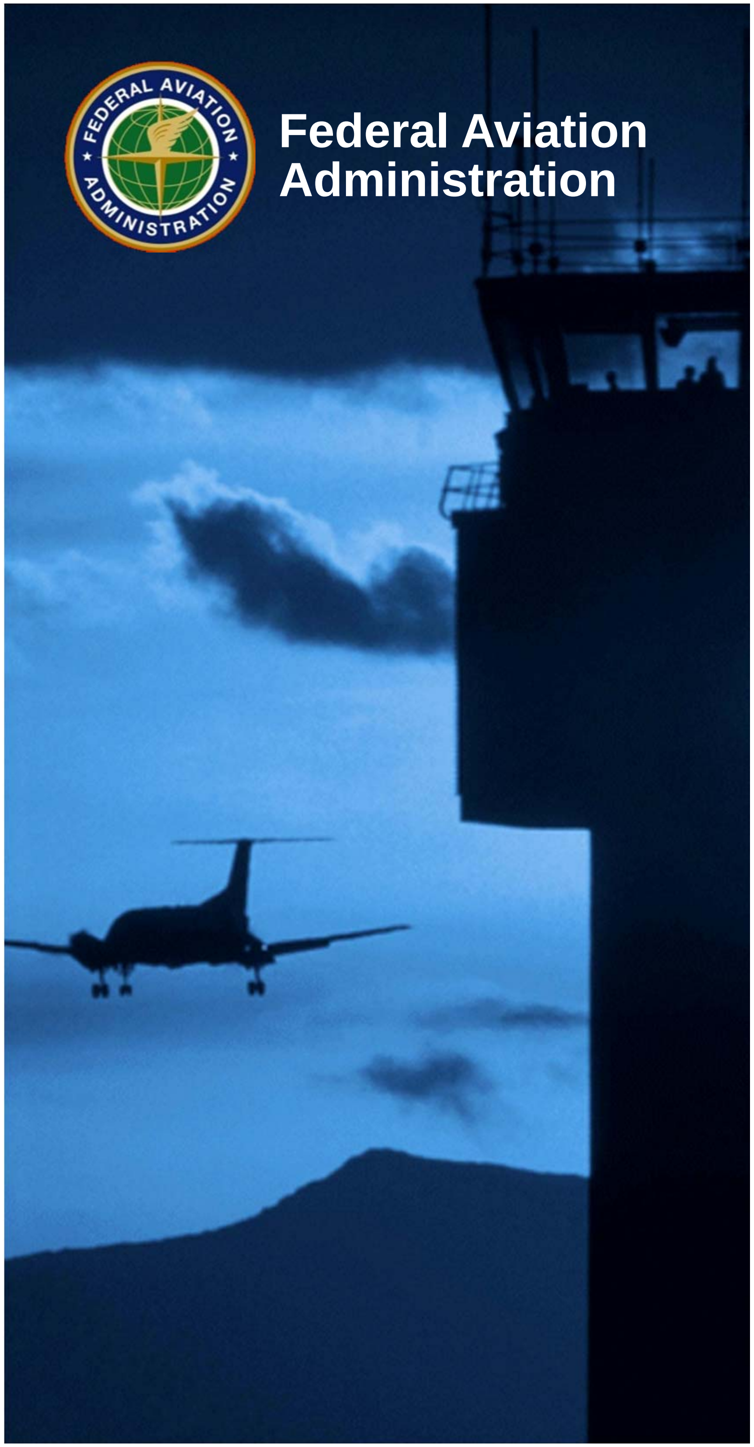
Non-Linear Modeling for Turbine Engine Impact Events



Presented to: FAA Analytical Methods in Aircraft Certification Workshop
Blacksburg, VA

By: Chip Queitzsch
FAA Chief Scientist for Engine Dynamics

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Agenda

- **33.94 Fan Blade Out regulation and where analysis fits**
- **Material modeling research to support non-linear dynamic analysis models**
- **Application examples**
  - UEDDAM fragment barrier modeling
  - FBO blade containment modeling study
  - Open Rotor program test and analysis

33.94 FBO Regulation
and
Where Analysis Fits

What do the 33.94 Blade Containment and Rotor Unbalance tests require?

"it must be **demonstrated by engine tests** that the engine is capable of ***containing damage without catching fire*** and ***without failure of its mounting attachments*** when ***operated for at least 15 seconds***, …….

(1) Failure of the most critical compressor or fan blade while operating at maximum permissible r.p.m. ………"

<u>The rule is prescriptive</u>

When can Analysis be used to supplement 33.94 test compliance?

- **Post 33.94 certification test to fix test shortfalls**
- **With major and minor design changes in the same engine model:**
  - **Mount changes**
  - **Accessory changes**
  - **Casing, rotor, or plumbing changes**
- **With derivative engine models (amended TC's):**
  - **Modified containment**
  - **New fan section**
- **Analysis has not been accepted for containment**
  - **Supplemental fan rig test used to demonstrate containment**

FAA Policy Developed for Analysis Use

- **The policy ANE-2006-33.94-2 provides structured method to use when applying analysis**
- **Limitations:**
  - **Analysis is only permitted for a derivative engine from a baseline engine that has undergone 33.94 certification testing**
  - **Analysis use is permitted on a case by case basis**
  - **Analysis methods must be validated**

Validation should be tied to the parent engine FBO certification test, other relevant experience can support validation demonstration

Preparing to use analysis in certification

Ideally, the applicant has:

- Performed a number of previous FBO tests
  - Has experience with success, failure, and design changes
- Performed significant analysis preparing for previous FBO tests
  - Understands event details and how to mitigate risk in tests
- Included significant instrumentation on previous FBO tests
  - Gained insight into the event time history characteristics
- Performed significant test/model correlation in earlier programs to understand past successes and failures
- Performed significant rig and lab studies to correlate modeling methods with design features and technologies
- Performed one or more validation exercises

While not all are mandatory, these practices help prepare an applicant for successful use of analysis

Engine Modeling & Analysis Methods

- An engine structural model typically includes a combination of analysis methods, test results, and empirical data.
- Typical model elements:
  - Test demonstration of containment
  - Empirical fan rundown rate based on engine and rig test results
  - Engine dynamic FEA model for deflections and loads
  - Detailed FEA models for component stresses
- The engine model is an auditable combination of analysis, test, and empirical procedures, which must be reviewed with and accepted by the FAA.

Engine Model Validation

- The applicant must show that the engine model predicts outcomes
- Validation is established by Pre-test predictions and post test comparisons.
  - Differences are expected but must be shown to have little or no effect on compliance.
  - When differences exist a sensitivity study may be needed.
- Post test calculations are not sufficient for validations.
- Post test model refinement is expected and encouraged. Refinements should be based on physics, not numerical tweaks to improve answers.

Applicant Challenges

- **The first challenge is model correlation with the baseline test**
  - Pre-test predictions that do not match baseline test results
  - Unexpected failure modes uncovered by test
  - Insufficient instrumentation to provide correlation data
  - Inability to model complex non-linear response of some engine components
  - Modeling of tubes and hoses
- **The second challenge is model validation before starting the derivative analysis**
  - The baseline model has to be validated against the baseline test.
  - The baseline model is then updated to reflect the derivative configuration
  - Ability to model the differences must be validated
  - Determining which components to focus on and how close is adequate
- **Prior test/analysis experience is critical to developing a successful certification by analysis program**

AIA §33.94 Working Group

Background

- **Since 1984, when §33.94 was introduced there have been significant technology advancements:**
  - materials,
  - manufacturing processes and controls,
  - engine design,
  - analysis methodologies, and
  - part integrity.
- **Technology advancements may offer design and safety improvements but the prescriptive scope of the requirement may be limiting adoption.**

AIA §33.94 Working Group

Task

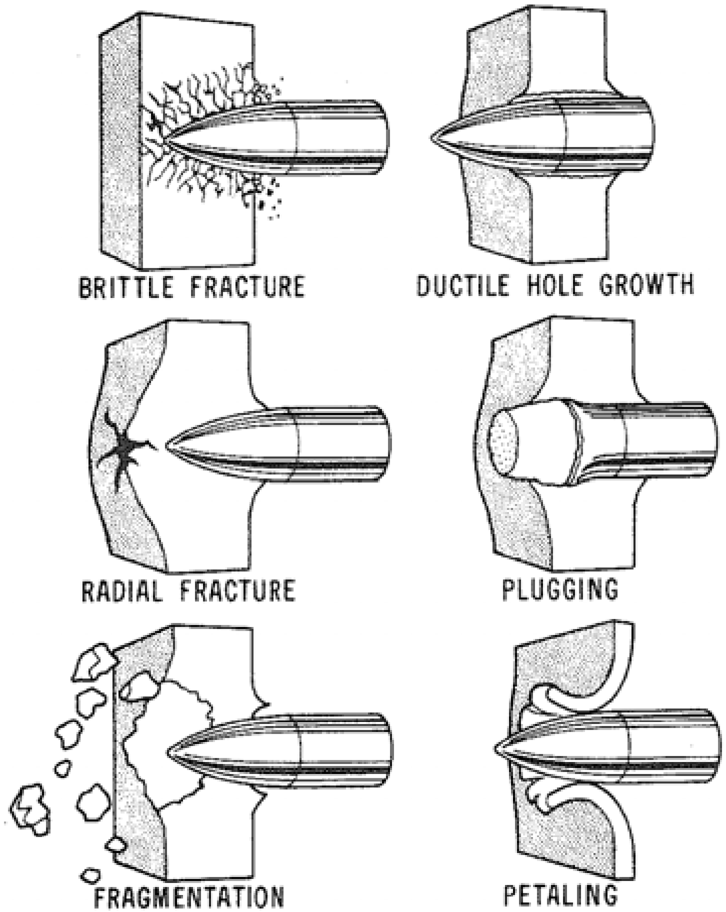
- Determine if there is a need to change the requirements of §33.94, as well as the associated advisory and policy documents.
- If changes are needed provide recommendations for changes to the requirements, advisory and policy documents.
- Provide a report to the AIA at the conclusion of the task.

Other Engine Analysis Applications

- **Bird Strike Critical Point Assessment**
  - Determine critical conditions for bird tests
  - Show whether ice slab or bird test is more critical and determine whether one test might serve for demonstration of the other requirement
- **Containment for other than highest energy location**
  - Show containment capability for stages other than the one tested
- **Overspeed**
  - Show that a rotor will not burst under the limiting overspeed condition

Material Modeling Research Supporting Non-Linear Dynamic Analysis Models

Introduction & Background



Different modes of material failure

An “ideal” material failure model provides accurate results for a broad range of impact conditions and material failure modes

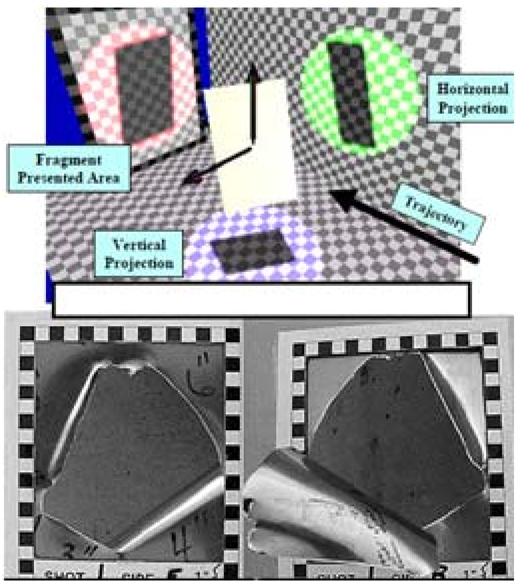
Introduction & Background

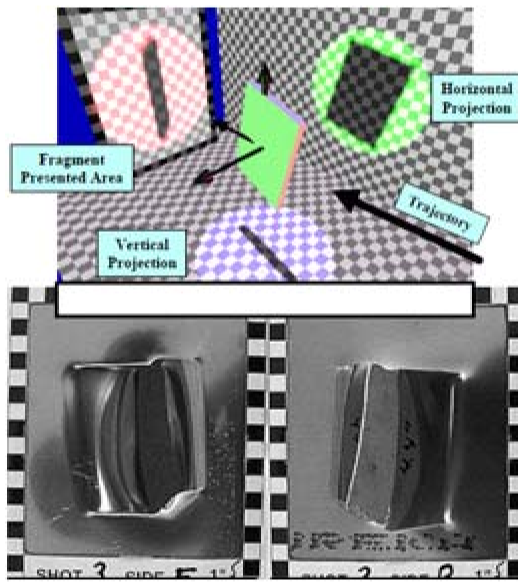
In response to NTSB recommendations following the Sioux City rotor burst initiated accident, FAA initiated a research program to reduce risk from rotor burst events

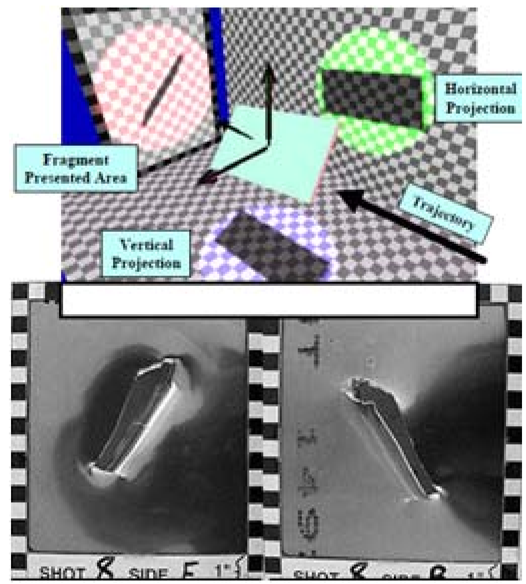
- Formed team with industry, academia, and other federal agencies (UCB, Stanford, ASU, GWU, GMU, OSU, Boeing, Livermore, NAWC, NASA)
- Assumed basic analysis and test tools were available and mature
- Began test and analysis program to characterize damage from fragments and protection necessary to reduce risk
- Ran into problems correlating analysis with test
- Discovered material failure modeling was more mature for some applications than others
  - Models worked well in low strain rate problems (vehicle crash)
  - Models worked well in high strain rate problems (ballistic)
  - Models did not correlate for mid range (rotor burst)
- Led to formation of the LS-DYNA Aerospace Working Group

Introduction & Background

Different modes of material failure result when the orientation of a complex fragment is varied



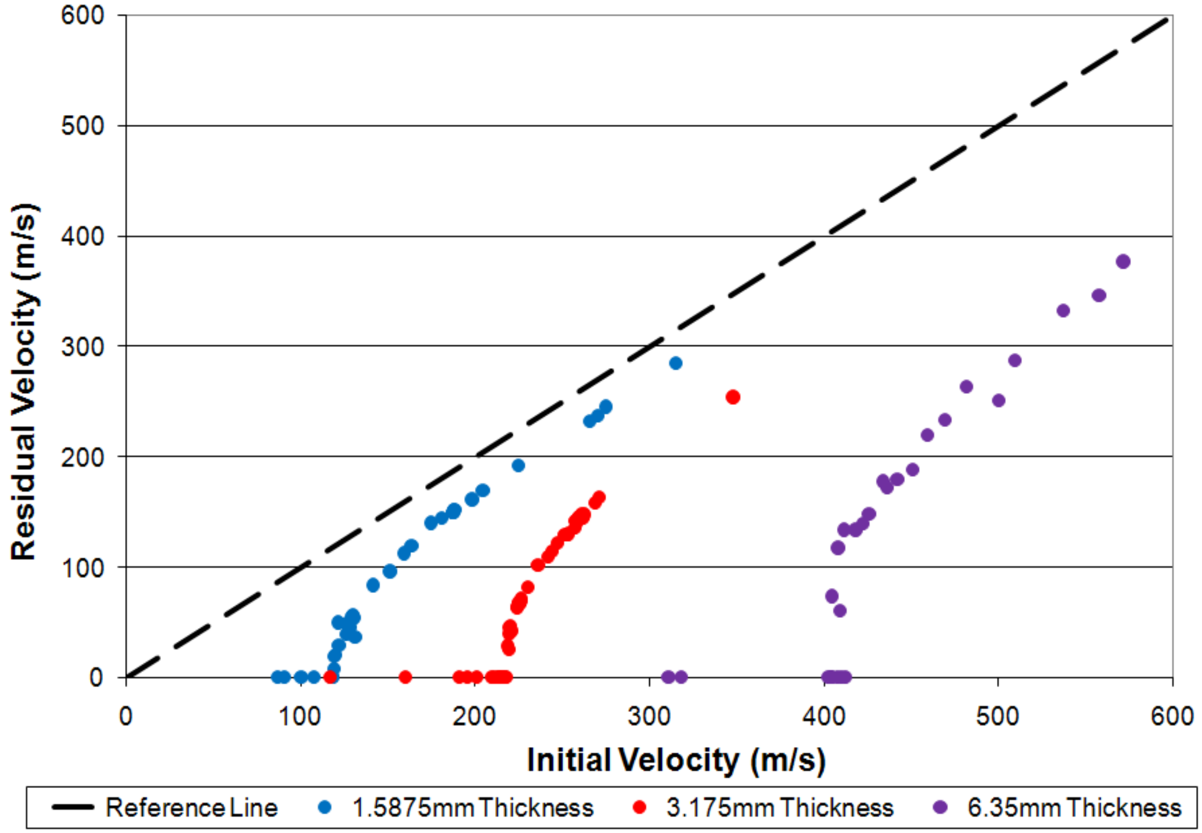




Introduction & Background

Example of high speed impact experiments

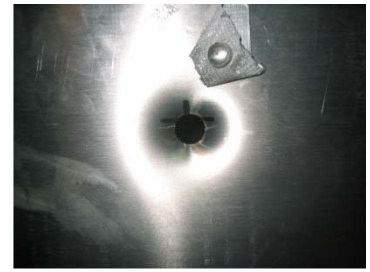
(conducted by University of California, Berkley)



Ballistic limit test results

½" spherical projectile

1.5875mm (1/16") target

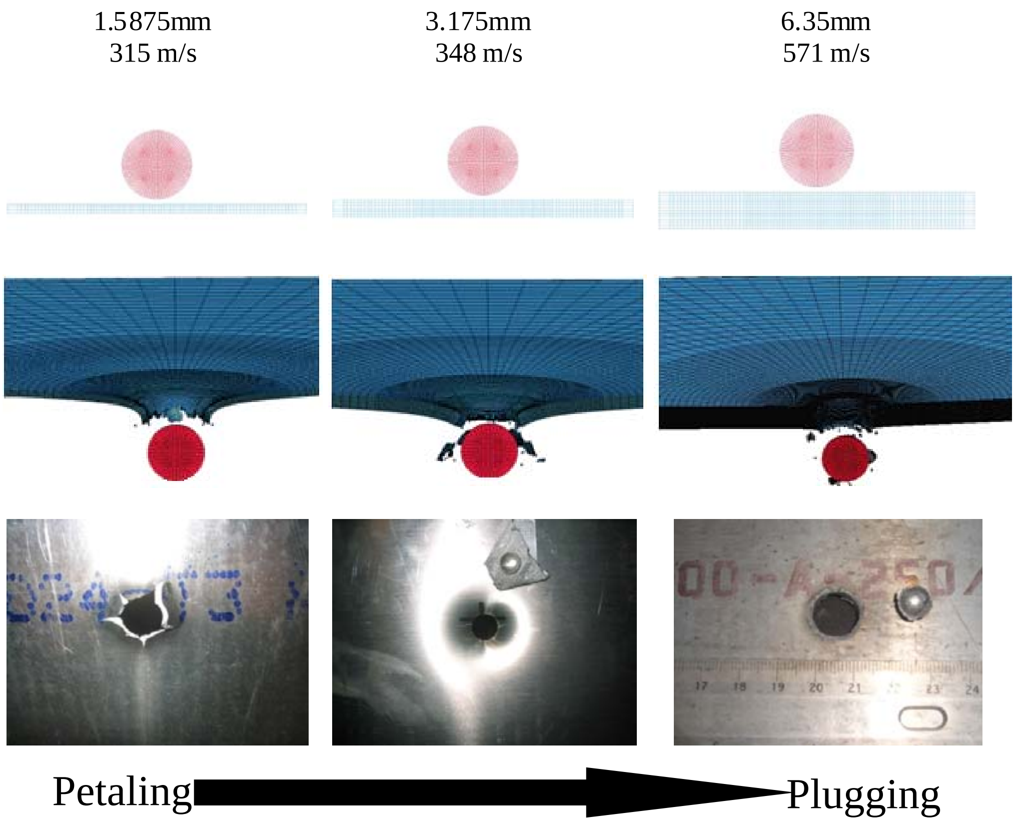


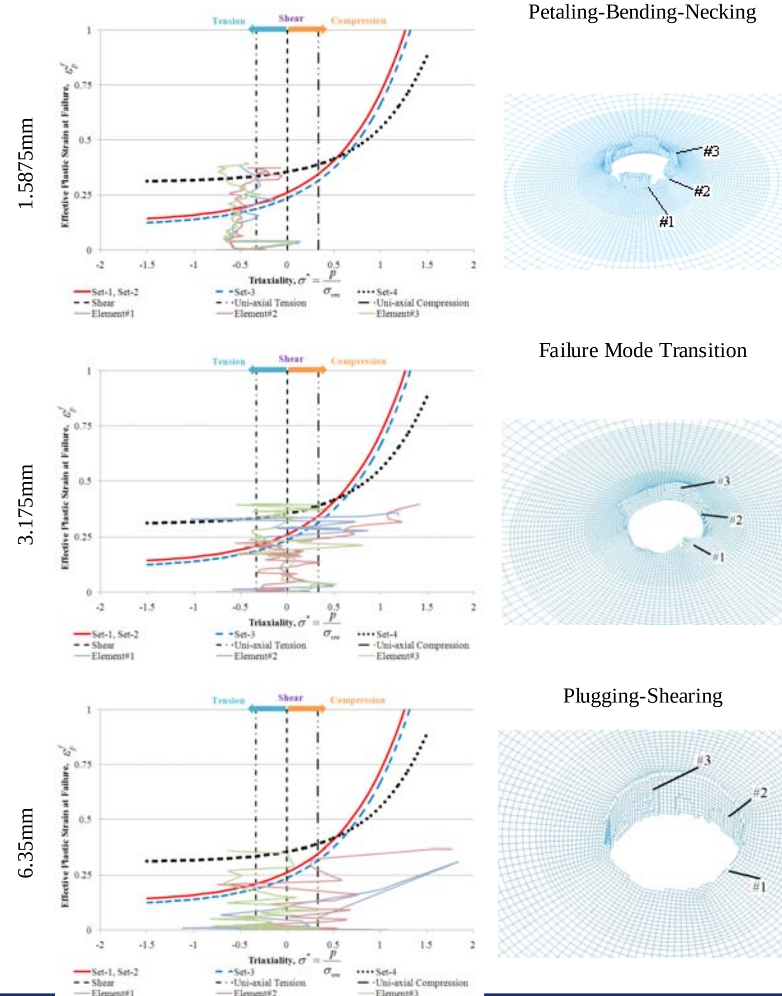
3.175mm (1/8") target

6.35mm (1/4") target

Introduction & Background

Transition of the failure modes could not be predicted using one common Johnson-Cook material model



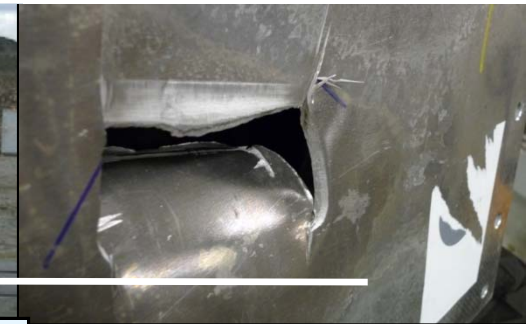


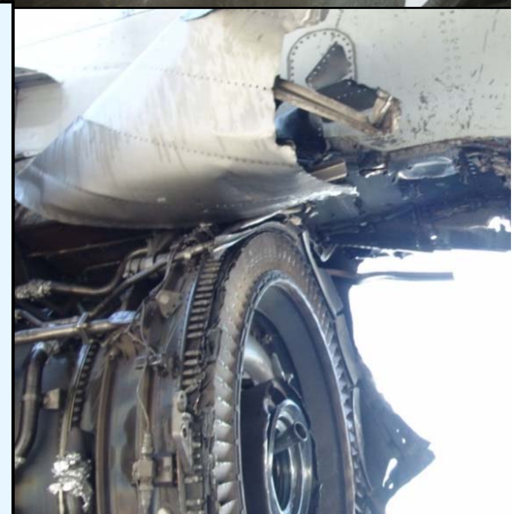
Material Model Research Objectives

Develop a tabulated, thermo-elastic/viscoplastic material model coupled with an accumulated regularized failure criterion that can incorporate high strain rate and temperature effects, and implement in LS-DYNA MAT_224

- Develop a failure locus as a function of equivalent plastic strain at failure, stress triaxiality and Lode angle parameter.
- Develop a testing program to characterize strain-rate and temperature dependent flow and failure surfaces.
- Implement the new material model into LS-DYNA
- Validate the new material model against material specimen and impact tests

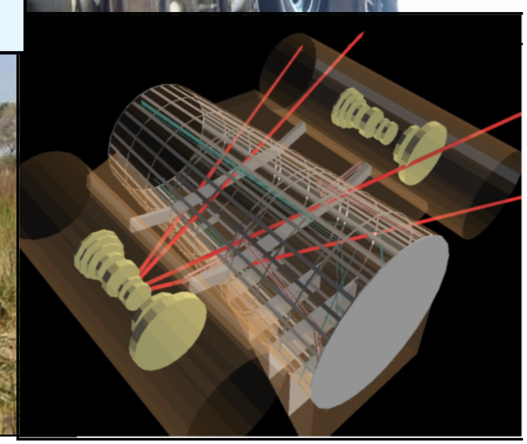
Targeted Applications



- **Fan Blade Out Containment**
  - Assess Redesigns & Derivatives
- **Containment Capability for Stages Not Requiring Test**
- **Aircraft Shielding Assessment for Rotor Burst Analysis**
- **Bird Strike Analysis**



Development of Material Failure Models for Aerospace Non-Linear Dynamics

- **MAT 224 – (in LS-DYNA)**
  Tabulated elastic/viscoplastic material model coupled with an accumulated regularized failure criterion that can incorporate high strain rate and temperature effects)
- **MAT 224_GYS – (in LS-DYNA)**
  Generalized isotropic yield surface model for pressure independent metal plasticity considering yield strength differential effect in tension, compression and shear stress states
  - **MAT 264 – (in LS-DYNA)**
    Fully-tabulated 3D anisotropic plasticity model for transient dynamics of metals

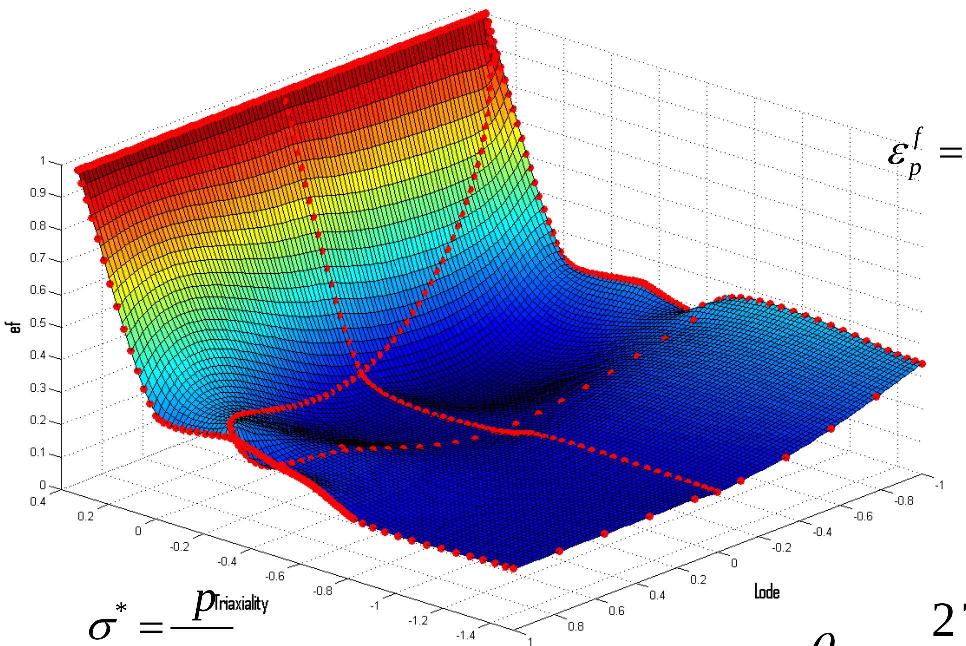
Mat_224 Material Model Development

$$\sigma_y = f\left(\varepsilon_p, \dot{\varepsilon}_p, T\right)$$

$$\varepsilon_p^f = f\left(\sigma^*, \dot{\varepsilon}_p, T\right) \Longrightarrow \varepsilon_p^f = f\left(\sigma^*\right) = f\left(\frac{p}{\sigma_{vm}}\right) = f\left(\frac{-\frac{1}{3}I_1}{\sqrt{I_1^2 + I_2}}\right)$$

Triaxiality

$$\varepsilon_p^f = f\left(\sigma^*, \theta_L\right) = f\left(\frac{p}{\sigma_{vm}}, \frac{27J_3}{2\sigma_{vm}^3}\right) = f\left(\frac{-\frac{1}{3}I_1}{\sqrt{I_1^2 + I_2}}, \frac{I_1^3 + \frac{9}{2}I_1 I_2 + I_3}{\left(I_1^2 + I_2\right)^{3/2}}\right)$$



$$\sigma^* = \frac{p}{\sigma_{vm}}$$

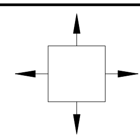
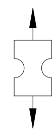
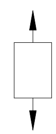
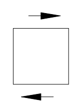
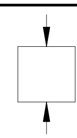
Product Triaxiality

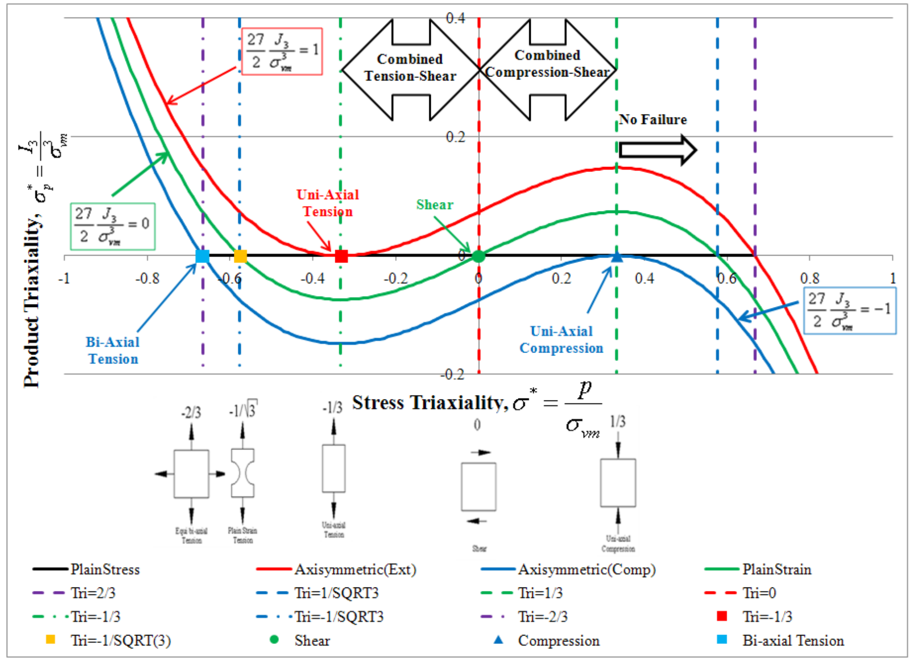
Lode Angle

$$\theta_L = \frac{27}{2}\frac{J_3}{\sigma_{vm}^3}$$

Third deviatoric stress invariant

Range of Stress States Needed to Characterize Failure Surface

	Stress Triaxiality	Product Triaxiality	Lode Angle Parameter	Illustration
Biaxial stress Tension	$-\frac{2}{3}$	0	-1	
Uni-axial Stress Tension, Confined Lateral	$-\frac{1}{\sqrt{3}}$	0	0	
Uni-axial Stress Tension	$-\frac{1}{3}$	0	1	
Pure Shear	0	0	0	
Uni-axial Stress Compression	$+\frac{1}{3}$	0	-1	



Specimen Tests to Characterizing Failure Surface

#	Specimen Geometry/FE Model	Targeted Stress-state Values σ^*	σ_p^*	θ_L
1	Figure B-1	-0.333	0.0	1.0
2	Figure B-2	-0.41	0.0	0.9145
3	Figure B-3	-0.49	0.0	0.6167
4	Figure B-4	-0.577	0.0	0

#	Specimen Geometry/FE Model	Targeted Stress-state Values σ^*	σ_p^*	θ_L
11	Figure B-11	-0.577	0.0	0.0
12	Figure B-12	-0.666	0.0741	0.0
13	Figure B-13	-0.8	0.2453	0.0

#	Specimen Geometry/FE Model	Targeted Stress-state Values σ^*	σ_p^*	θ_L
18	Figure B-17	-0.666	0.0	-1.0
19	Figure B-18	-0.577	0.0741	-1.0
20	Figure B-19	0.0	0.0	0.0

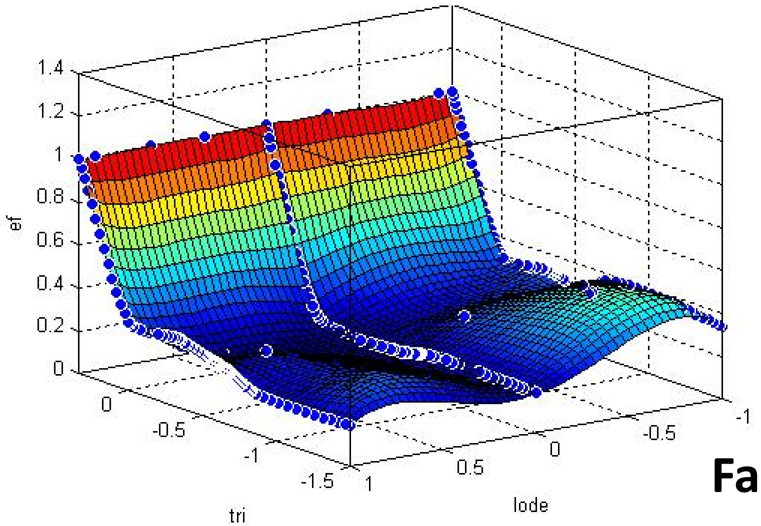
#	Specimen Geometry/FE Model	Targeted Stress-state Values σ^*	σ_p^*	θ_L
5	Figure B-5	-0.333	0.0	1.0
6	Figure B-6	-0.41	0.0063	1.0
7	Figure B-7	-0.49	0.0283	1.0
8	Figure B-8	-0.577	0.0741	1.0
9	Figure B-9	-0.666	0.1481	1.0
10	Figure B-10	-0.8	0.3194	1.0

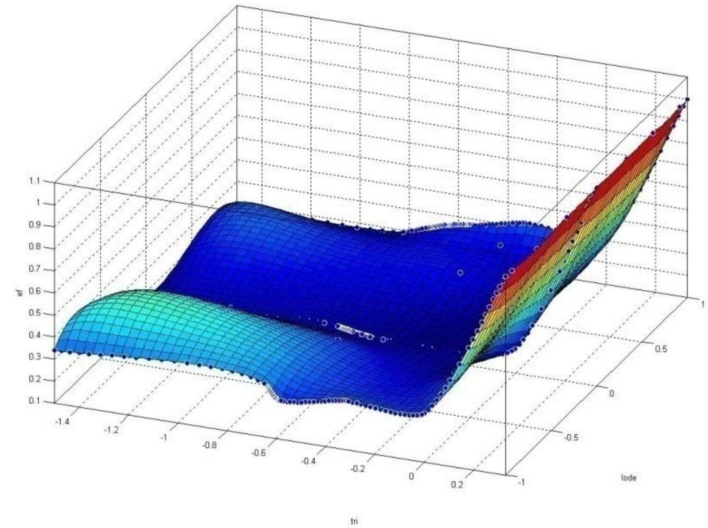
#	Specimen Geometry/FE Model	Targeted Stress-state Values σ^*	σ_p^*	θ_L
14	Figure B-14	+0.333	0.0	-1.0

#	Specimen Geometry/FE Model	Targeted Stress-state Values σ^*	σ_p^*	θ_L
15	Figure B-15	0.0	0.0	0.0

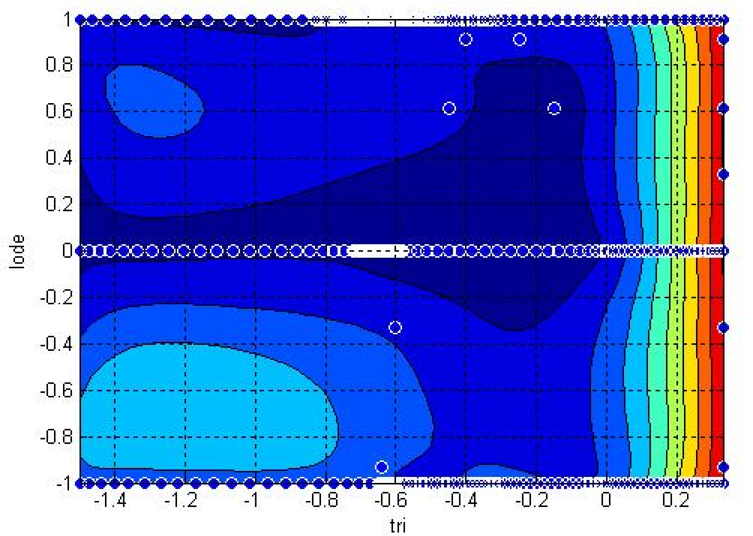
#	Specimen Geometry/FE Model	Loading Proportions	Targeted Stress-state Values σ^*	σ_p^*	θ_L
16	Figure B-16	$\frac{\sigma_x}{\tau_{xy}} = 1.973$	-0.2505	0.0	0.9145
17		$\frac{\sigma_x}{\tau_{xy}} = 0.848$	-0.1466	0.0	0.6167

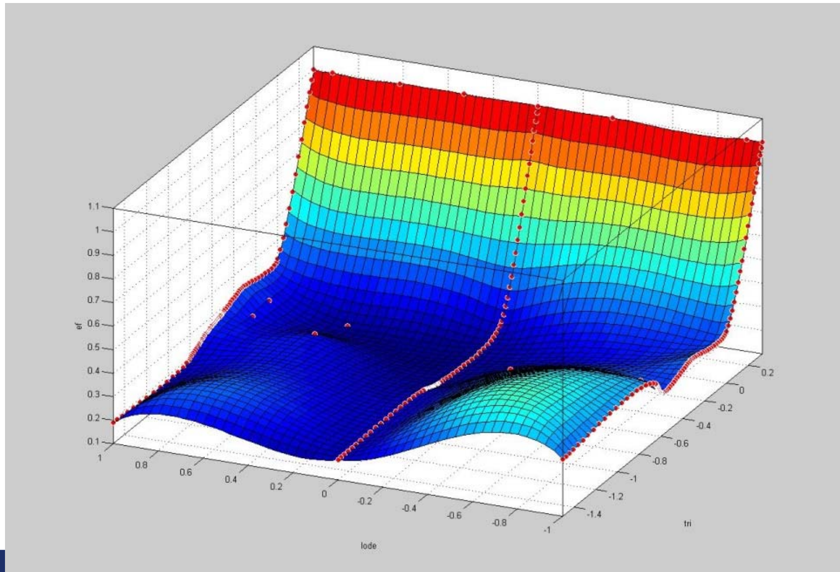
MAT_224 Material Model





Failure surface for Al2024-T351





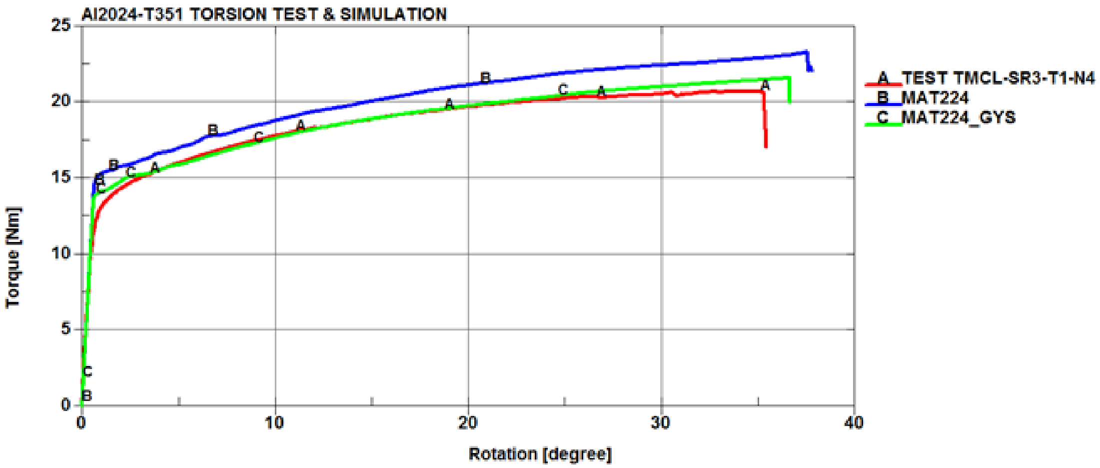
Generalized Isotropic Yield Model MAT_224_GYS

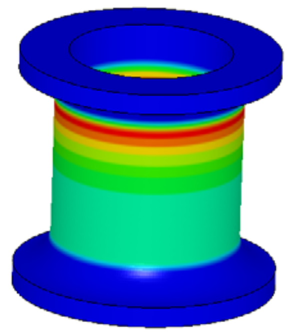
- **The MAT_224 yield function is not able to correctly represent a material with a *plastic* strength differential (tension ≠ compression)**
  - MAT_224 is fully isotropic
- **MAT_224_GYS introduces a Generalized Isotropic Yield Surface model for pressure independent metal plasticity**
  - Considers yield strength differential effects in tension, compression and shear stress states
- **Tensile/compressive asymmetry is important for accurate modeling of HCP metals (e.g. Titanium)**

Simulation of Experimental Data Using MAT224_GYS

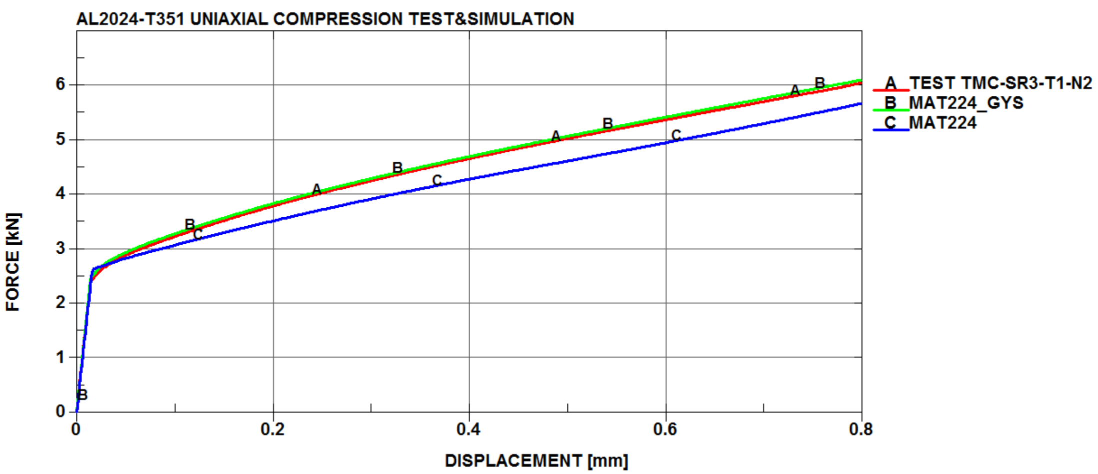
- **Differences in the Tension-Compression and Torsion for Aluminum (Al2024-T351) have been successfully simulated using MAT224_GYS.**
  - MAT224_GYS and MAT224 force-deflection output has been compared for uni-axial compression test
  - GYS accurately predicts torque-rotation for the torsion test
- **Tension-Compression asymmetry of Ti64 has been successfully simulated using MAT224_GYS.**
  - MAT224_GYS and MAT224 force-deflection output has been compared for uni-axial compression test

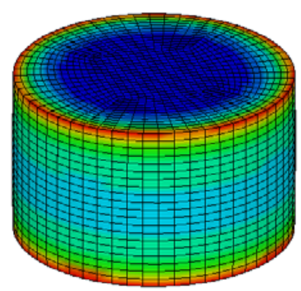
Al2024 Torsion & Uni-Axial Compression Tests and Simulations





Torsion Test

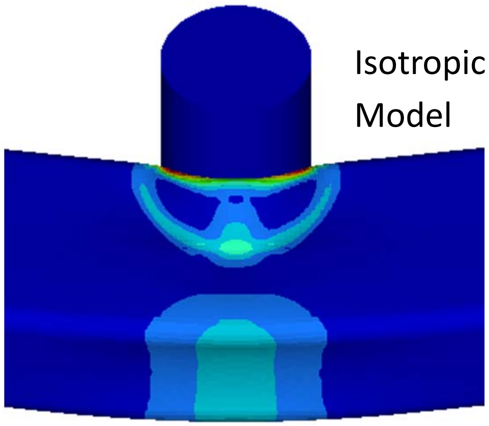




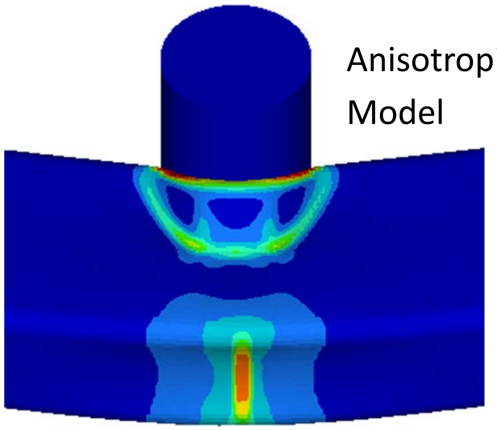
Uni-Axial Compression Test

Anisotropic Material Model – MAT_264

- **Anisotropy can be extremely pronounced for certain materials and manufacturing processes**
  - Forged and hollow core Ti fan blades
  - Cast turbine blades
  - Extrusions
- **Lankford Coefficient (R-Value)**
  - A measure of the anisotropy of the plastic flow
- **If the R-Value is 1, then the material is isotropic**
  - Extruded magnesium or aluminum can have R-Values as low as 0.4 and as high as 2.0
  - Similar variations occur and may be selectively optimized in the materials and manufacturing processes used for certain high energy engine parts (i.e. blades)
- **Anisotropy will influence the localization of plastic deformation and failure**



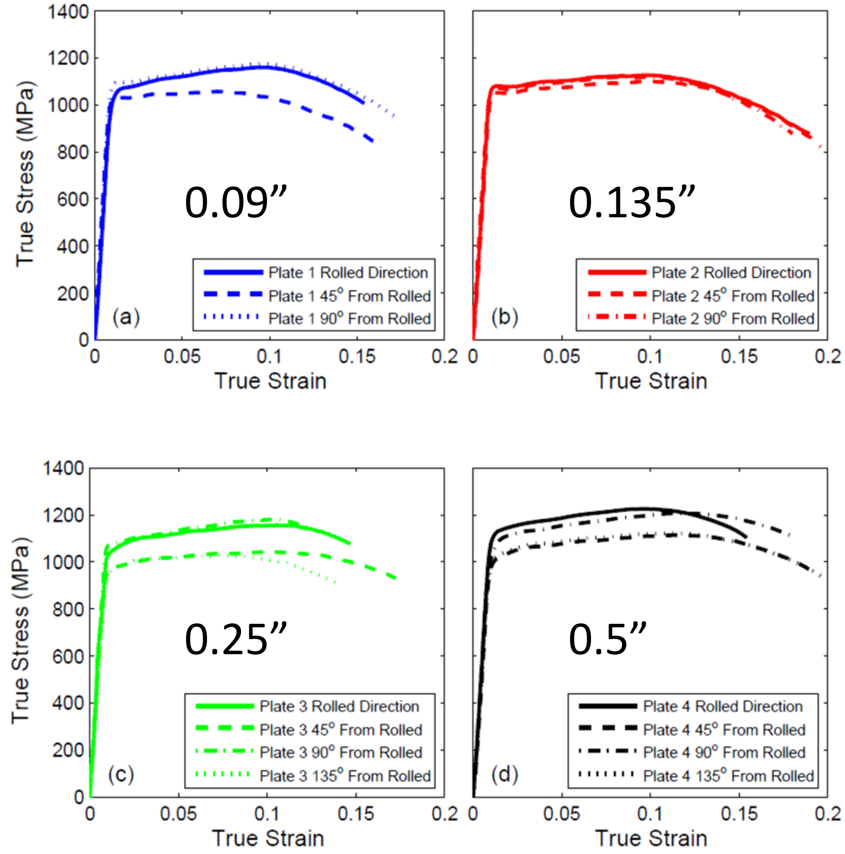
Isotropic Model



Anisotropic Model

Anisotropy – currently available models

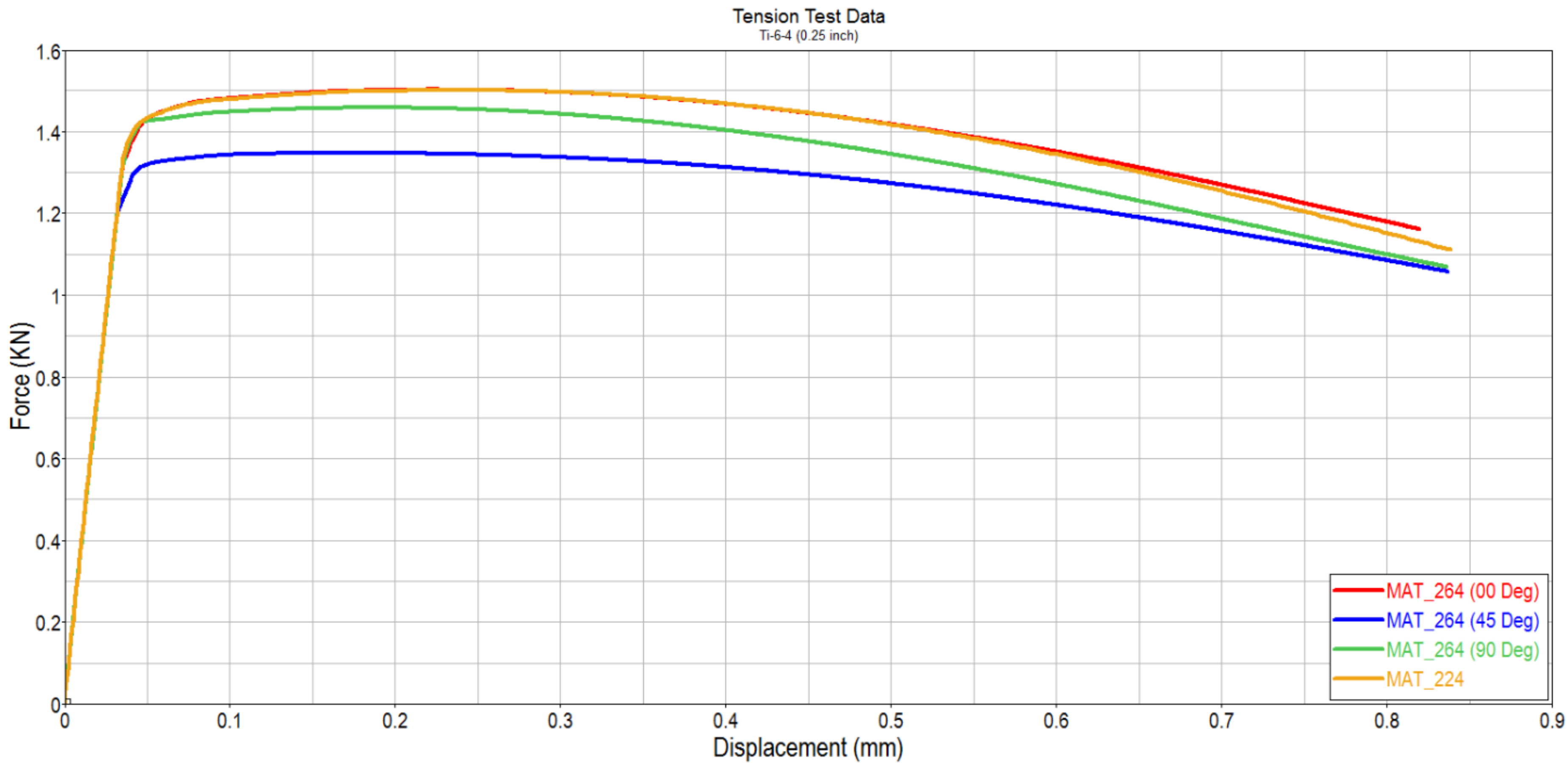
- **Current approaches, both in aerospace and automotive, are based on *isotropic* material models and failure models**
- **Available *anisotropic* material models tend to focus on manufacturing applications**
  - No rate and temperature dependency
  - These models tend to rely on parameterized inputs as opposed to tabulated hardening
  - The only tabulated anisotropic model is non-associated and only for plane stress applications
  - Designed for relatively small deformations



Approach – MAT264

- Model simulates anisotropic plastic deformation
- Tabulated hardening curves allow simulation of test data *(in all directions)* for large deformations beyond necking
- Simulates asymmetric tensile/compressive response (typical for HCP metals) will be included
- Includes rate and temperature dependencies
- Model produces identical results to MAT_224 when implemented with isotropic/symmetric material properties, and produces identical results to MAT_224_GYS when implemented with isotropic/asymmetric material properties

Benefit of Anisotropic Material Model MAT_264



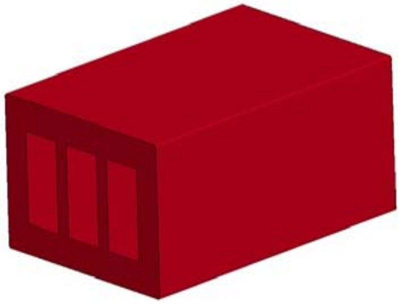
Future Material Model Development

1. **Complete validation for MAT_264 (2016 – 2017)**
2. **Develop failure surfaces/models for anisotropic materials (2017 – 2018)**
3. **Develop composite material models (2015 - 2019)**

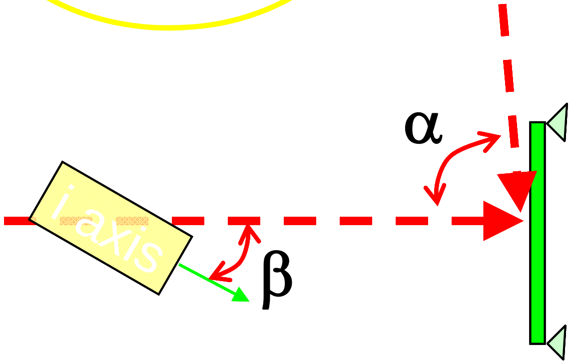
Future Work – Apply to Fragment Impact Studies

Typical Small Fragments

The HP turbine blade root mass, size, and tangential velocity make it a very significant fragment.



Generic Rectangular Projectile model used to assess impact obliquity sensitivity



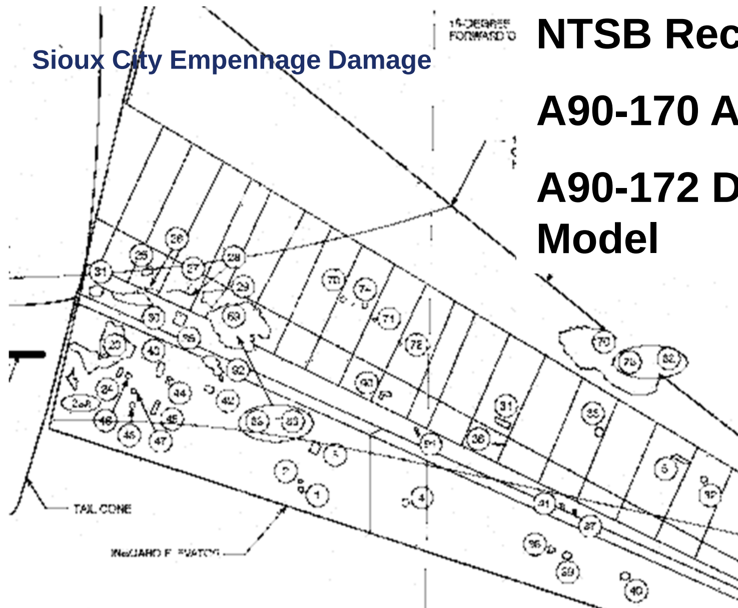
Secondary Benefit: develop statistical penetration risk model supporting UEDDAM

Application examples

- **UEDDAM fragment barrier modeling**
- FBO blade containment modeling study
- Open Rotor program test and analysis

UEDDAM – Uncontained Debris Damage Assessment Model

- R&D task initiated under ARAC PPIHWG to include analysis of multiple fragments impacting multiple locations
  - Directive resulting from Sioux City
- UEDDAM is leveraged from existing DoD vulnerability assessment tools
  - Joint work with NAWC, China Lake
- UEDDAM provides statistical assessment of debris pattern and uses statistical models to assess probability of damage
- Barrier shielding analysis will be performed with LS-DYNA
  - Results used to create statistical models of barrier capability for UEDDAM

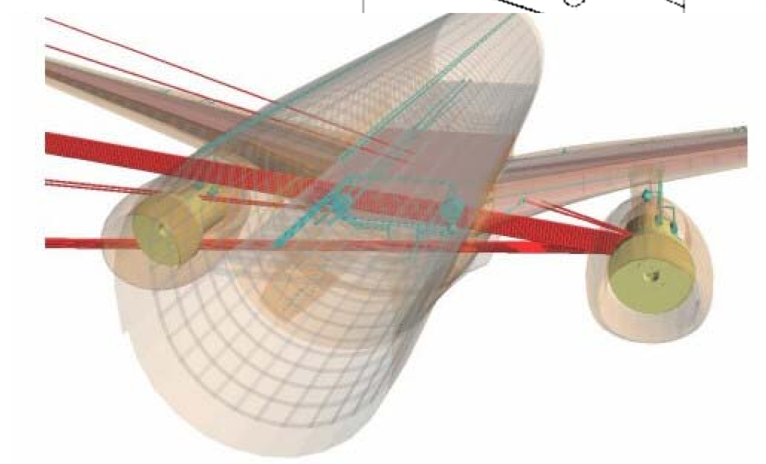


Sioux City Empennage Damage

NTSB Rec's

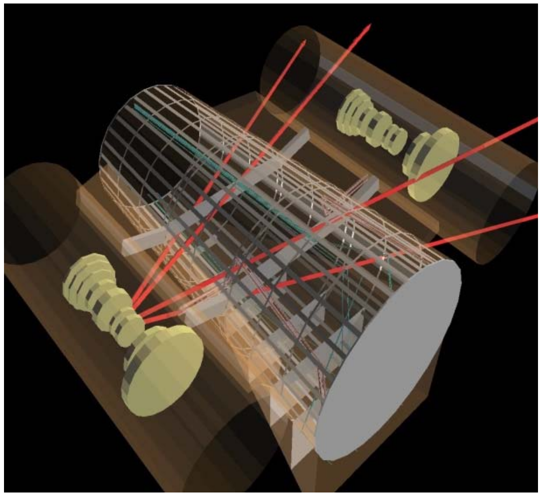
A90-170 AC20-128

A90-172 Debris Model



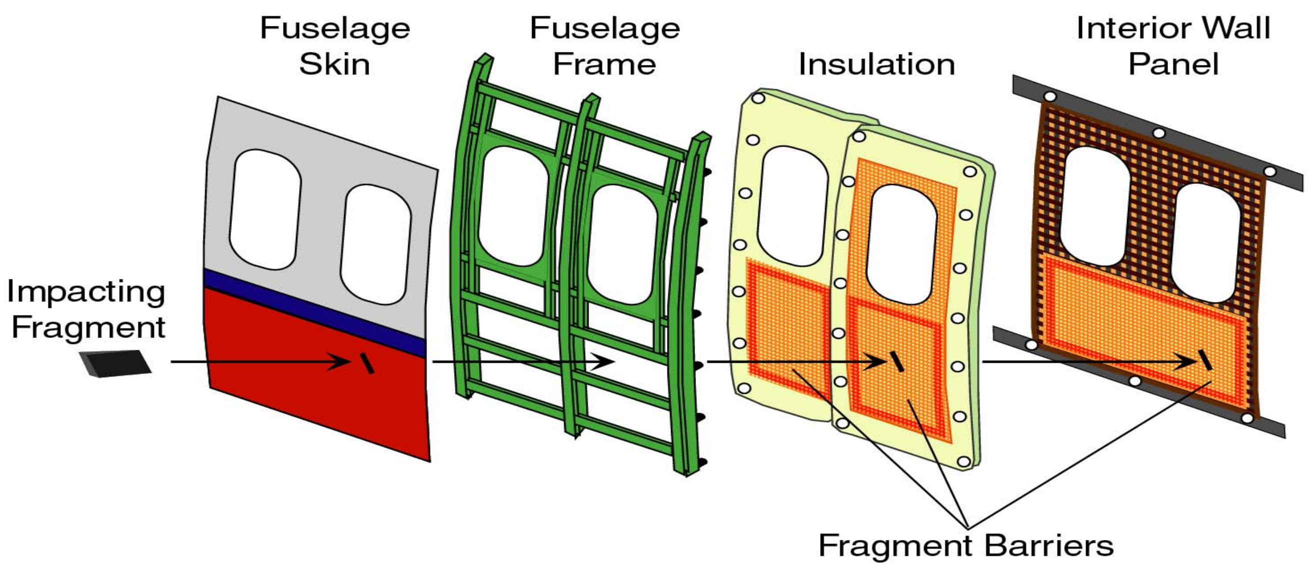
Rotor-burst Research with UEDDAM

- **Once specific vulnerability is established, mitigation studies include:**
  - System separation and redundancy
  - Move critical components to shield with aircraft structure
  - Develop additional protective barrier
  - LS-DYNA used for detailed design and analysis of impact events



Barrier Design example

- **Fabric Shielding**
  - SRI international initiated work
  - SRI Teamed with UC Berkeley and Boeing for aircraft shielding
  - LS-DYNA used for detailed design and analysis of impact events



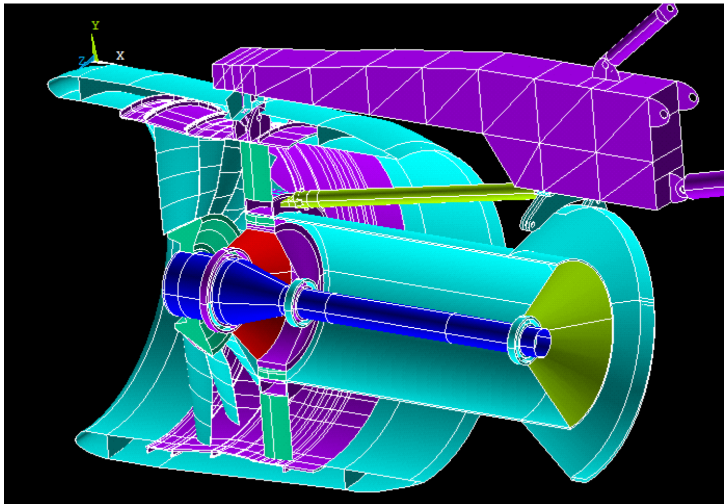
Application examples

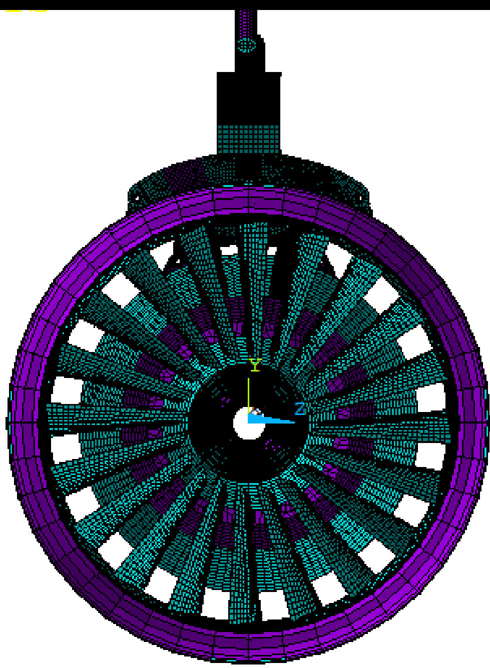
- UEDDAM fragment barrier modeling
- **FBO blade containment modeling study**
- Open Rotor program test and analysis

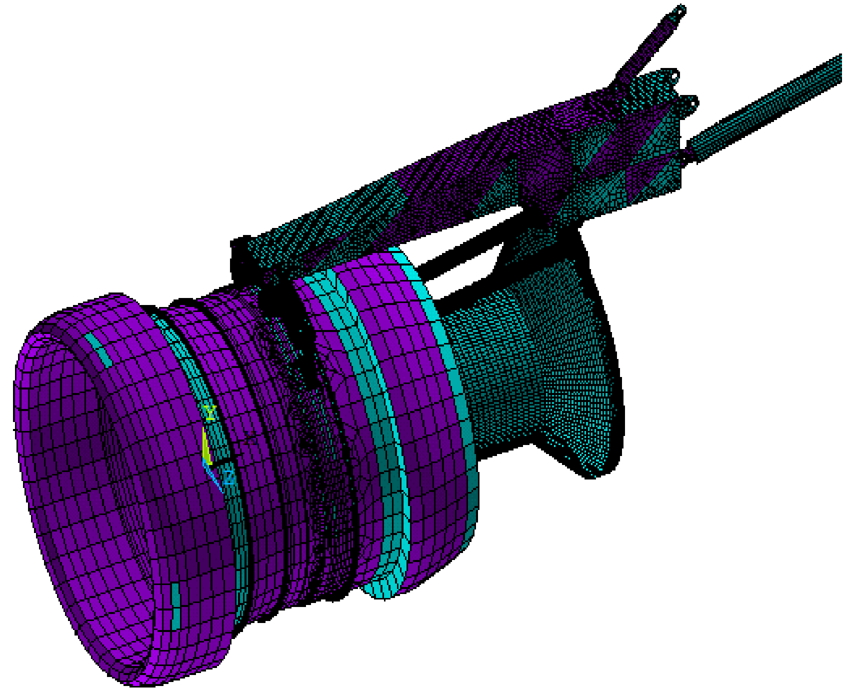
Fan Blade Out Rig Model

- **Develop a small diameter fan rig model that:**
  - Has fan dynamic characteristics of modern wide chord high bypass turbofan engine
    - 40" dia fan, 20 blades, integrally bladed disk, solid wall containment
  - Is capable of simulating the initial containment event
    - Blade release, impact with trail blade, containment, fragmentation
- **Model will be used for:**
  - Material model development studies
  - Containment method studies
  - Fan/case interaction studies
  - Initial event dynamics studies

Fan Rig Model



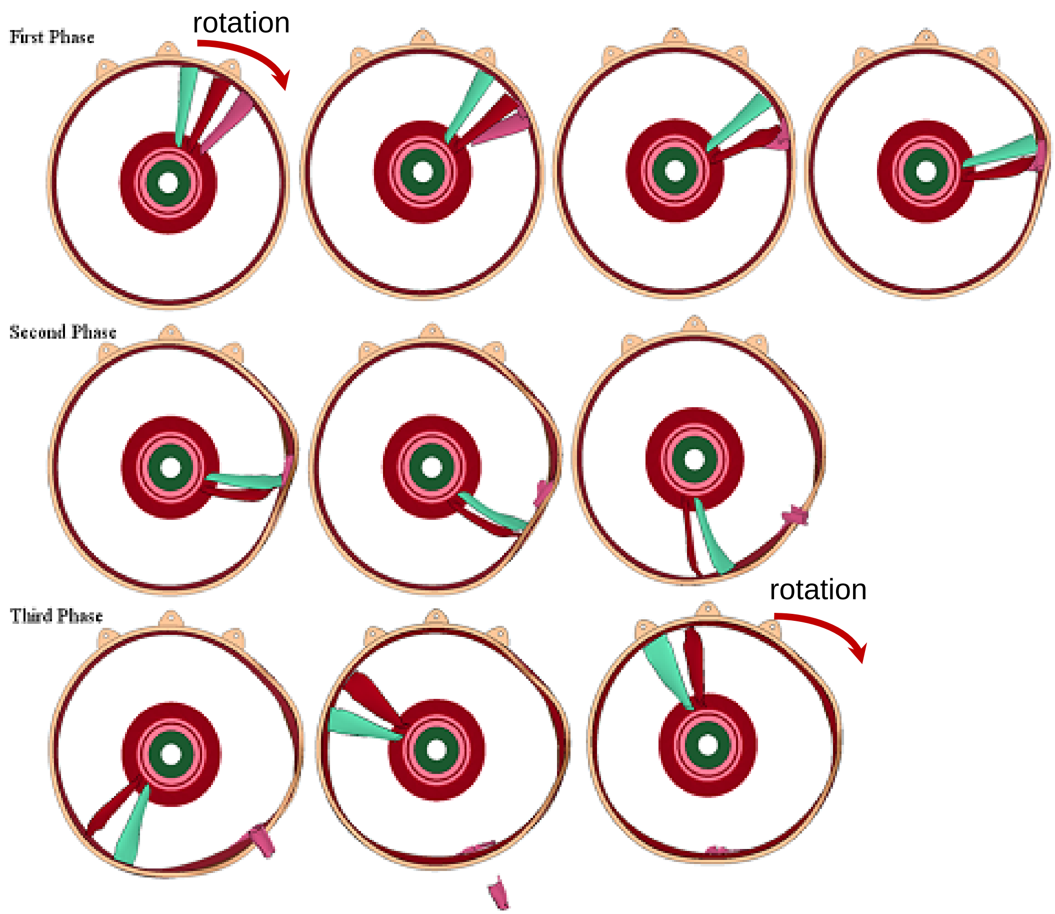




Fan Blade Out Rig Model

- **Simulates a development test rig, not a full engine**
- **Fan rigs are used by Engine OEM's to develop and validate containment systems**

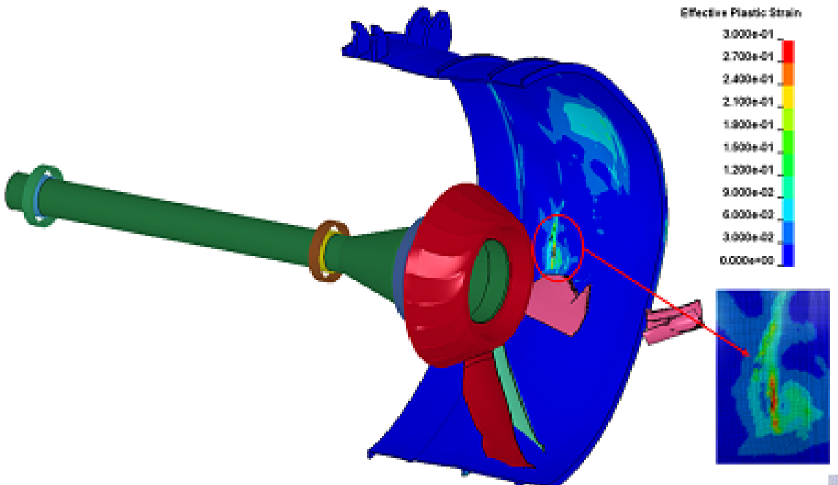
First Three Phases of Blade Containment



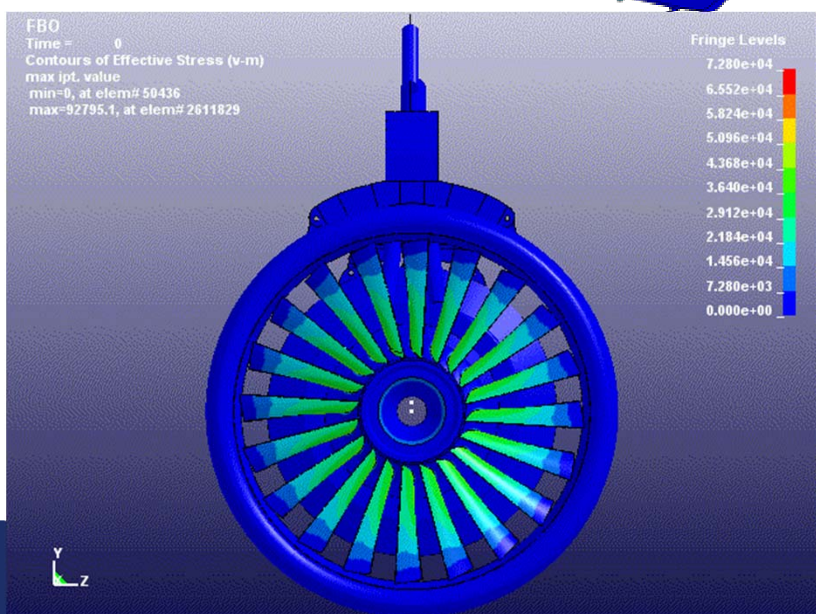
1. Release & Trajectory to Impact
2. Containment
3. Blade fragmentation

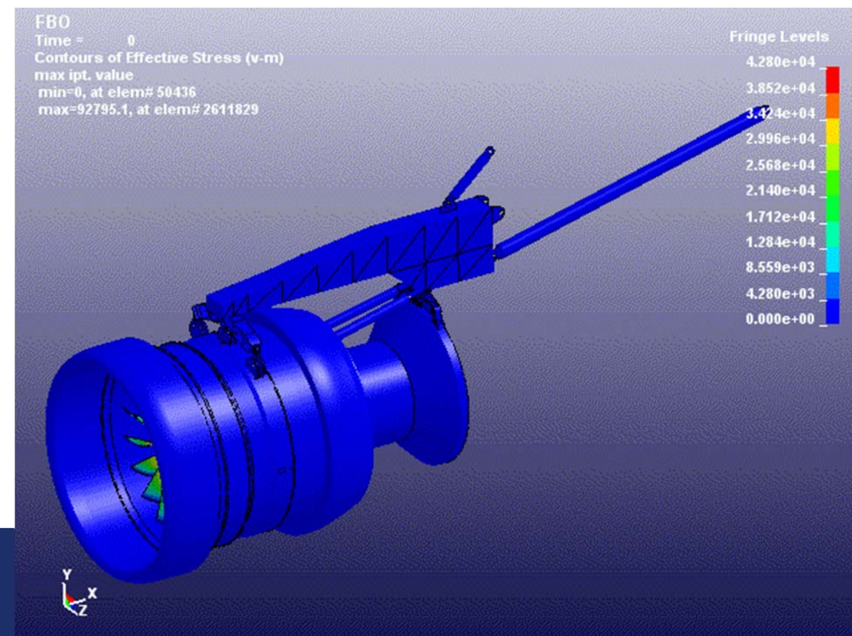
(Phases 4 & 5 are run down and windmill)

Damage to the Containment Case at the Footprint of Root Impact



Accurate replication of the blade out event is critical for accurately predicting case containment capability

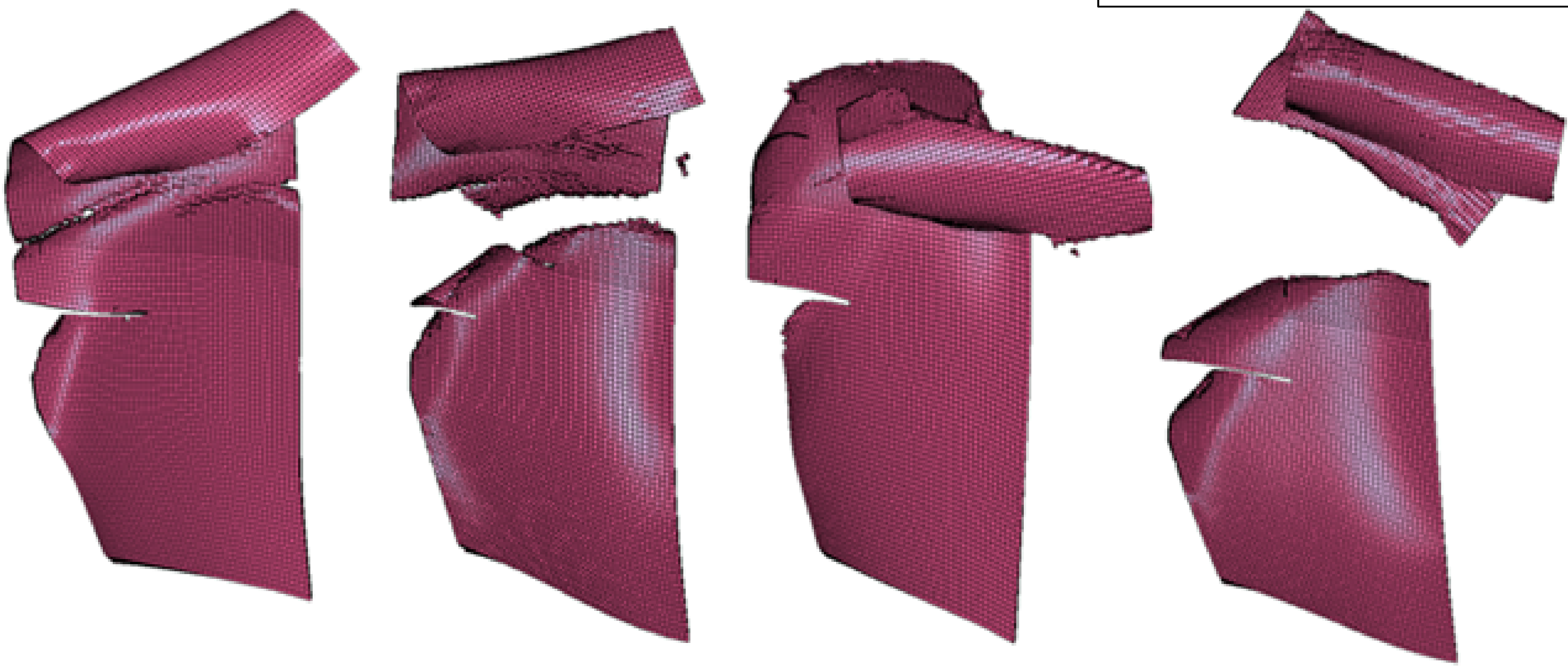




Effect of Material Model on Blade Break-up

Four simulations using "similar" material models

- 3 with MAT_224
- 1 with Johnson-Cook



Rate Dependent Piecewise Linear Plasticity Model Effective Plastic Strain at Failure 0.2

Rate Dependent Piecewise Linear Plasticity Model Effective Plastic Strain at Failure 0.18

Rate Dependent Piecewise Linear Plasticity Model Effective Plastic Strain at Failure 0.15

Johnson-Cook Model

Predicted Failure is highly dependent on the accuracy of the material model

FBO Containment Modeling

Status Today

- **Many OEM's have developed a level of modeling that allows them to address certain problems that have arisen in FBO testing**
- **To date, no OEM has developed a sufficiently predictive capability to use analysis in place of test for *containment* certification**
- **Analysis is used for derivative certification where containment has been demonstrated in the baseline model test and changes to containment via rig test**
  - Analysis addresses: safe shut down, will not catch fire, and mount integrity

Application examples

- UEDDAM fragment barrier modeling
- FBO blade containment modeling study
- **Open Rotor program test and analysis**

Analysis and Testing of a Composite Fuselage Shield for Open Rotor Engine Blade-Out Protection

Collaborative Program with:

- NASA Glenn Research Center, Cleveland, Ohio
- FAA William J. Hughes Technical Center, Atlantic City, NJ
- Naval Air Warfare Center, Weapons Division, China Lake, CA

Background – what is an open rotor?

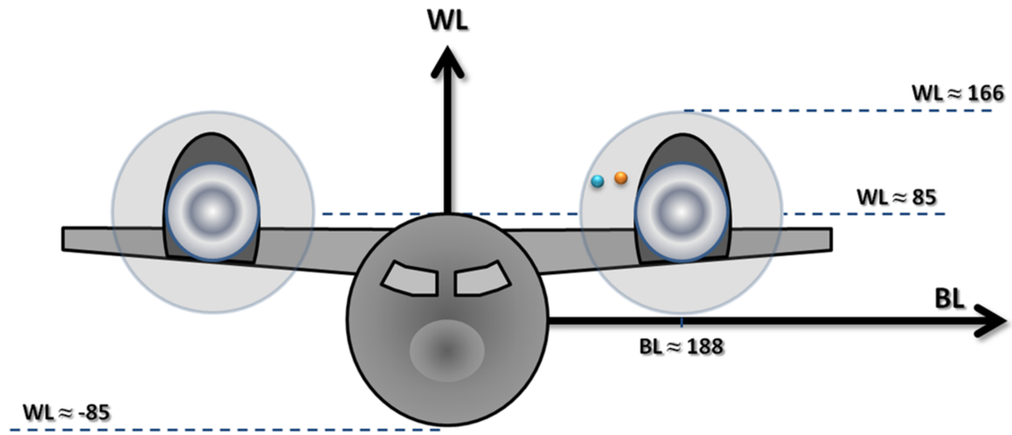
- In the 1980s open rotor engines were developed for improved fuel efficiency
- Technical challenges and lower fuel prices eventually reduced interest
- There has been recent renewed interest in these engines
- FAA goal is equivalent level of safety as ducted fan engines
- FAA investigating feasibility of fuselage shielding for open rotor engines

GE UnDucted Fan (UDF)

Pratt & Whitney/Hamilton Standard/Allison 578–DX

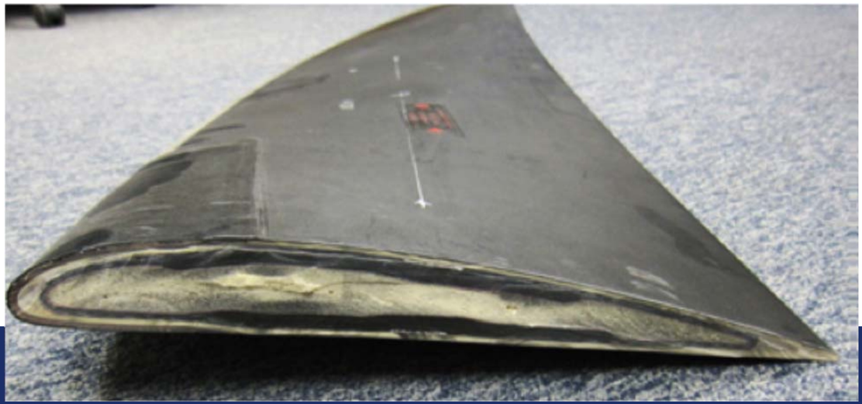
FAA Open Rotor Shielding Feasibility Study

- **FAA selected a medium range aircraft configuration with a high wing and wing mounted open rotor engines**



- Trajectory analyses conducted at NASA/GRC to predict the blade release angles for the worst case impact scenario
- Computational analyses conducted at NASA/GRC to predict minimum composite shield thickness to prevent penetration
- LS-DYNA predictions based on model correlation with small scale ballistics testing
- Test configuration design – worst case scenario
- Full scale subcomponent test conducted at China Lake Naval Air Warfare Center

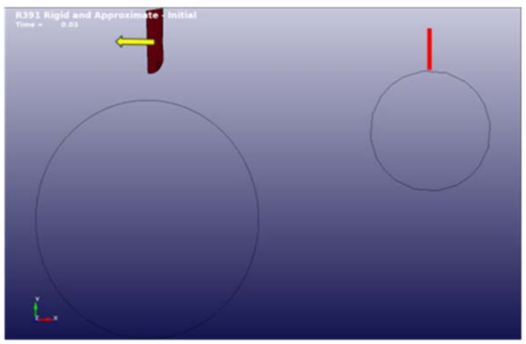
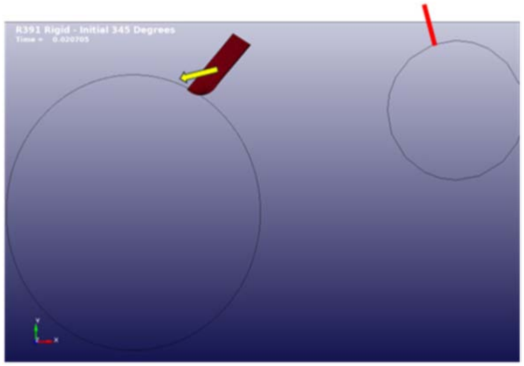
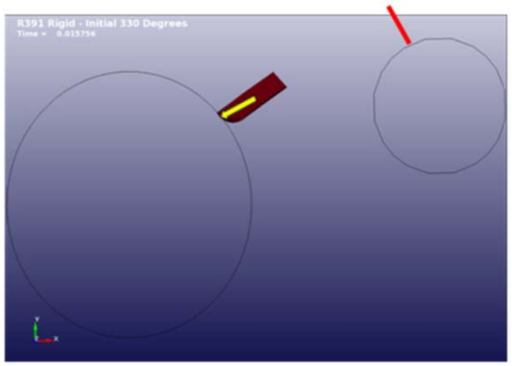
Blade

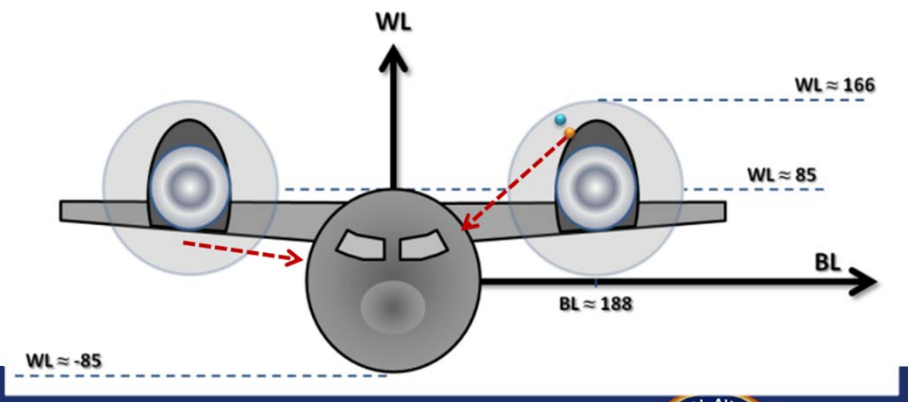


- Overall length: 41.25”
- Weight: 15.11 lb

Shielding Feasibility Study

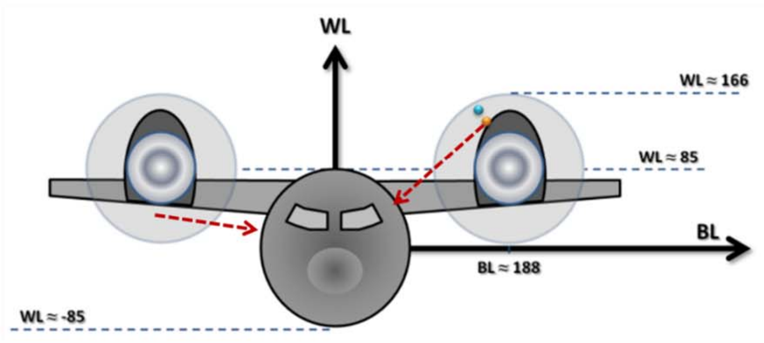
- **Trajectory analysis predicted blade release angles for the blade to impact the fuselage with a normal velocity vector aligned with the long axis of the blade.**

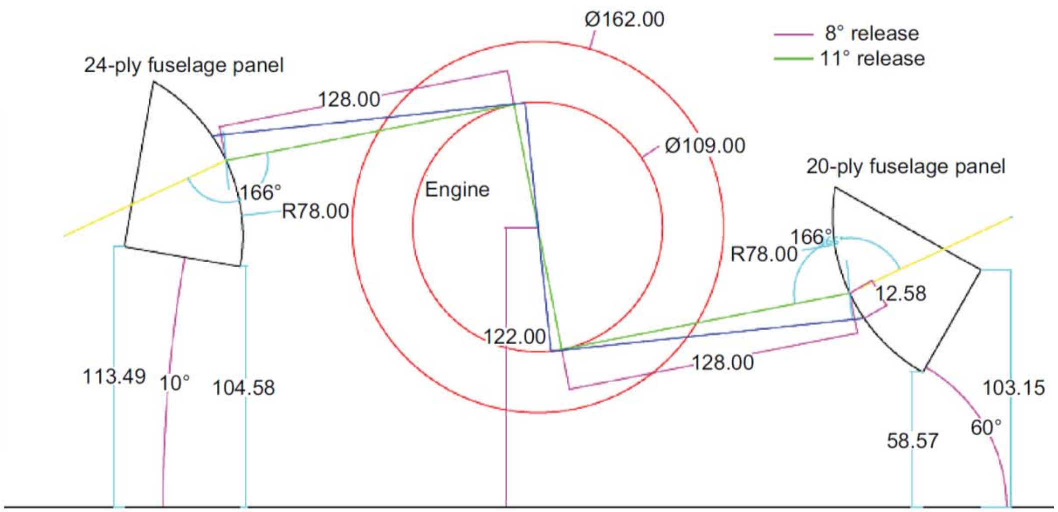






FAA Feasibility Study

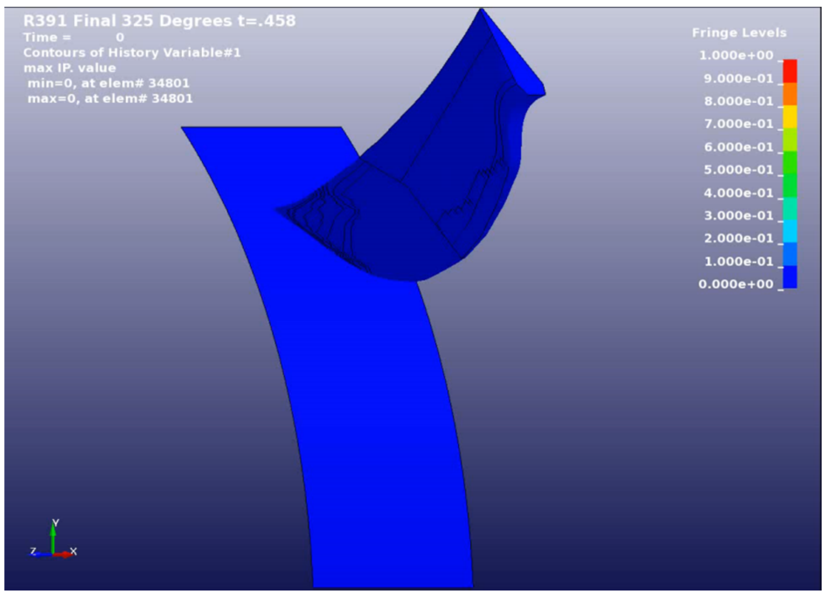
- **Test Configuration Design**

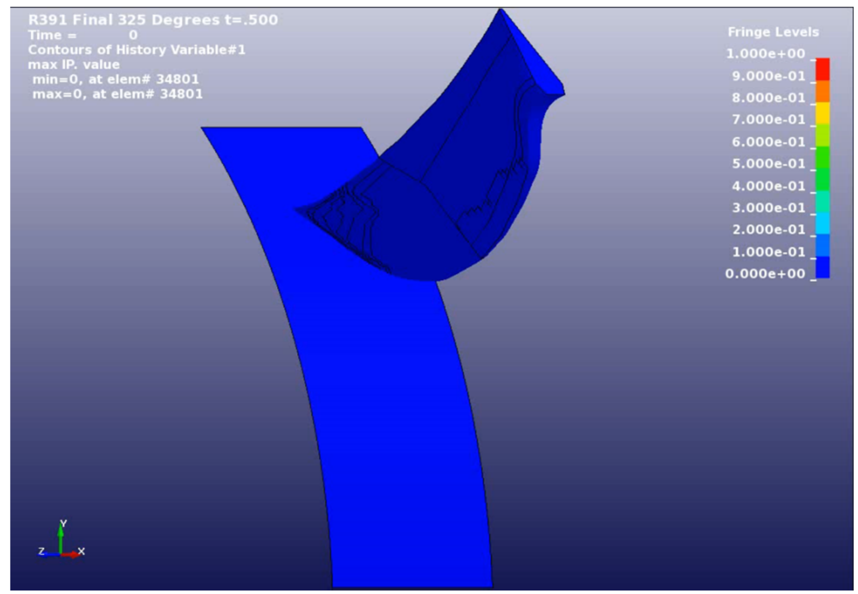




Pre-test Predictions

- Pre-test simulations predicted that a 20 ply composite panel would allow the blade to penetrate and a 24 ply panel would prevent penetration





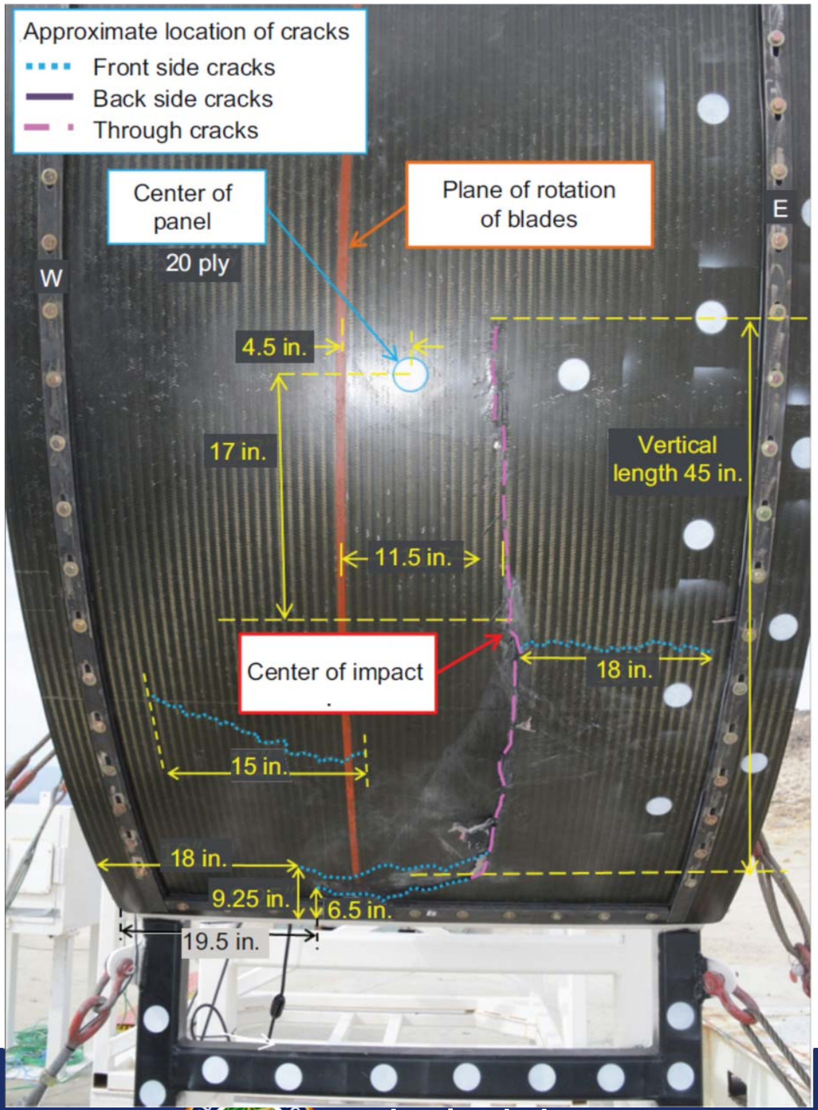
Dynamic Open Rotor Composite Shield Test

Test Observations

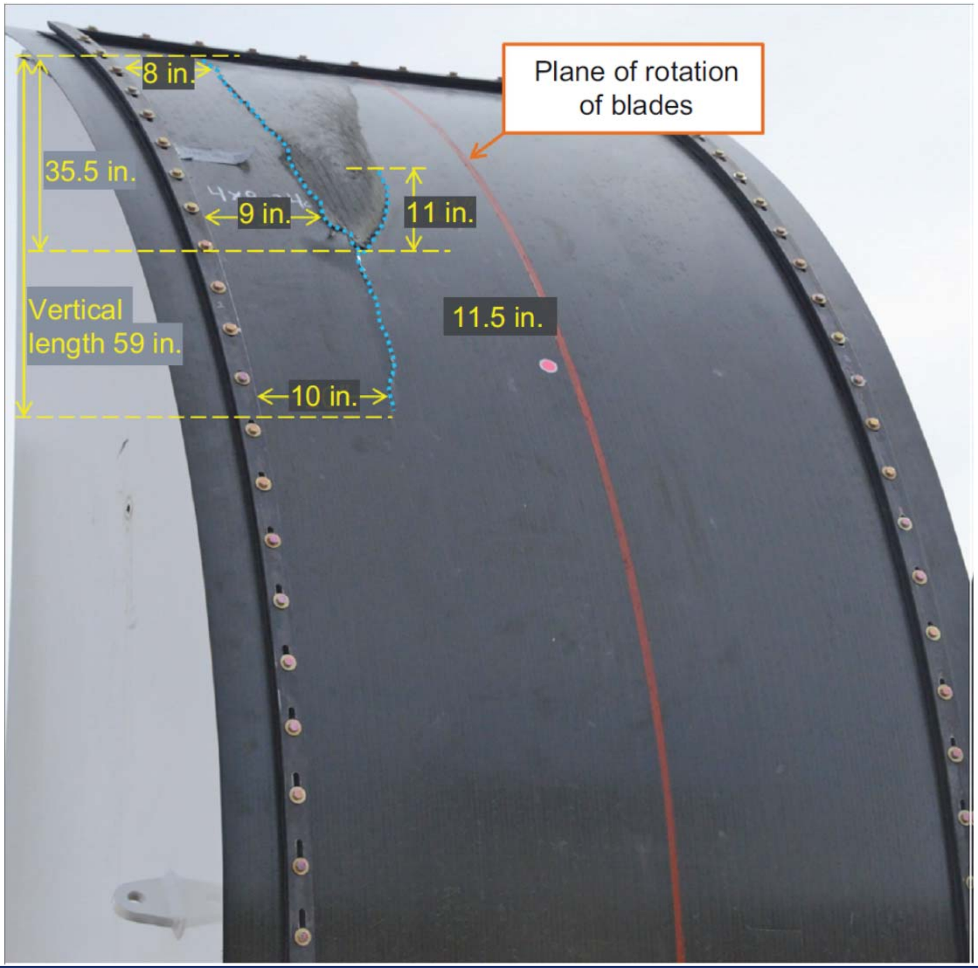
- Blade separation occurred at desired clock position
- Blades separated cleanly from root section
- Blades traveled to target panels impacting end on (~90 degree impact)
- Both blades impacted the target panels
- Impact
  - 24 ply panel - Deflected blade with no through crack
  - 20 ply panel – Blade penetrated panel

Test Results – 20 Ply Panel

- Blade caused one long longitudinal tear through the panel and four front side cracks that did not extend through to the backside
- Blade completely penetrated the panel
- Model did predict penetration would occur, but did not accurately predict the damage



Test Results – 24 Ply Panel



Open Rotor Shielding Test Findings

- Good global *correlation* with pretest predictions
- 24 Ply panel deflected the blade and did not have a thru failure
  - Localized, non-penetrating damage occurred
- 20 Ply panel was cracked completely through
  - Blade completely penetrated panel
  - Model did predict penetration would occur, but did not accurately predict the degree of damage
    - Crack was longer than pretest prediction.

Open Rotor Shielding Program Conclusions

- Composite shielding may be a feasible solution to fuselage shielding for open rotor engines
- For counter-rotating blades (2 rotors) shielding weight added estimated to be less than 250 lb.
- ***Advances in composite impact models needed to predict accurate failure modes and to be predictive rather than correlative***

Closing Comments

- **Use of Analysis is becoming more prevalent**
- **To substitute analysis for test requires significant effort by the applicant:**
  - Demonstration of modeling expertise
    - Includes prior test/analysis demonstrations on which modeling experience & capability have been correlated
  - Validation of model predictive capability
    - Recognize that validation is different from correlation
  - Ability to close loop between predictions and expectations from predictions
    - i.e. use of other tests to validate key components
  - The model and modeling process must be auditable

FAA Resources For Non-Linear Analysis

- **FAA 33.94 Fan Blade Out Rule Owner**
  Engine & Propeller Directorate (ANE)
  - Jay Turnburg (781) 238-7116
- **FAA Containment and Impact R&D**
  W.J. Hughes Technical Center
  - Bill Emmerling (609) 485-4009
  - Dan Cordasco (609) 485-4970
- **FAA Chief Scientist for Engine Dynamics**
  - Chip Queitzsch (703) 915-5351

Organizations Participating in the FAA Non-Linear Analysis R&D Program

- **Government Agencies**
  - NASA Glenn Research Center
  - Naval Air Warfare Center, China Lake
  - Lawrence Livermore Laboratory
- **Universities**
  - George Mason University
  - Ohio State University
  - Arizona State University
  - George Washington University
  - University of California, Berkeley
  - Stanford
- **Industry**
  - Boeing
  - Honeywell
  - Pratt & Whitney
  - Stanford Research Institute

Questions?