Damage Tolerance and Durability of Fiber-Metal Laminates for Aircraft Structures

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The Joint Advanced Materials and Structures Center of Excellence

FAA Sponsored Project Information

- **Principal Investigators & Researchers**

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Background

- **GLARE (GLAss fiber REinforced aluminum) laminates**
  - Hybrid composites consisting of alternating thin metal layers and glass fibers

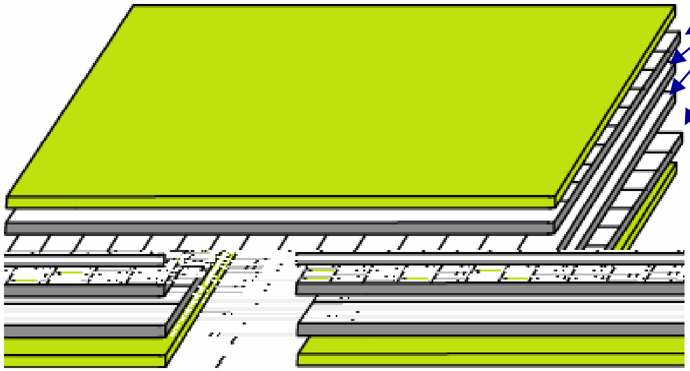
- **Advantages of GLARE**
  - High specific static mechanical prospe and low density
  - Outstanding fatigue resistance
  - Excellent impact resistance and damage tolerance
  - Good corrosion and durability
  - Easy inspection like aluminum structur
  - Excellent flame resistance

Project Scope

To develop methodologies for guiding material development, property optimization and airworthiness certification:

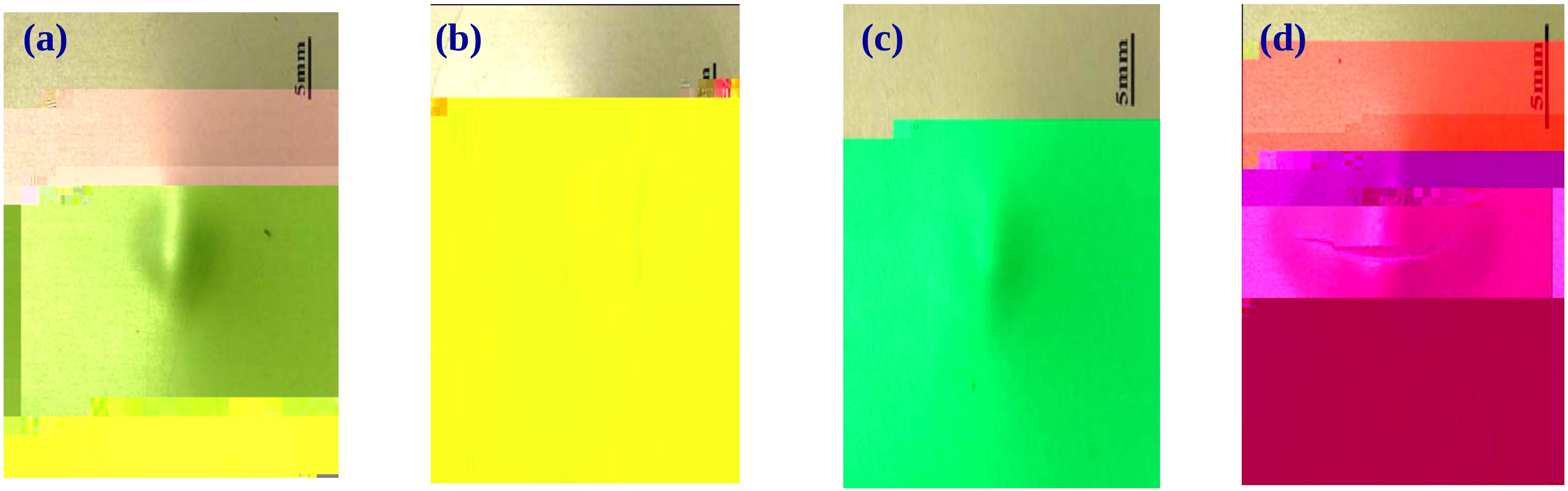
- Residual Strength Modeling and Validation
  --open-hole notch strength
  --residual strength after impact
  --open-hole notch strength after fatigue
- Impact Behavior and Numerical Simulation
- Post-Impact Fatigue Behavior
- Fatigue Crack Initiation/Growth Modeling and Validation
- Information System for Certification

Materials / GLARE 4 and GLARE 5



<GLARE 5-2/1>

Impact damage in Glare Laminates



(a) Dent damage (E=10.8 J) GLARE 5

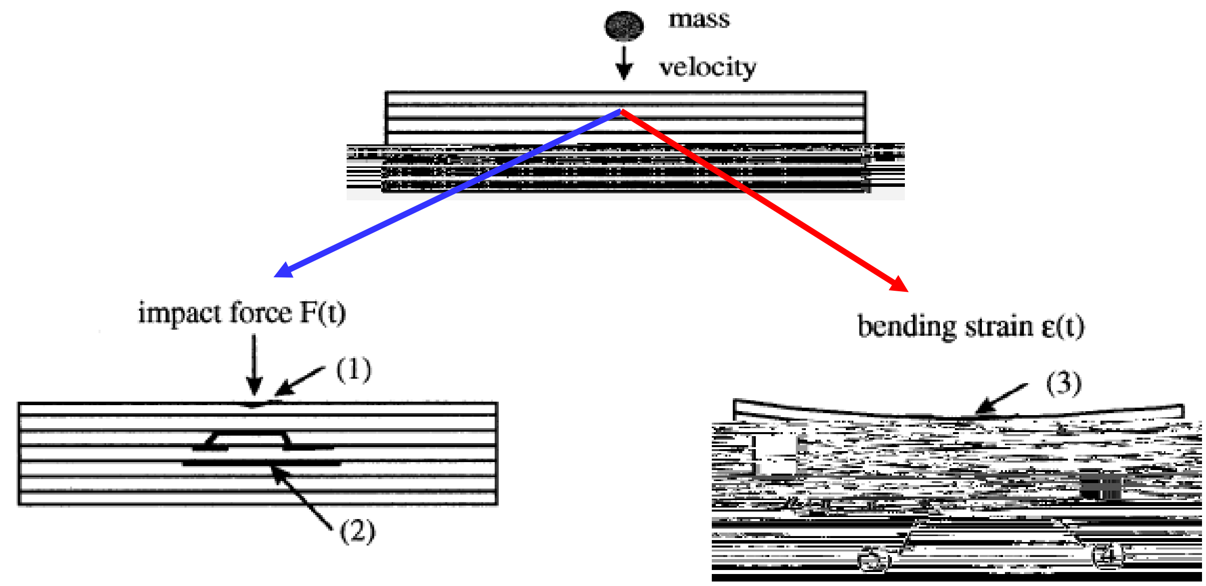
(b) Crack damage (E=18.1 J) GLARE 5

(c) Dent damage (E=10.8 J) GLARE 4

(d) Crack damage (E=18.1 J) GLARE 4

Impact Modeling strategies for FMLs

FMLsFMLsFMLsFMLsFMLsFMLs



Numerical Analysis of Impact

FEM simulation for dynamic contact

VUMAT for developing failure of composite layer

Impact force & 3-D Stress analysis

Ç **investigating impact force and stress distribution at outer aluminum layer and at inner composite layer**

Detect damage & Update stiffness

Ç **Failure of aluminum layer**

Ç **Failure of composite layer**

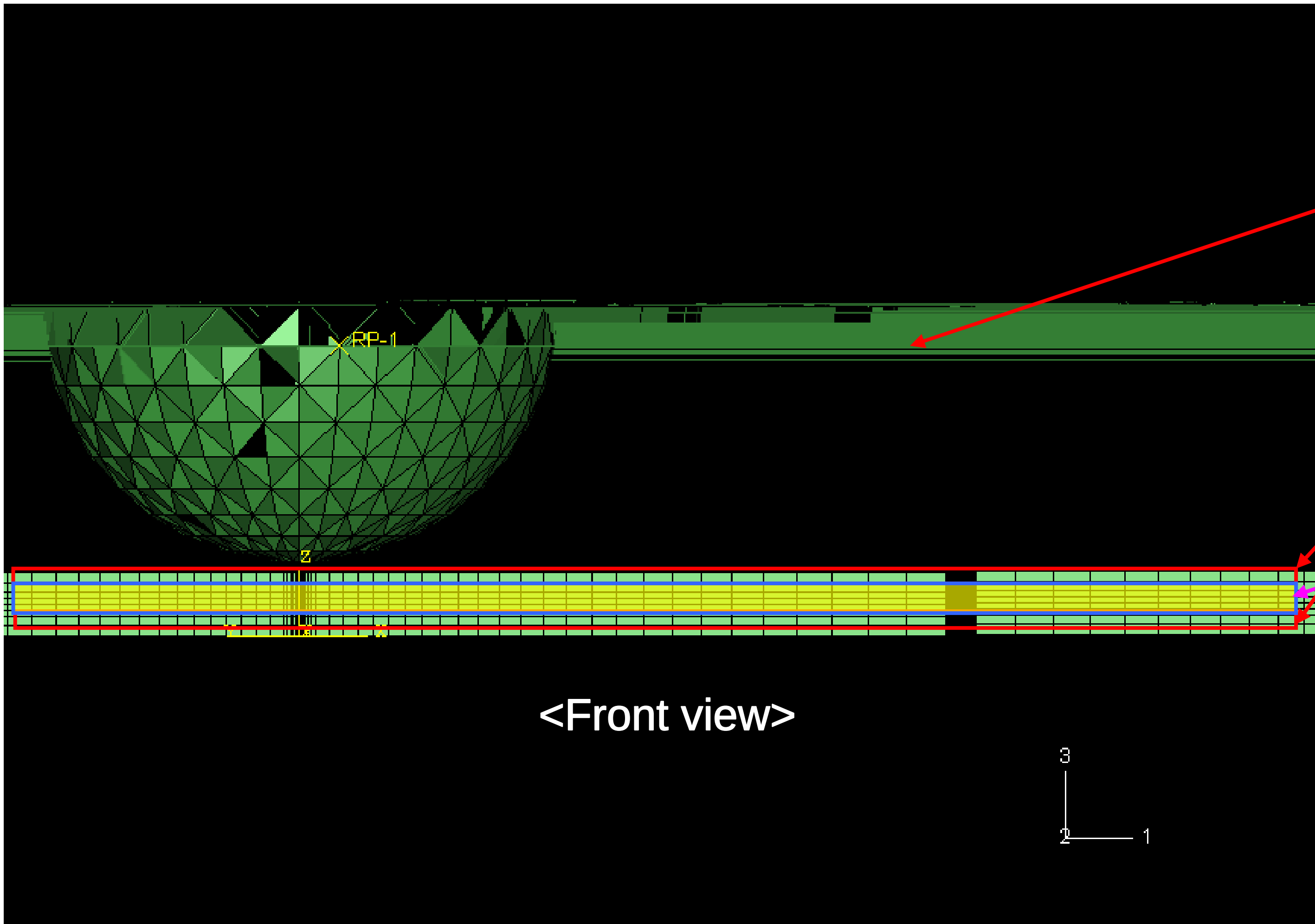
Composite failure

Matrix & Fiber failure

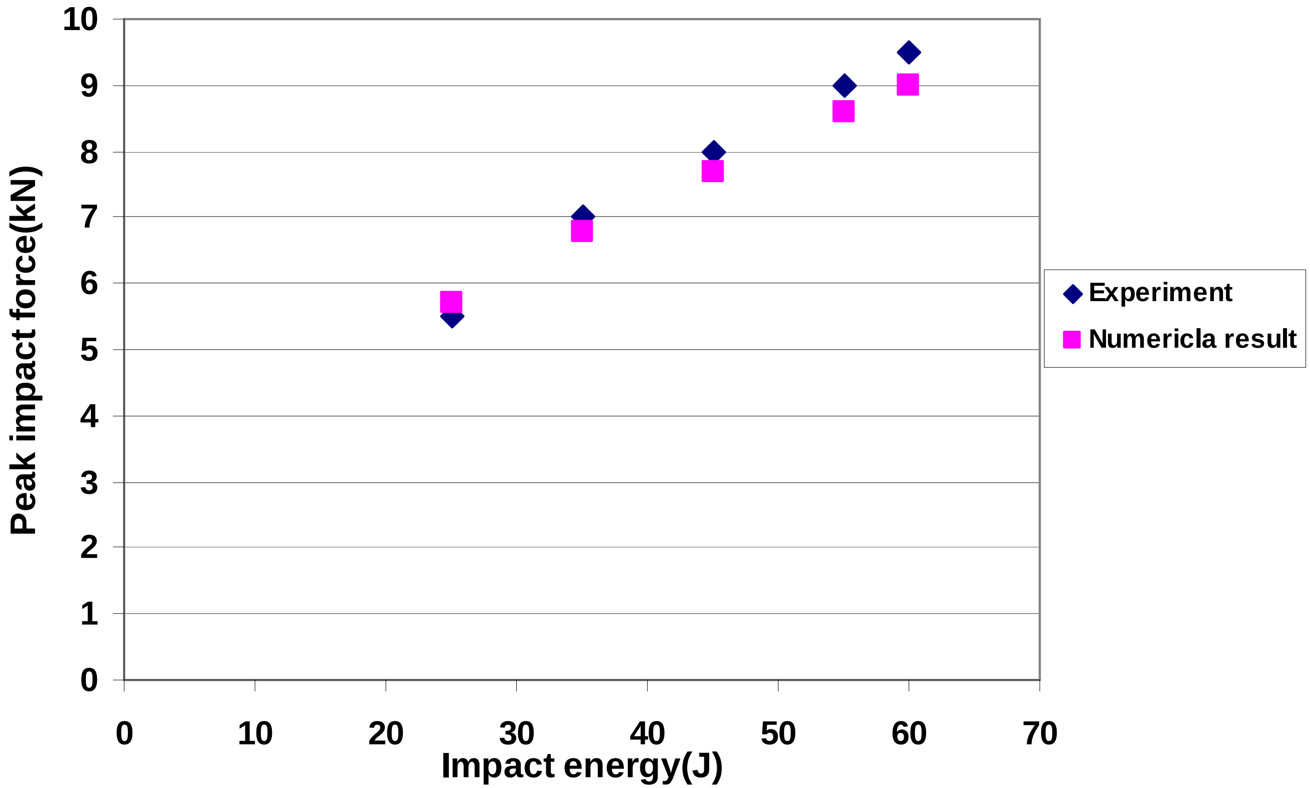
Delamination zone

residual property and structural integrity

Mesh geometry for GLARE 5-2/1(Cont'd)



Numerical results for AL 2024-T3



Experiment data was obtained from literature "Impact damage in Fiber Metal Laminates, Part 1: Experiment", 2005, AIAA

Numerical result for peak impact

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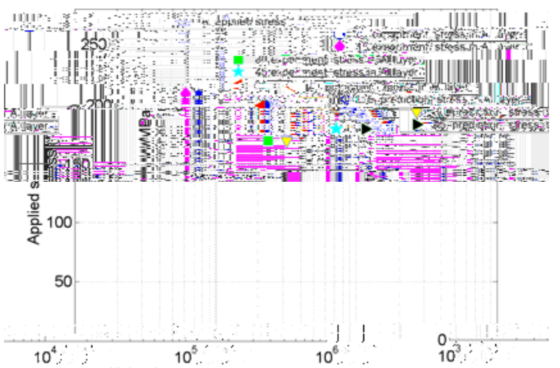
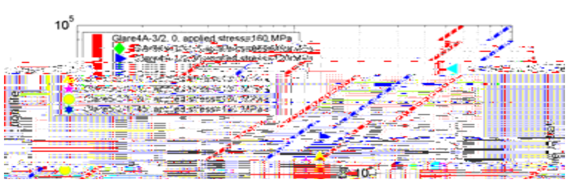
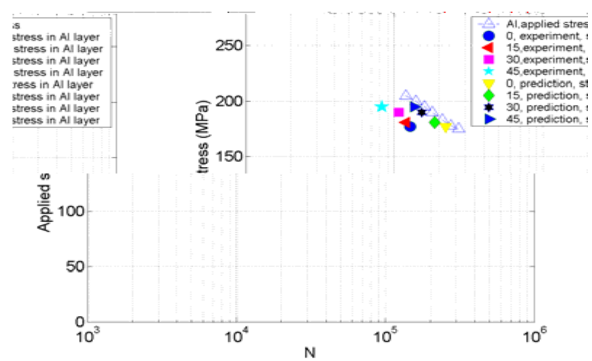
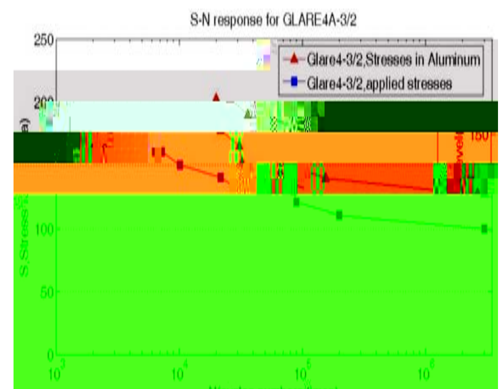
Crack initiation life in Glare laminates

- Crack initiation occurs in the metal layers of Glare laminates under fatigue loading.
- The crack initiation life was obtained experimentally and analytically (lamination theory).
- Top-left: Glare4A-3/2   Top-right:Glare5-2/1
- Bottom-right: comparison of experimental results v.s. predicted results
- Bottom-left:*S-Ni* curve for Glare laminates.









Prediction of fatigue crack growth rate

Calculation of bridging stress intensity factor

- Using crack opening displacement relationship

[illegible]

- The governing equation is expressed as

$$\sigma_{br} = M_{ij}^{-1} N \qquad N = u_{\infty}(x) - \delta_{pd}(x) - (\sigma_e / E_e) f(x)$$

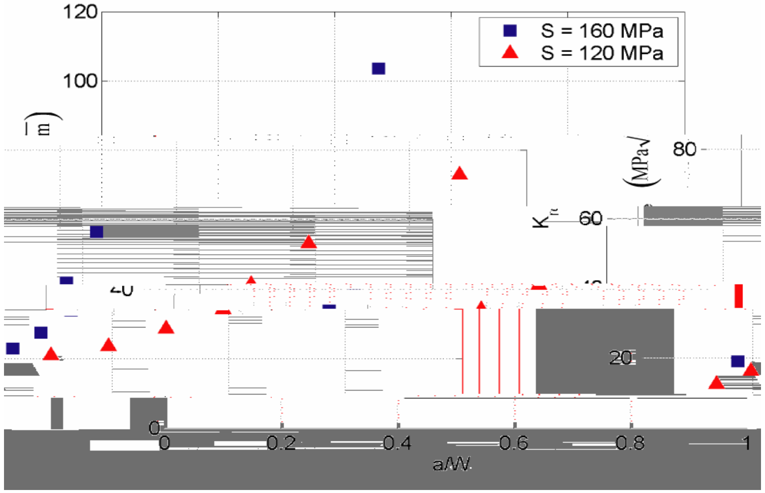
$$M_{ij} = \int_0^a \frac{u_{br}(x_i, x_j)}{\sigma_{br\_Al}(x_j)} dx_j - \frac{f(x_i)}{E_e} \delta(i, j)$$

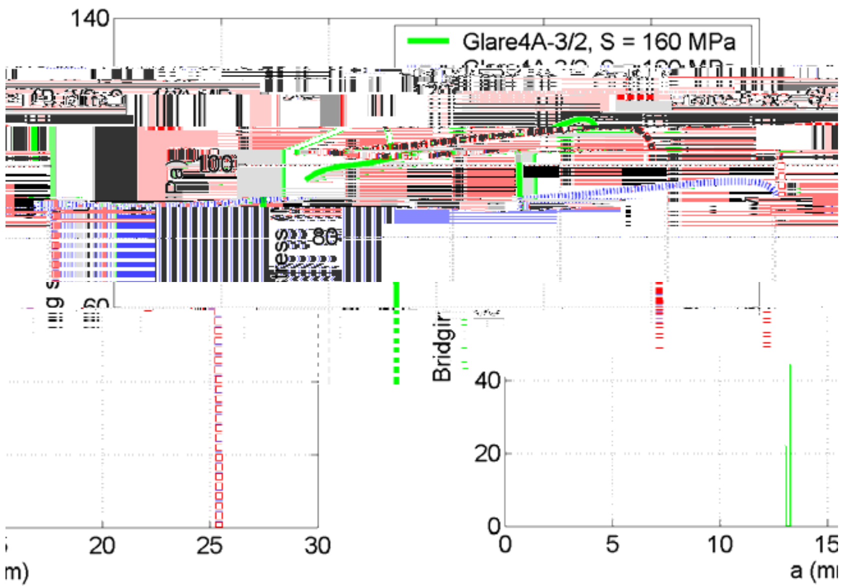
- Bridging stress intensity factor

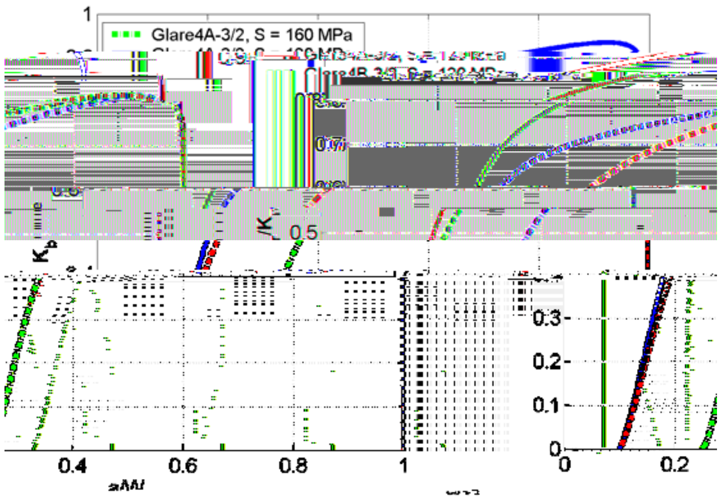
$$K_{III} = \frac{2\sigma_{br,Al} dx_j}{[illegible]} \frac{a}{[illegible]} \left(1 + \frac{1}{[illegible]} (1+\nu) \frac{f^2}{[illegible]} \right)$$

Bridging stress and stress intensity factors

- Top: The remote SIF increased as crack length increased but not proportionally.
- Bottom-right: The normalized bridging SIF increased as crack length increased.
- Bottom-left: Distribution of bridging stress

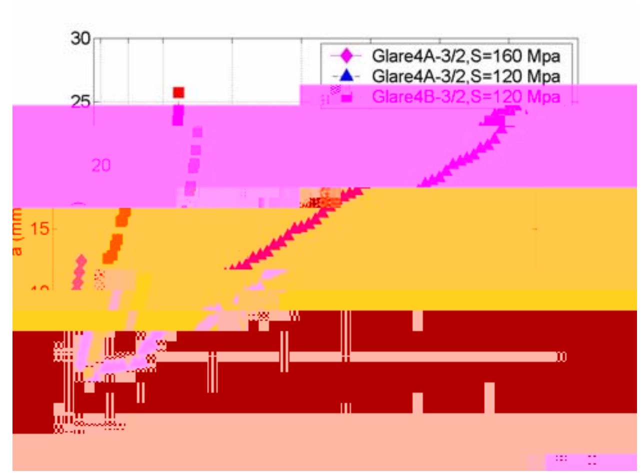


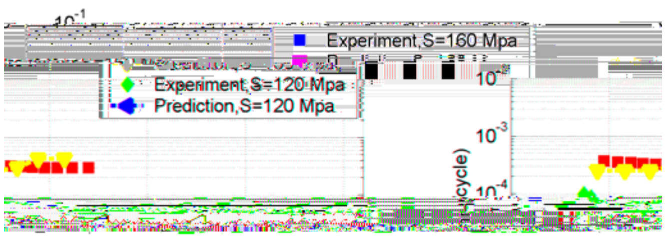


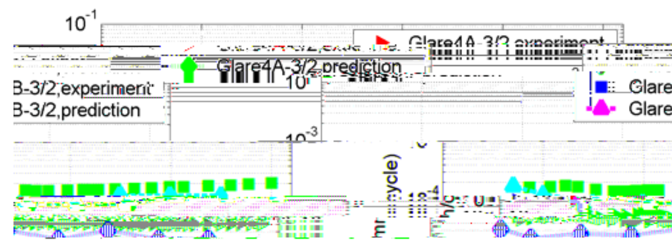


Prediction v.s experimental results

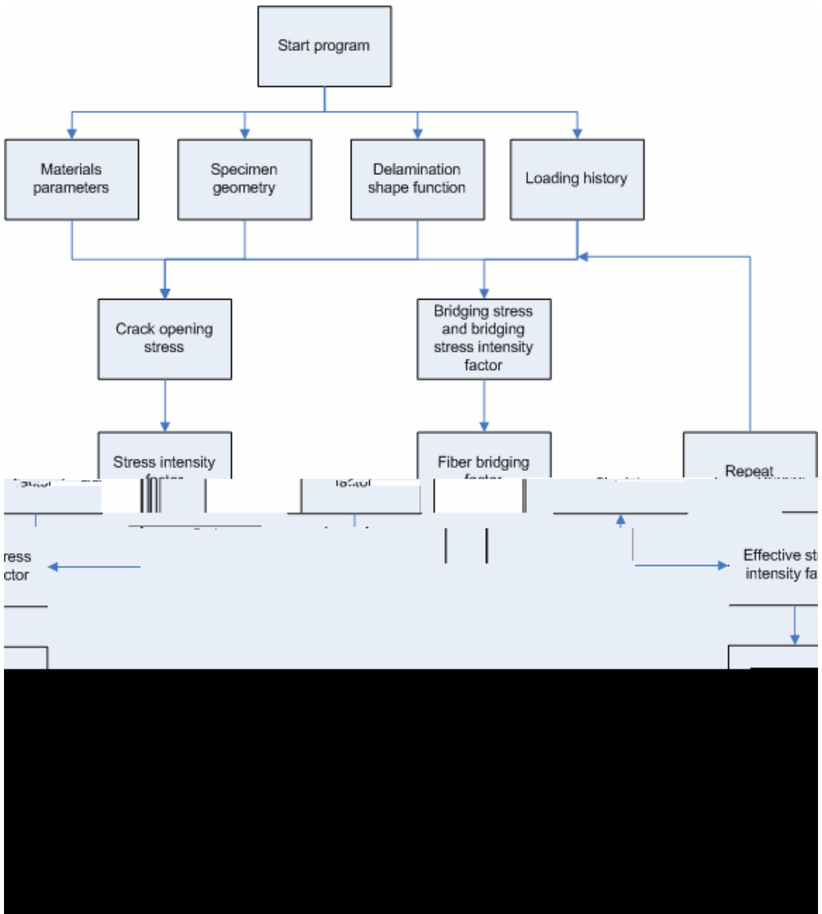
- Using 3-D FEM and 2-D bridging stress approach.
- A constant crack growth rates was approximately reached under constant fatigue loading for Glare laminates.







Fatigue life prediction under variable-amplitude fatigue loading



$$\Delta K_{eff,k} = ((\sigma_{\max,k} - \sigma_{o,k})\sqrt{\pi a_{k-1}}F)(1-\beta_k)$$

$$\Delta a_k = a_k - a_{k-1} = C\left(\Delta K_{eff,k}\right)^n$$

$$\sigma_{op} = \left(A_0 + A_1 R\right)\sigma_{max}, \text{ for } 0 > R \geq -1$$

$$A_0 = \left(0.825 - 0.34\alpha + 0.05(\alpha)^2\right)\left[\cos\left(\frac{\pi}{2}\frac{\sigma_{\max}}{\sigma_{\text{flow}}}\right)\right]^{1/\alpha}$$

$$A_2 = \left(1 - A_0 - A_1 - A_3\right)$$

$$A_3 = \left(2A_0 + A_1 - 1\right)$$

Newman J.C., A crack opening stress equation for fatigue crack growth, Int. J. Fract. 24, R131–R135, 1984.

Prediction results of block spectrum loadings

- The Glare laminates experienced high-low loading sequence had better fatigue resistant ability than that subject

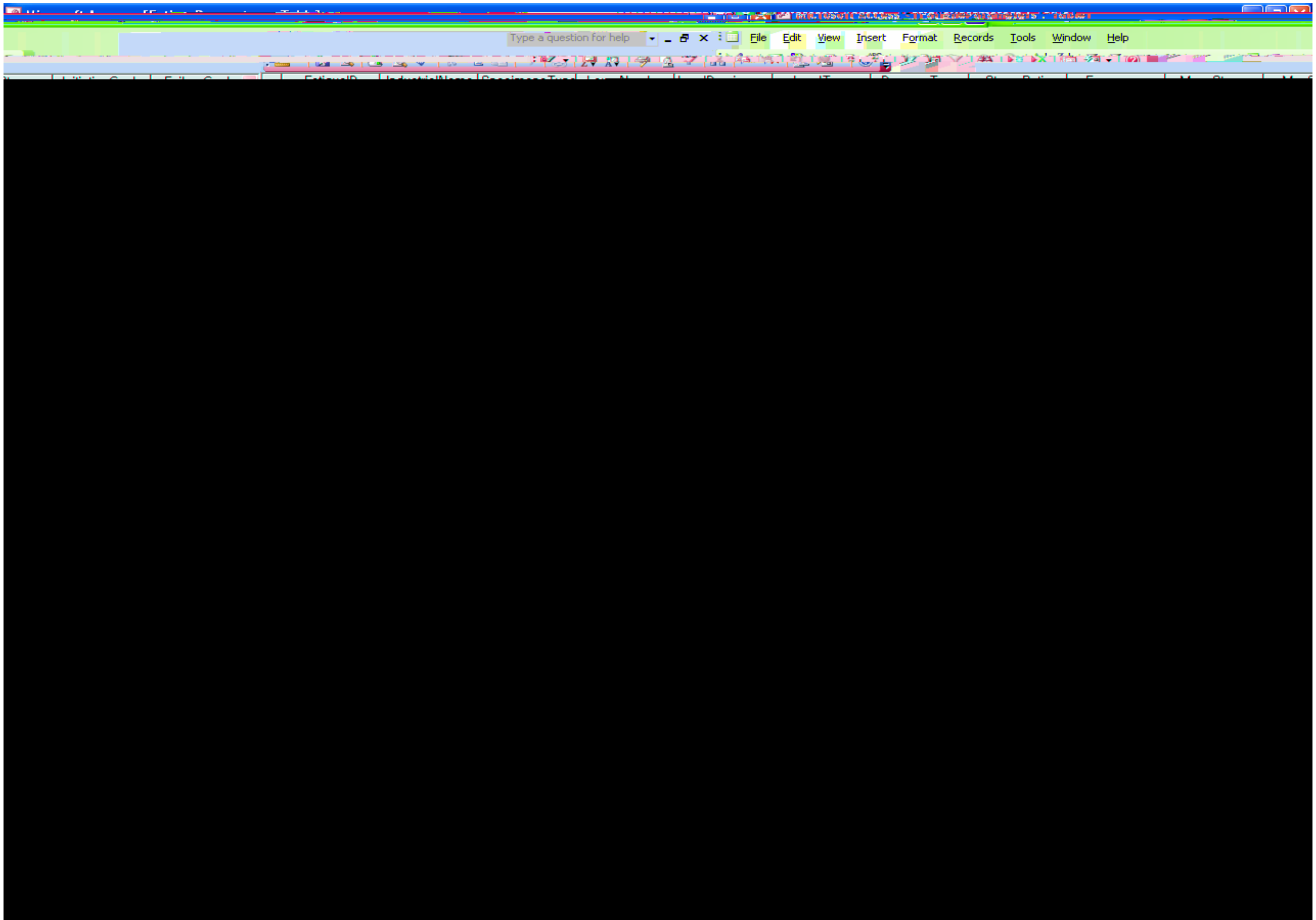
Highlights of Fatigue Analysis and Work In Progress

- **Analytical and numerical analysis of fatigue crack initiation and**

Information system for fiber metal laminates

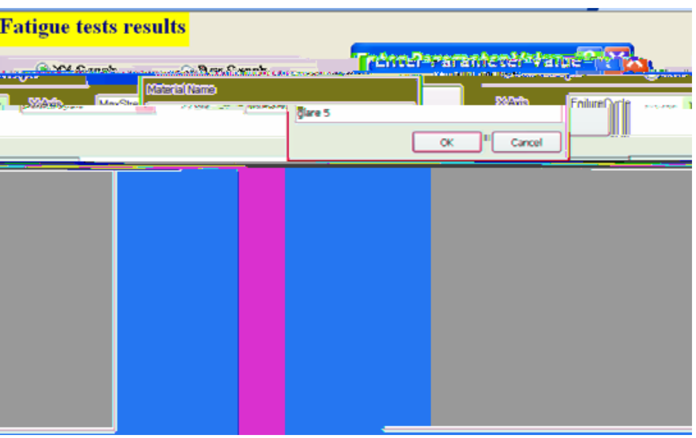
- Database for GLARE laminates: collect and compile experimental data from published literatures.
- The developed information system for the GLARE provides analysis over multiple sets of data collected under different experimental studies
- It allows for the comparison of different GLARE with various geometry and loading condition

Updated database for fatigue behavior



Data retrieval system for fatigue behavior

* Given query   Material name: GLARE 5-2/1



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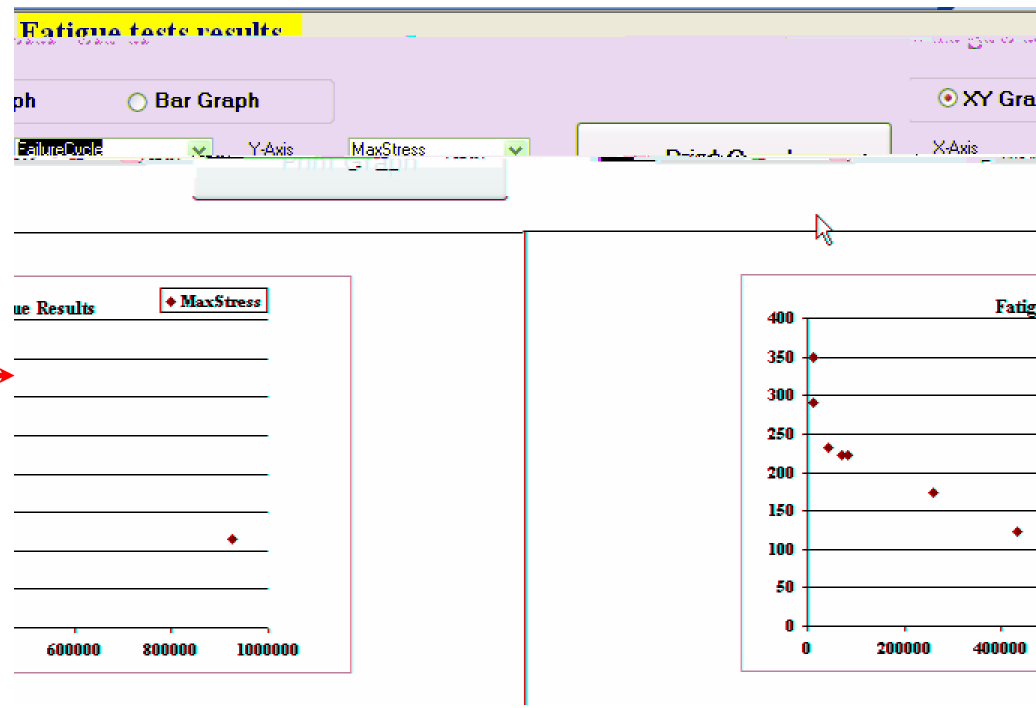
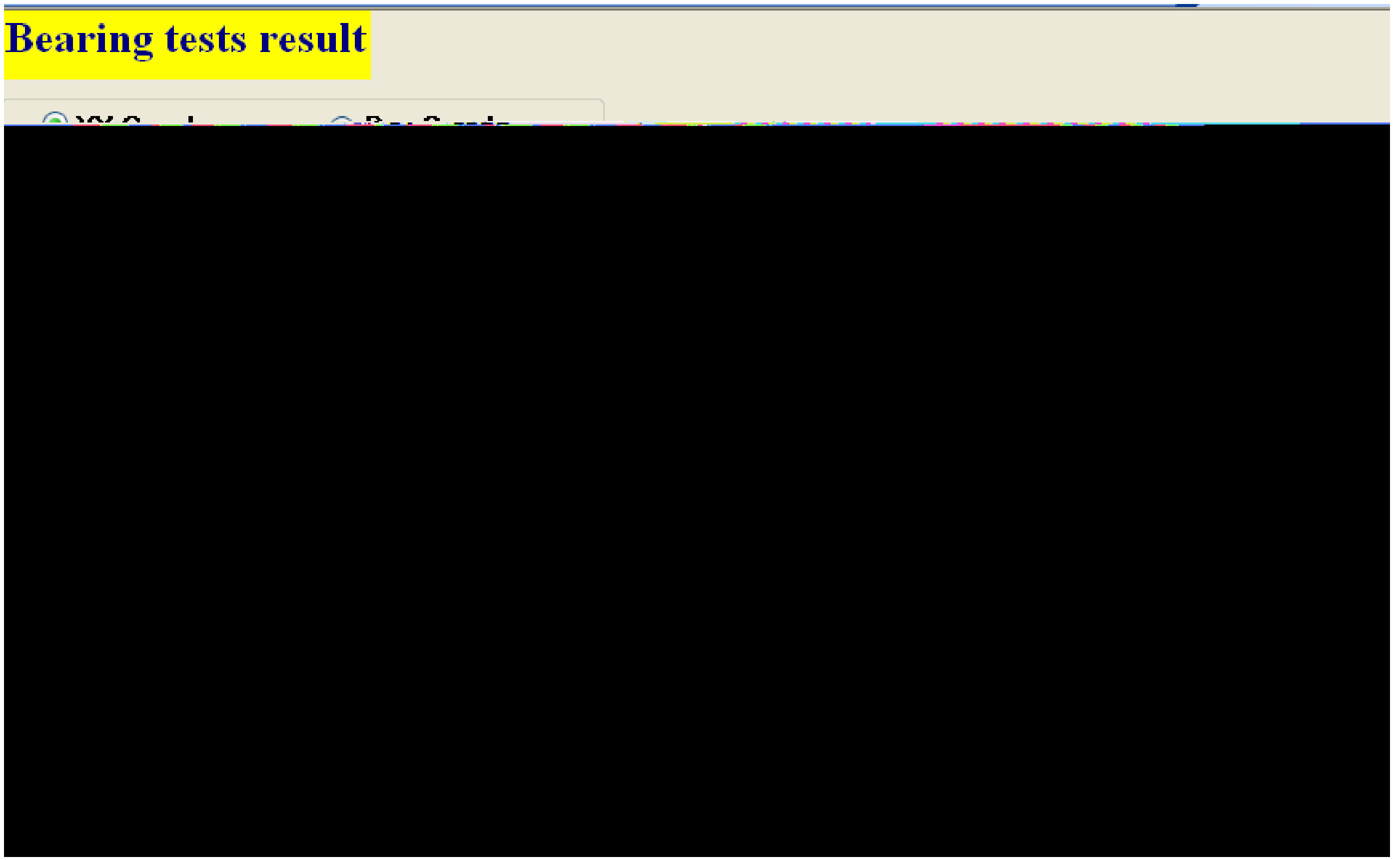


<Max. stress vs. Number of cycles>

Data retrieval system for bearing behavior

Given query: GLARE 3-3/2-Bolt



<W/D vs. Bearing ultimate strength>

A Look Forward

- **Benefit to Aviation**

  --Development of analytical models validated by experiment and the information system are critical to design optimization and to support the airworthiness certification.

- **Future needs**

  --fatigue damage evolution under variable amplitude fatigue

  --Constant and variable amplitude fatigue of mechanically fastened joints

  --New generation of fiber metal laminates