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

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FAA Sponsored Project Information

- **Principal Investigators & Researchers**

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- **FAA Technical Monitor**
  - **Mr. Curtis Davies**

- **Other FAA Personnel Involved**
  -

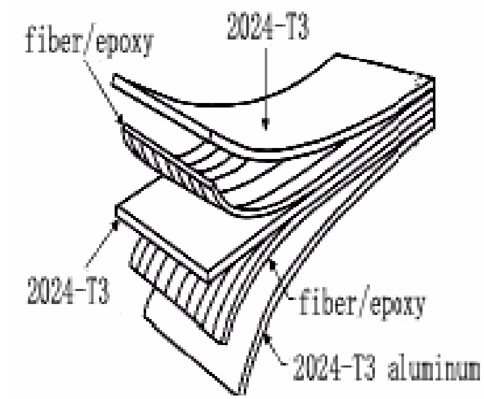
- **Industry Participation**
  -Raytheon Missile Systems, Airbus

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

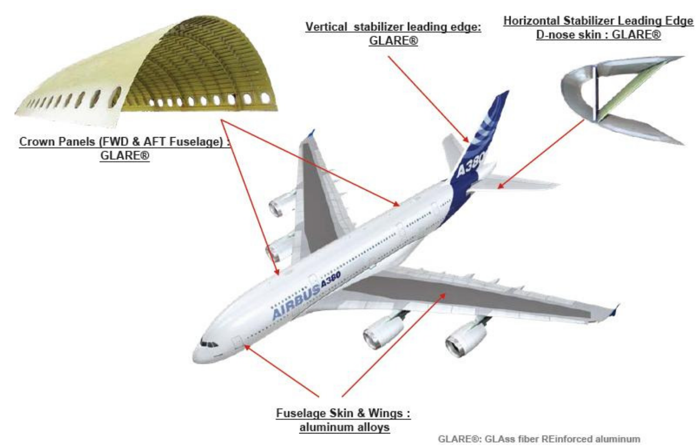
- Motivation and Key Issues
  - **Fiber metal laminate is a new generation of primary structure for pressurized transport fuselage. However, there are limited and insufficient information available about mechanical behavior of FML in the published literature, and some areas still remains to be further 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 (S2-glass fiber reinforced Al) laminates**
  - Hybrid composites consisting of alternating thin metal layers and glass fiber/epoxy layers



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



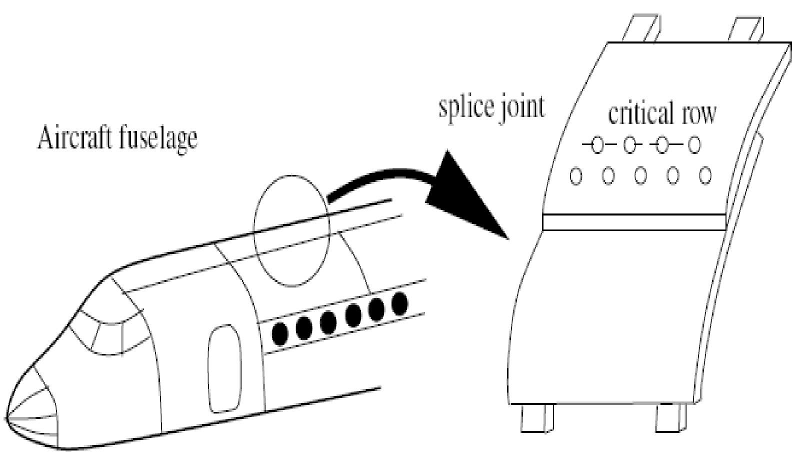
Project Scope

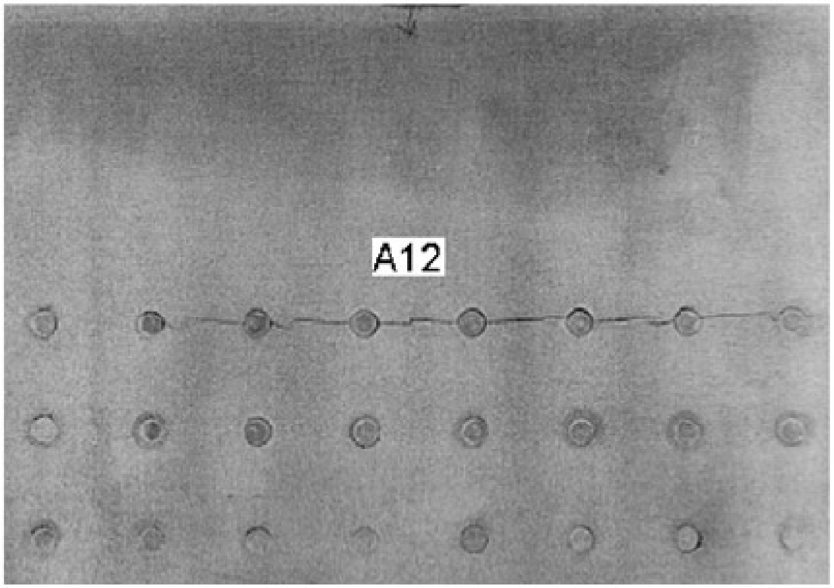
To develop methodologies for guiding material development, property optimization and airworthiness certification:

- **Residual Strength Modeling and Validation**
  --open-hole notch strength
  --residual strength after impact
  --open-hole notch strength after fatigue
- **Impact and Post-Impact Fatigue Behavior**
- **Numerical Simulation of single and Multiple Impact**
- **Fatigue Crack Initiation/Growth Modeling and Validation**
  --constant amplitude fatigue
  --variable amplitude fatigue
- **Multi-site Damage**
  --fatigue
  --impact
- **Information System for Certification**

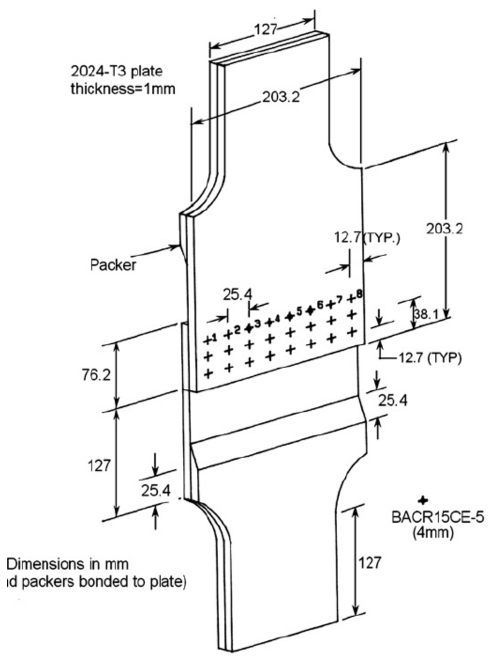
Multi-Site Damage (MSD)

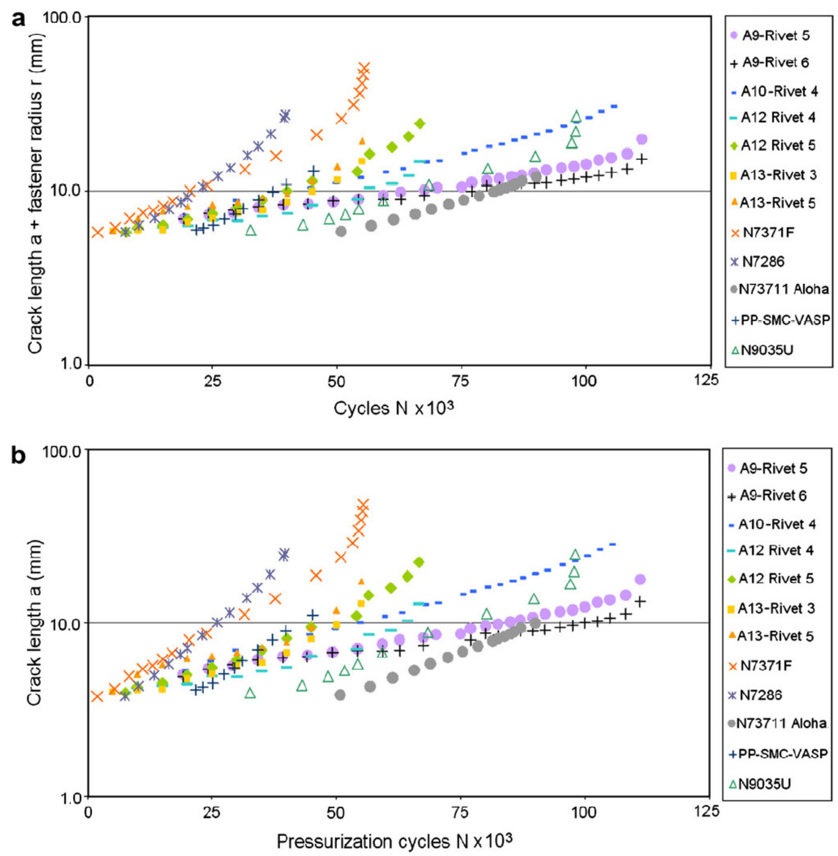
- **Multi-site fatigue damage occurred in in-service airliner fuselage, for instance, Aloha airline accident in 1988.**
- **MSD can also be induced by corrosion, and impact.**





Crack growth in aluminum with MSD

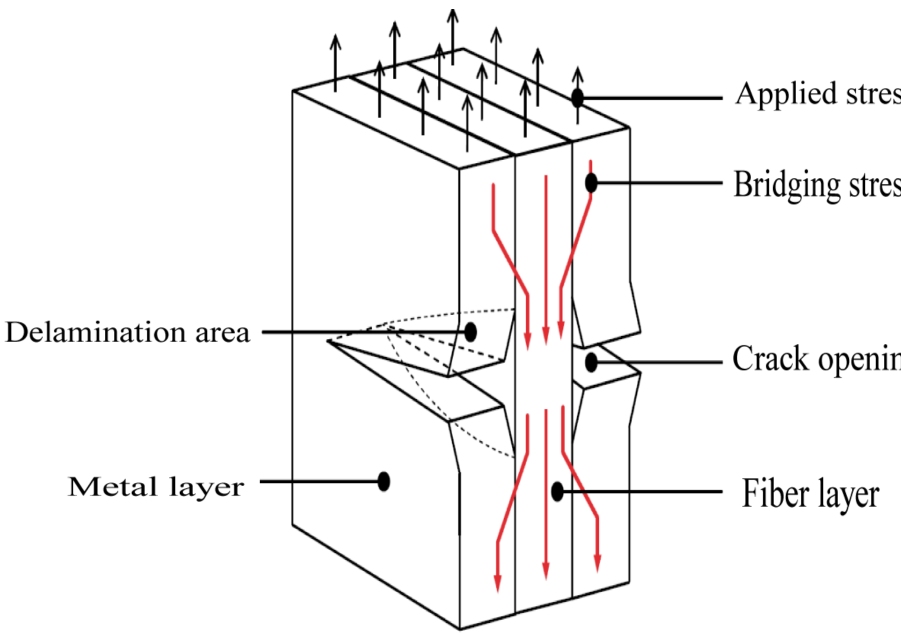


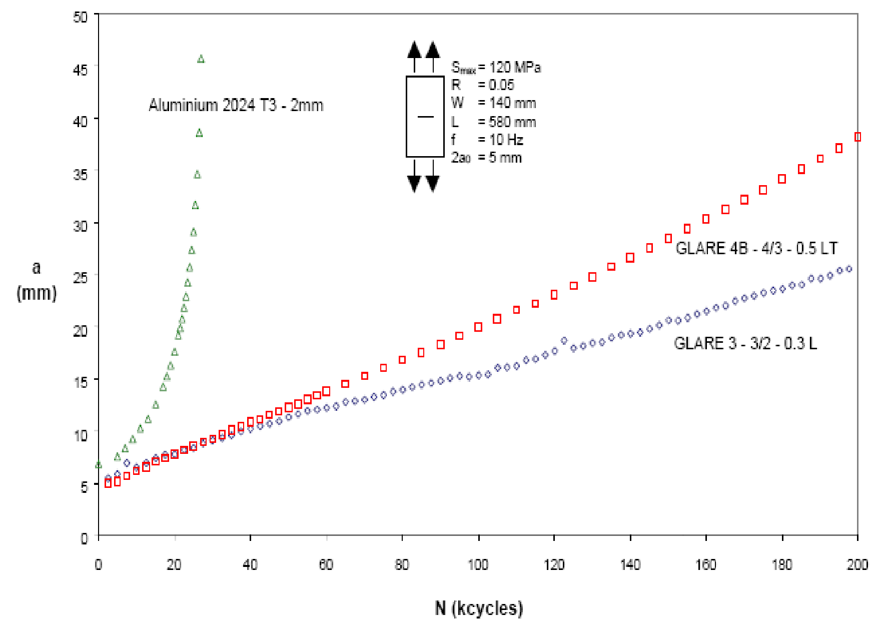


Jones, R; Molent, L; Pitt, S, Understanding crack growth in fuselage lap joint, Theoretical and applied fracture mechanics 2008 v49,n1, p38--50

Crack growth in fiber metal laminates

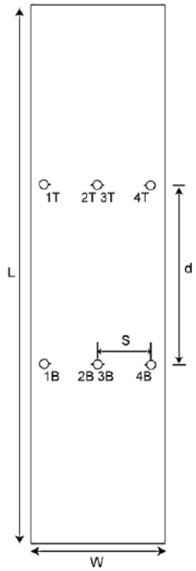
- Left: bridging mechanism in FML.
- Right: fatigue life of monolithic Al alloy and GLARE laminates.



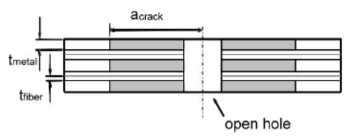


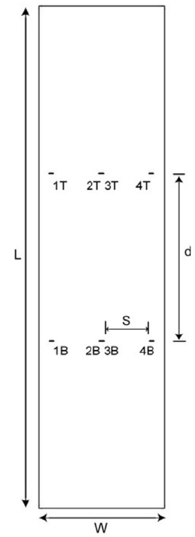
Vlot A, Gunnink JW, editors. Fibre metal laminates—an introduction. Kluwer Academic Publishers; 2001.

Configuration of specimens with MSD

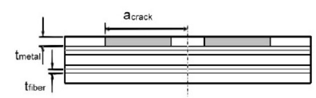


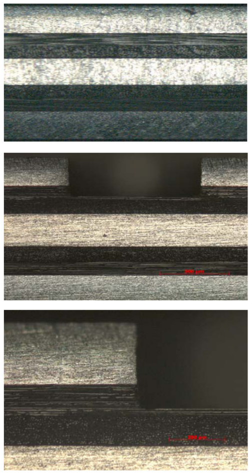
W = 75 mm
L = 300 mm
d = 100 mm
s = 30 mm
r = 2.5 mm
starter notch = 1 mm



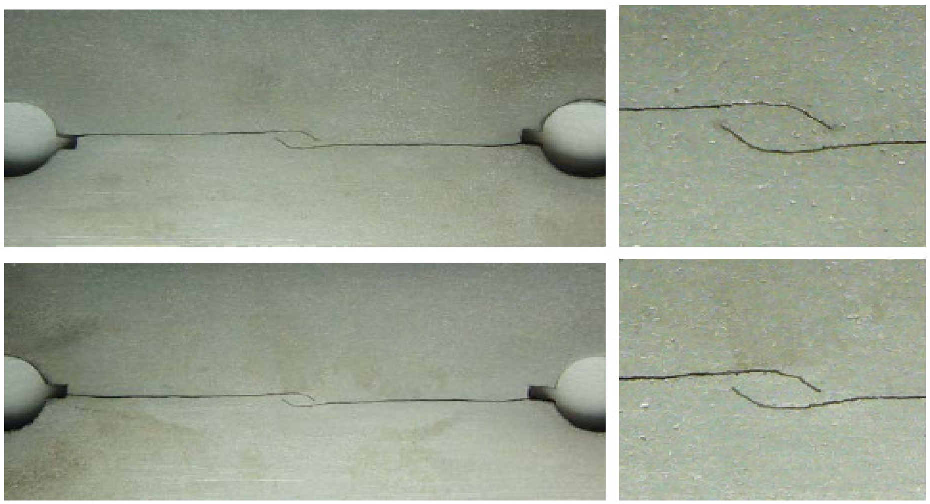


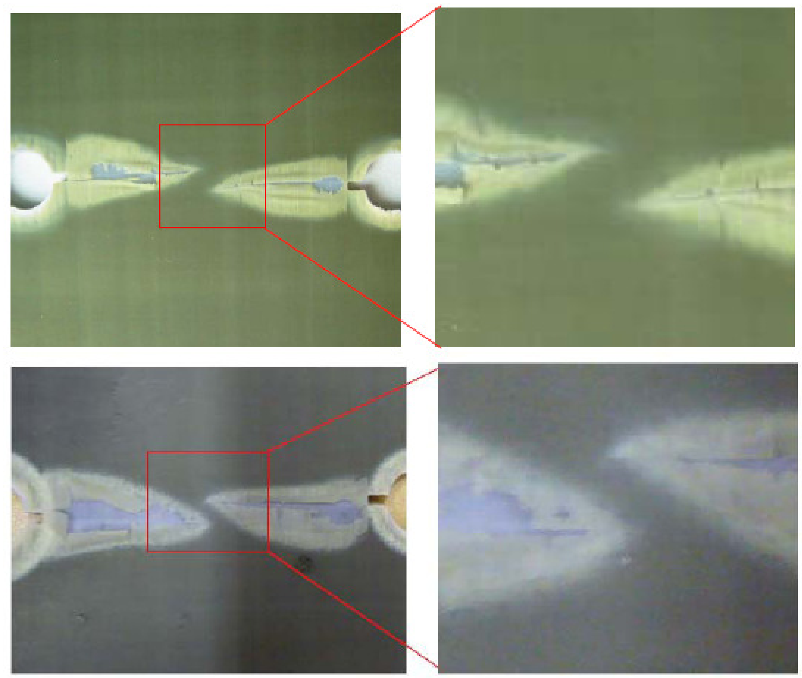
W = 75 mm
L = 300 mm
d = 100 mm
s = 30 mm
surface slit = 4 mm





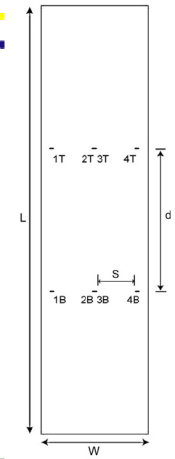
Crack propagation in FMLs--I. Through-thickness open holes



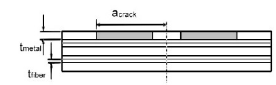


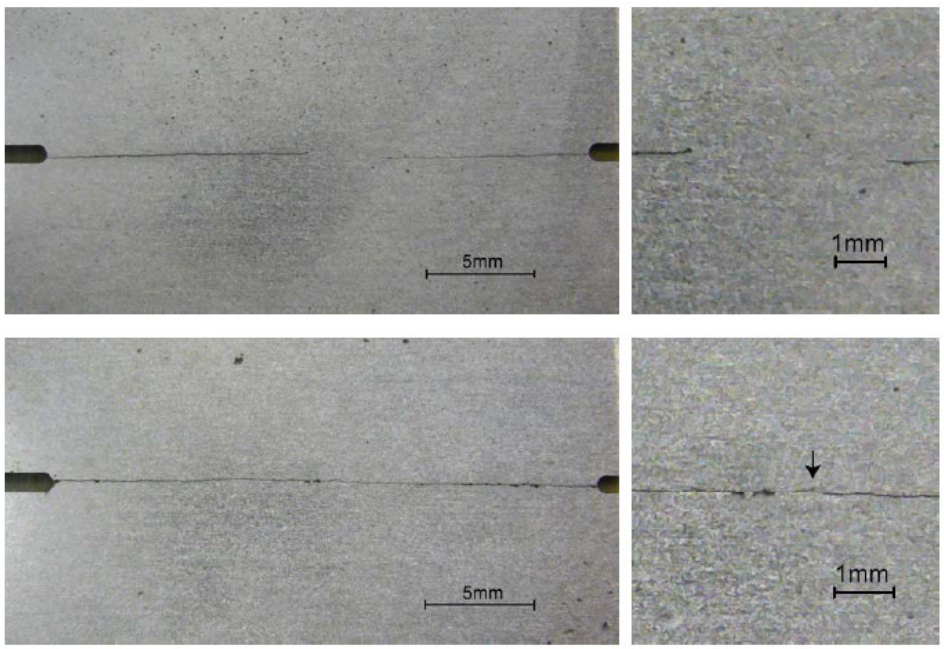
Crack propagation in FMLs--II. Surface crack

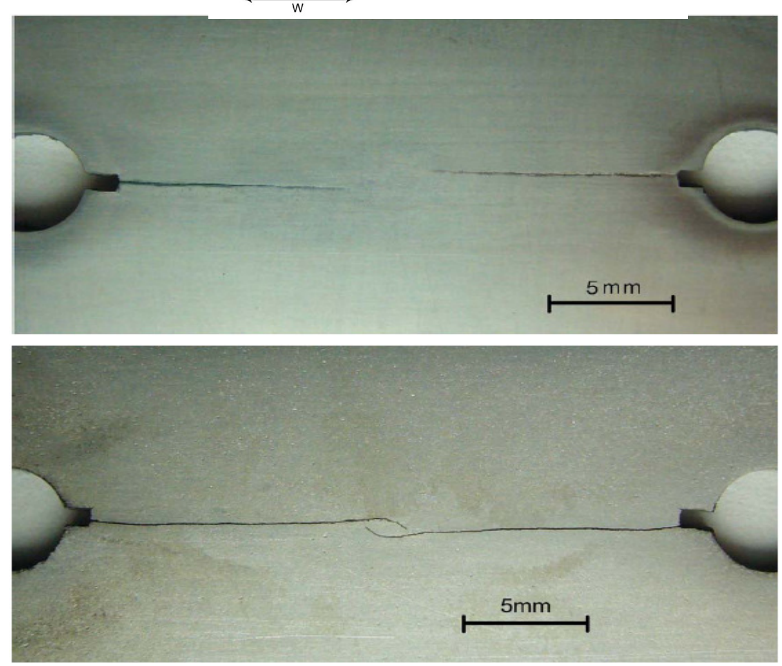
- Left: Surface cracks
- Right: Through-thickness cracks
- Top: Non-leading surface crack propagation
- Bottom: Leading surface cracks and link-up



W = 75 mm
L = 300 mm
d = 100 mm
s = 30 mm
surface slit = 4 mm

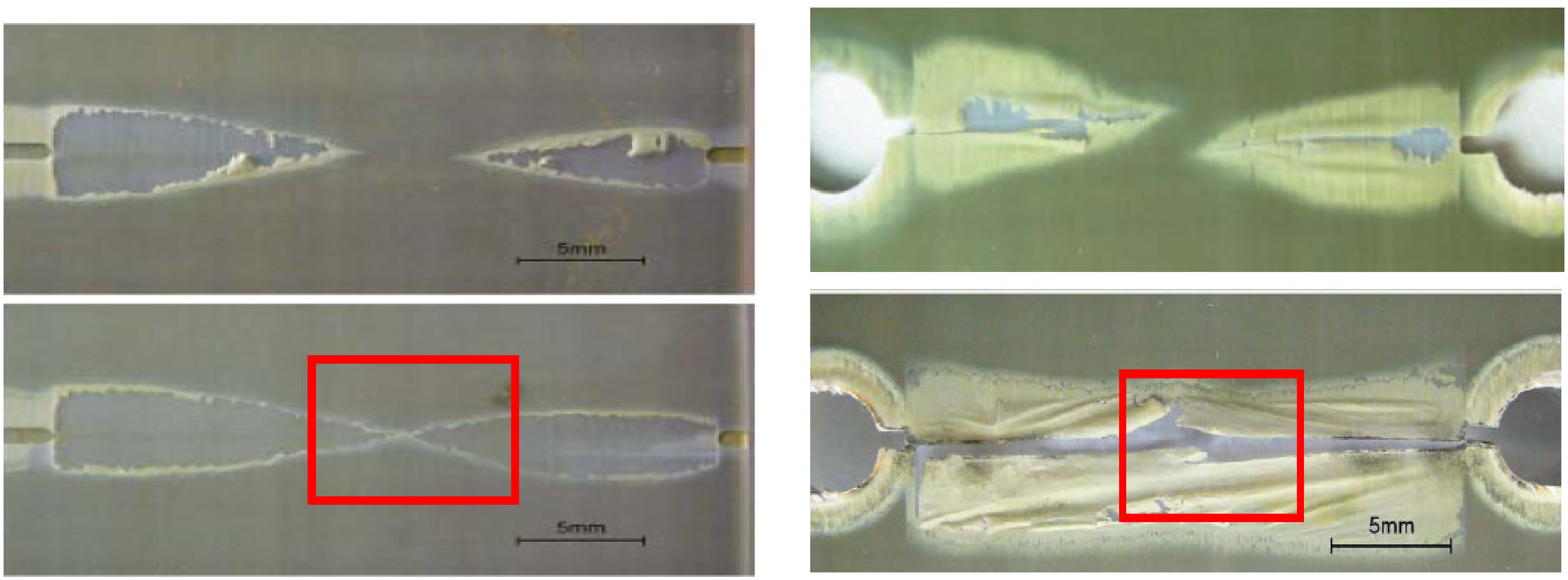






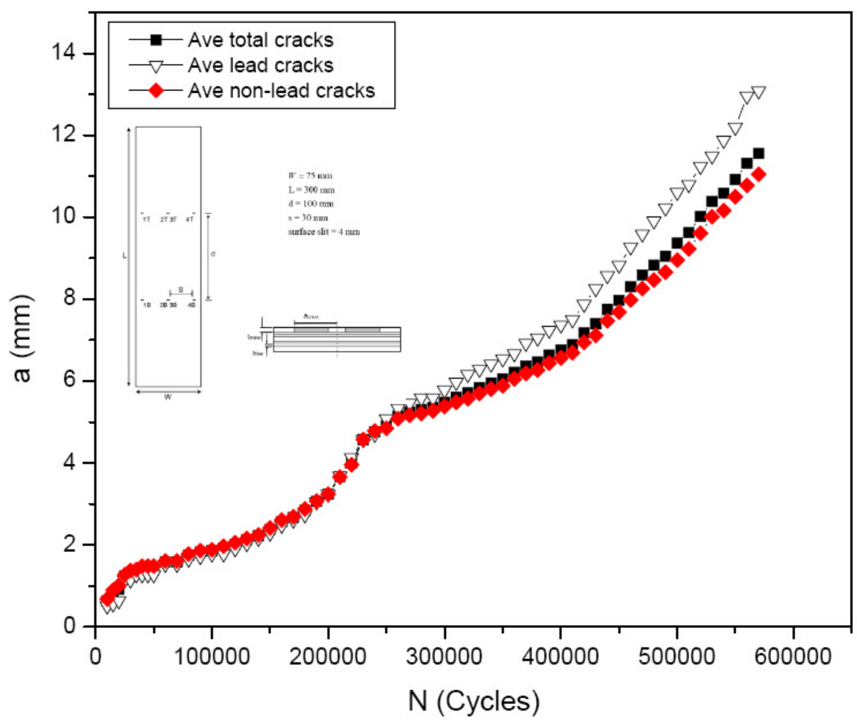
Delamination in metal/prepreg interface

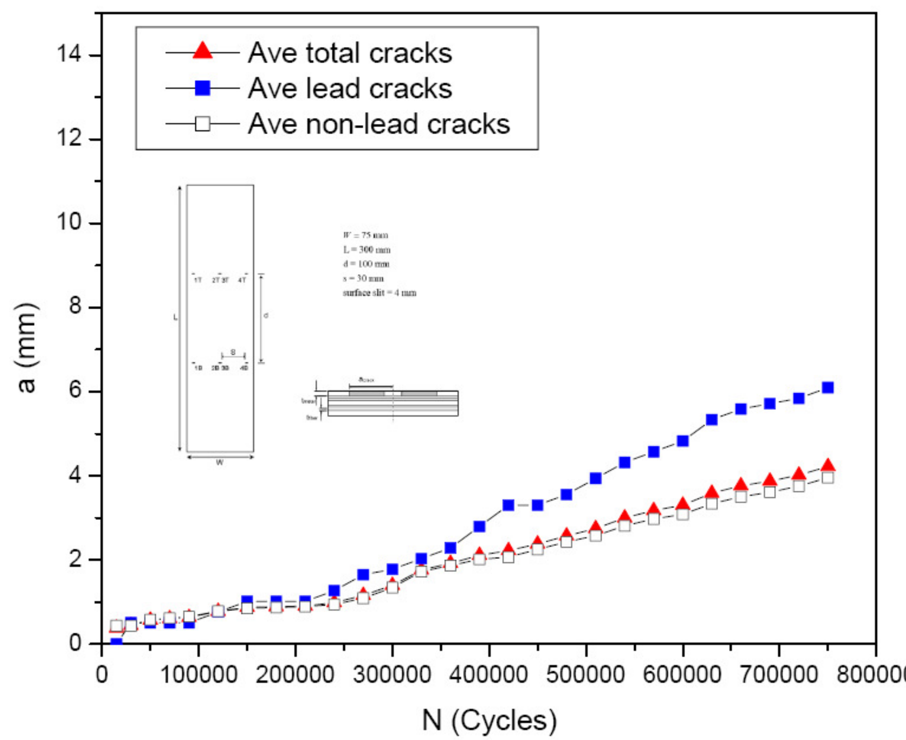
- Left: Surface cracks
- Right: Through-thickness cracks
- Top: Non-leading delamination propagation
- Bottom: Leading delaminations link-up



Lead and non-lead surface crack growth

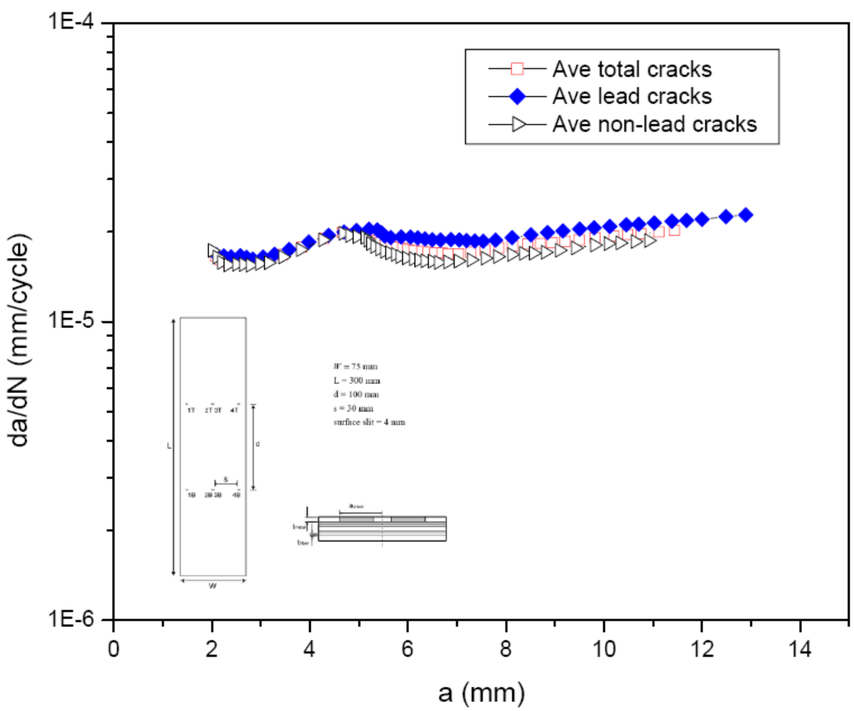
- Left: Maximum applied stress = 120 MPa
- Right: Maximum applied stress= 100 MPa

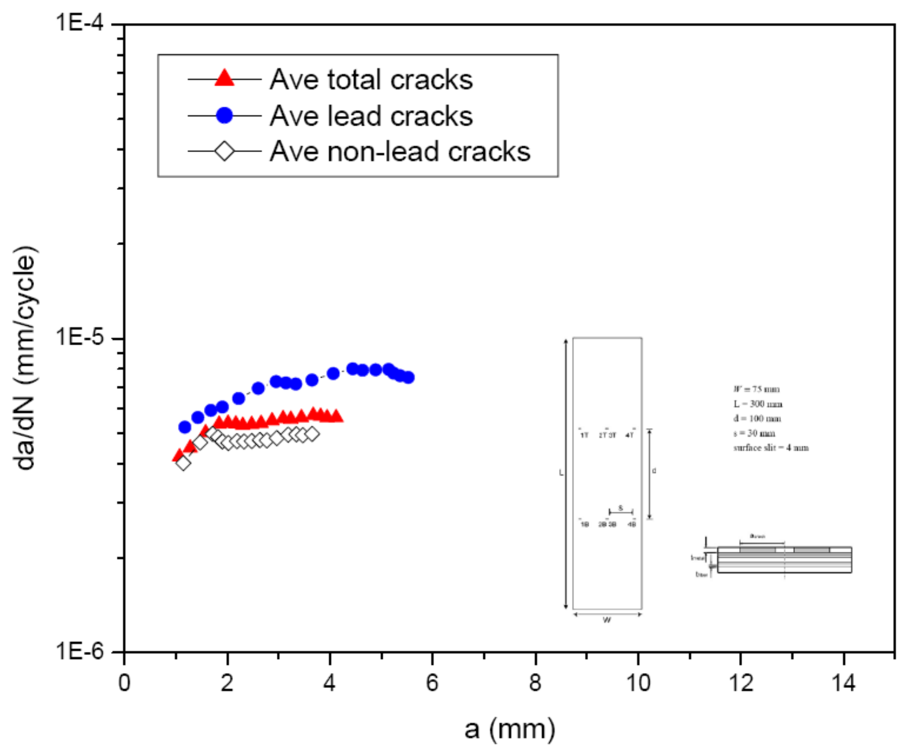




Lead and non-lead surface crack growth rates in FMLs

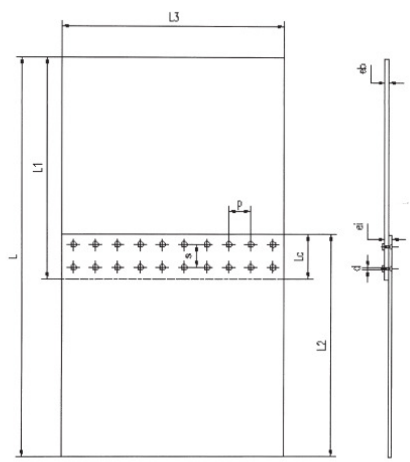
- Left: Maximum applied stress = 120 MPa
- Right: Maximum applied stress= 100 MPa





MSD crack growth in Al-2024 and FMLs

- Applied stress=100 MPa, R=0.1, on Al panel.



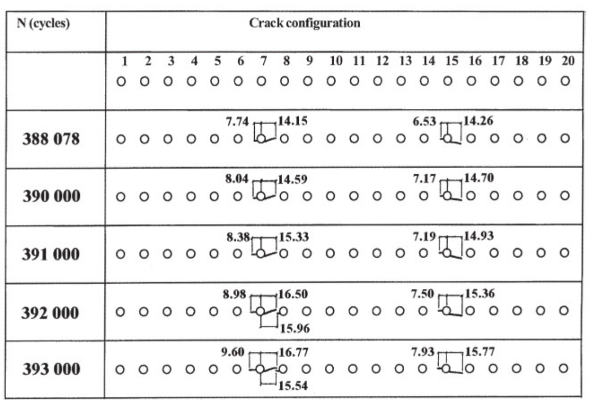


Table 1
Loading history[a]

Specimen	Critical row[b]	Initial defects[c]	N_{SPATE}	N_f	N_{i_f}	% N_{i-f}	$N_{1st\ link\text{-}up\_f}$[f]	$N_{1st\ link\text{-}up\_f}$[g]	% $N_{1st\ link\text{-}up}$[f]	% $N_{1st\ link\text{-}up}$[g]	Observations
#1	B		234000	257841							
#2	B			215034	10000	4.65	3034	6319	1.41	2.94	One lead crack starting at hole 8
#3	B			298737	63750	21.34	2085	162	0.70	0.05	3 MSD cracks, hole 9, hole 12, hole 13
#4	B	B		130000 [d]							
#5	A	B		399620 [d]	11542 [e]		6620 [h]	750 [i]	1.66	0.19	2 MSD cracks, hole 7, hole 15
#6	A			672277							
#7	A		560450	572000	22000	3.85					2 MSD cracks, hole 13, hole 20
#8	A			805450	95450	11.85	1051	4950	0.13	0.61	2 MSD cracks, hole 10, hole 13
#9	A	B		323350	26471	8.19		12350		3.82	One lead crack starting at hole 11
#10	A	B		237750	21750	9.15	2750	1150	1.16	0.48	One lead crack starting at hole 13

Average MSD lead crack growth rates (mm/cycle):

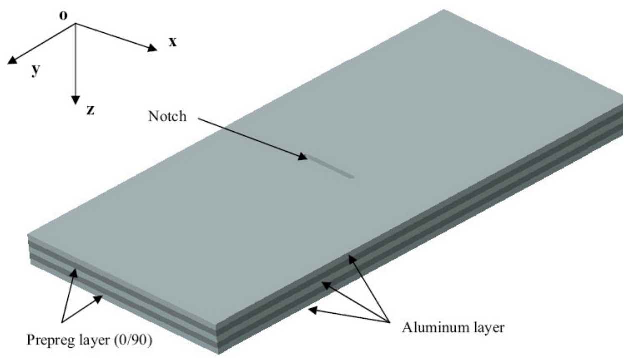
2024-Al: 4.2E-4

Through-thickness GLARE3-3/2: 7.83E-5

Surface-cracked GLARE3-3/2:8.81E-6

Silva, Lucas F.M., Gonçalves, J.P.M.; et al.Multiple-site damage in riveted lap-joints: experimental simulation and finite element prediction, *International Journal of Fatigue*, v 22, n 4, p 319-338, 2000.

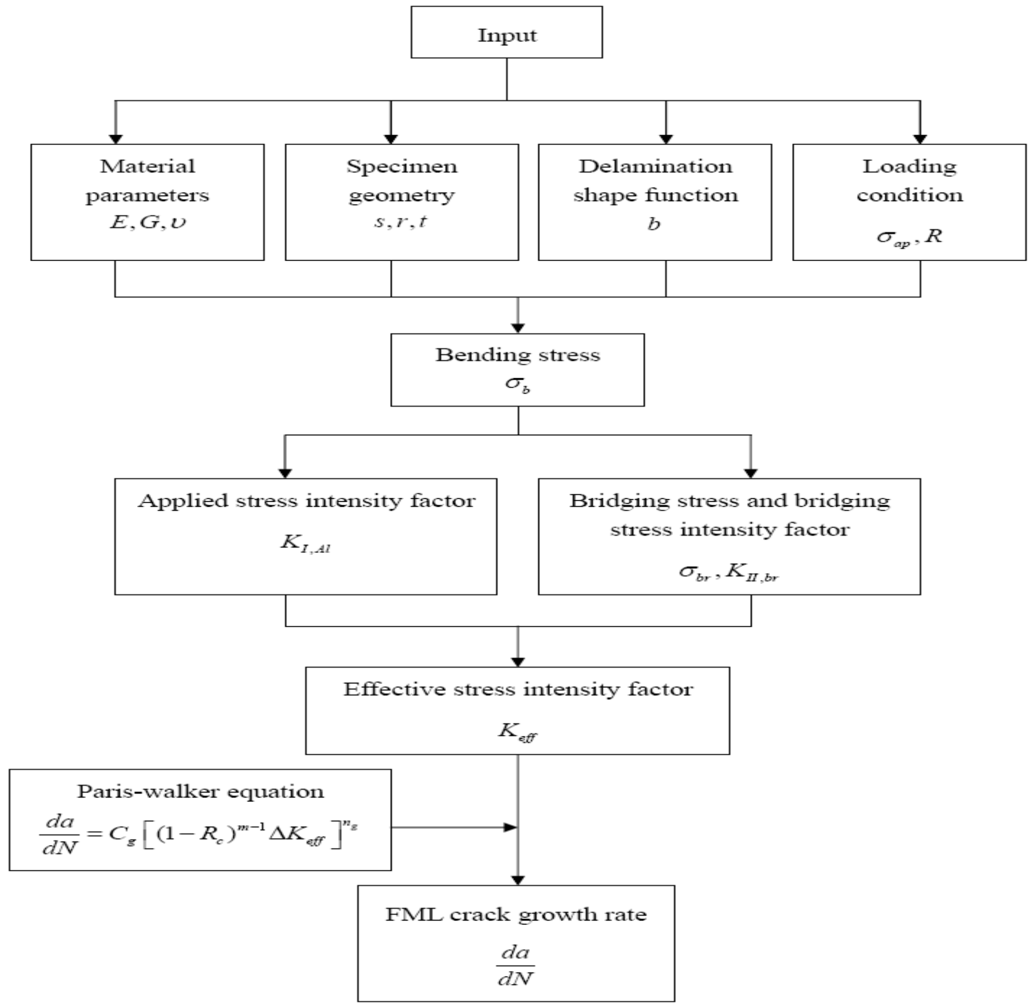
Prediction model of surface crack growth



$$\frac{da}{dN} = C_g \left[(1 - R_c)^{m-1} \Delta K_{eff} \right]^{n_g}$$

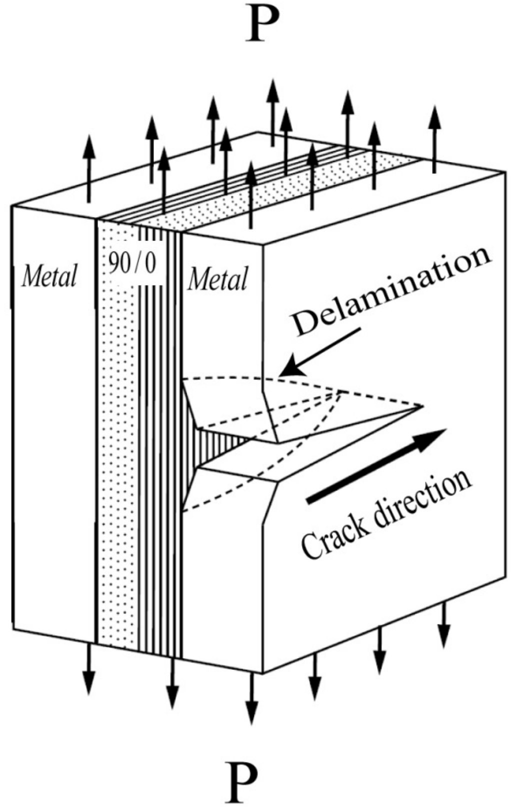
$$\Delta K_{eff} = (K_{I,Al} - K_{II,br})$$

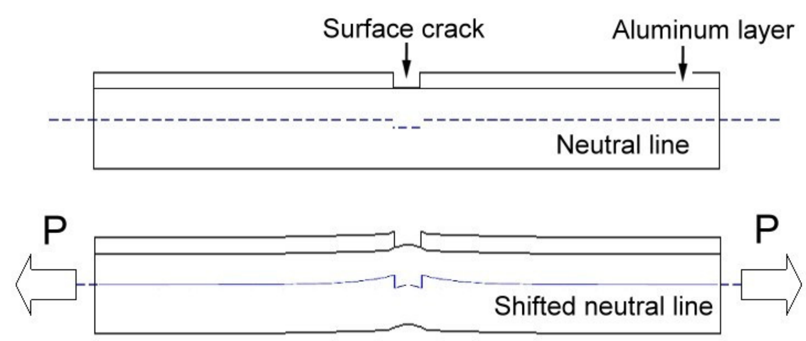
$$\frac{db}{dN} = C_b (\Delta \sqrt{g})^{n_b} = C_b (\sqrt{g_{\max}} - \sqrt{g_{\min}})^{n_b}$$



Bridging and secondary bending effect in FMLs

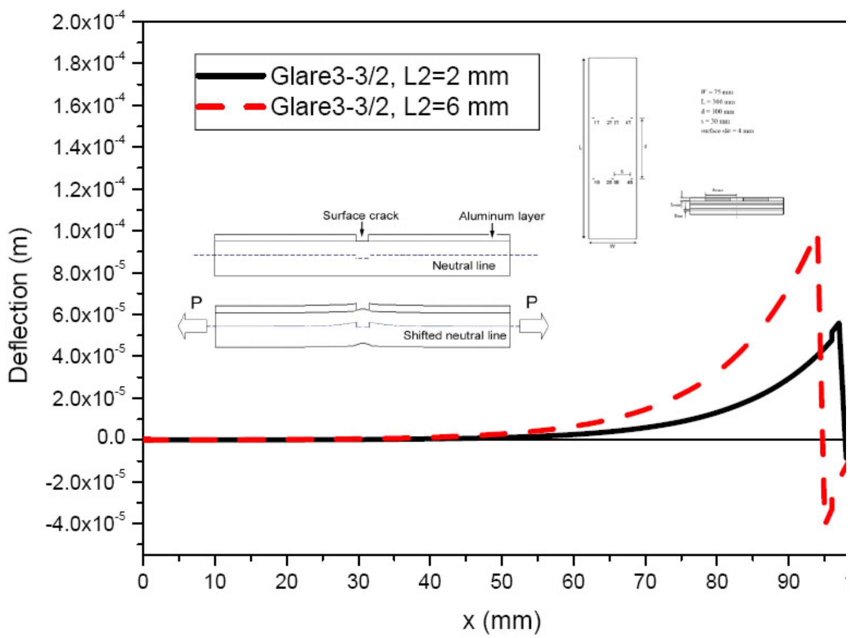
- Left: Fiber bridging effect in FMLs with surface cracks.
- Right: Secondary bending effect in curvature change of neutral line.

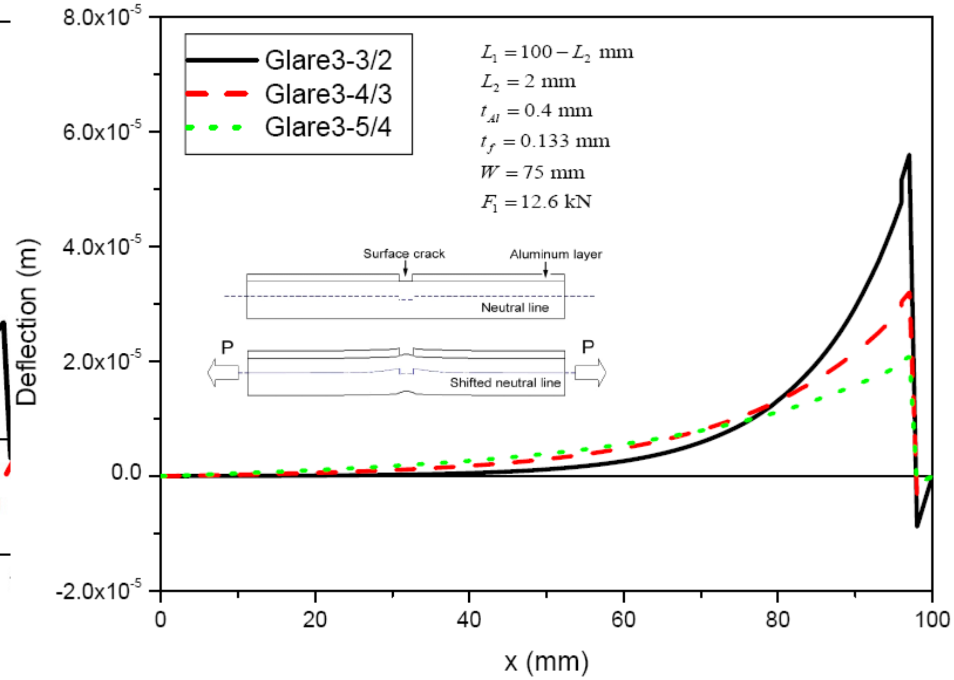




Role of crack length in deflection of neutral line in FMLs

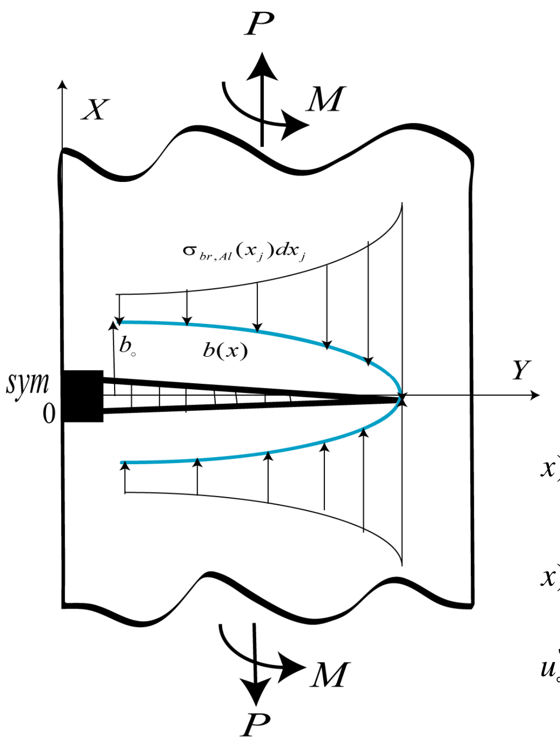
- Curvature: Using beam theory to obtain the displacement of neutral line shift.
- Right: Deflection decreases as laminates thickness increases.
- Left: Deflection increases as crack advances.

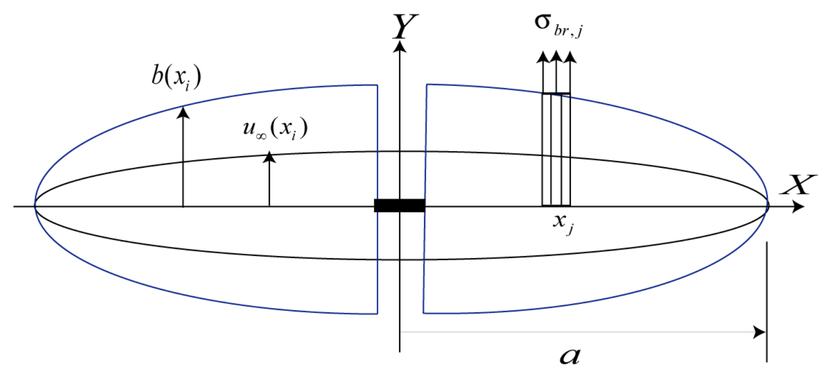




Crack opening relations in FMLs

- Total crack opening= applied load induced crack opening + secondary bending moment induced crack opening





$$x) - u_{br}(x) = \delta_f(x) + \delta_{pp}(x) + \delta_{Al}(x)$$

$$x) - u^b_{br}(x) = \delta^b_f(x) + \delta^b_{pp}(x) + \delta^b_{Al}(x)$$

$$u'_\infty(x) - u'_{br}(x) = \delta'_f(x) + \delta'_{pp}(x)$$

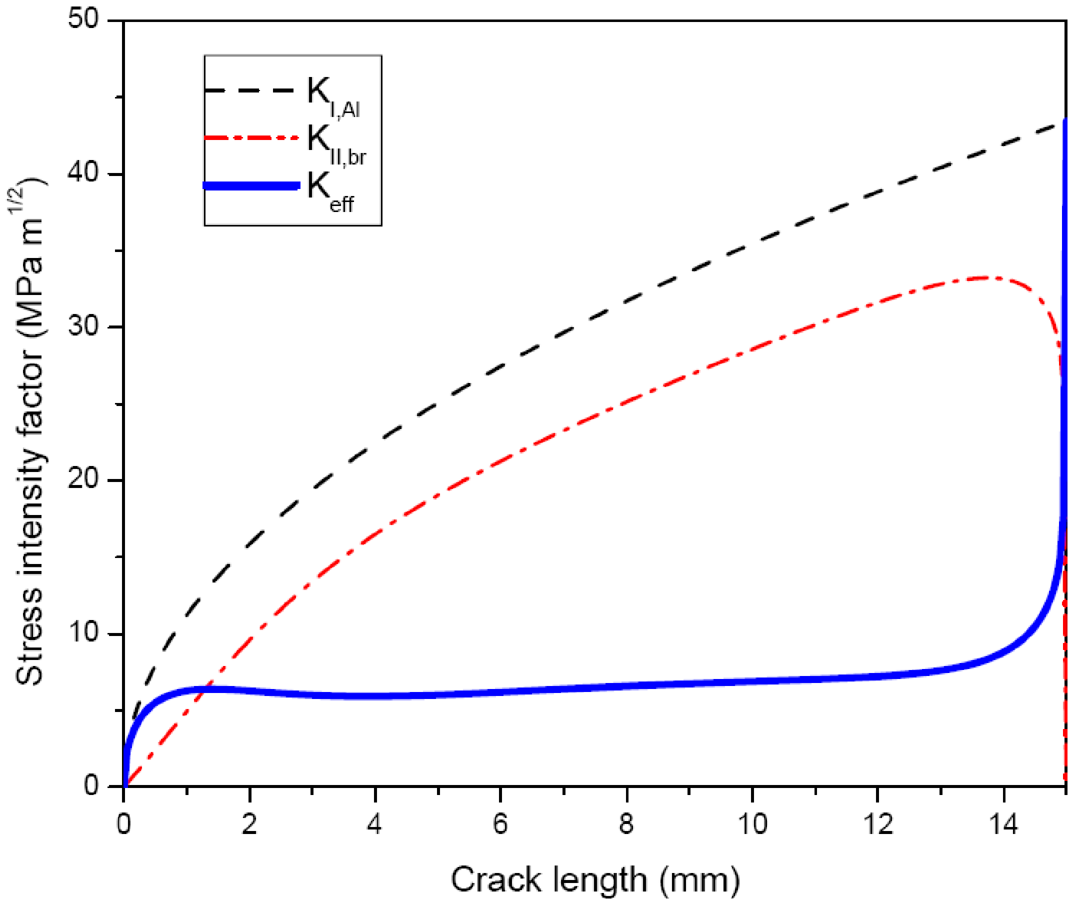
$$\sigma_{br} = H_j^{-1} Q$$

$$H = u'_\infty(x) - \delta'_{pp}(x) - \frac{\sigma_f}{E_f} b(x)$$

$$Q_j = \sum \frac{u'_{br}(x_i, x_j)\Delta x_j}{\sigma_{br}(x_j)} - \frac{b(x_i)}{E_f}\delta(i, j)$$

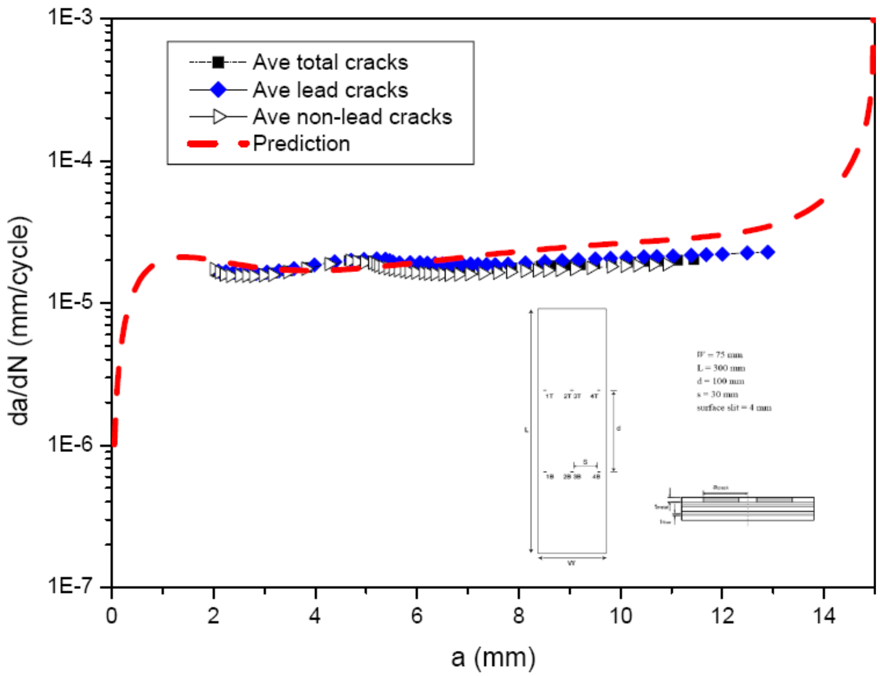
Effective stress intensity factor

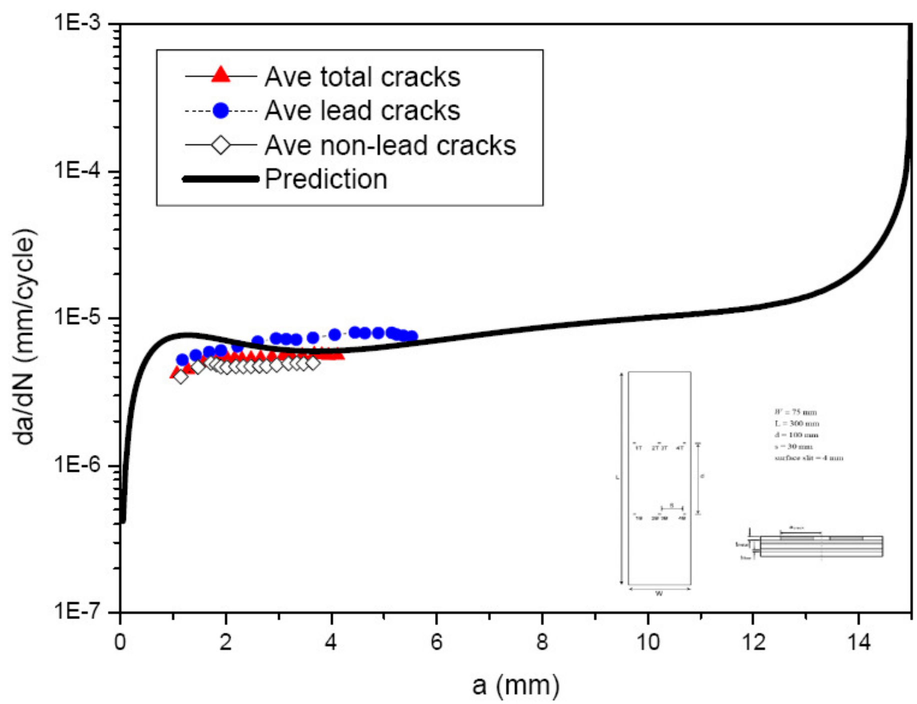
- Surface crack growth in FMLs



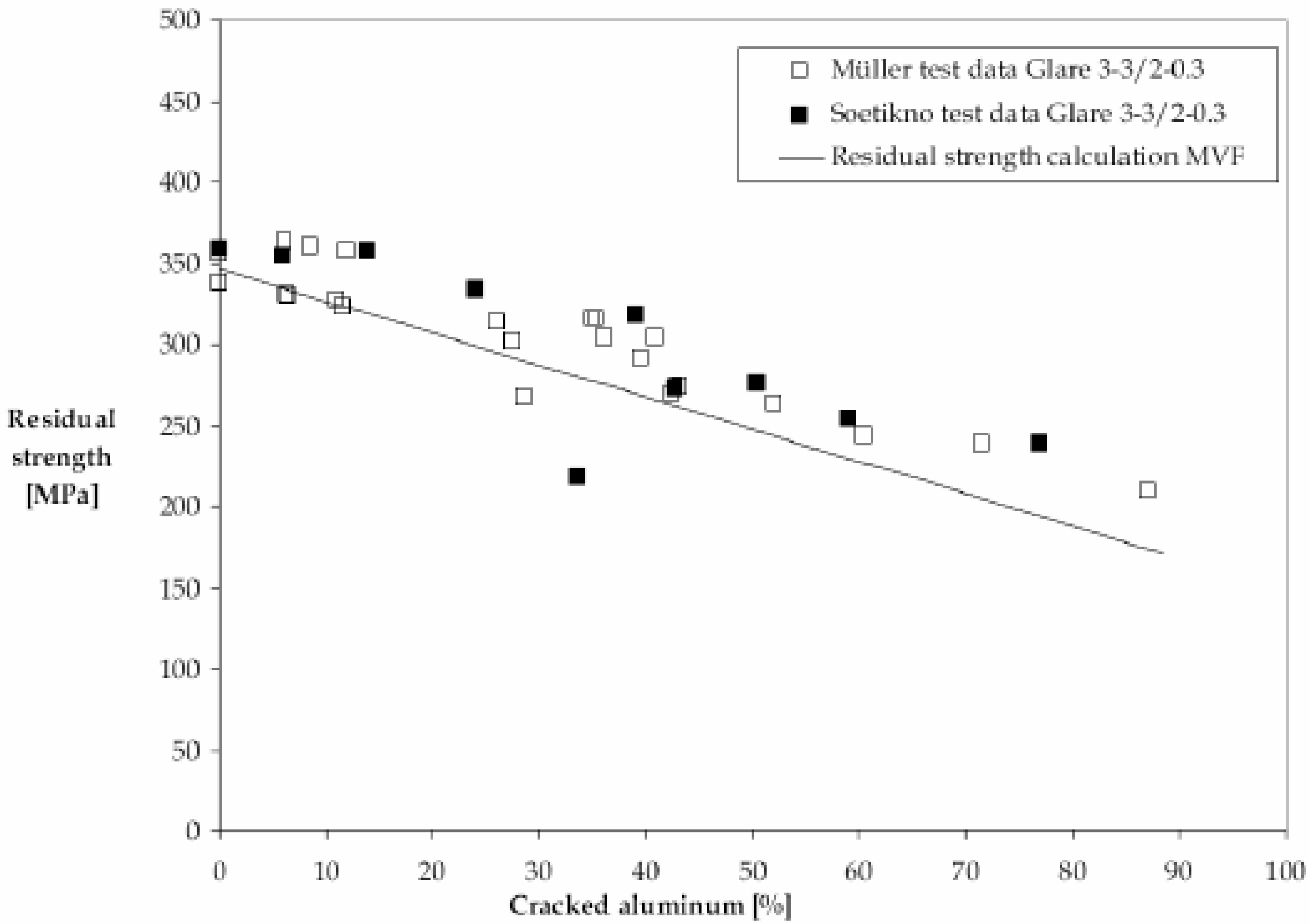
Comparison of surface crack growth in FMLs

- Left: Maximum applied stress = 120 MPa
- Right: Maximum applied stress= 100 MPa

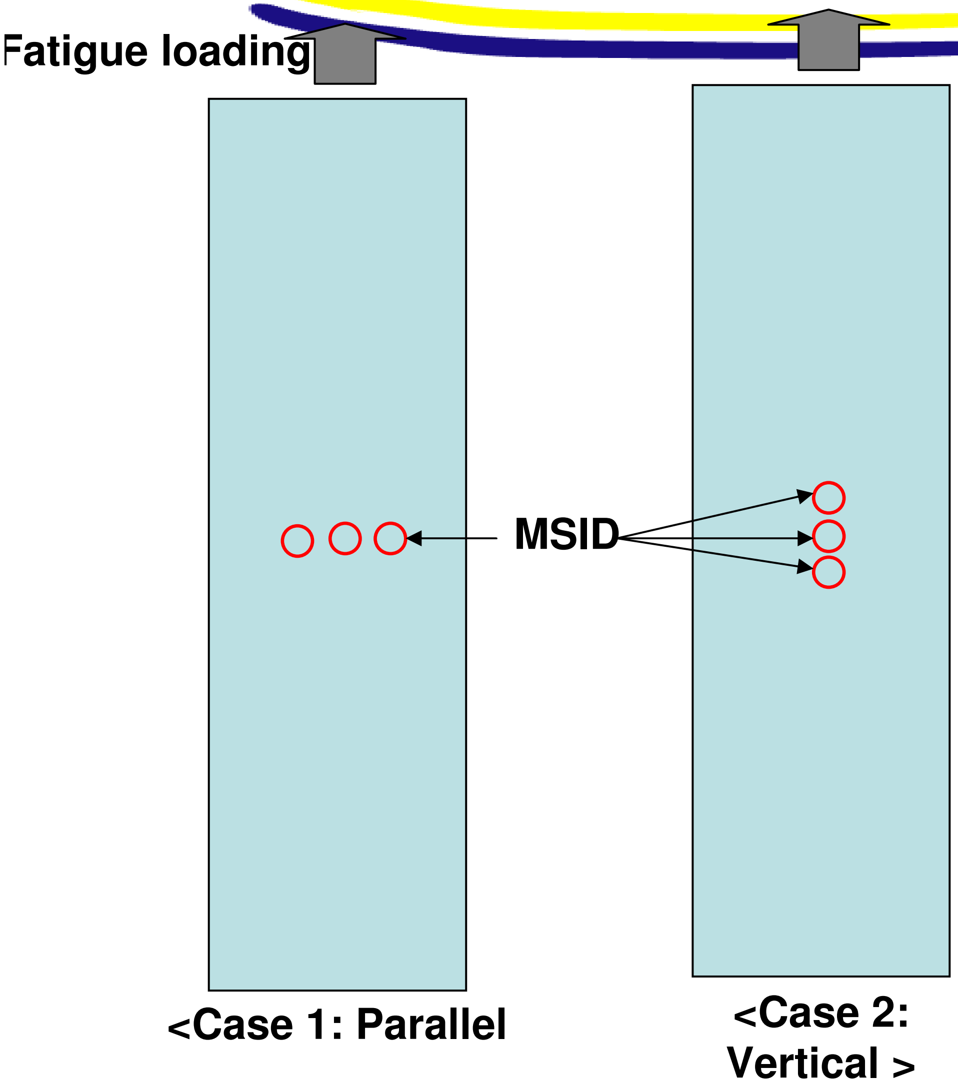




Residual strength in fiber metal laminates



Multi-site Impact Test



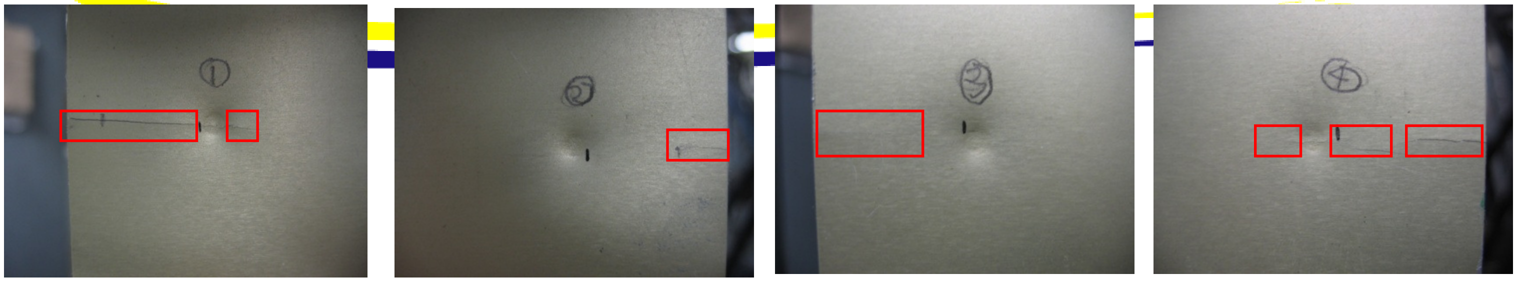
- Investigate crack trajectory and crack growth
- Investigate crack propagation on aluminum layer and on composite layer after removing aluminum layer.
- Investigate delamination shape
- Compare single impact fatigue behavior with multiple impacts fatigue behavior

Fatigue Test After Multi-site Impact Damage

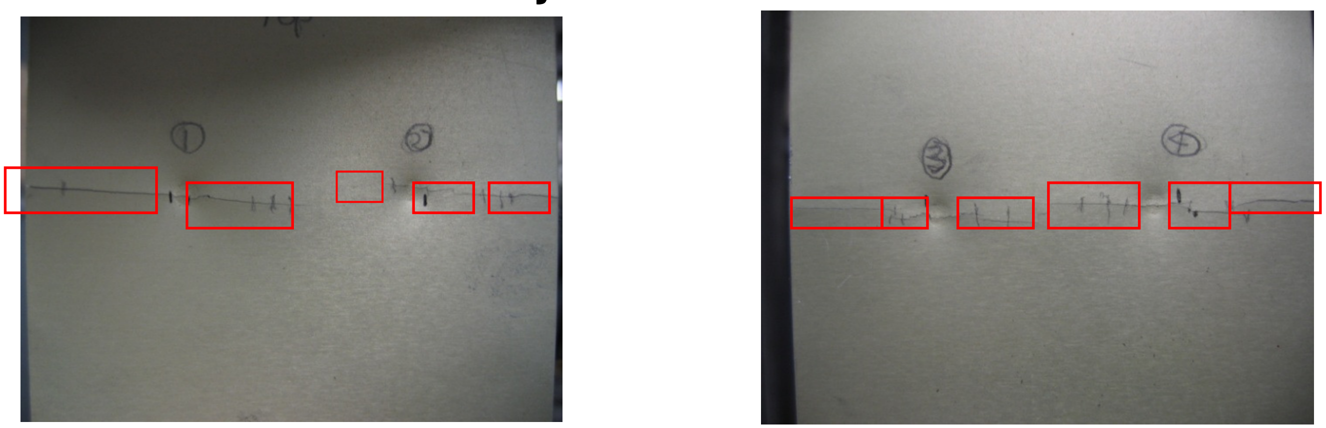
- Fatigue test
  - Load ratio R=0.1
  - Cyclic loading
  - Applied impact energy: 4J and 8J
  - Load level: 20% (116.2 MPa), 30% (174.3 MPa), 40% (232.4 MPa) 60% (348.6 MPa) of PITS (Post-Impact Tensile Strength)
  - Frequency: 5 Hz

<Instron for fatigue test>

Crack Propagation at 174.3 MPa (30% Stress Level)-1



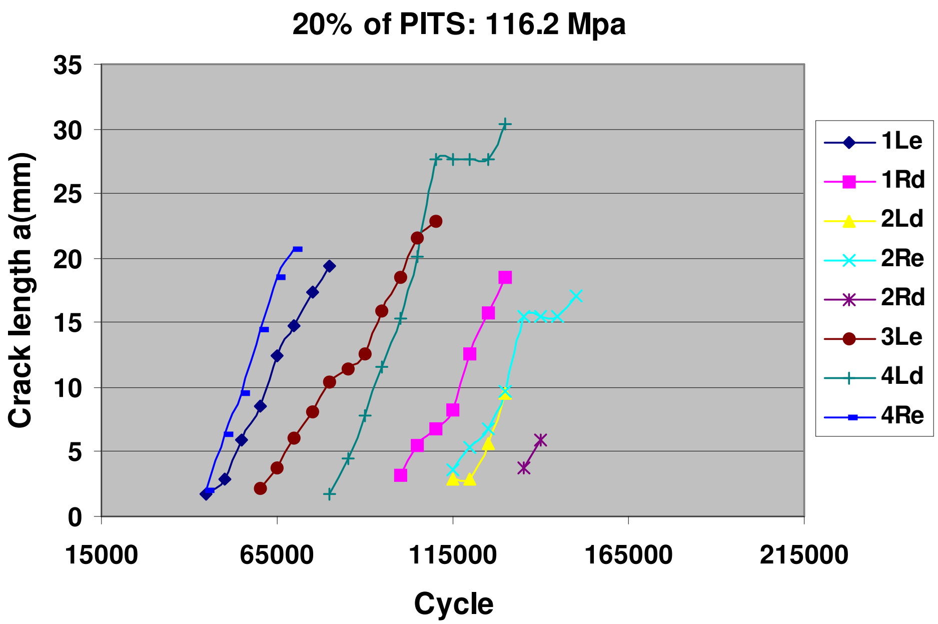
cycle : 55202

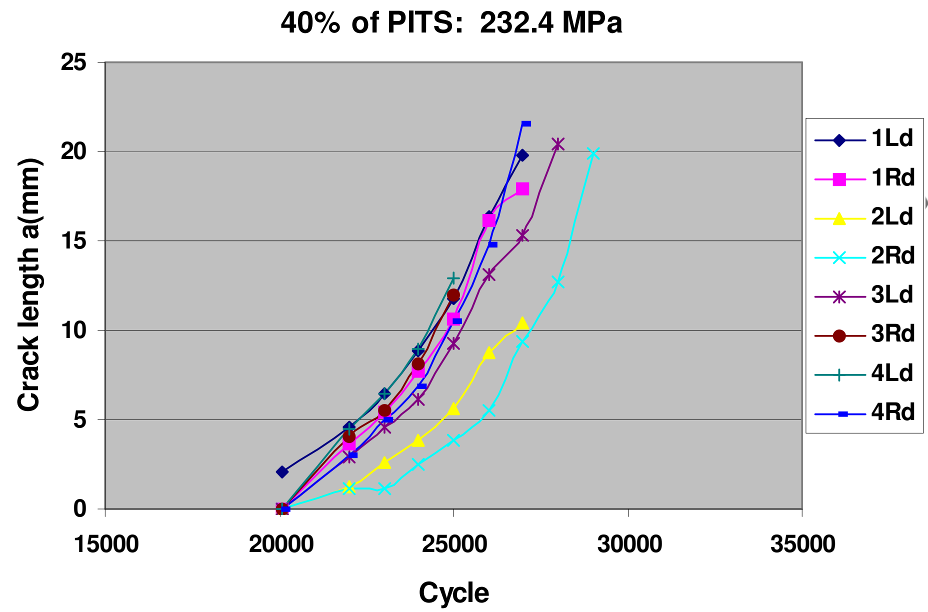


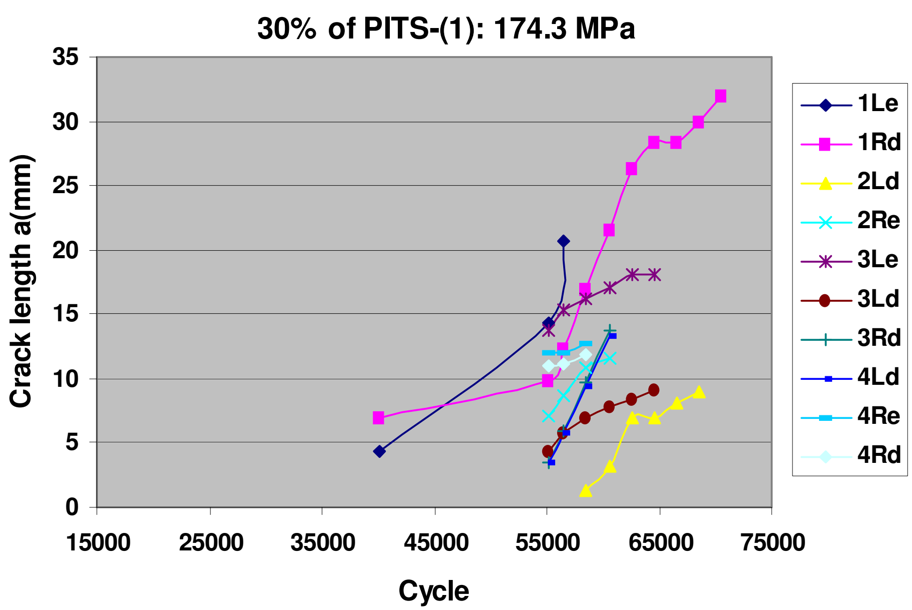
Cycle : 60548

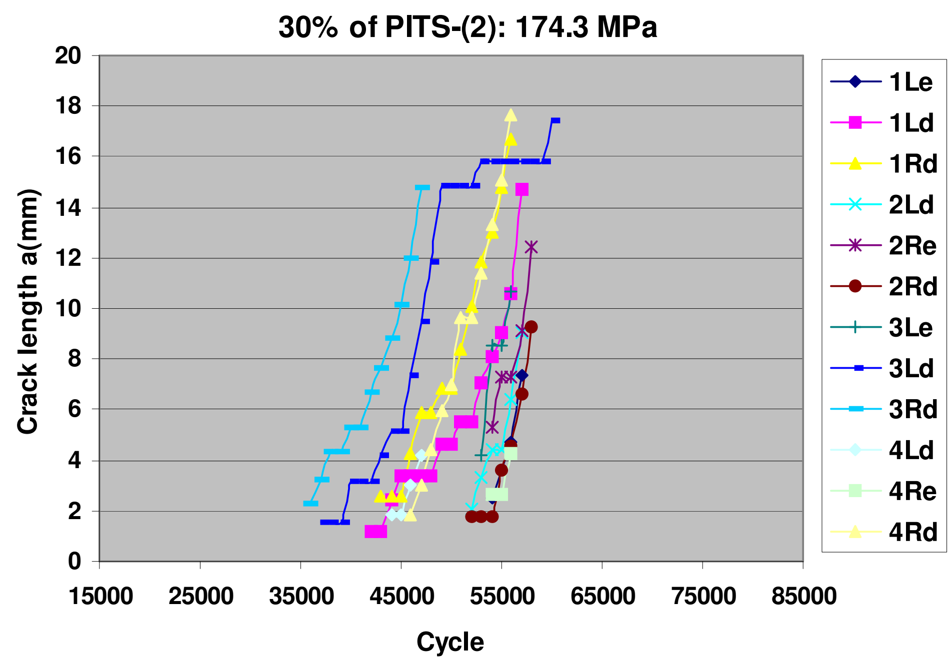
Unit: mm

No/ Cycle	1E	1L	1R	2L	2R	2E	3E	3L	3R	4L	4R	4E
55202	14.34	0	6.93	0	0	7.09	13.67	4.27	3.49	3.49	11.04	12.02
60548	20.72	0	16.93	5.11	0.75	11.64	17.03	7.79	13.68	13.27	11.88	12.72

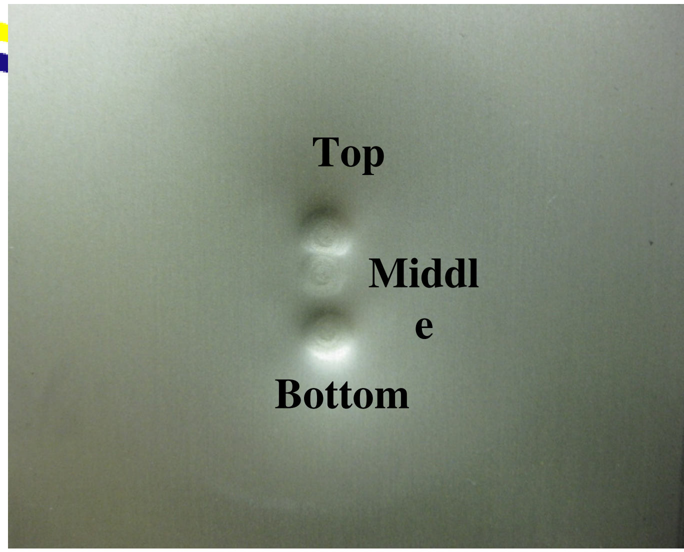

20% of PITS: 116.2 Mpa
Crack length a(mm)
Cycle
1Le
1Rd
2Ld
2Re
2Rd
3Le
4Ld
4Re


40% of PITS: 232.4 MPa
Crack length a(mm)
Cycle
1Ld
1Rd
2Ld
2Rd
3Ld
3Rd
4Ld
4Rd

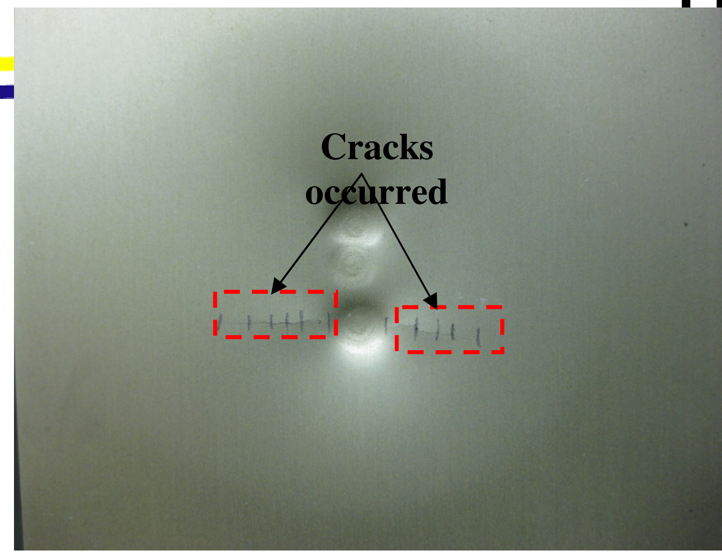

30% of PITS-(1): 174.3 MPa
Crack length a(mm)
Cycle
1Le
1Rd
2Ld
2Re
3Le
3Ld
3Rd
4Ld
4Re
4Rd


30% of PITS-(2): 174.3 MPa
Crack length a(mm)
Cycle
1Le
1Ld
1Rd
2Ld
2Re
2Rd
3Le
3Ld
3Rd
4Ld
4Re
4Rd

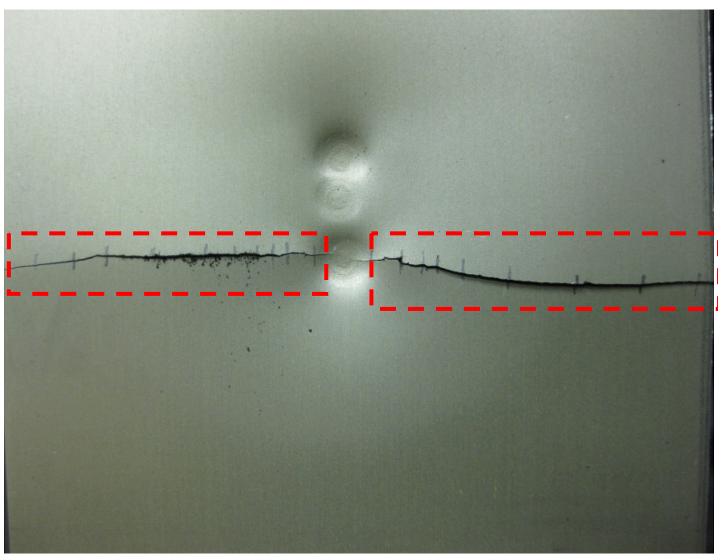
Crack Growth under σ=174.3 MPa (30% Stress Level)



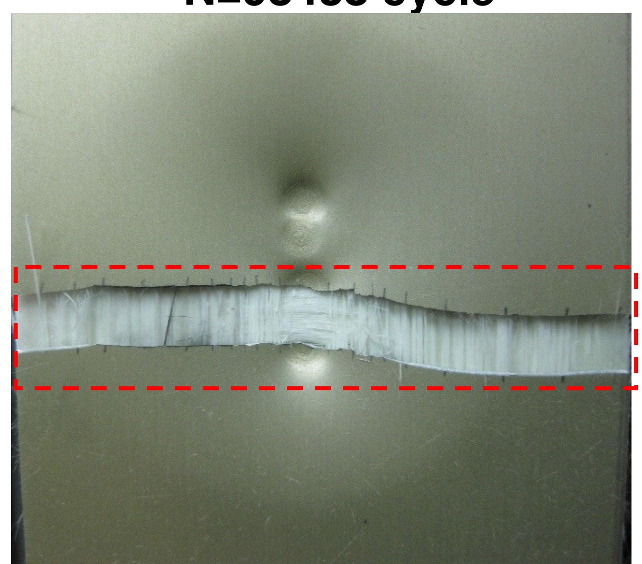
N=0 cycle



N=98438 cycle

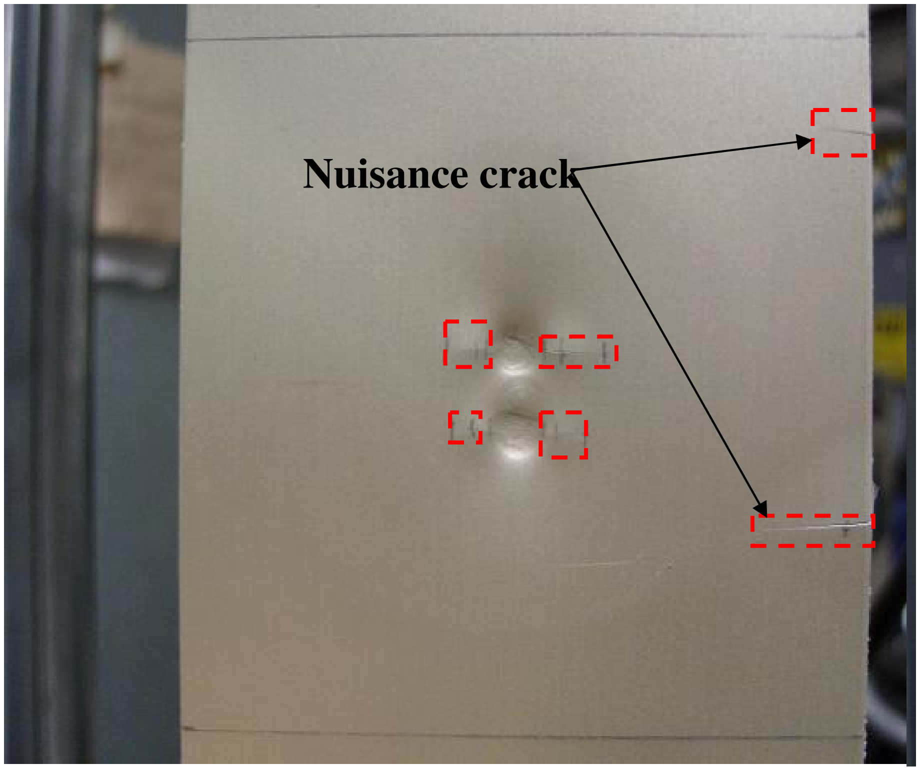


N=121902 cycle (crack arrived at the end of

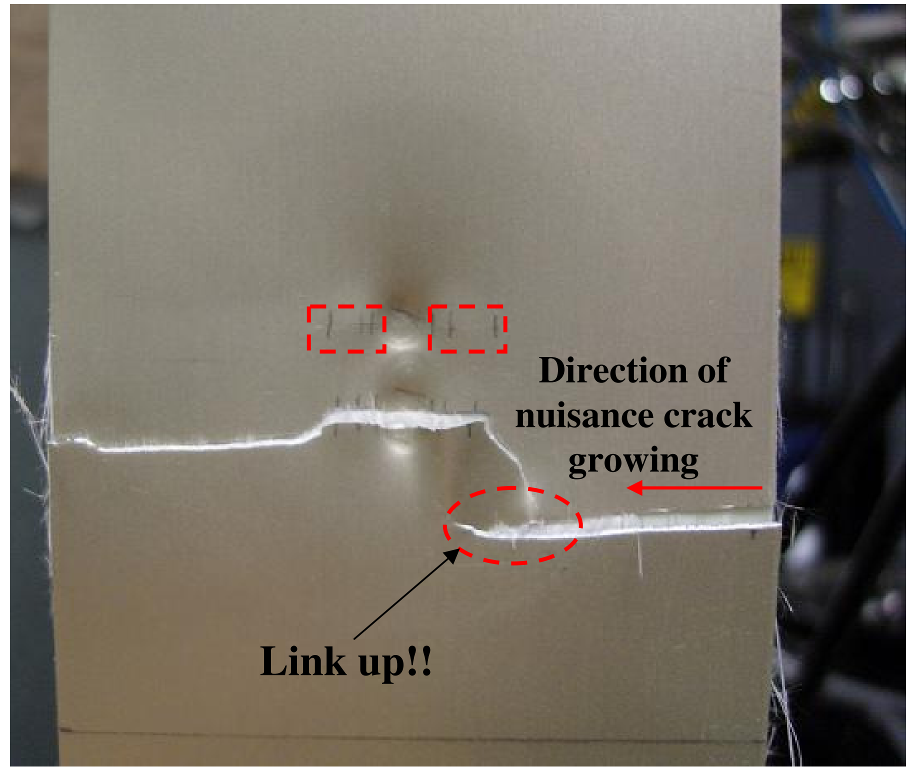


N=156599 cycle (Failed)

Crack Growth under σ=348.6 MPa (60% Stress Level)



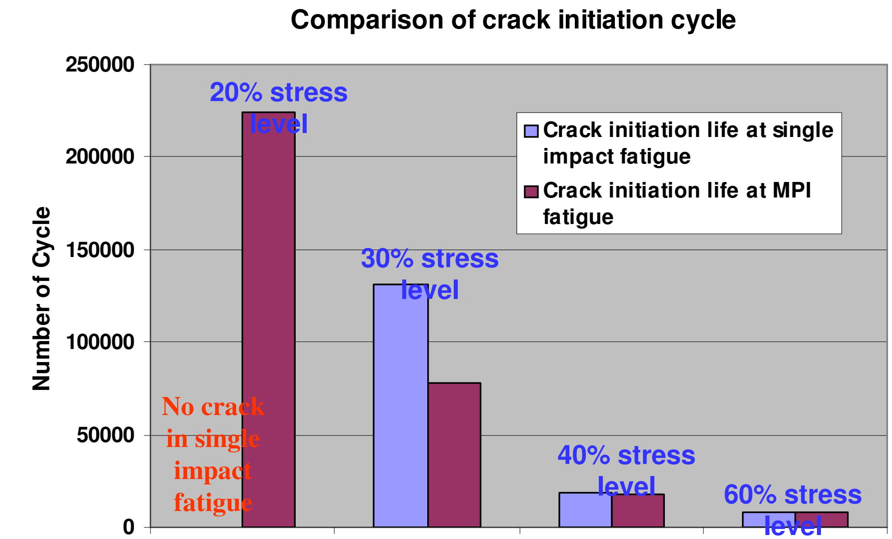
N=8501 cycle

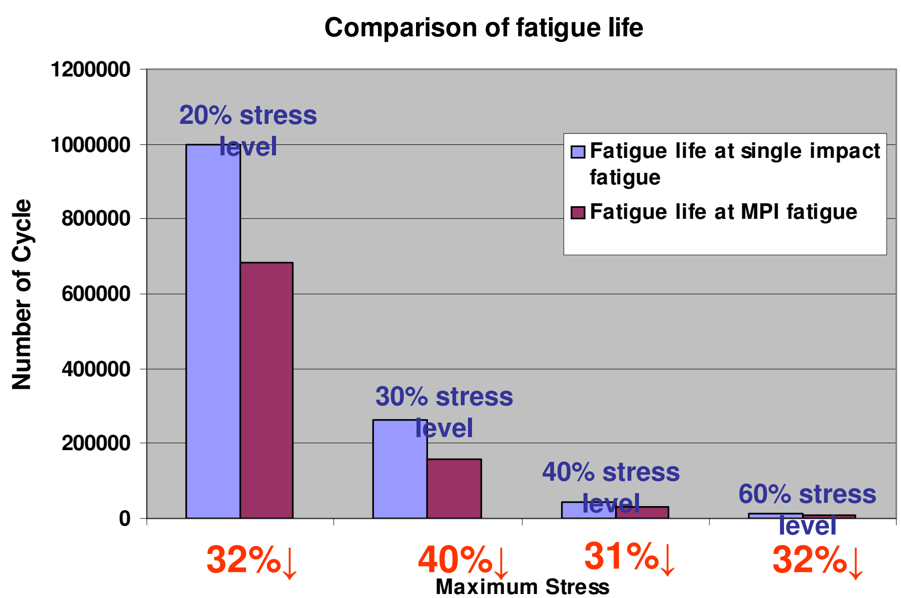


N=8579 cycle (Failed)

At σ=348.6 MPa, GLARE 5-2/1 failed due to nuisance cracking from the edge.

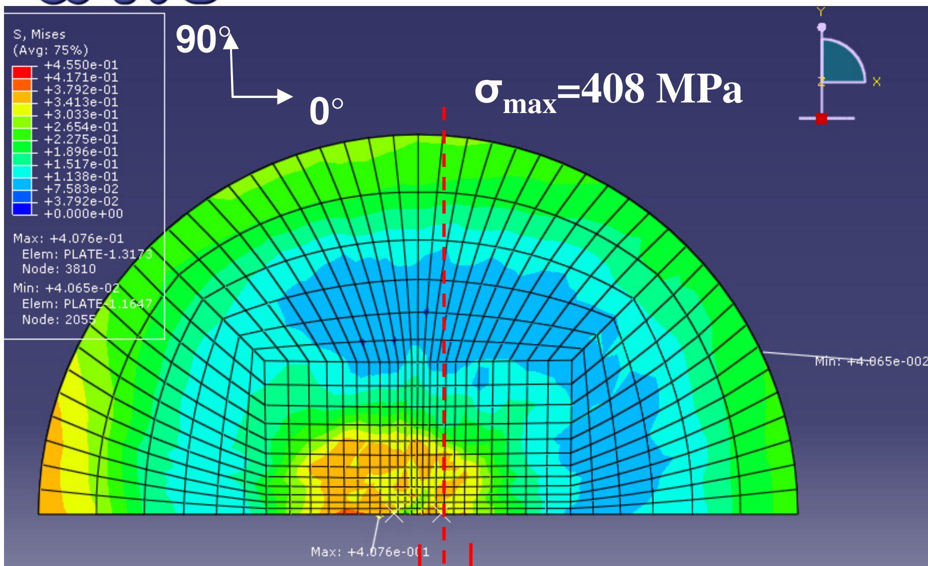
Fatigue after Single Impact vs. Multi-site Impact



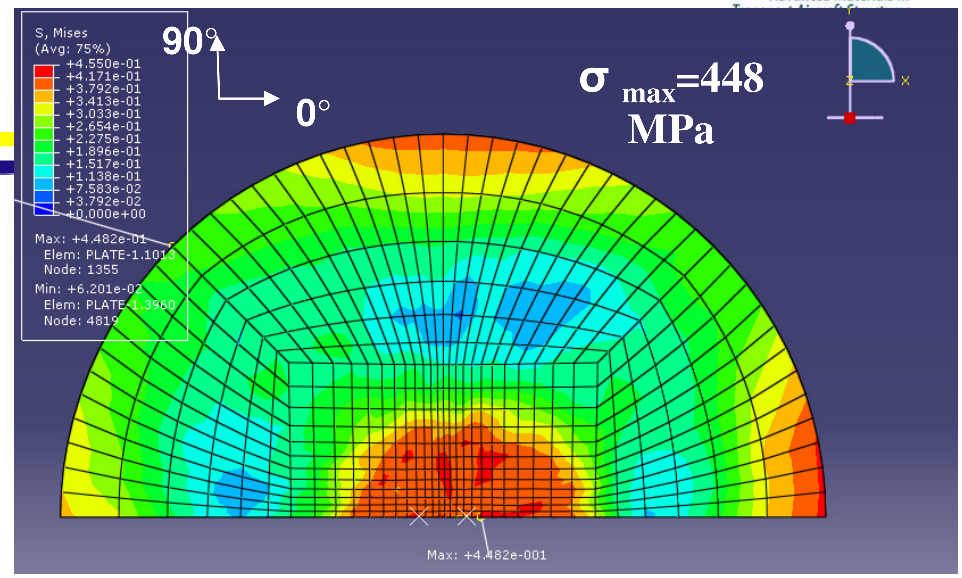


- **Fatigue crack initiation life after MSI is usually shorter than that with single impact. This reason is caused by the reduction of strength of aluminum layer.**
- **The residual strength of composite layer may be decreased by multiple impacts. So, fiber bridging from the composite layers may not play a significant role. Therefore, fatigue life after MSI is shorter than that subjected to single impact.**

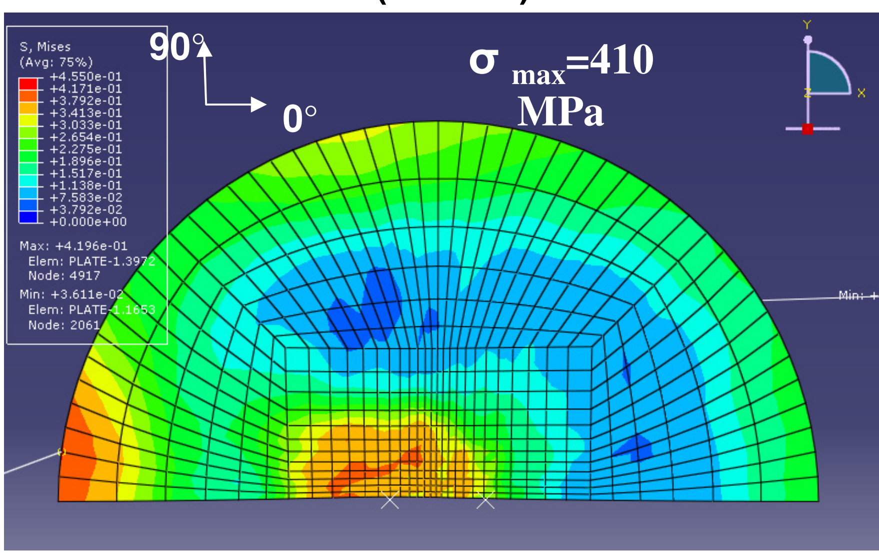
Von-Mises Stress on Impacted Al Layer



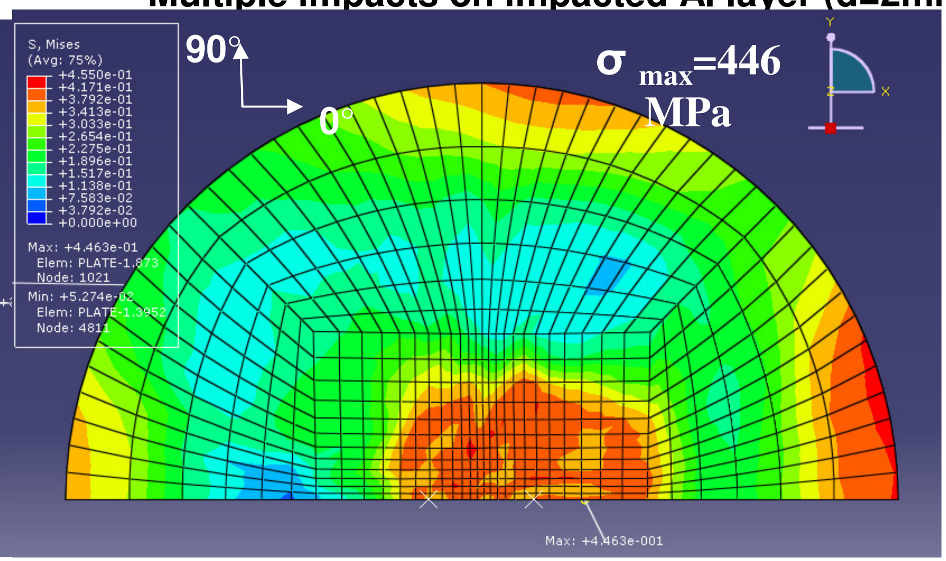
Single impact on impacted Al layer (d=2mm)



Multiple impacts on impacted Al layer (d=2mm)



Single impact on impacted Al layer



Multiple impacts on impacted Al layer (d=4mm)

Summary

- The fatigue behavior of Glare with MSD is superior to that of the monolithic Al alloy.
- Fatigue crack initiation life after MSID is usually shorter than that with single impact. This reason is caused by the reduction of strength of aluminum layer.
- The residual strength of composite layer may be decreased by multiple impacts. So, fiber bridging from the composite layers may not play a significant role. Therefore, fatigue life after MSID is

  shorter than that subjected to single impact.

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**

  --MSD under variable amplitude loading

  --Lightning strike resistance

Lightning Strike Resistance of GLARE