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

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- **Other FAA Personnel Involved**
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- **Industry Participation**
  -Raytheon Missile Systems

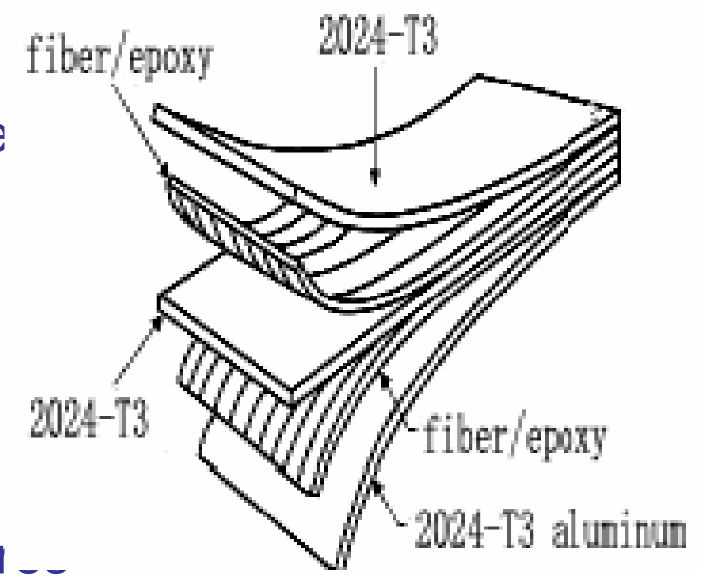
Damage Tolerance and Durability of Fiber-Metal Laminates for Aircraft Structures

- Motivation and Key Issues
  - **Fiber metal laminate is a new generation of primary structure for pressurized transport fuselage. However, there are limited and insufficient information available about mechanical behavior of FML in the published literature, and some areas still remains to be further verified by more detailed testing and analysis.**
- Objective
  - **To investigate the damage tolerance and durability of bi-directionally reinforced GLARE laminates. Such information will be used to support the airworthiness certification and property optimization of GLARE structures**
- Approach
  - **To develop analytical methods validated by experiments**
  - **To develop information system**

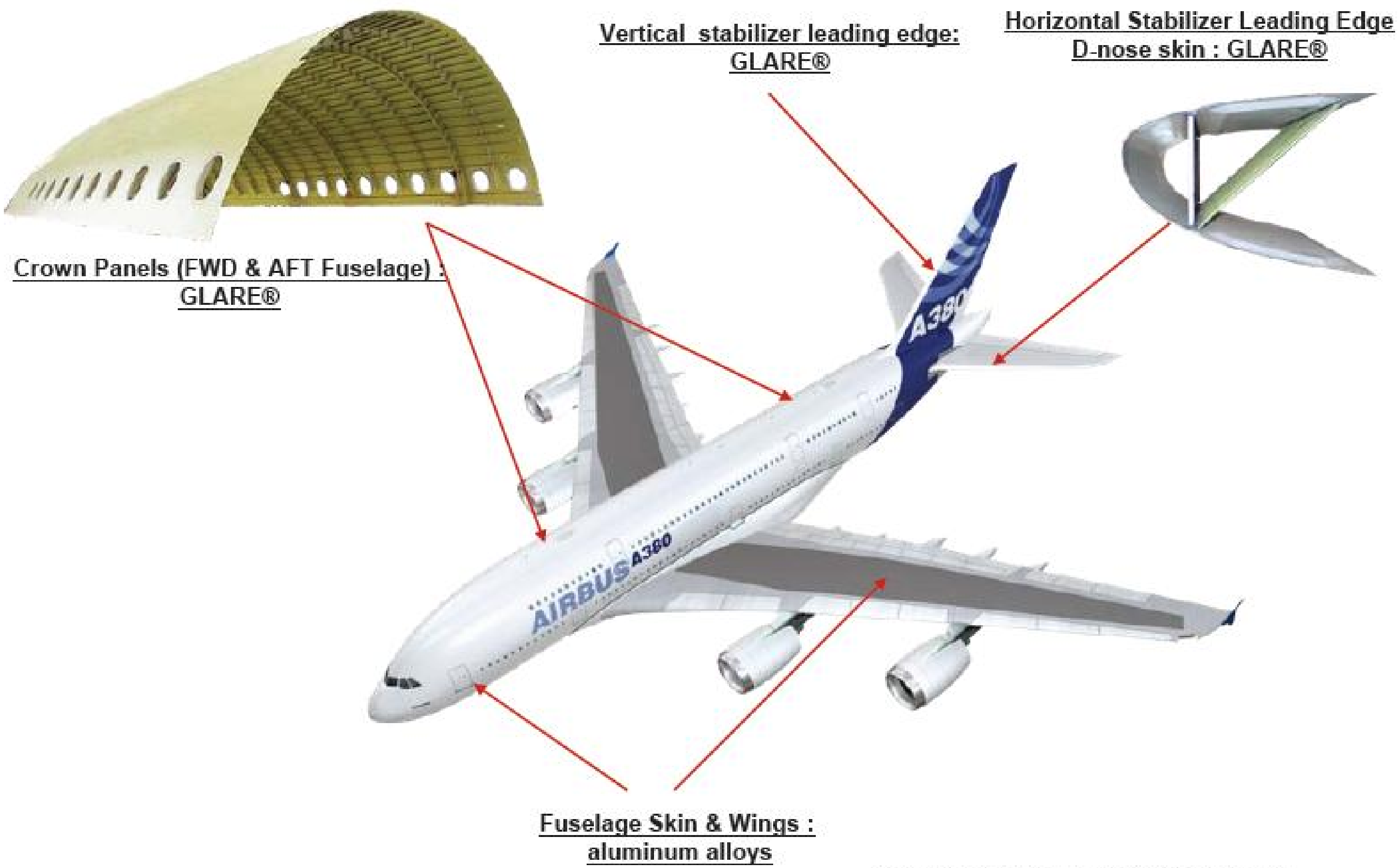
Background

- **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



Applications of GLARE in A380



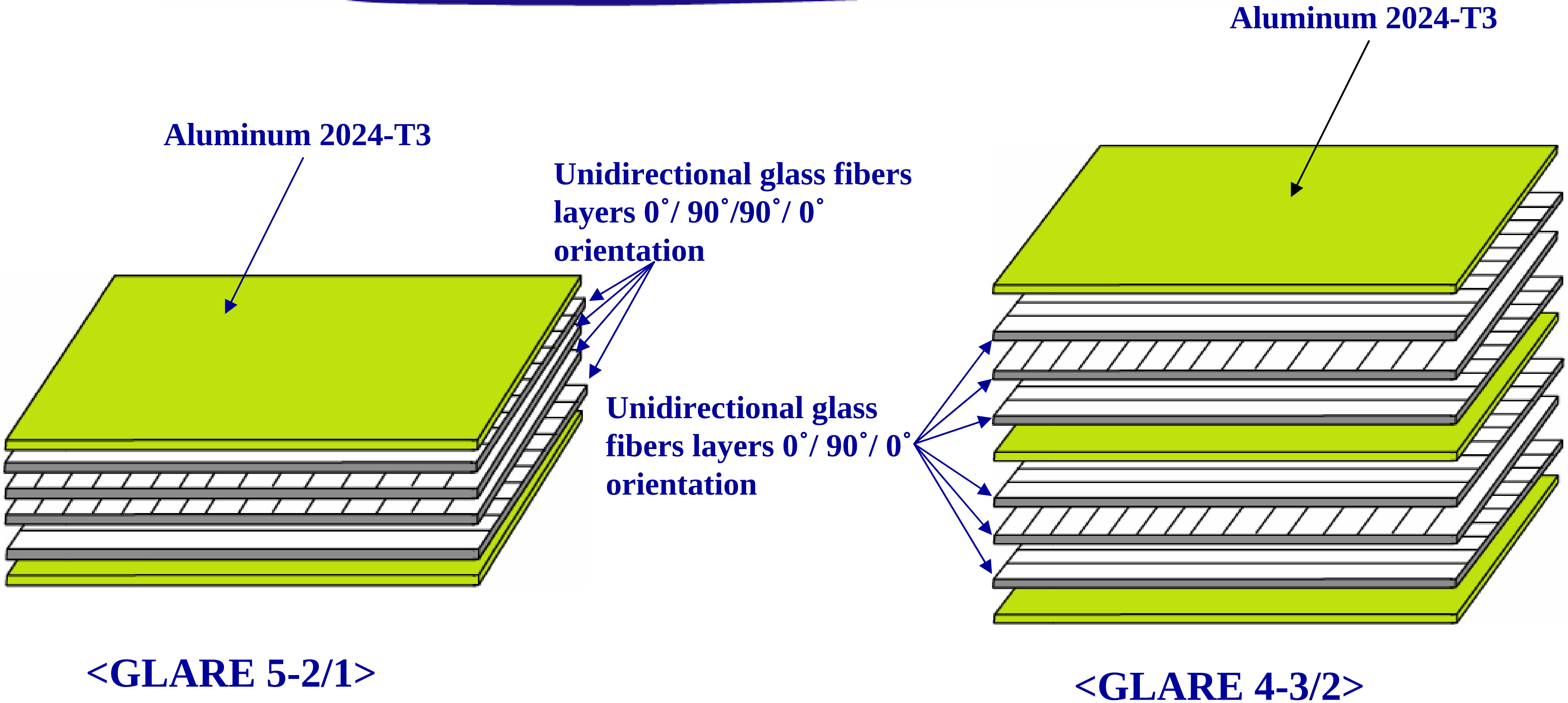
GLARE®: GLAss fiber REinforced aluminum

Project Scope

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

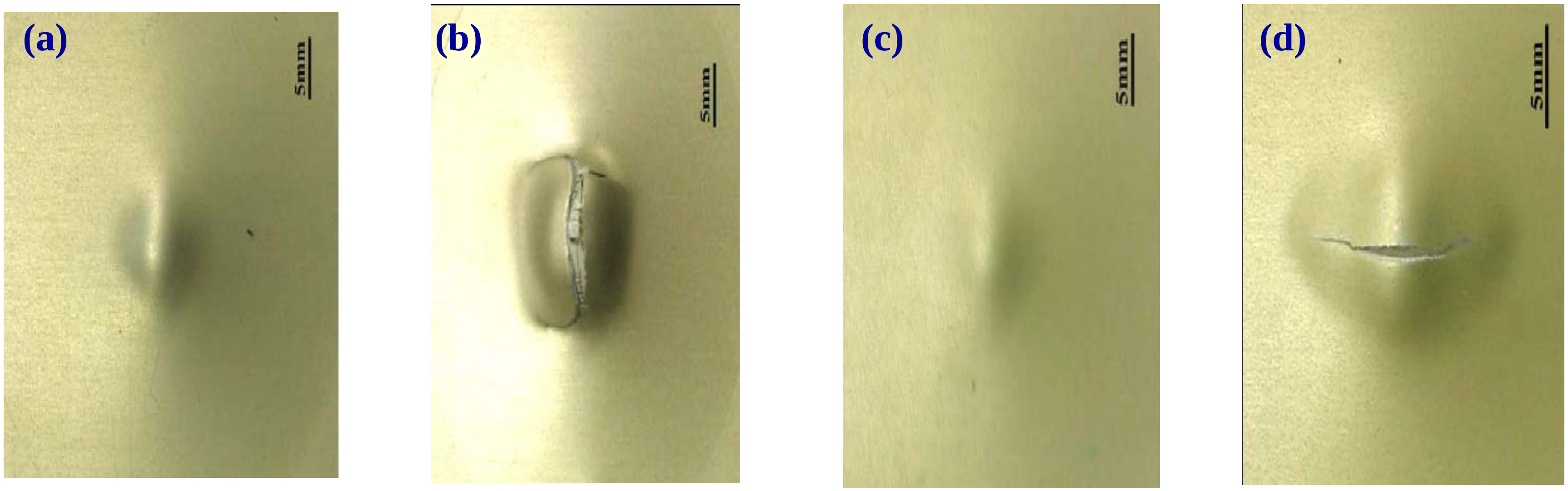
- **Residual Strength Modeling and Validation**
  --open-hole notch strength
  --residual strength after impact
  --open-hole notch strength after fatigue
- **Impact Behavior and Numerical Simulation**
- **Post-Impact Fatigue Behavior**
- **Fatigue Crack Initiation/Growth Modeling and Validation**
-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

Materials / GLARE 4 and GLARE 5



** Provided by Aviation Equipment, Inc. (Costa, Mesa, CA)*

Impact damage in Glare Laminates



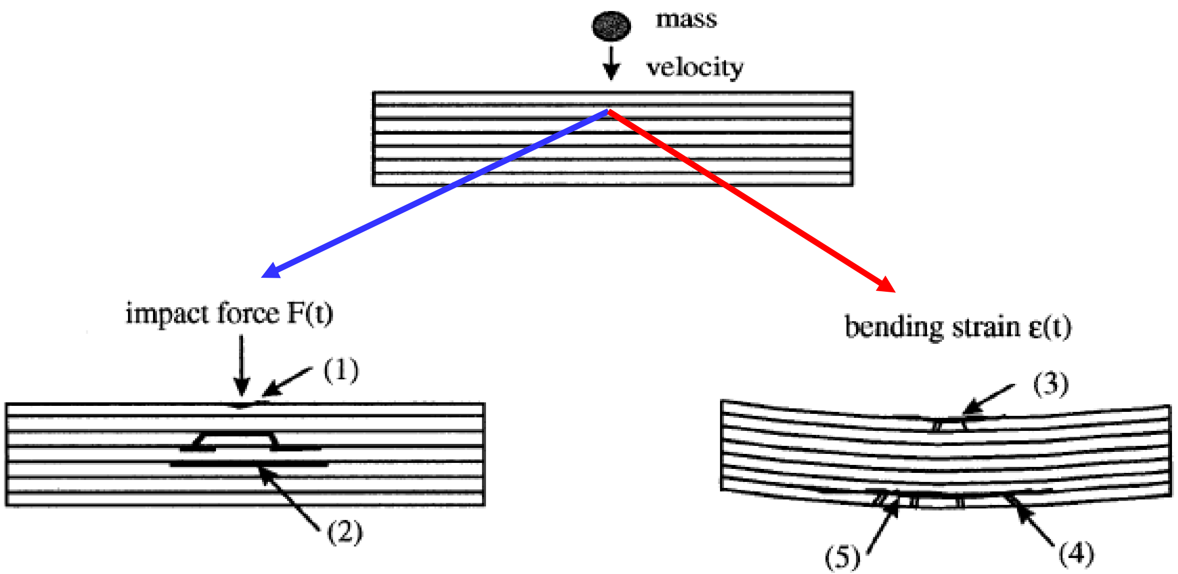
(a) Dent damage (E=10.8 J) GLARE 5

(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



(1) Contact damage or crushing or dent
(2) Internal delamination due to transverse shear stresses
(3) Failure on impact face due to compressive strains
(4) Al cracking on back face due to tensile strains
(5) Delamination due to back-face matrix cracking

Impact modeling is complex and challenging

Numerical Analysis of Impact

FEM simulation for dynamic contact

VUMAT for developing failure of composite layer

Impact force & 3-D Stress analysis

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

Detect damage & Update stiffness

- Failure of aluminum layer
- Failure of composite layer

Composite failure

Matrix & Fiber failure

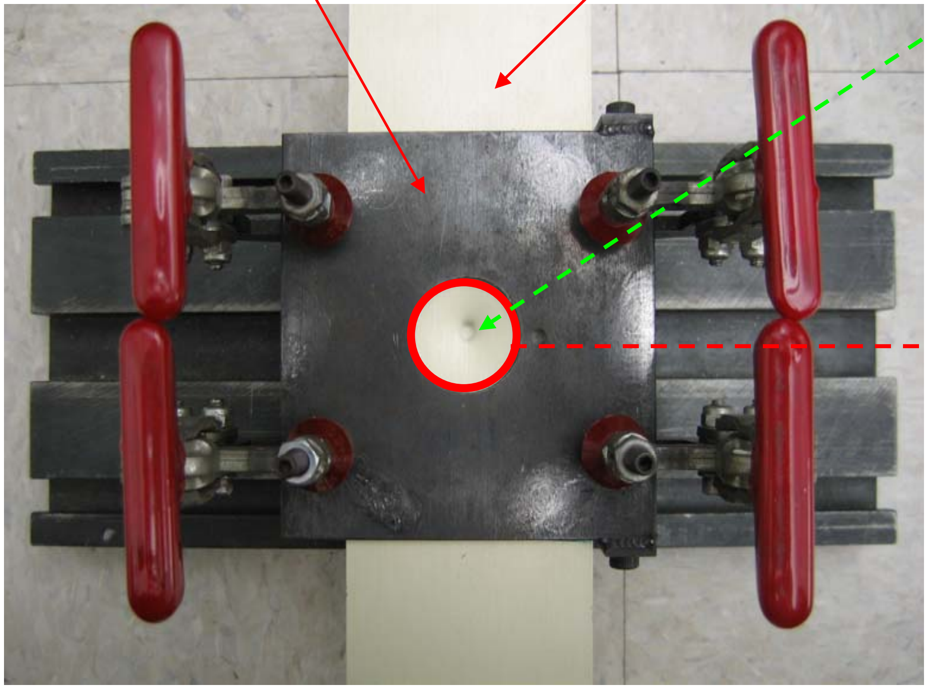
Delamination zone

residual property and structural integrity

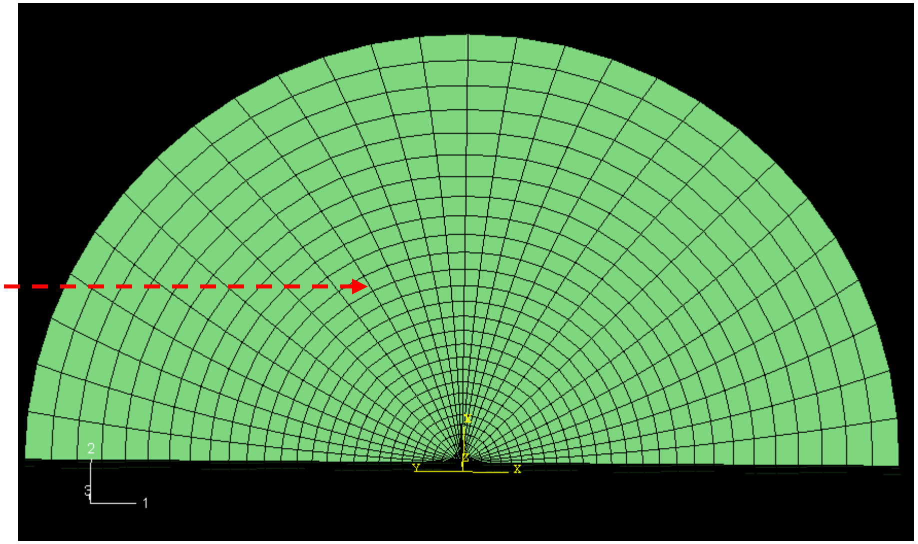
Numerical model (mesh geometry)

Fixture for impact test GLARE laminates Impact damage by steel impactor

<Mesh geometry>



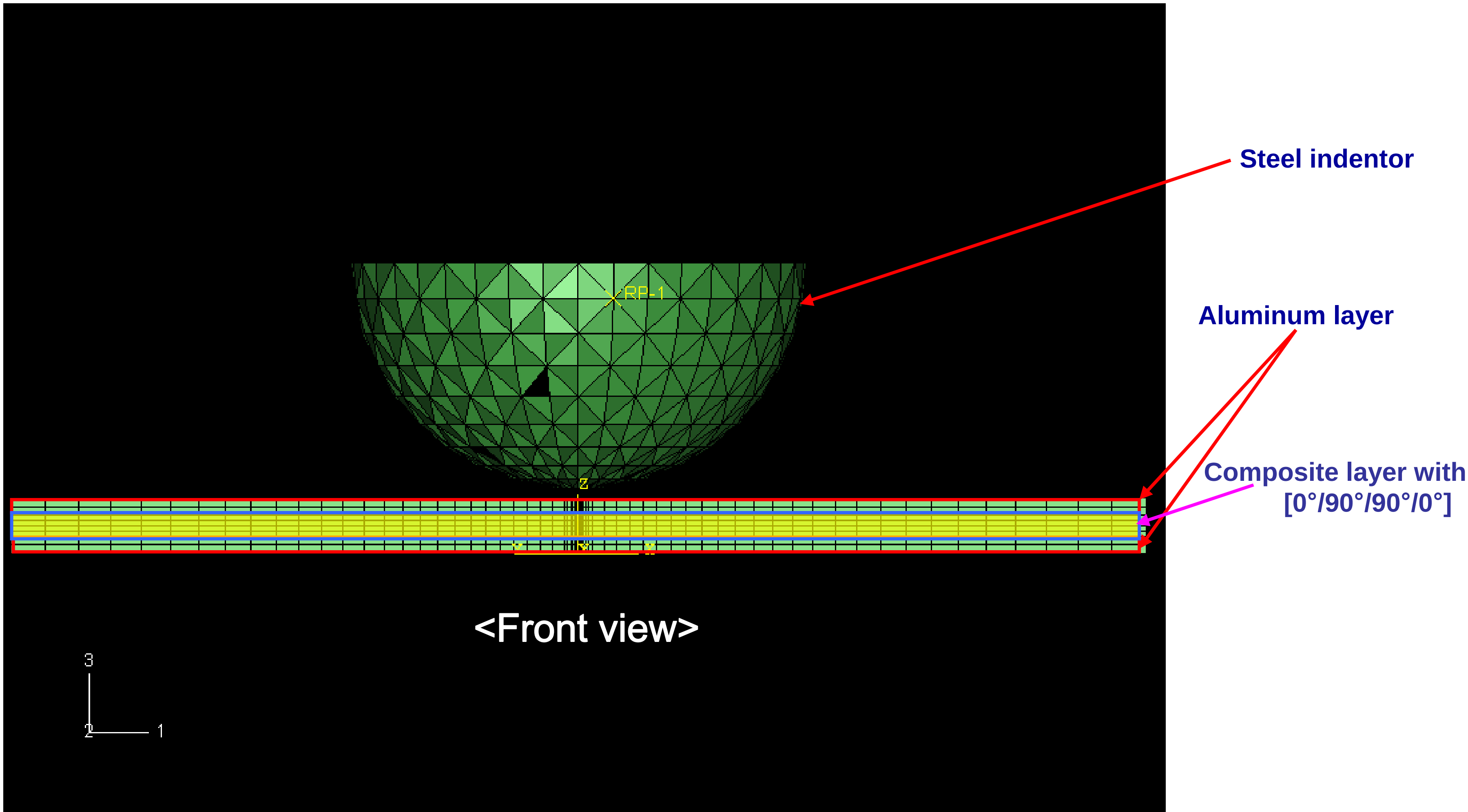
<Top view>



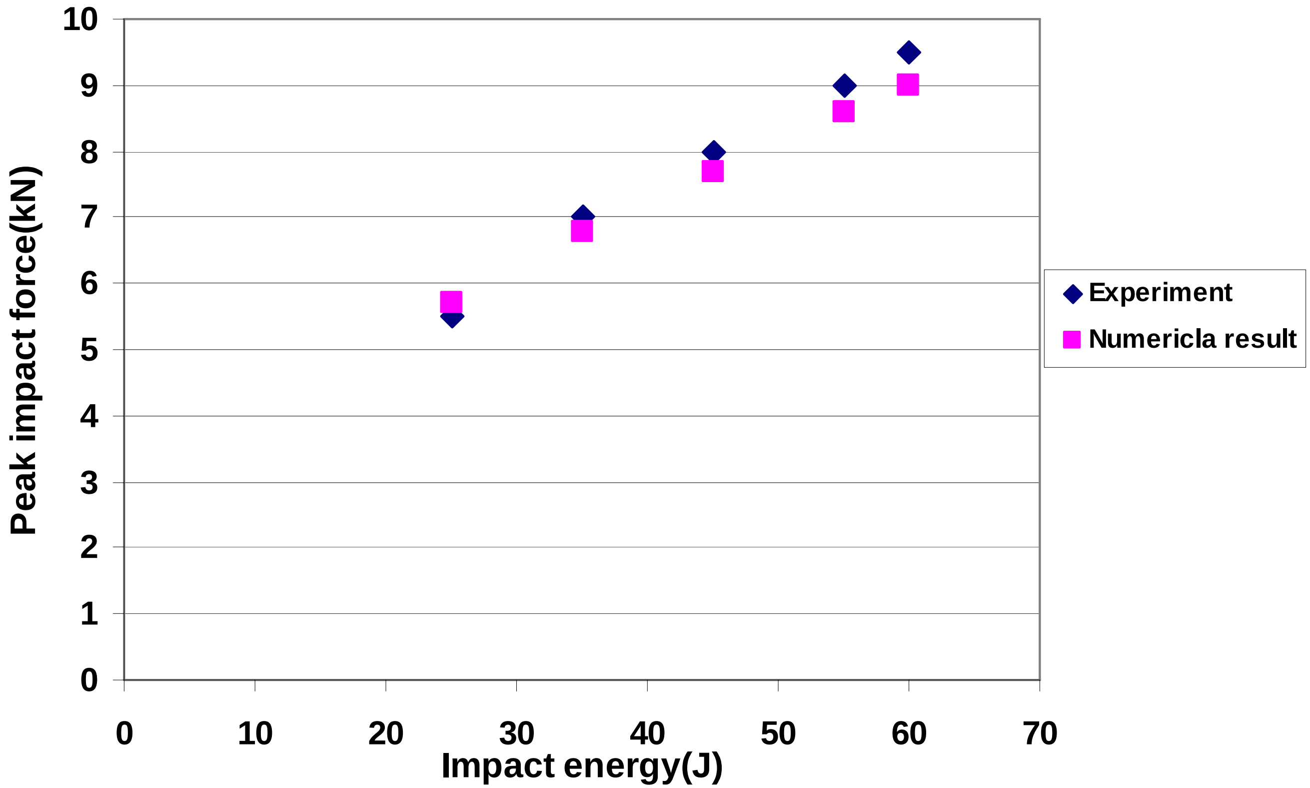
<Top view of FEM>

- The specimens were clamped between two steel plates with a 114.3 x 114.3 mm² circular central opening with 31.7 mm diameter in the impact fixture
- The weight of impactor: 6.29 Kg

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

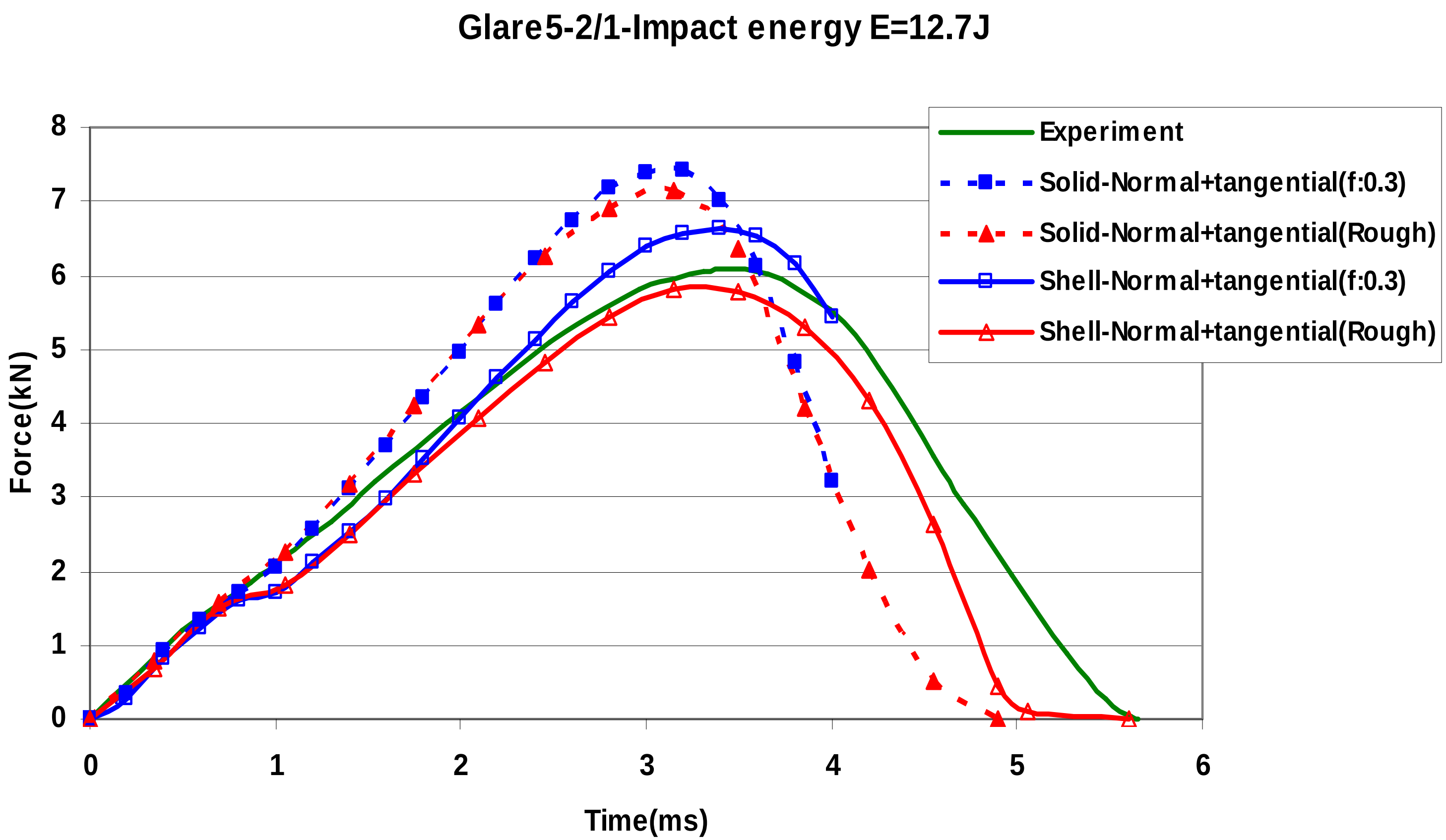


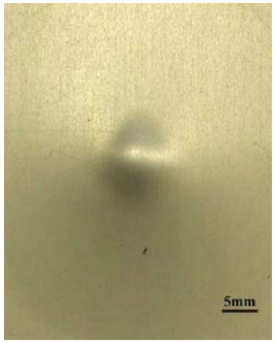
Numerical results for AL 2024-T3



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

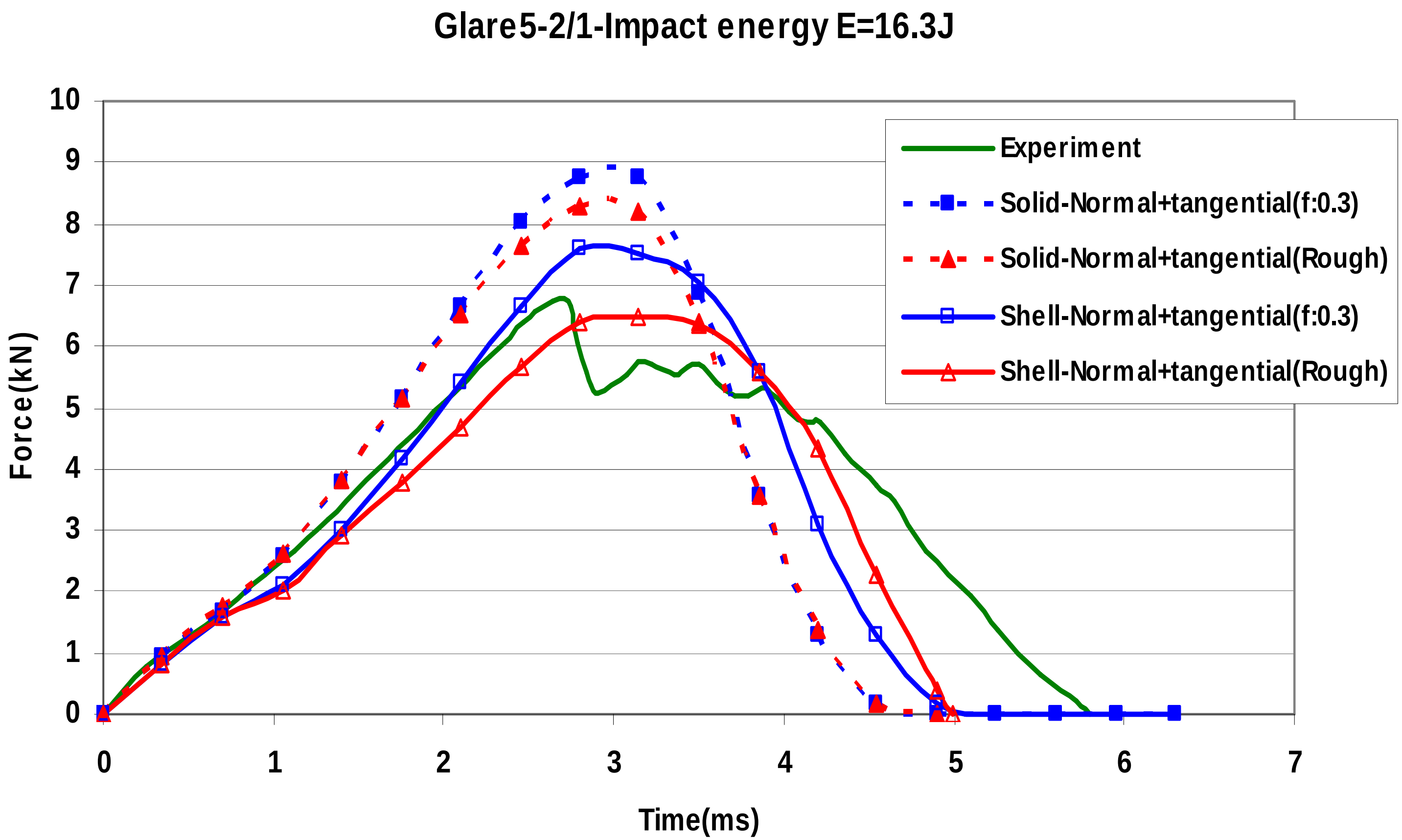
Numerical result for peak impact force

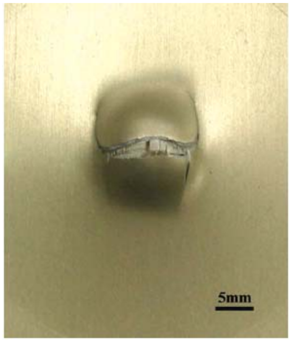




<BVID>

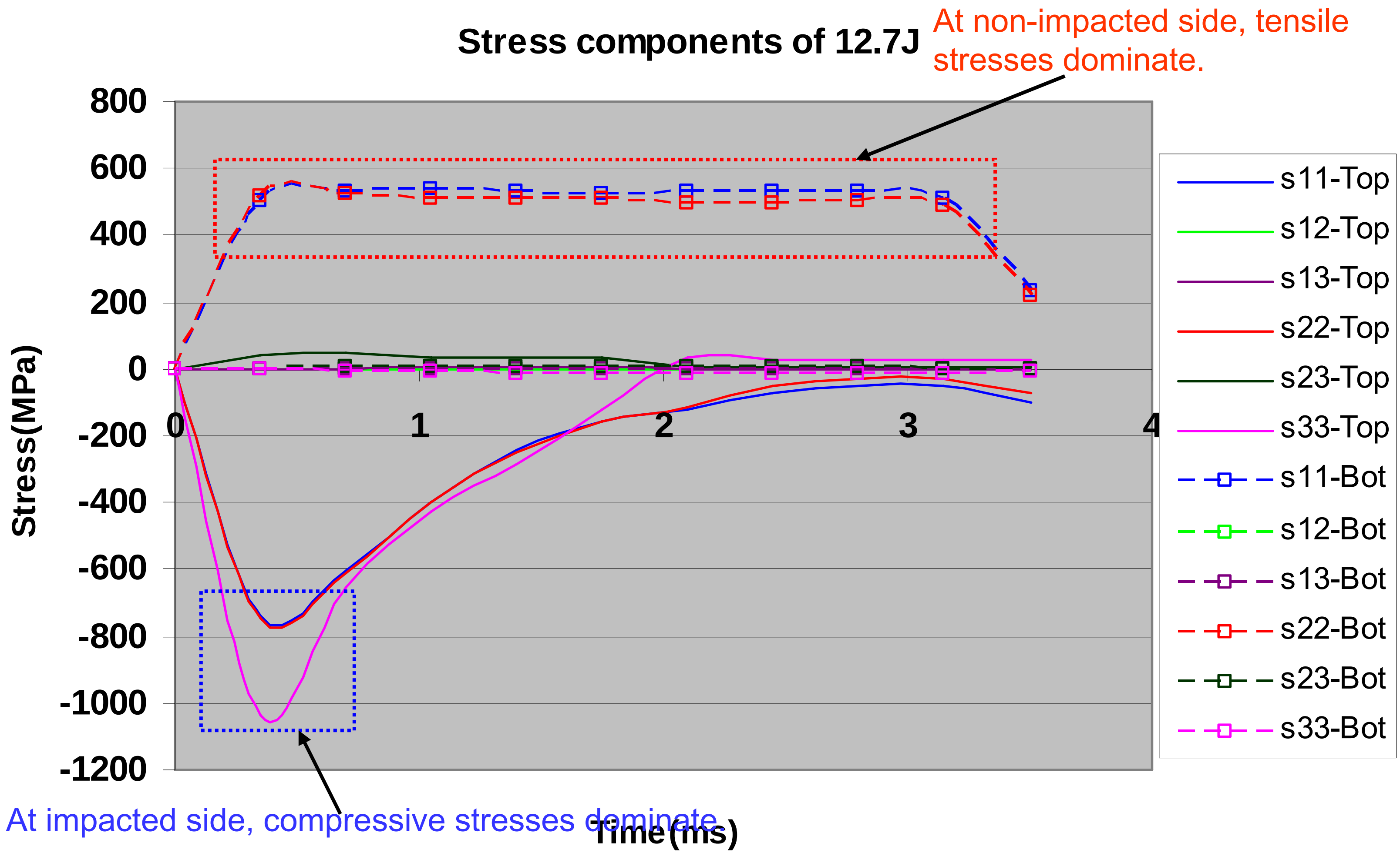
Numerical result for peak impact force





<CVID>

Stress components-E=12.7J (FEM)



Highlights of Impact Analysis and Work In Progress

- Numerical analysis of impact was conducted. Numerical results correlate well with experimental results for impact forces vs time relationships as well as the stress distribution on aluminum layers on both impacted and non-impacted sides.

- In order to predict the occurrence of composite failure and the delamination size, VUMAT (user subroutine to define material behavior) of numerical analysis is currently being developed. This will enable us to investigate not only failure, the size of delamination of inner composite layers as well as the structural integrity under different impact energies.

- Therefore, when impact damage like BVID (barely visible impact damage) and CVID (clearly visible impact damage) is detected on the aircraft, the numerical predictions can be used for assessing the state of damage as well as the structural integrity.

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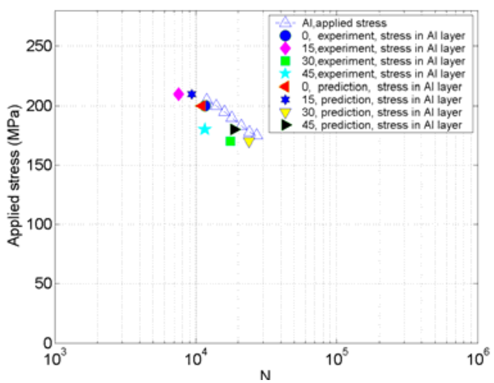
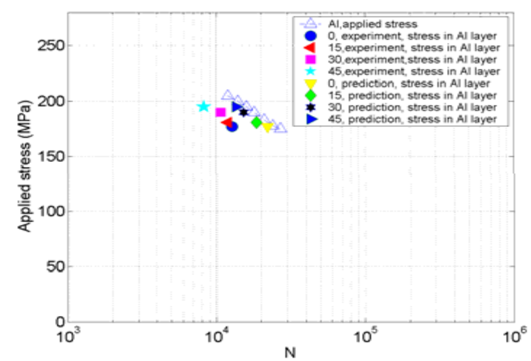
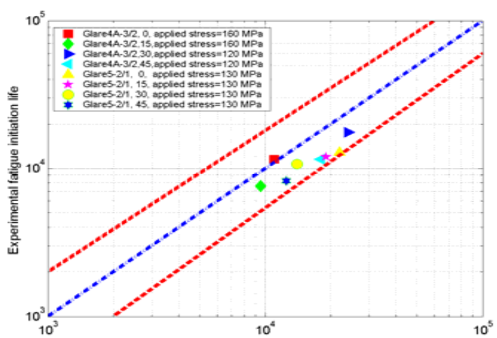
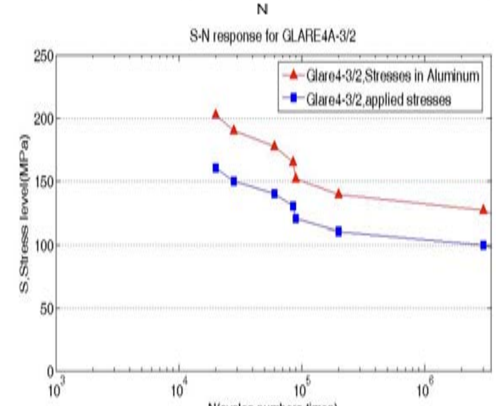
Crack initiation life in Glare laminates

- 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

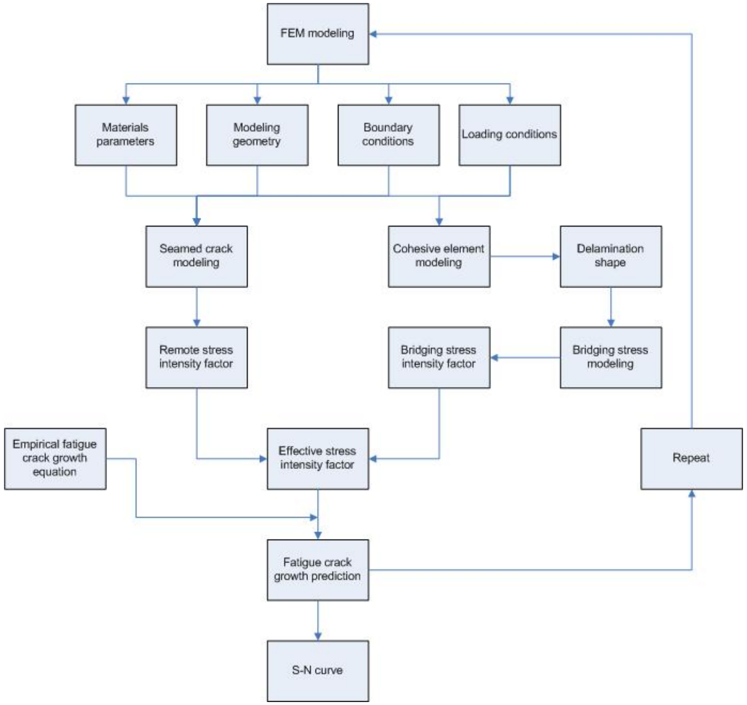
- Paris-type fatigue crack growth law:

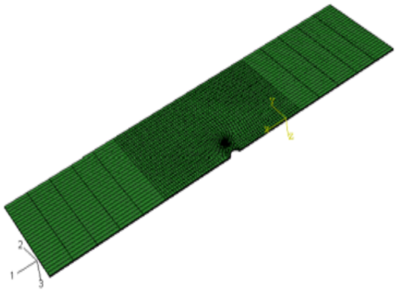
$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^{n}, \text{ where } C = 5\times10^{-11} \text{ and } n = 4.07$$

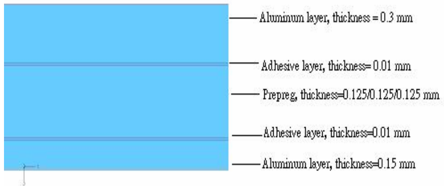
- The effective stress intensity factor is the subtraction of remote and bridging stress intensity factor.

$$K_{eff} = K_{re} - K_{br}$$

$$\Delta K_{eff} = \Delta K_{re} - \Delta K_{br} = \left(K_{re} - K_{br}\right)\times\left(1-R\right)$$







Calculation of bridging stress intensity factor

- Using crack opening displacement relationship

$$\delta_c(x)+\delta_{ad}(x)=u_\infty(x)-u_{br}(x)+\Delta$$

- The governing equation is expressed as

$$\sigma_{br}=M_j^{-1}N \qquad N=u_\infty(x)-\delta_{ad}(x)-(\sigma_c/E_c)f(x)$$

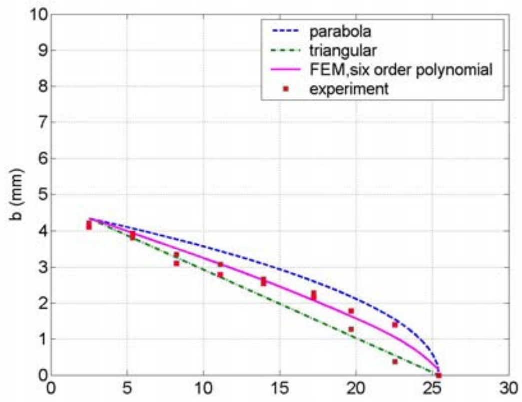
$$M_j=\int_0^a \frac{u_{br}(x_i,x_j)}{\sigma_{br,Al}(x_j)}dx_j-\frac{f(x_i)}{E_c}\delta(i,j)$$

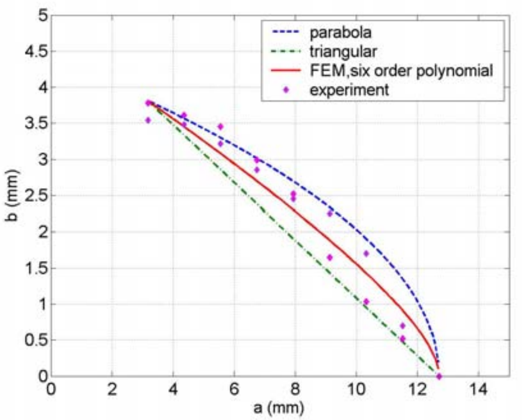
- Bridging stress intensity factor

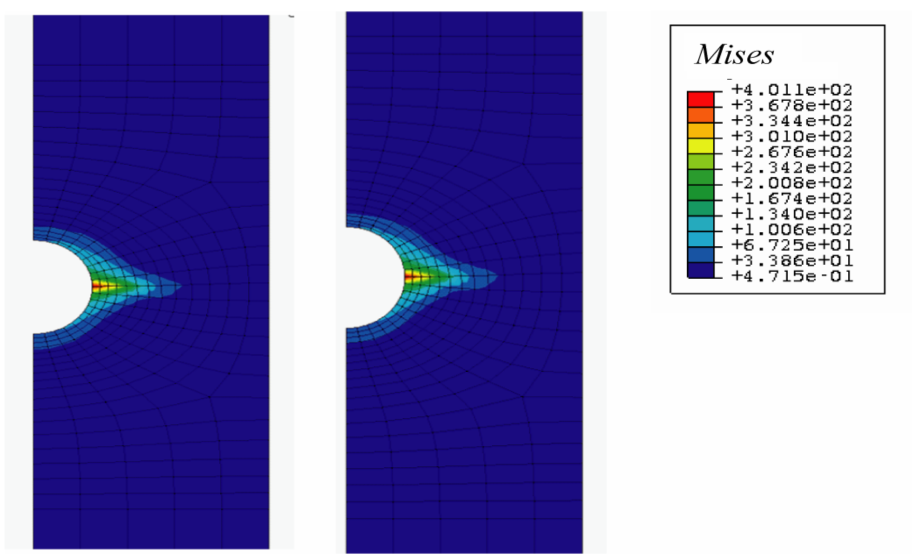
$$K_{br,j}=\frac{2\sigma_{br,Al}dx_j}{\sqrt{\pi a}}\frac{a}{\sqrt{a^2-x_j^2+f^2}}\left(1+\frac{1}{2}(1+\nu)\frac{f^2}{a^2-x_j^2+f^2}\right)$$

Damaged area (Delamination zone)

- Using FEM (ABAQUS standard), the damaged area was able to be predicted using cohesive elements with setup of failure criteria.
- Top-right and bottom-right: Delamination profiles with different notch radii.
- Bottom: Damage initiation and propagation.

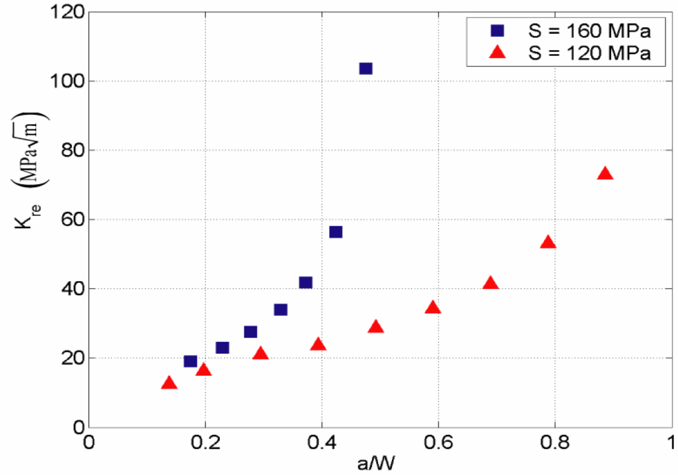


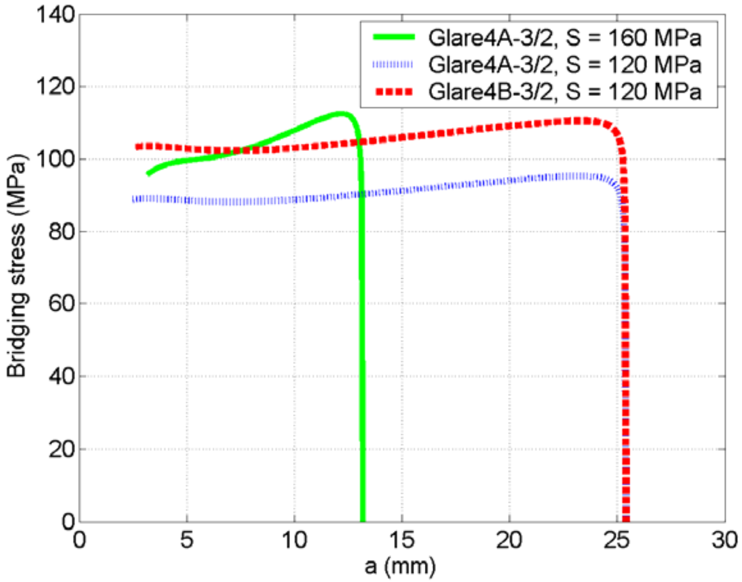


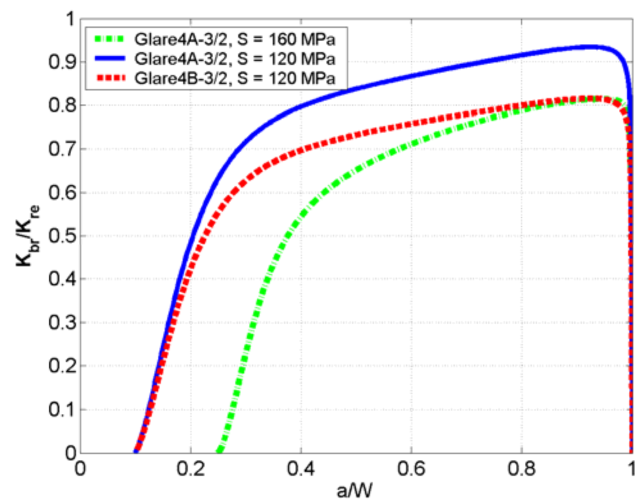


Bridging stress and stress intensity factors

- 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

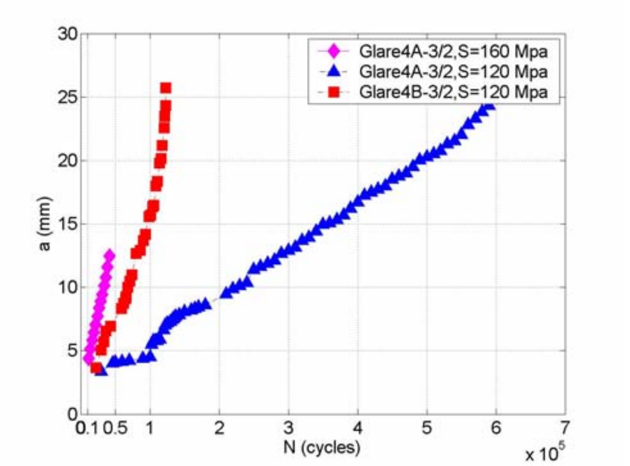


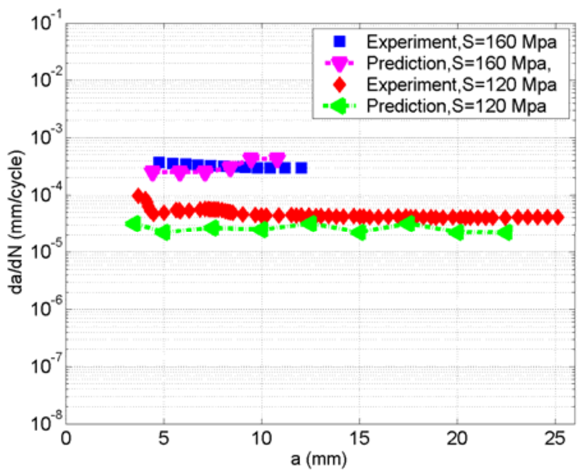


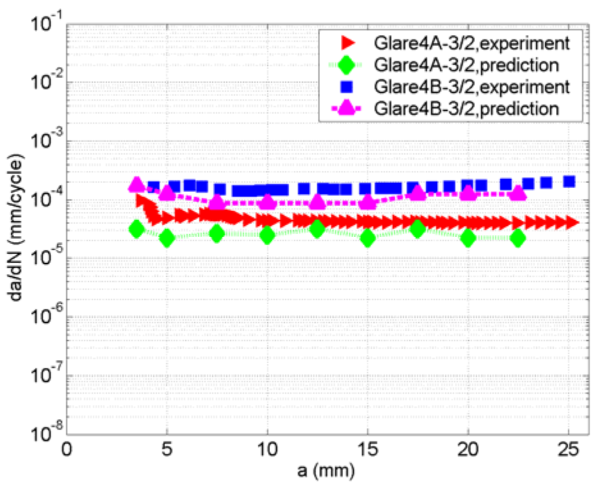


Prediction v.s experimental results

- 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.

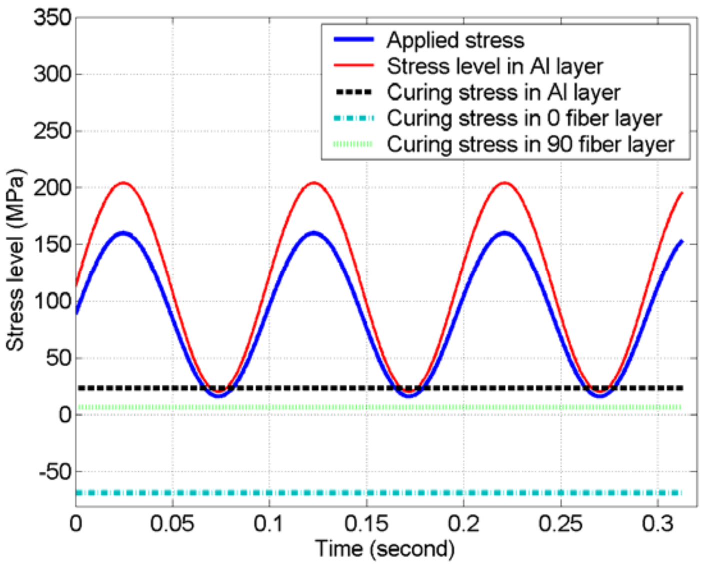


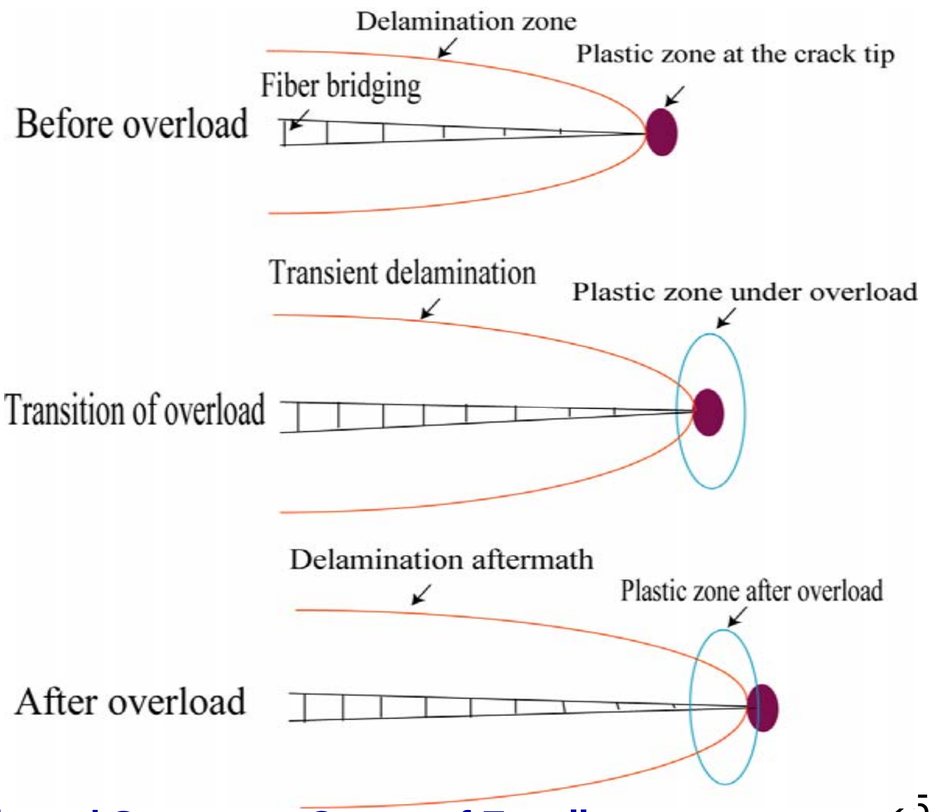




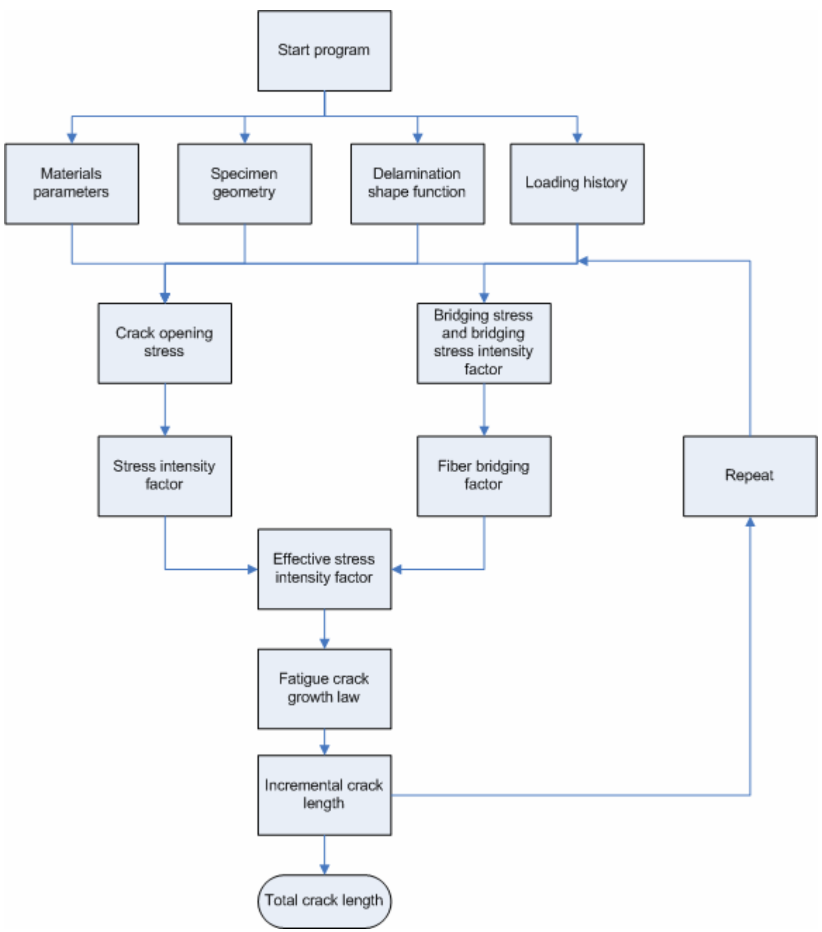
Mechanism of crack growth under variable-amplitude fatigue loading

- Mechanism of crack growth in notched Glare laminates under variable amplitude fatigue loading.
- Left: Real stress level in each layer.
- Right: Plastic retardation and fiber bridging effect at crack tip.





Fatigue life prediction under variable-amplitude fatigue loading



$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^n = C\left(K_{eff}(1-R)\right)^n,$$

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

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

$$\beta = K_{br} / K_{re}$$

$$\sigma_{op} = \left(A_0 + A_1 R + A_2 (R)^2 + A_3 (R)^3\right)\sigma_{\max}, \text{ for } R \geq 0$$

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

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

$$A_1 = (0.415 - 0.071\alpha)\left(\frac{\sigma_{\max}}{\sigma_{\text{flow}}}\right)$$

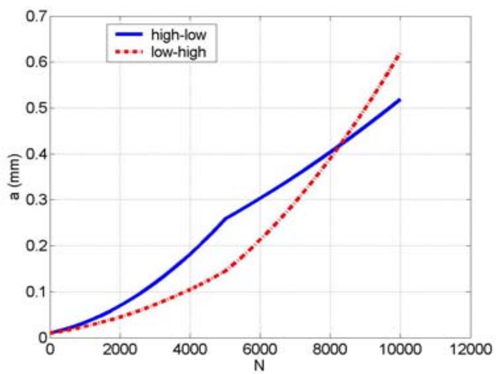
$$A_2 = (1 - A_0 - A_1 - A_3)$$

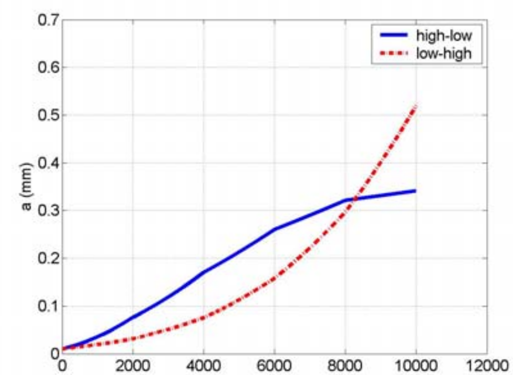
$$A_3 = (2A_0 + A_1 - 1)$$

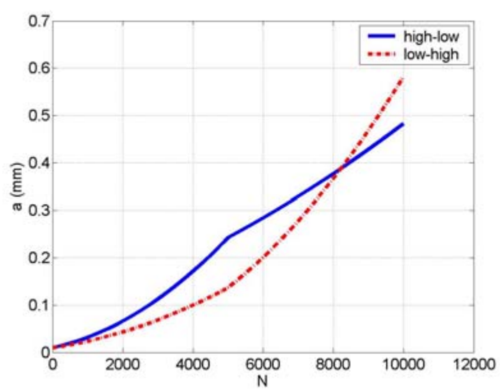
Newman J.C., A crack opening stress equation for fatigue crack growth, Int. J. Fract. 24, R131–R135, 1984.

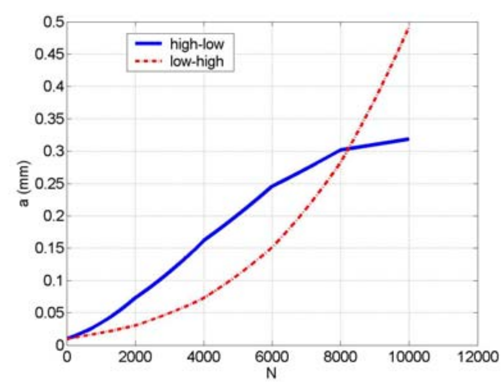
Prediction results of block spectrum loadings

- The Glare laminates experienced high-low loading sequence had better fatigue resistant ability than that subject to low-high loading sequence due to the strain hardening effect.
- Top: two-block and five-block spectrum loadings with R = 0.05 (Glare4A-3/2)
- Bottom: two-block and five-block spectrum loadings with R = 0.1(Glare4A-3/2)



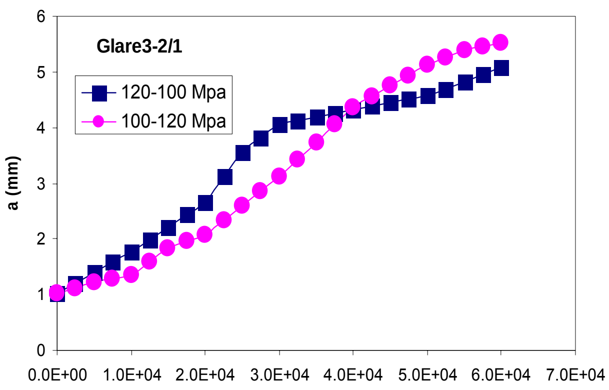


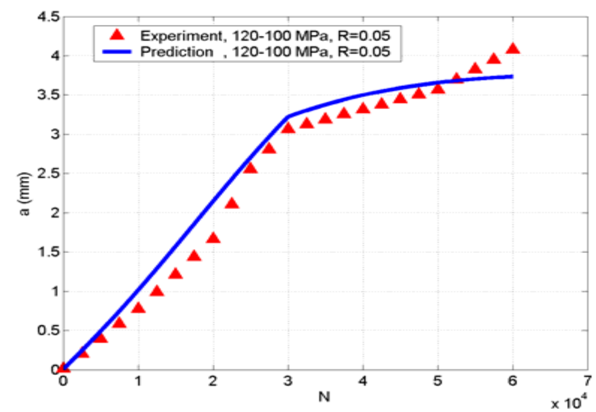


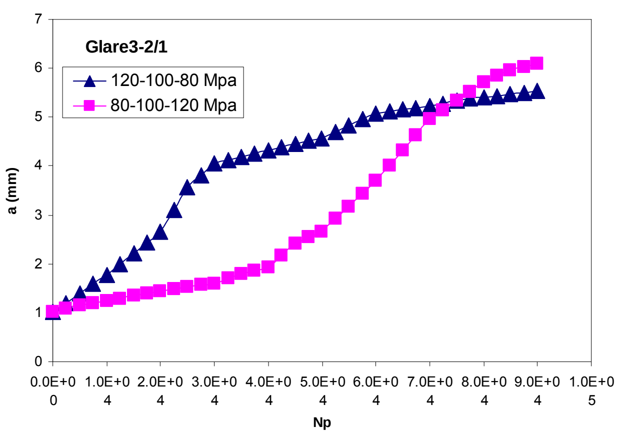


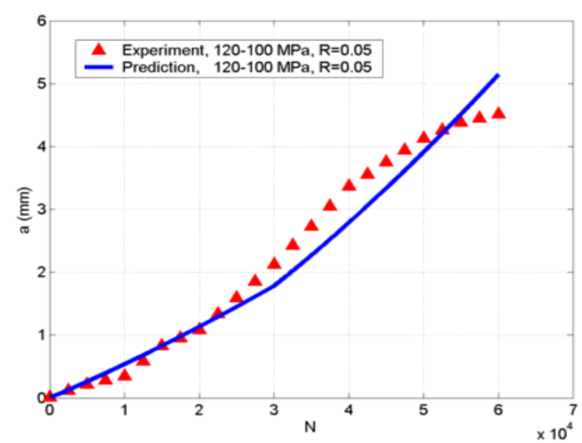
Experimental and predicted results under block spectrum loading sequences

- Glare laminates under high-low loading sequence had better fatigue resistance than those subjected to low-high loading sequence.









Highlights of Fatigue Analysis and Work In Progress

- Analytical and numerical analysis of fatigue crack initiation and growth under constant-amplitude and variable-amplitude fatigue loading was conducted. The predicted results correlate well with experimental results.

- The validated methodologies enable us to predict the crack initiation life and fatigue crack growth rates of fiber metal laminates with different geometries and loading conditions.

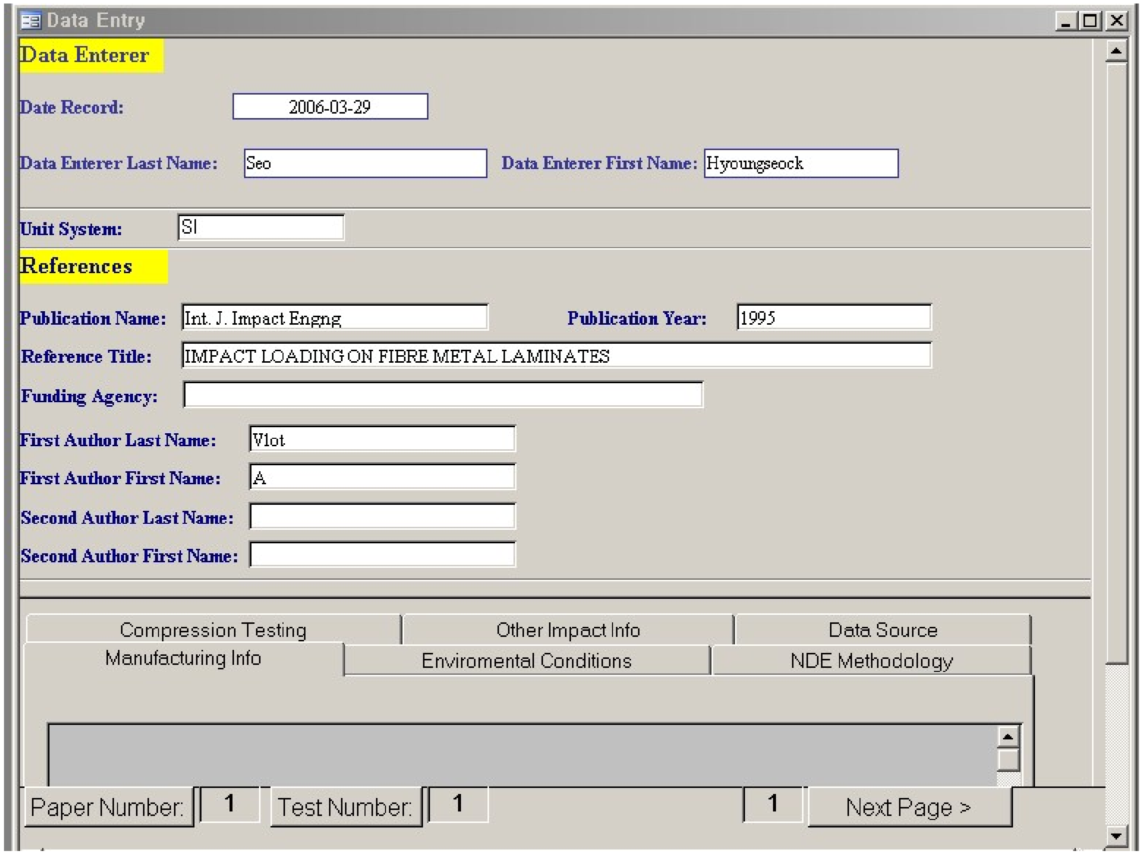
- Therefore, it allows us to set an inspection and maintenance schedule to ensure the structural integrity and safety. It is also feasible to optimize the FMLs to create a “fatigue-insensitive” structure.

- Further study for variable amplitude fatigue behavior is needed for different types of in-service loading and environmental conditions.

Information system for fiber metal laminates

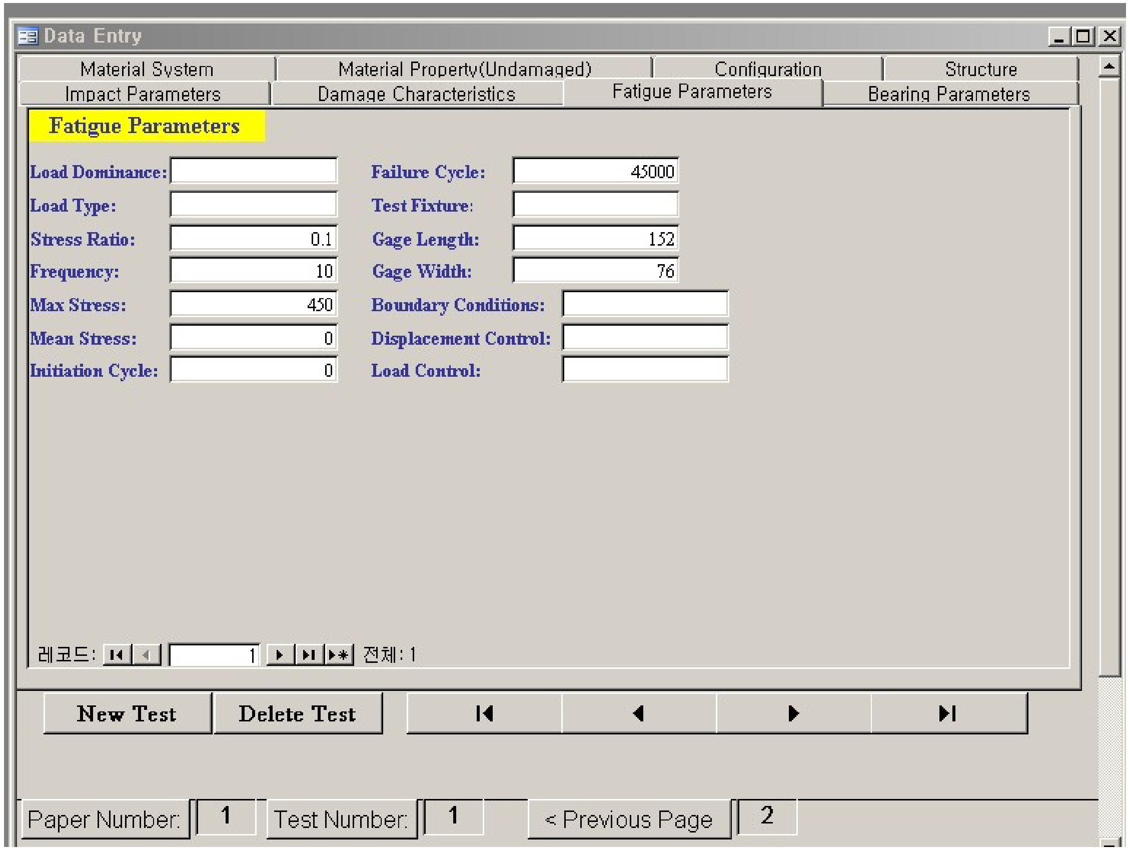
- Database for GLARE laminates: collect and compile experimental data from published literatures.
- The developed information system for the GLARE provides analysis over multiple sets of data collected under different experimental studies
- It allows for the comparison of different GLARE with various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

Data entry system



- The first configuration is to compile the information from literatures related to GLARE
- It consists of the following tables: authors, data enterer, and references, notes, data source

Data entry system (cont'd)



- This configuration is to compile the information about damage tolerance and durability of GLARE from literatures.
- It consists of the impact, fatigue and bearing parameters etc.

Updated database for fatigue behavior

Microsoft Access - [FatigueParameters : Table]

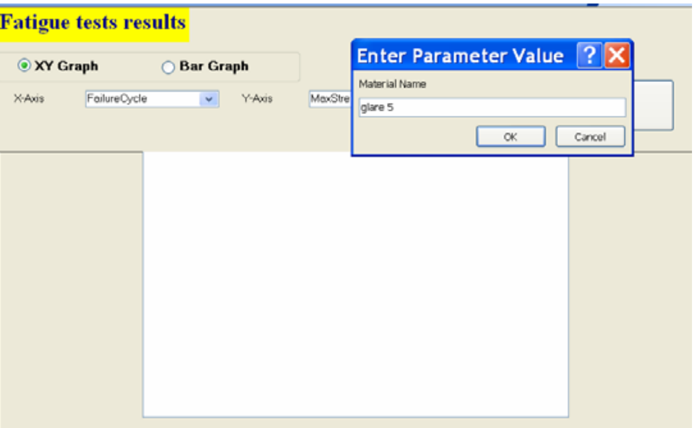
FatigueID	IndustrialName	SpecimensType	LayerNumber	LoadDominance	LoadType	DamageType	StressRatio	Frequency	MeanStress	MaxStress	InitiationCycle	FailureCycle
1	GLARE 3	Rect,	4/3	T-T	Const, Amp	notch	0,05	10		80		
2	GLARE 3	Rect,	4/3	T-T	Const, Amp	notch	0,05	10		100		
3	GLARE 3	Rect,	4/3	T-T	Const, Amp	notch	0,05	10		120		
4	GLARE 3	Rect,	6/5	T-T	Const, Amp	notch	0,05	10		80		
5	GLARE 3	Rect,	6/5	T-T	Const, Amp	notch	0,05	10		100		
6	GLARE 3	Rect,	6/5	T-T	Const, Amp	notch	0,05	10		120		
7	GLARE 3	Rect,	8/7	T-T	Const, Amp	notch	0,05	10		80		
8	GLARE 3	Rect,	8/7	T-T	Const, Amp	notch	0,05	10		100		
9	GLARE 3	Rect,	8/7	T-T	Const, Amp	notch	0,05	10		120		
10	GLARE 3	Rect,	2/1	T-T	Const, Amp	impact	0,05	7		223		12700
11	GLARE 3	Rect,	2/1	T-T	Const, Amp	impact	0,05	7		223	52000	9720
12	GLARE 4	Rect,	2/1	T-T	Const, Amp	impact	0,05	7		223	28000	5700
13	GLARE 4	Rect,	2/1	T-T	Const, Amp	impact	0,05	7		223	18000	6120
14	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,05	7		223	30000	8400
15	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,05	7		223	48000	7175
16	GLARE 3	Dogbone	3/2	T-T	Const, Amp	unnotch	0,05	10		175	10000	
17	GLARE 3	Dogbone	3/2	T-T	Const, Amp	unnotch	0,05	10		125	100000	
18	GLARE 3	Dogbone	3/2	T-T	Const, Amp	unnotch	0,05	10		100	800000	
19	GLARE 2	Rect,	3/2	T-T	Const, Amp	unnotch	0,1	10		1100		12
20	GLARE 2	Rect,	3/2	T-T	Const, Amp	unnotch	0,1	10		800		100
21	GLARE 2	Rect,	3/2	T-T	Const, Amp	unnotch	0,1	10		500		1000
22	GLARE 2	Rect,	3/2	T-T	Const, Amp	unnotch	0,1	10		300		100000
23	GLARE 2	Rect,	3/2	T-T	Const, Amp	unnotch	0,1	10		250		150000
24	GLARE 3	Rect,	5/4	T-T	Const, Amp	notch	0,05	5		110		150000
25	GLARE 3	Rect,	5/4	T-T	Const, Amp	notch	0,05	5		147		40000
26	GLARE 3	Rect,	5/4	T-T	Const, Amp	notch	0,05	5		196		10000
27	GLARE 2	Rect,	12/11	T-T	Const, Amp	notch	0,04			150		
28	GLARE 2	Rect,	12/11	T-T	Const, Amp	notch	0,04			250		
29	GLARE 2	Rect,	12/11	T-T	Const, Amp	notch	0,04			360		
30	GLARE 2	Rect,	12/11	T-T	Const, Amp	notch	0,04			450		
31	ARALL 1	Rect,	3/2	T-T	Const, Amp	notch	0,1			86		100000
32	GLARE 4	Rect,	3/2	T-T	Const, Amp	impact	0,1	10		116	150785	101078
33	GLARE 4	Rect,	3/2	T-T	Const, Amp	impact	0,1	10		232	17813	12503
34	GLARE 4	Rect,	3/2	T-T	Const, Amp	impact	0,1	10		349	6477	740
35	GLARE 4	Rect,	3/2	T-T	Const, Amp	impact	0,1	10		81	292584	100259
36	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,1	10		116	120000	92700
37	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,1	10		174	130879	26087
38	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,1	10		232	18828	4218
39	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,1	10		290	11648	1364
40	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,1	10		349	7747	1266
41	GLARE 5	Rect,	2/1	T-T	Const, Amp	impact	0,1	10		122	115000	43354
42	ARALL 1	Rect,	3/2	T-T	Const, Amp	notch	0,33	10		147		3000
43	ARALL 1	Rect,	3/2	T-T	Const, Amp	notch	0,33	10		118		6000
44	ARALL 1	Rect,	3/2	T-T	Const, Amp	notch	0,33	10		88		17000
45	ARALL 2	CT	3/2	T-T	Const, Amp	notch	0,1	50				
46	ARALL	Dogbone	4/3	T-T	Twist block	notch			70	91		160000
47	ARALL	Dogbone	4/3	T-T	Twist block	notch			100	130		39866
48	ARALL	Dogbone	3/2	T-T	Twist block	notch			70	91		
49	ARALL	Dogbone	3/2	T-T	Twist block	notch			100	130		
50	GLARE 1	Rect,	2/1	T-T	OL	notch	0,1	1				
51	GLARE 1	Rect,	2/1	T-T	OL	notch	0,1	2,5				
52	GLARE 1	Rect,	2/1	T-T	OL	notch	1,5	5				
53	GLARE 1	Rect,	2/1	T-T	OL	notch	2	10				

Record: 1 of 151

Datasheet View

Data retrieval system for fatigue behavior

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



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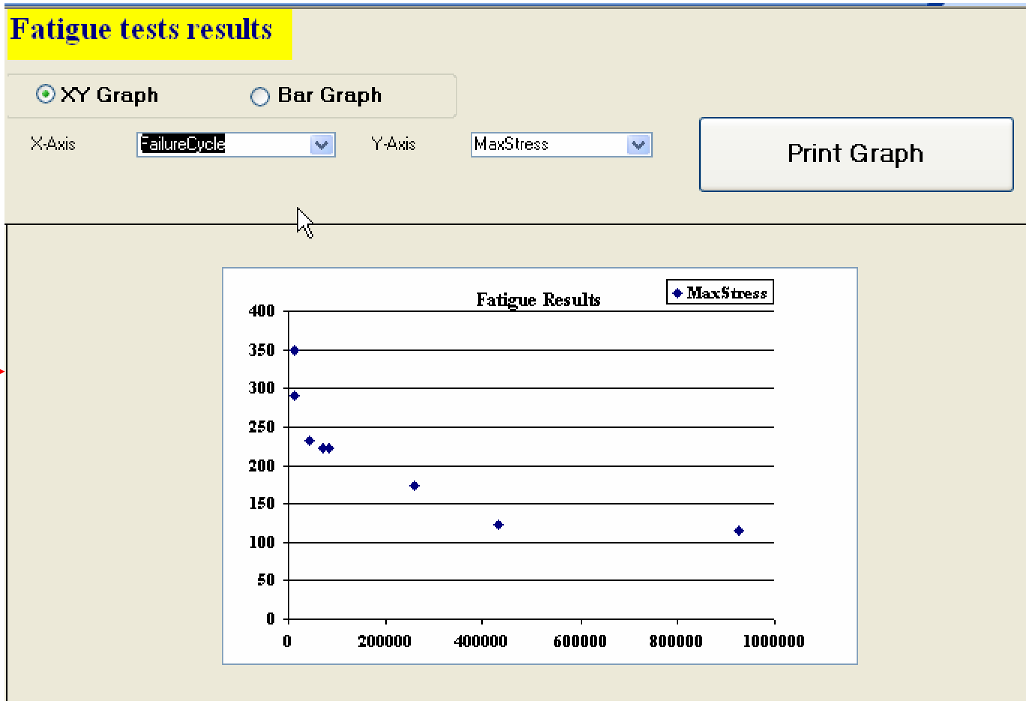
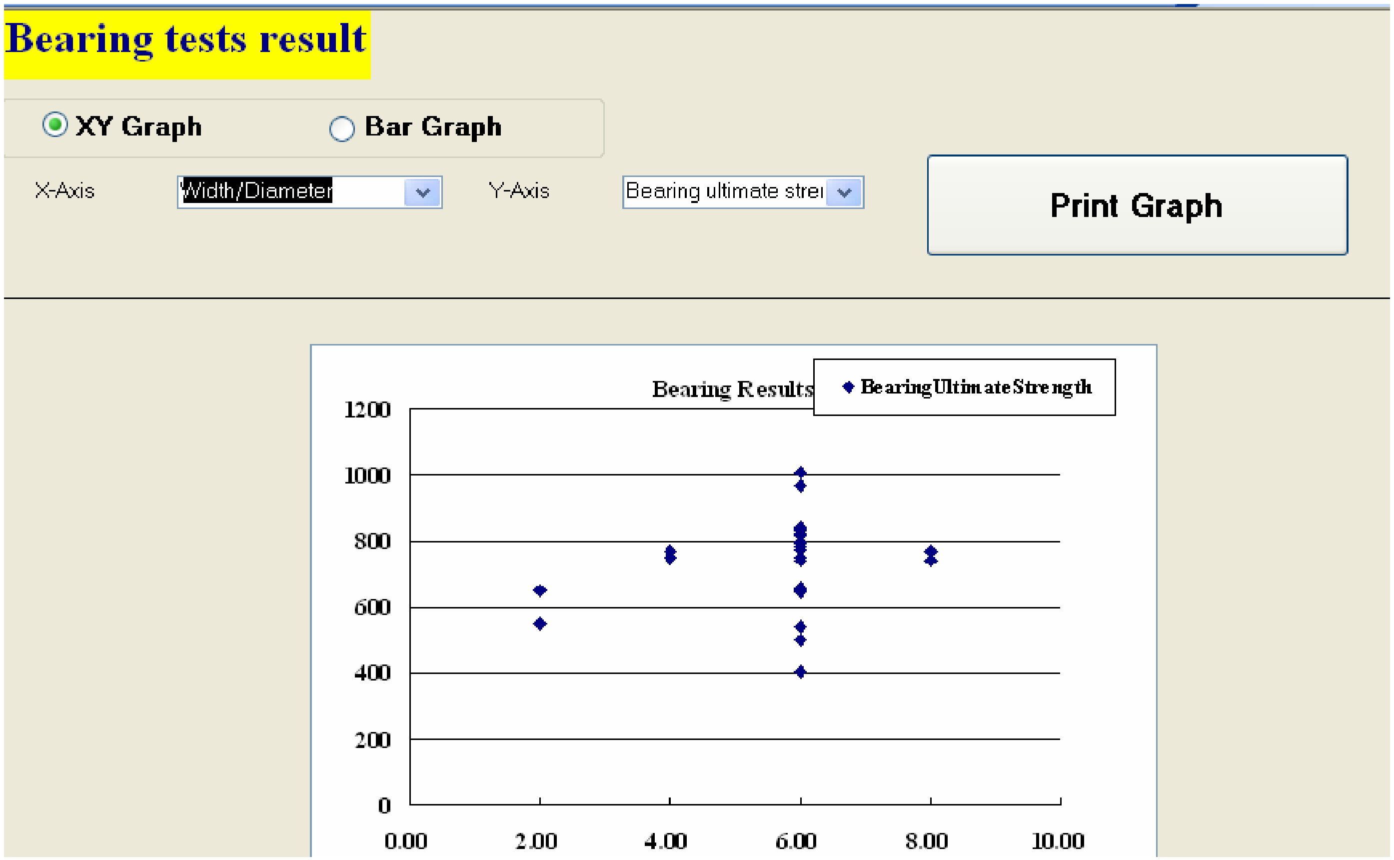


<Max. stress vs. Number of cycles>

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