Damage Extension and Failure Behavior of CFRP Specimens in Open Hole Compression Tests and Analytical Simulation

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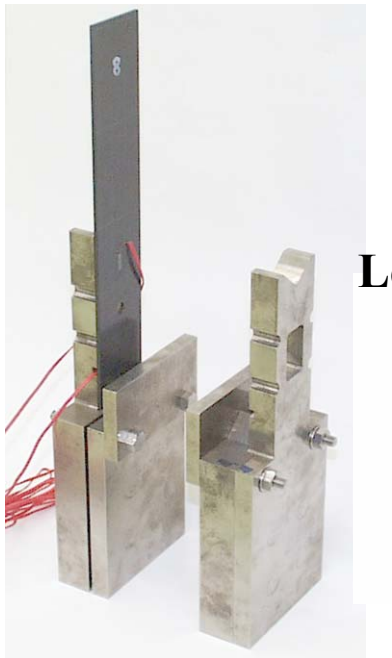
Topics 1 : Effectiveness of NAL-III OHC Test Method
Topics 2 : Understanding of Failure Mechanism
Topics 3 : FEM Analysis
- **Focus : Evaluation of Ply Damage and Delamination Extension**

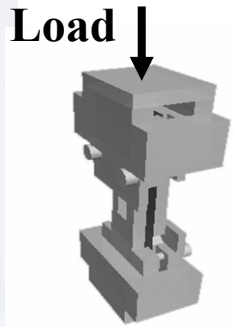
Open Hole Compression Test (OHC) : One of the Most Critical Strengths in Design and Certification of Composite Structures

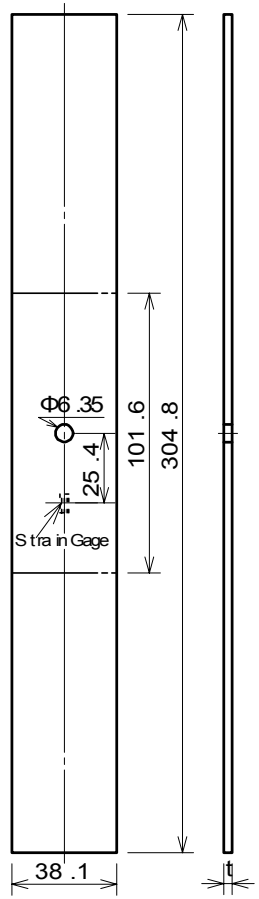
Effectiveness of NAL-III OHC Test Method

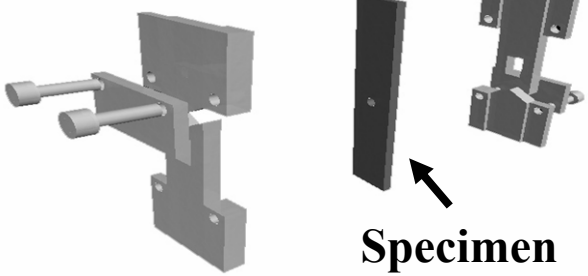
Detail of OHC test Fixture and Specimen

SACMA 3R-94

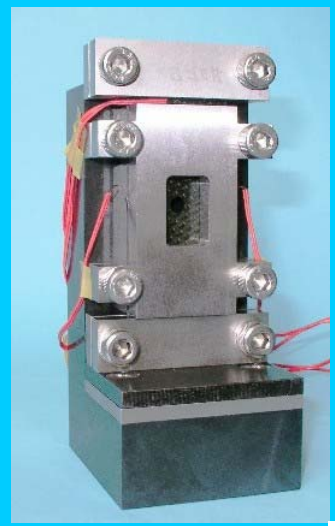


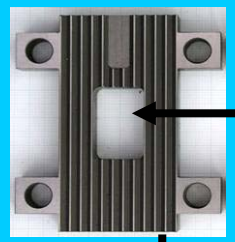


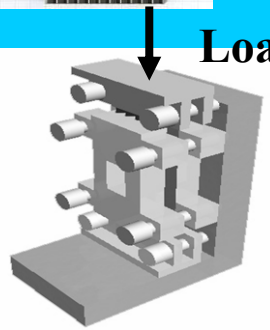


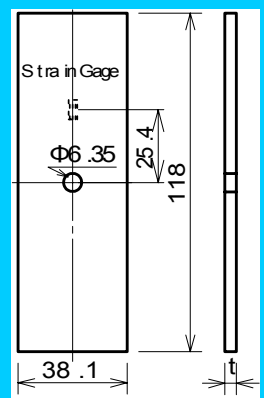


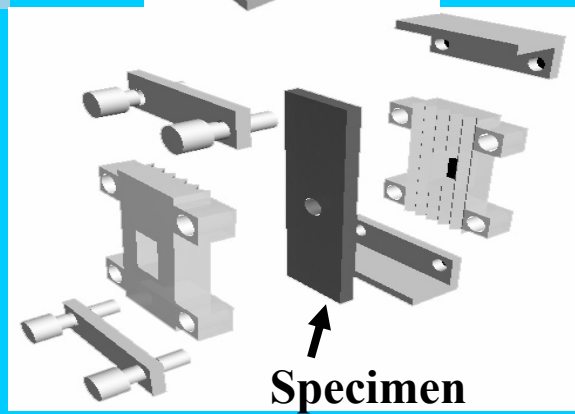
NAL-III Test Method







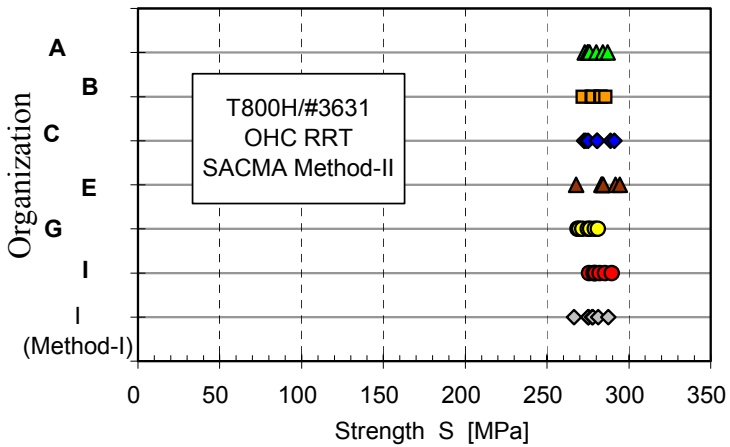
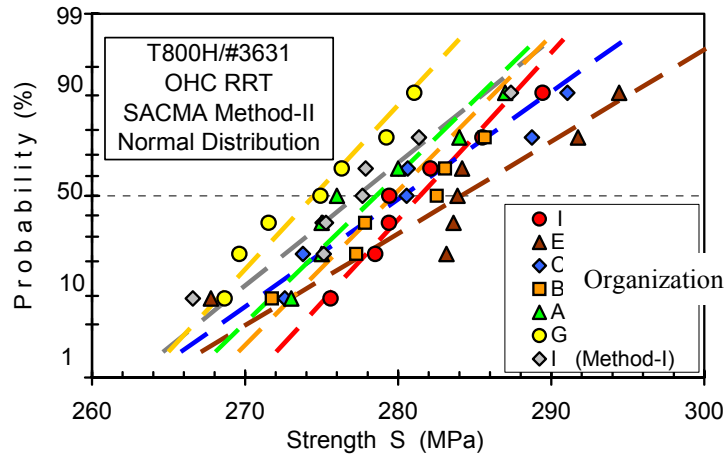
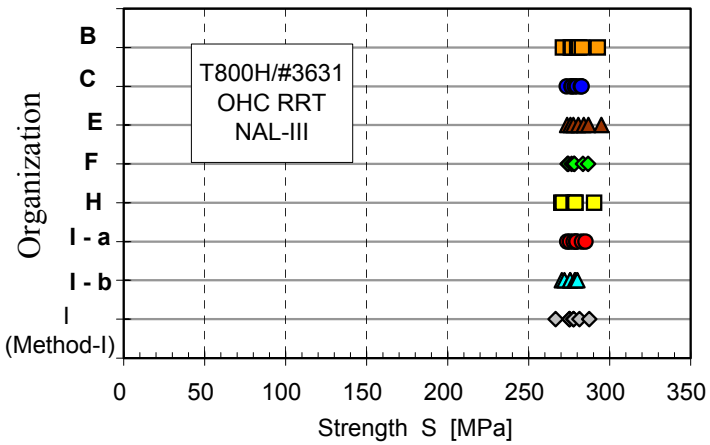
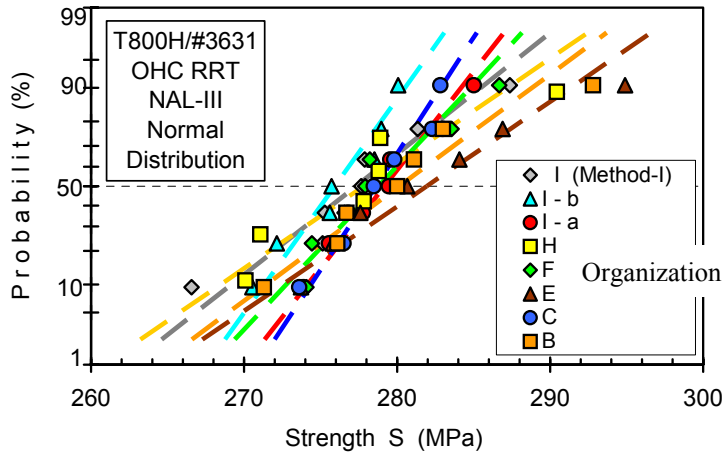




Effective OHC Test Method : NAL-III

- Incentive: Low Cost by Reducing Specimen Length
- Introduction of End Sub Fixture : Prevention of Brooming Failure
- Common Window Size with SACMA

Round Robin Test Results of SACMA and NAL-III OHC Test Method

	Comparison of the results	Strength distributions plotted on the probability paper
SACMA Method-II Round Robin Test 6-Organization T800H/#3631 UD 16plies 2002		
NAL-III Method Round Robin Test 6-Organization T800H/#3631 UD 16plies 2002-2003		

Proof of validity of OHC test result of NAL-III

- Comparison of Test Results : Almost Identical in Both Methods

Understanding of Failure Mechanism

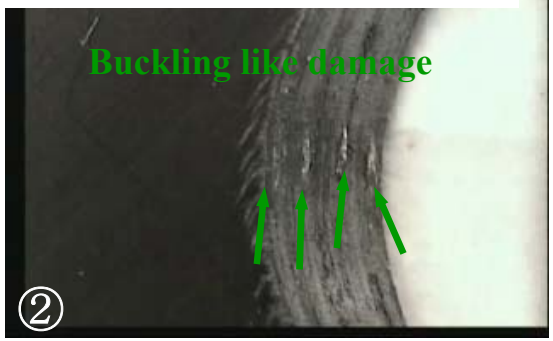
Typical Damage Evolution Behavior

IM600/QC101 - NAL-III test method

Load/Fracture Load ≒0%

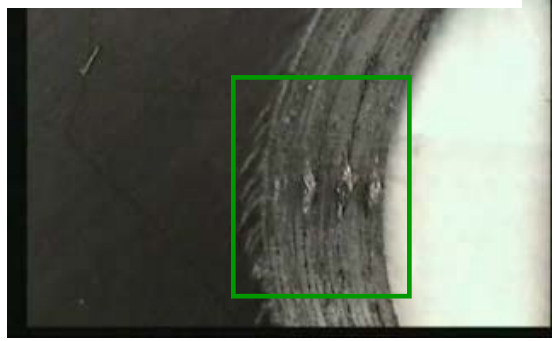
OHC specimen
$[(45/0/-45/90)_2]_{sym}$

Load/Fracture Load ≒24%



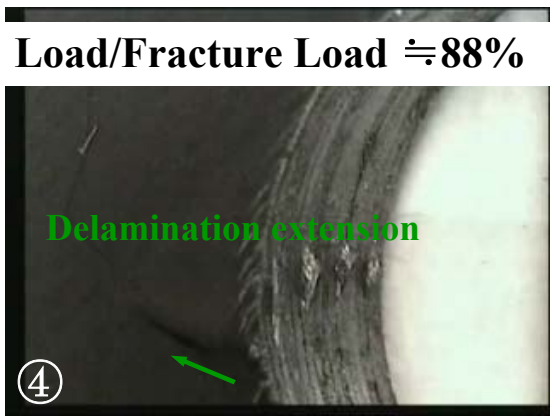
Buckling-like damage in hole edge area of 0° lamina

Load/Fracture Load ≒76%



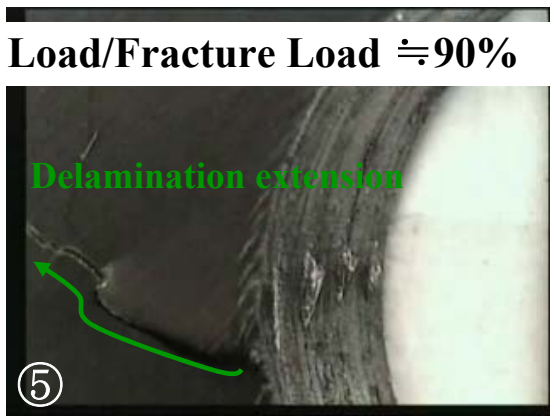
Transverse cracks and delaminations are observed.

Load/Fracture Load ≒88%



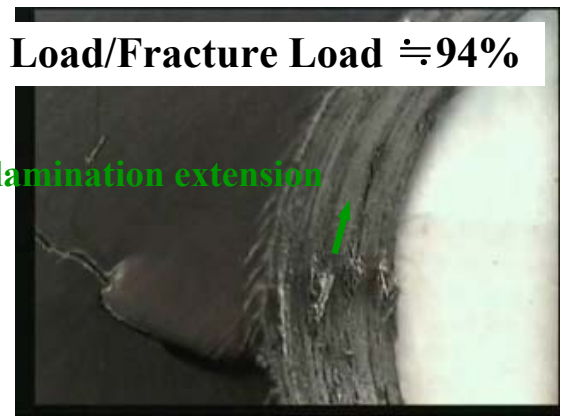
The buckling-like initial damage at the hole edge is the most probable onset of delamination.

Load/Fracture Load ≒90%

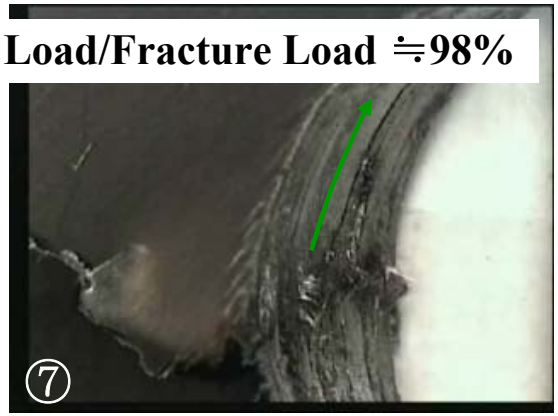


The delaminations occurred in interface between 0° lamina and 45° lamina near the specimen surface.

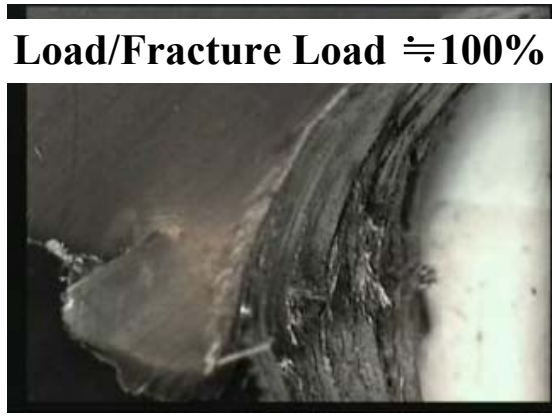
Load/Fracture Load ≒94%



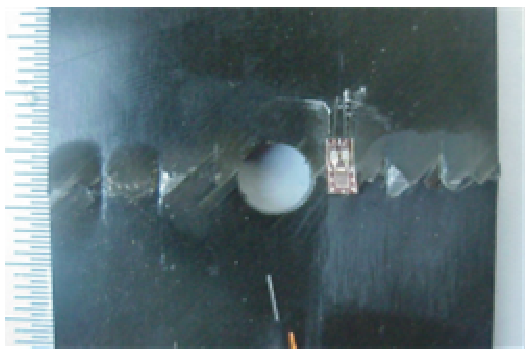
Transverse cracks and delaminations Evolution



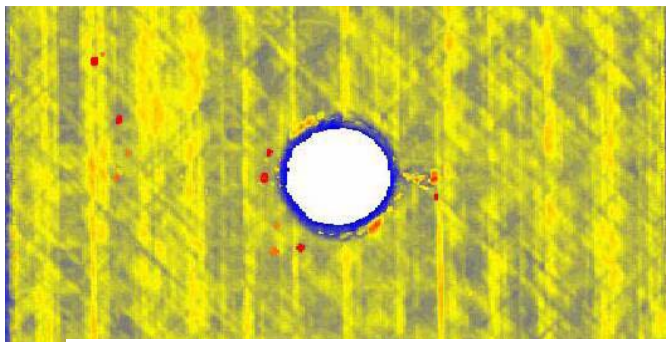
Critical delaminations evolution toward applied load



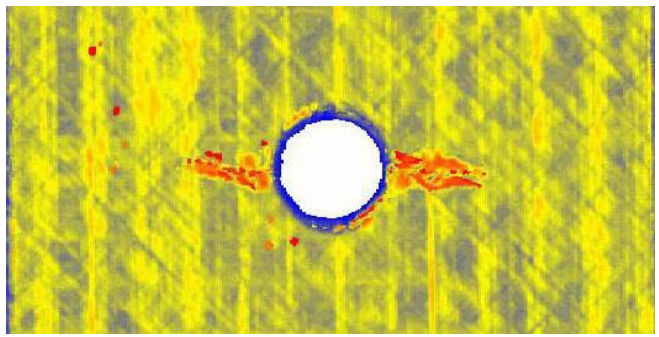
Final failure



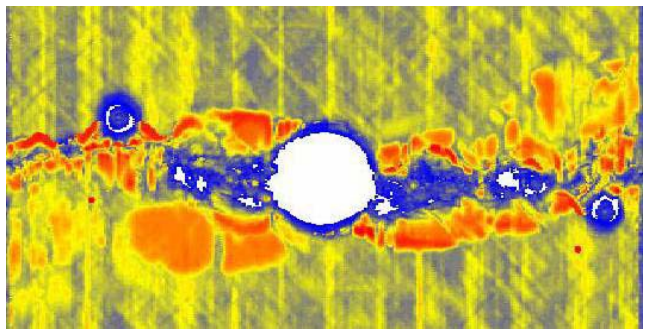
Fracture Specimen



Load/Fracture Load ≒80%



Load/Fracture Load ≒90%



Load/Fracture Load ≒100%

Fracture Progress image of Ultrasonic C-scan

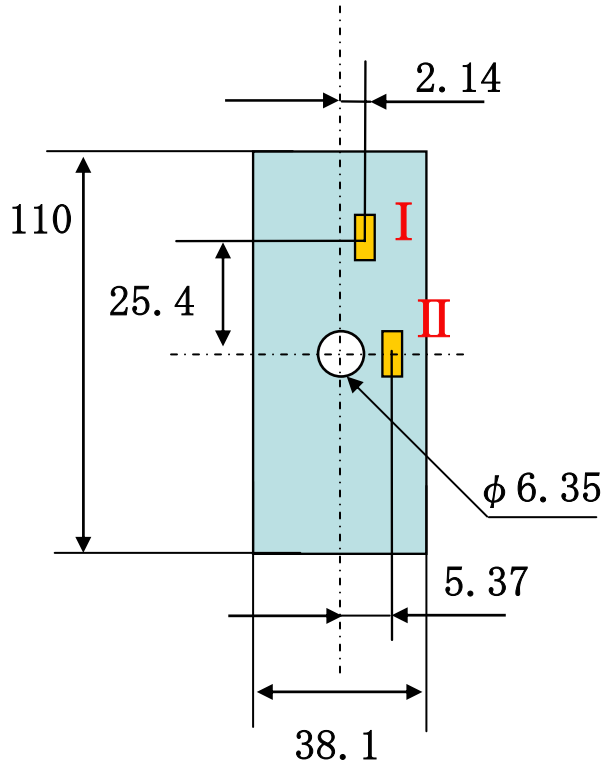
Core of Experimental Findings

- Initial Buckling like damage : Relatively Low Stress
- Trigger of Final Failure : Surface Delamination Buckling in 45° Ply

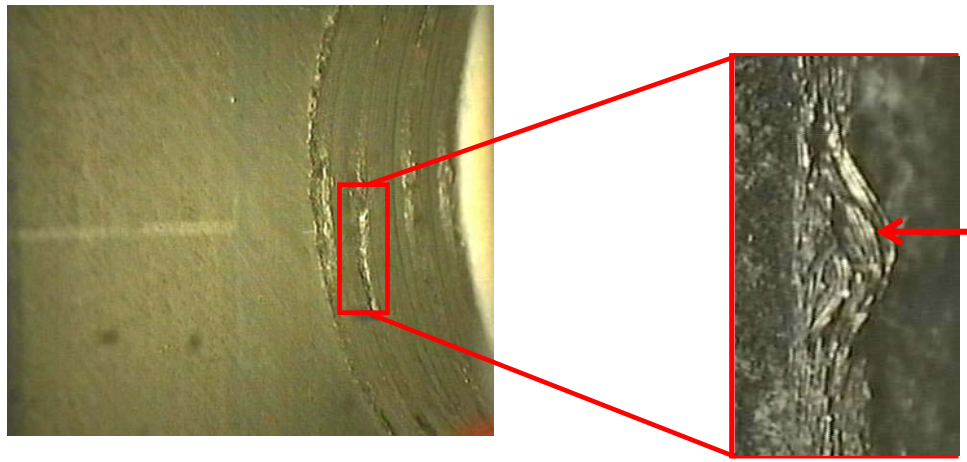
FEM Analysis

Evaluation of Stress Concentration in 0° Ply
$[(45/0/-45/90)_2]_{sym}$- IM600/QC133 OHC Specimen

Linear Elastic FEM Analysis

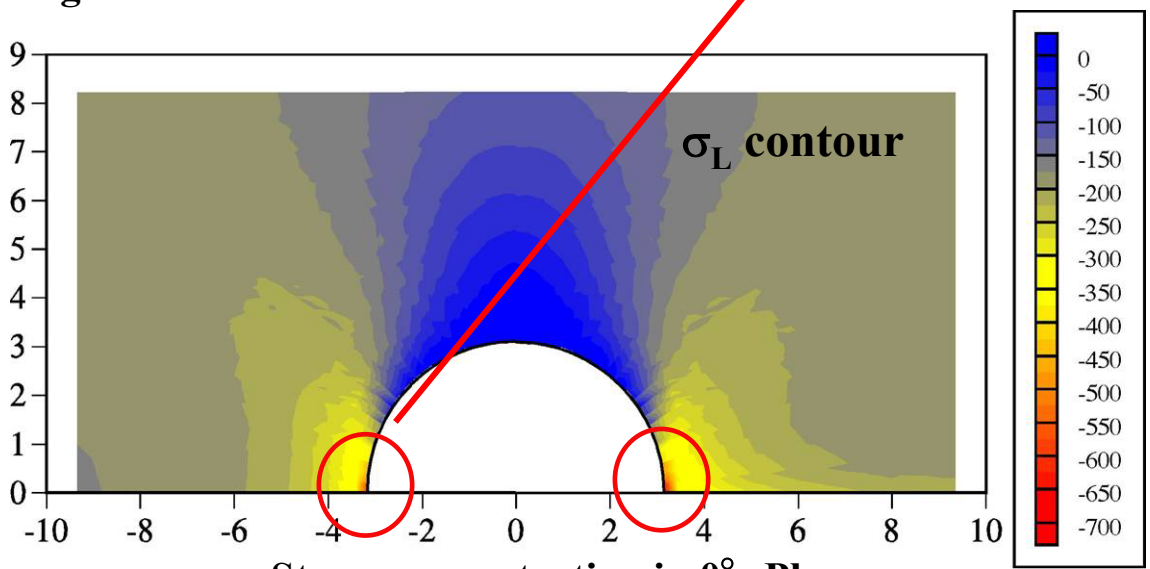


NAL-Ⅲ specimen



Buckling like damage

Buckling-like damage in hole edge area of 0° lamina



Stress concentration in 0° Ply

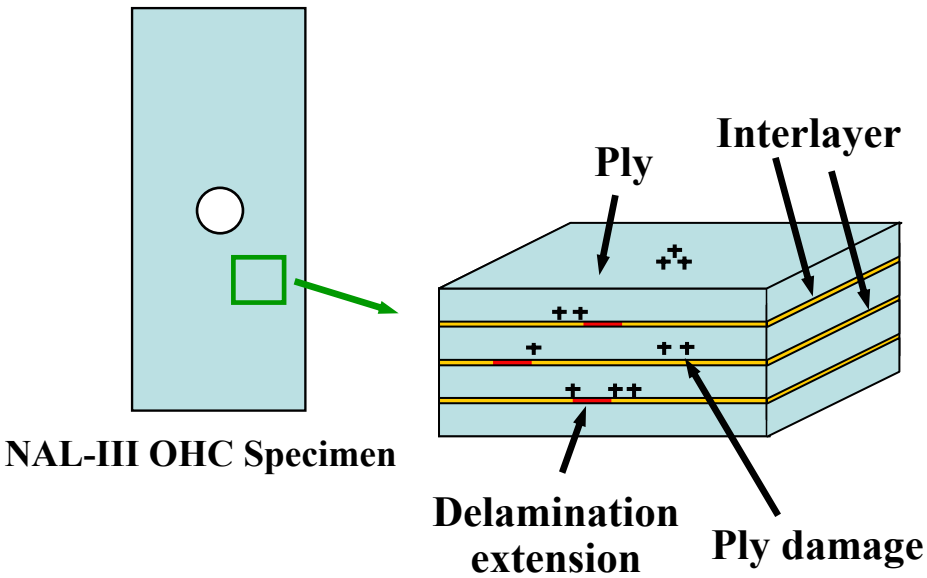
Evaluation of Ply Damage and Delamination Extension
Pre-analysis : $[0/90]_2$ OHC Specimen

Non-linear FEM Analysis

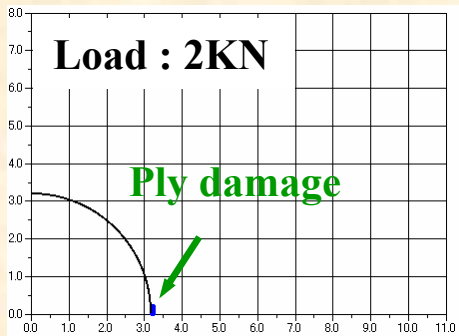
Analytical Results

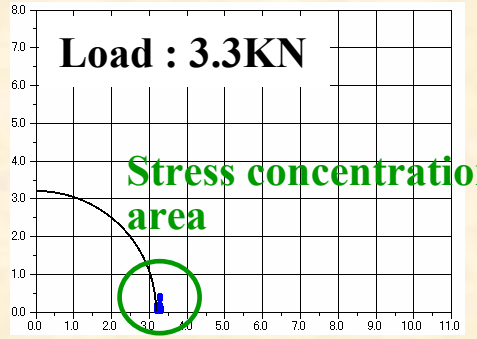
Outline of Analytical Method

- Non-linear FEM is applied to evaluate ply damage and delamination extension behavior.
- Ply Damage extension is judged by using stress criterion.
- Delamination extension is judged by using energy release rate.



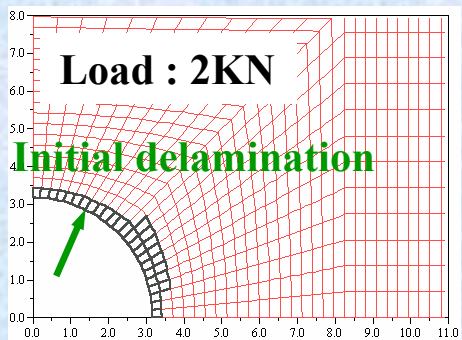
Analytical Model

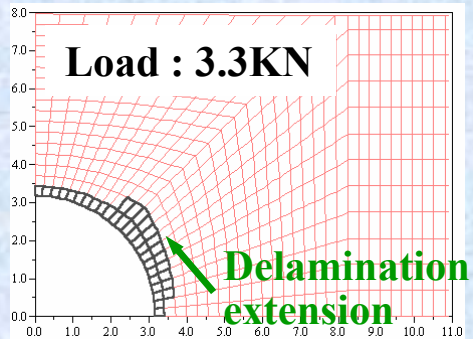




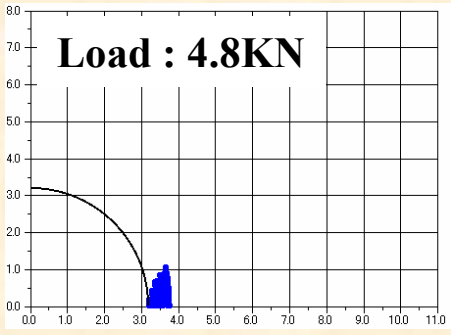
The initial ply damage is observed in hole edge area of 0° lamina

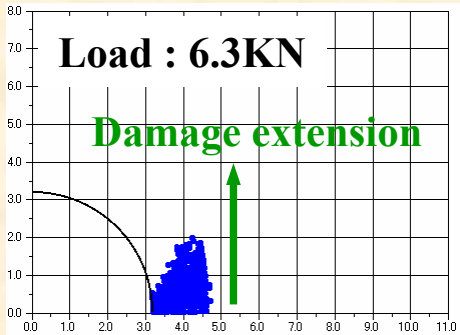
Damage Extension in 0° Ply

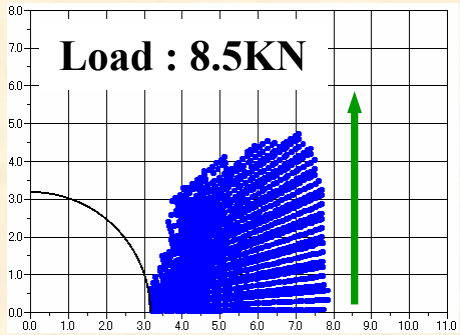




Delamination Extension between 0° Ply and 90° Ply





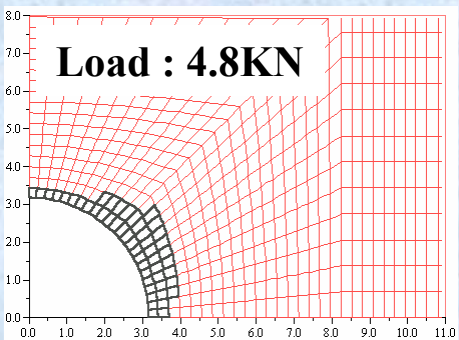


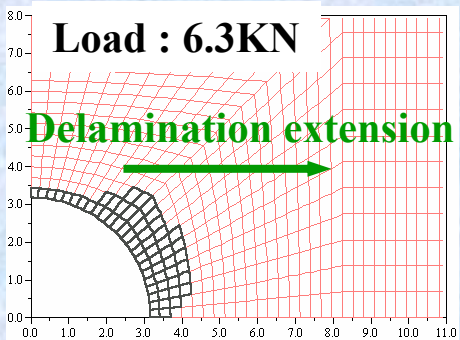
With the increase of the load, the ply damage area extends to load applied direction.

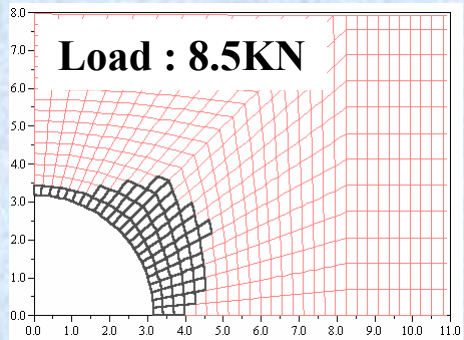
Damage Extension in 0° Ply

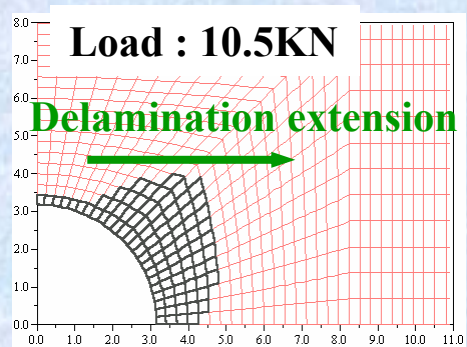
Core of Analytical Findings : Ply Damage

- The initial ply damage is observed in hole edge area of 0° lamina.
- The initial ply damage area will be the most highest stress concentration area.
- The ply damage area extends to load applied direction.









With the increase of the load, the delaminations propagate transversely to the applied load.

Delamination Extension between 0° Ply and 90° Ply

Core of Analytical Findings : Delamination

- The delaminations propagate transversely to the applied load.
- All delamination extension behaviors have the features of mode II fracture in present results.