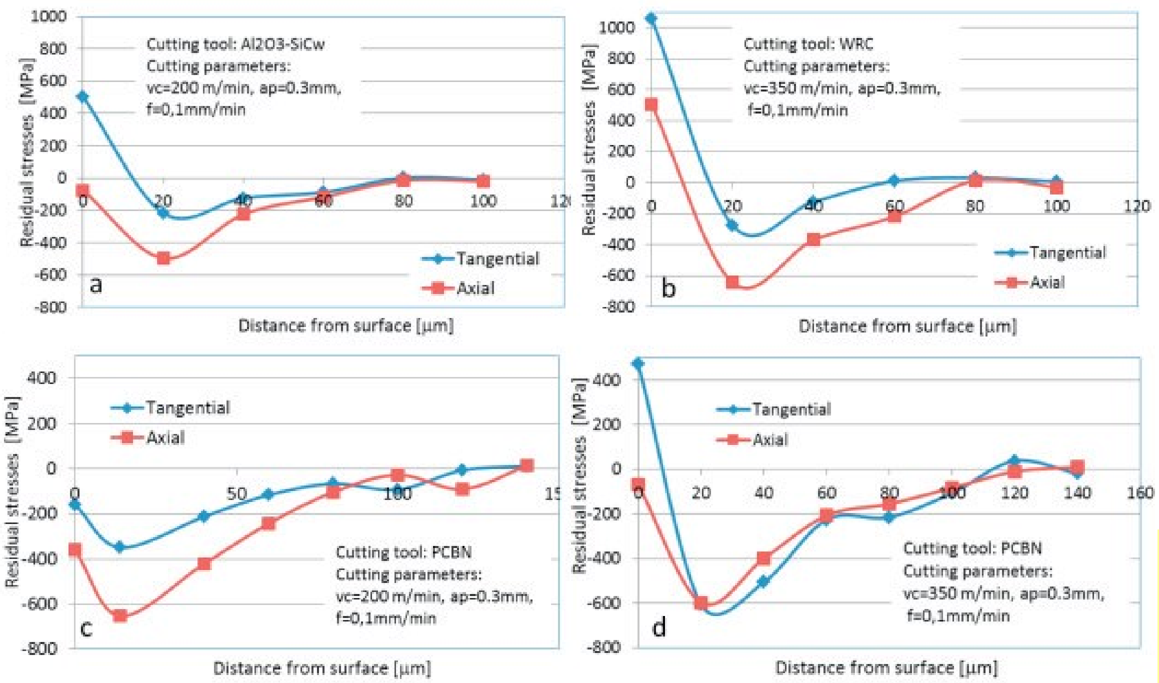
… An equivalent initial crack 0.03" radius has been used to simulate the effects of residual compressive stresses induced with machine driven fasteners …"

Industry Trends (*in RS context*)

- **Moving towards more aggressive design and manufacturing practices**
  - ***Faster, hotter, lighter, lower cost…***
- **Development of RS *measurement* technologies**
- **Development of RS *modeling* technologies**
- **Development of ICME frameworks**
- **Digital twin / digital thread**
- **…**

Residual Stress – Friend or Foe…

- ***Unfavorable*** **near-surface RS resulting from machining may significantly reduce component's LCF life (by 10x or more)…**

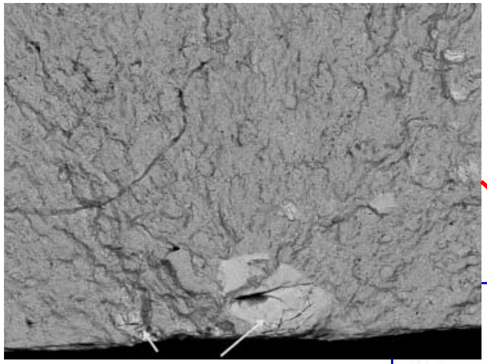


Challenge:
Magnitude (and even sign) of RS can be a function of:
- ***Cutting speed***
- ***Cutting tool / insert***
- ***Cutting direction***
- ***Etc.***

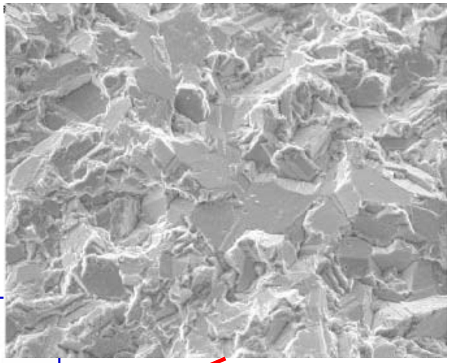
Reference: J. Zhou et al, "*Analysis of Subsurface Microstructure and Residual Stresses in Machined Inconel 718 with PCBN and Al2O3SiCw Tools*", 2014, Procedia CIRP, (13), 150-155.

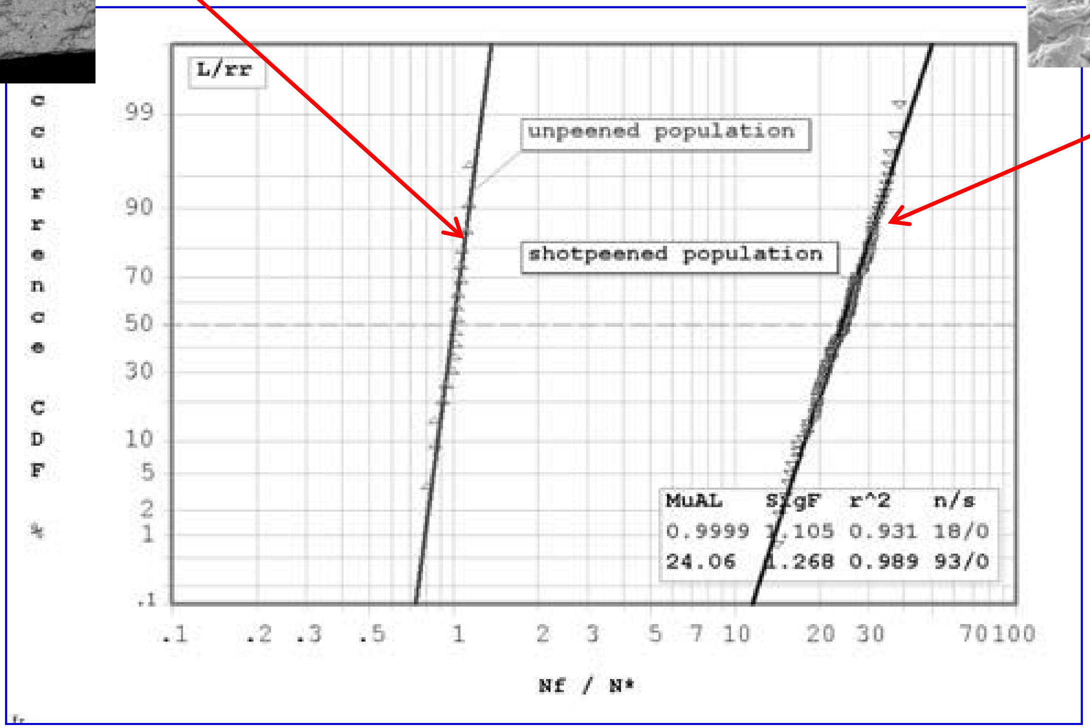
- ***Favorable*** **(machining-induced or engineered) RS may improve component's LCF life (by 10x or more) → *see next slide***

Example: Mitigating Effect of Material Inclusions with Shotpeening



Reference: M. Gorelik et al, "*Role of Quantitative NDE Techniques in Life Management of Gas Turbine Components*", GT2006-91337, Proceedings of TurboExpo 2006, Barcelona, Spain, May 8-11, 2006.

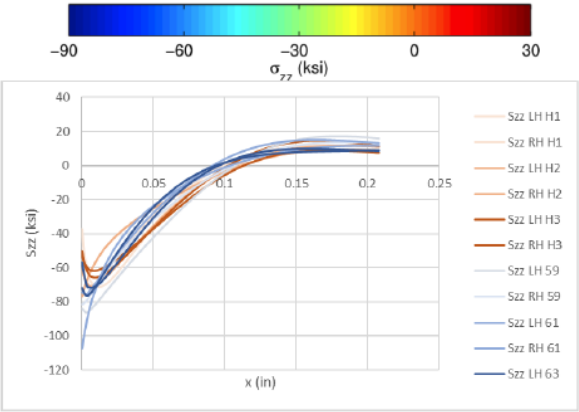




RS Measurement vs. Modeling

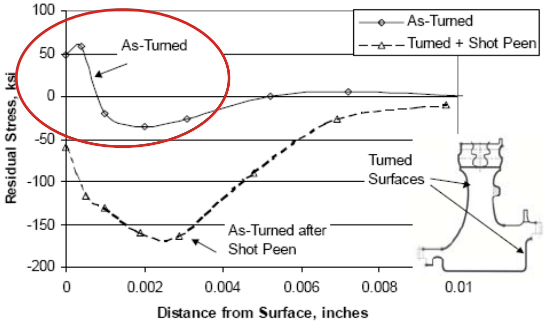
Measurement / modeling capabilities for beneficial *engineered residual stresses* continue to advance

Modeling Techniques



Unfavorable residual stresses *resulting from manufacturing process* may significantly reduce component's safe life (by 10x or more), as well as DT capabilities

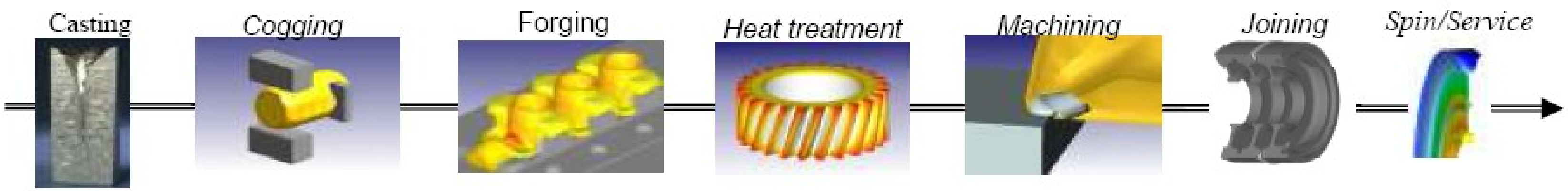
Measurement Techniques



Near surface residual stress gradient for a turned surface before and after shot peening.

Fatigue predictions (LCF) in the presence of RS in general represent a more significant challenge than DT assessment

Integration with Manufacturing
Process Simulation



Link DEFORM output with DARWIN input

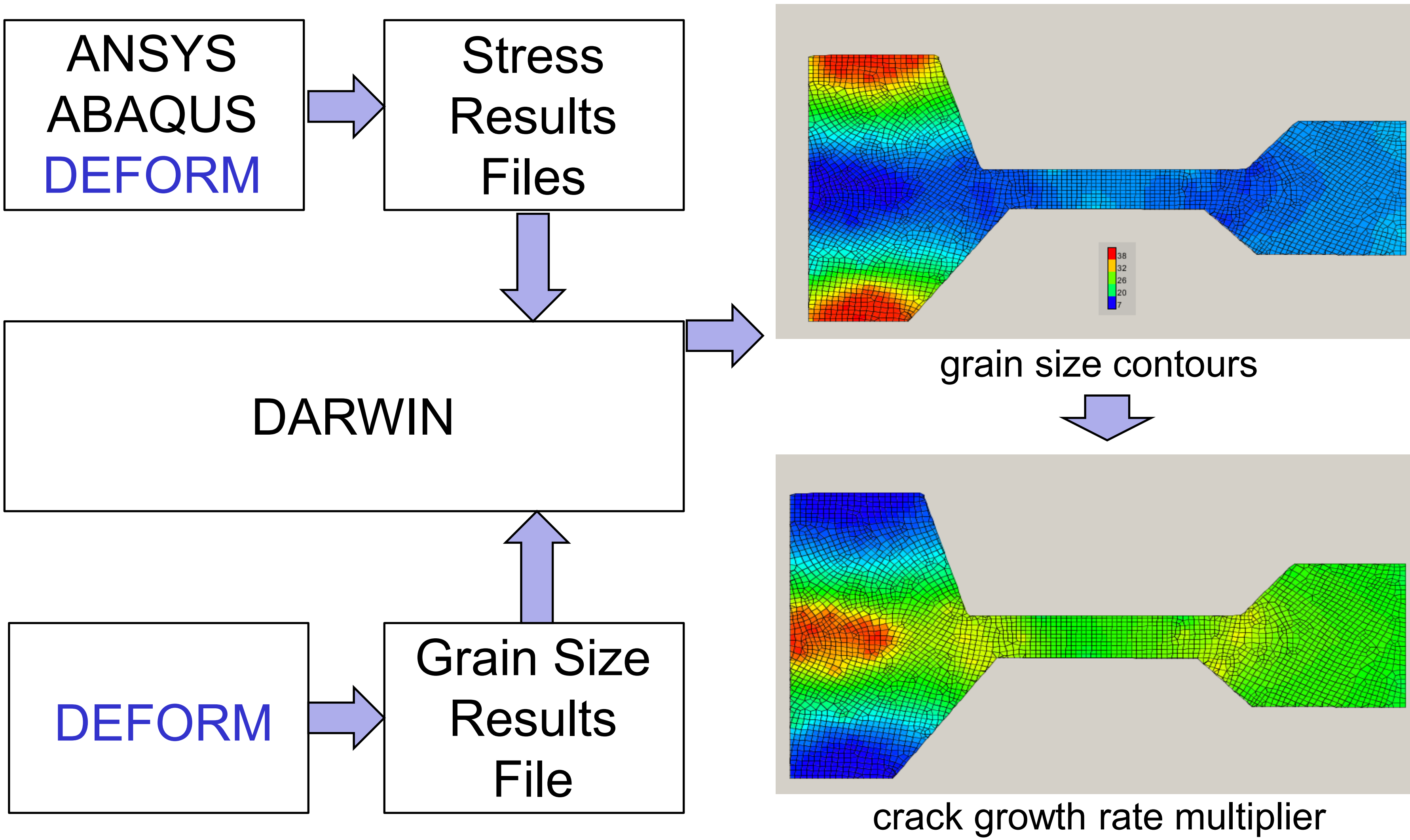
- Finite element geometry (nodes and elements)
- Finite element stress, temperature, and strain results
- Residual stresses at the end of processing / spin test
- Location specific microstructure / property data
- Tracked location and orientation of material anomalies

DEFORM™ → DARWIN

Design Environment for FORMing

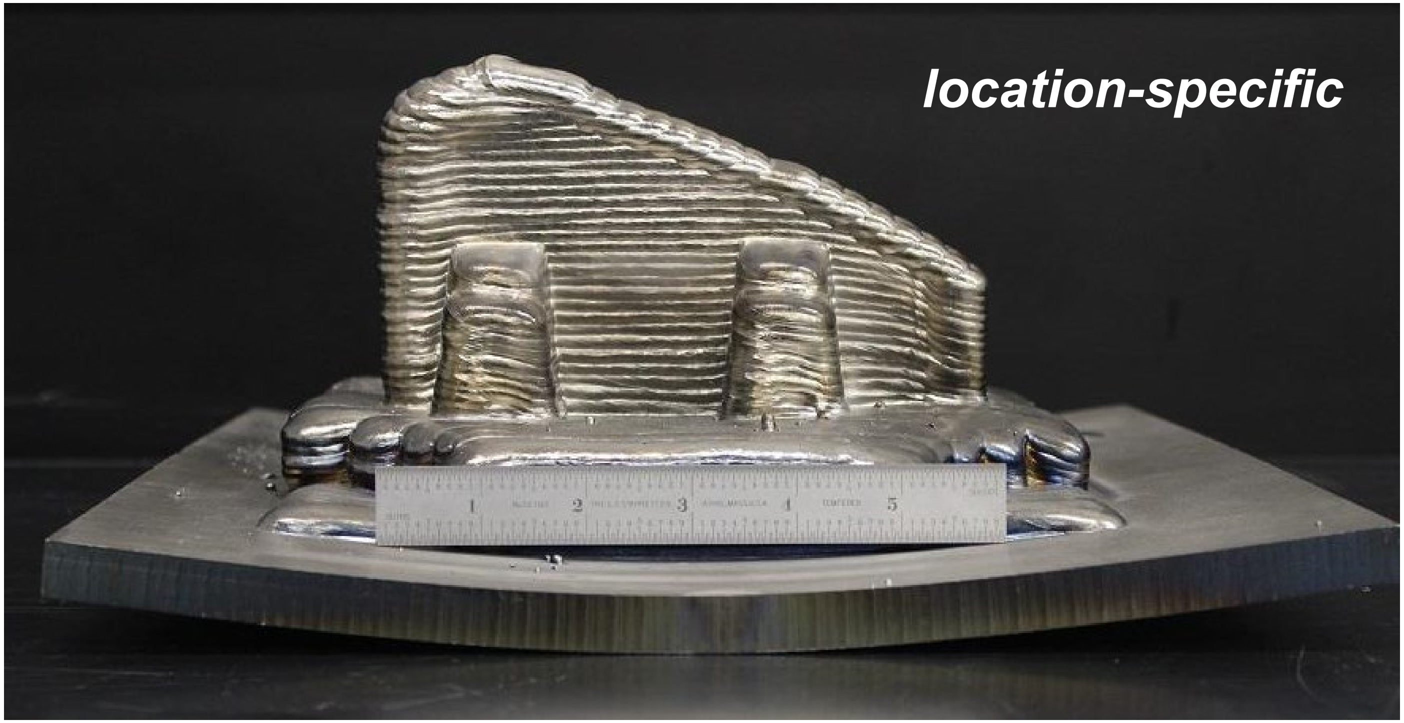
Reference: C. McClung, "*Structural Integrity Assessment for Aviation Parts with Inherent or Induced Material or Manufacturing Anomalies*", presented at the 2nd FAA – AFRL AM Workshop, Aug. 30-Sept. 1, 2016, Dayton, OH.

Influence of Location-Specific Residual Stress and Microstructure on Life & Risk



Reference: C. McClung, "***Structural Integrity Assessment for Aviation Parts with Inherent or Induced Material or Manufacturing Anomalies***", presented at the 2nd FAA – AFRL AM Workshop, Aug. 30-Sept. 1, 2016, Dayton, OH.

New Tech - RS in AM Parts

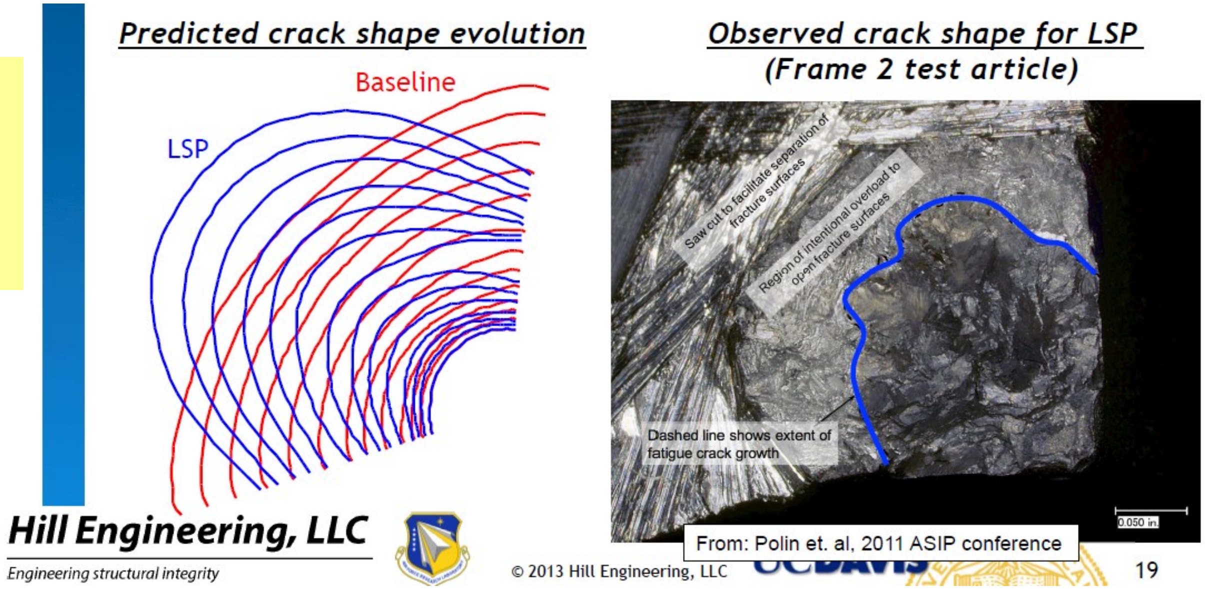


Crack Initiation (LCF)

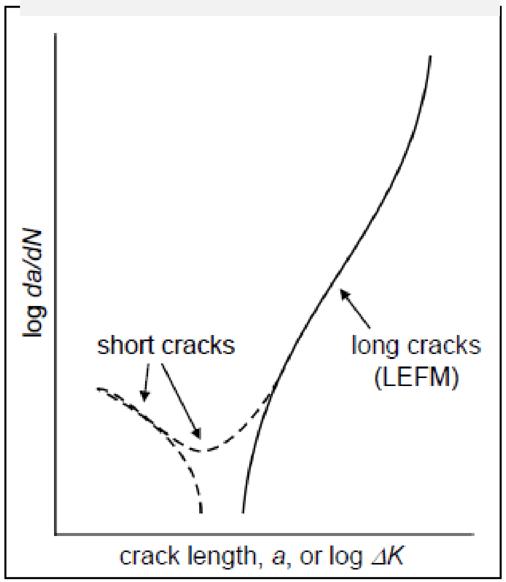
Crack Propagation (DT)

Fracture Mechanics Considerations

Reference: M. Hill et al, "*Correlation of 3D fatigue crack growth in residual stress bearing materials*", AFGROW Workshop, Sept. 10-11, 2013.

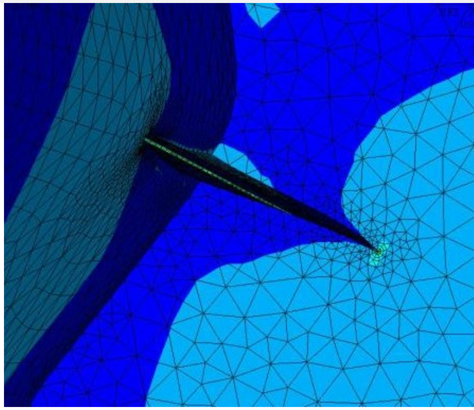


Short Crack Behavior



Complex geometries and stress fields, and small scales (e.g. near-surface RS gradients) require application of advanced Fracture Mechanics concepts *such as 3-D FM and short crack behavior*.

3D Fracture Mechanics



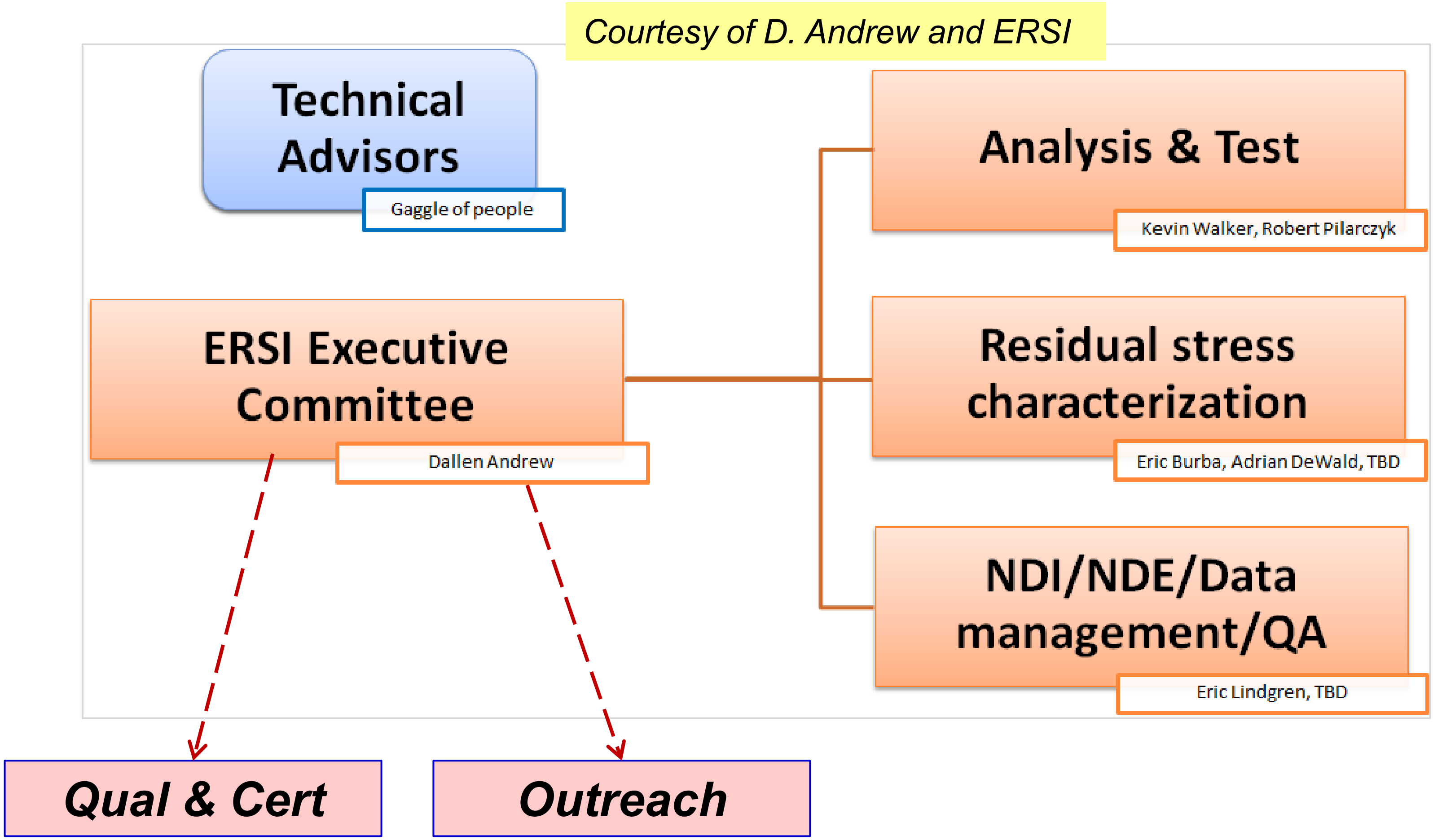
Fracture Mechanics Considerations (cont.)

- **Accurate fracture mechanics analysis (in the absence of RS) is a highly complex discipline that has many attributes, including (*but not limited to*) –**
  - ***Account of 3-D stress state***
  - ***Account of elastic-plastic material behavior***
  - ***Hold time effects***
  - ***Peak overload effects***
  - ***Complex 3-D part geometry and 3-D crack geometry / path***
  - ***Small crack behavior***

A "challenge" question –

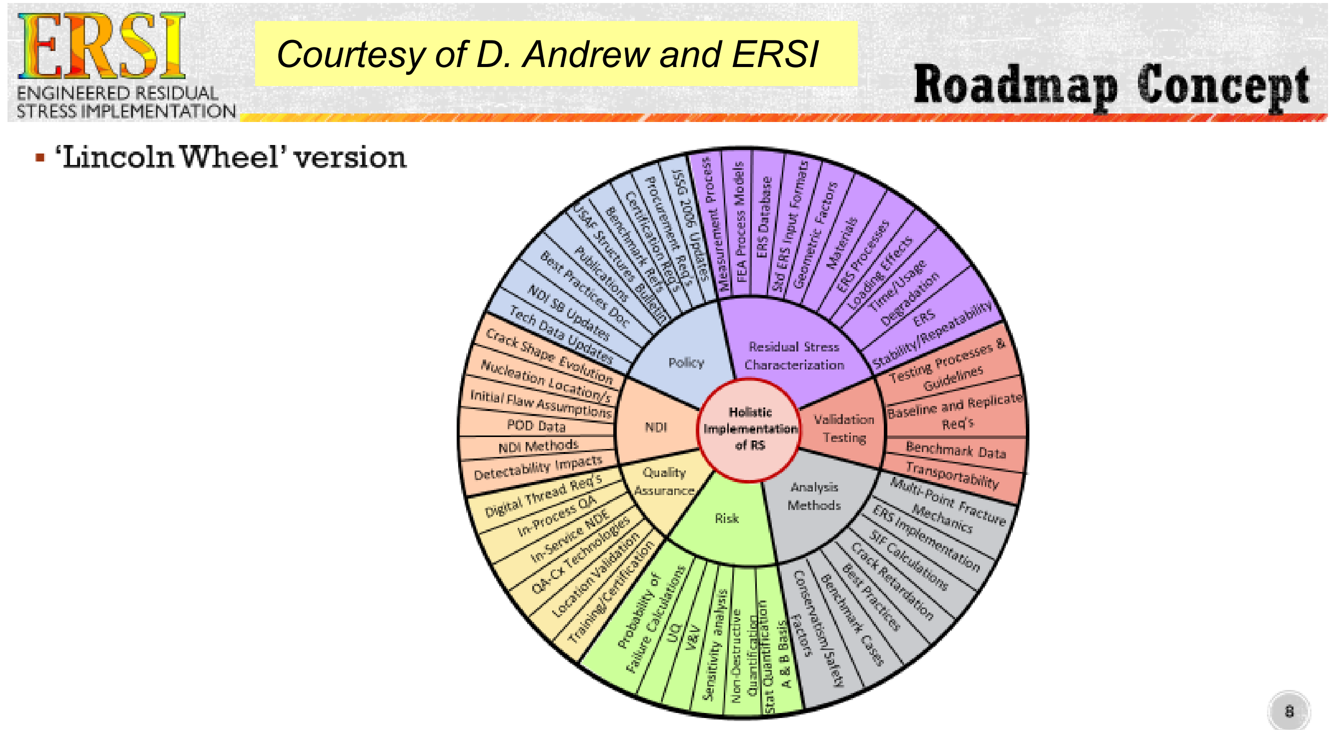
➢ ***Can we define a simplified FM framework that can be used to characterize the key beneficial effects of residual stresses as a "figure of merit" that can be linked to meaningful design or certification criteria***
  - **Note: have examples of successful applications from other F&DT areas**

Potential Expansion of the ERSI Structure



Regulatory Considerations

Roadmap Considerations

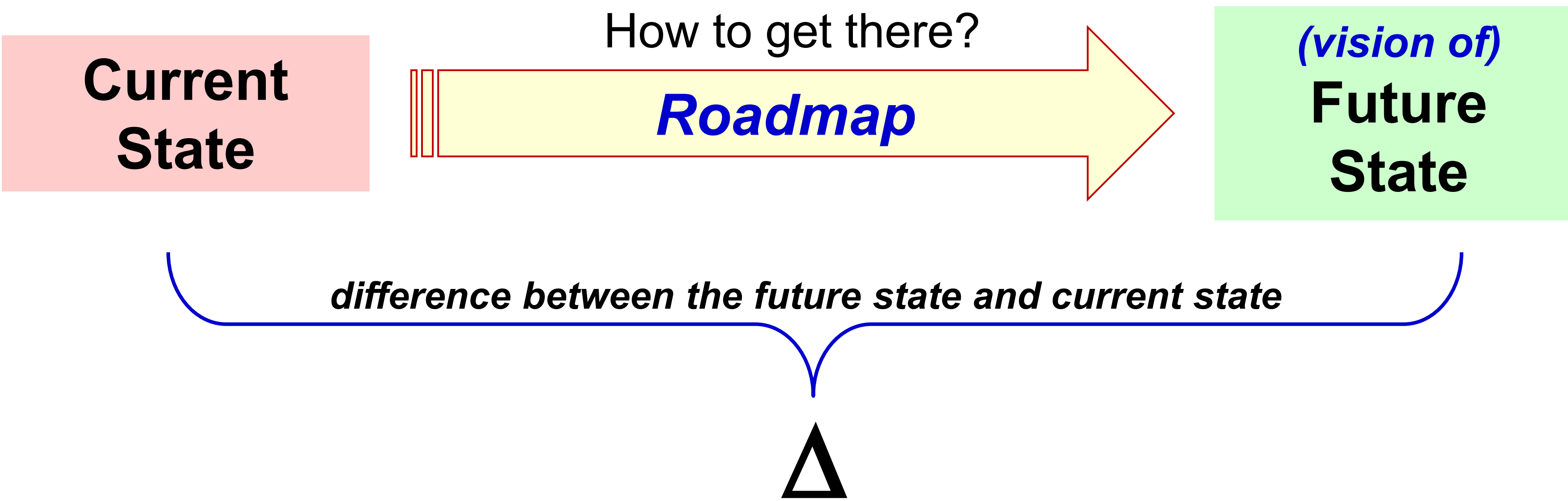


- **A very thorough list of relevant categories**
- **However, does not provide the current status or prioritization considerations for implementation**

Roadmap Considerations (cont.)

"Roadmap" means different things to different people

One interpretation →



ERSI – *Future* Scope Considerations

- **Military vs. Civil Aviation (?)**
- **Product types – airframe structures / propulsion systems / rotorcrafts / … (?)**
- **Engineered vs. manufacturing-induced (?)**
- **For engineered RS – type of technology (?)**
  - **Cx of holes / shot peening / LPB / LSP / …**
- **Primary use (?)**
  - More accurate life prediction / credits
  - Safety enhancements
  - Part of manufacturing QA
  - *Other..?*

Discussion…

Michael Gorelik, PhD, PMP

Chief Scientist, *Fatigue and Damage Tolerance*

Aviation Safety

Federal Aviation Administration

michael.gorelik@faa.gov