LS-DYNA® Peridynamics for Brittle Failure Analysis

A new physical based theory to predict the mixed mode damage process in brittle solid

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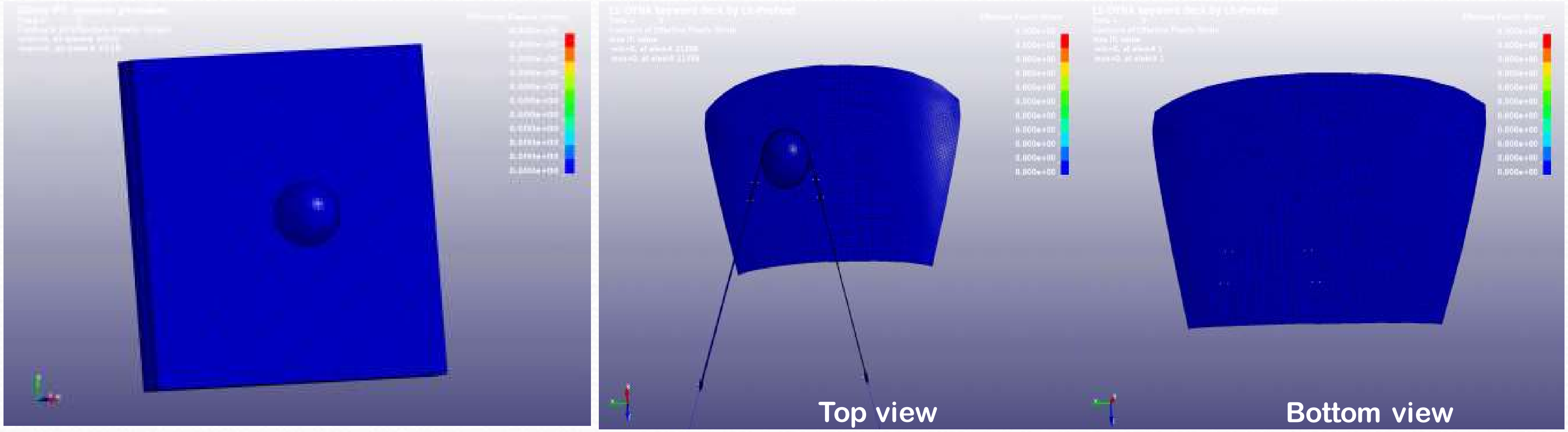
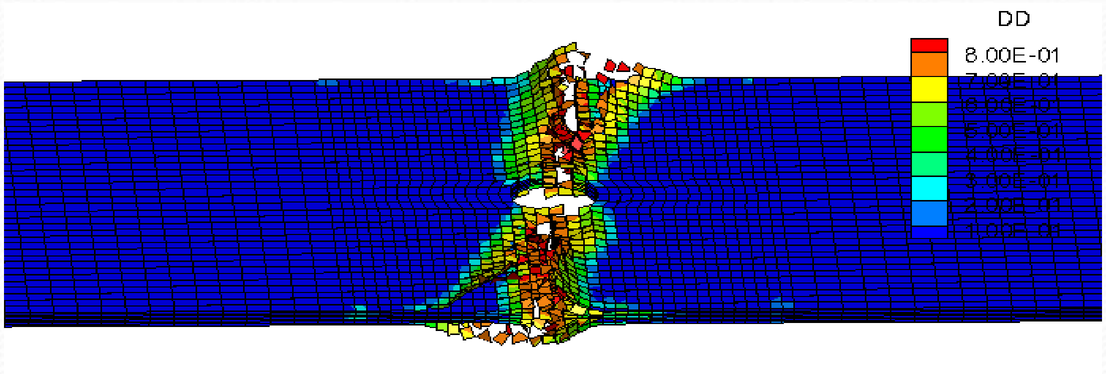
What is Peridynamics Designed for?

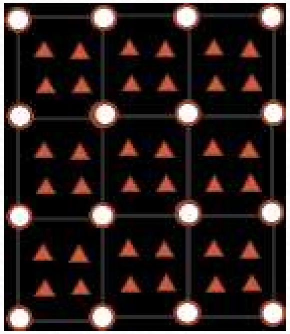


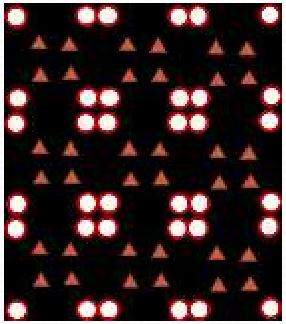


Complex damage evolution in brittle materials

Peridynamics Development History

1. Is a new nonlocal “theory” for material failure analysis.
2. Has bond-based and state-based peridynamic theories.
3. Was developed by Dr. Steward Silling at Sandia Nat. Lab. in 2000.
4. Conventional bond-based and state-based peridynamics do not work well for non-uniform discretization and have difficulties to prescribe boundary conditions and kinematic constraints.
5. To bypass the numerical problems in 4. , the bond-based peridynamics was implemented into LS-DYNA® using Discontinuous Galerkin (DG) Finite Element Method .
6. Only available in LS-DYNA (SMP/MPP) since 2016.





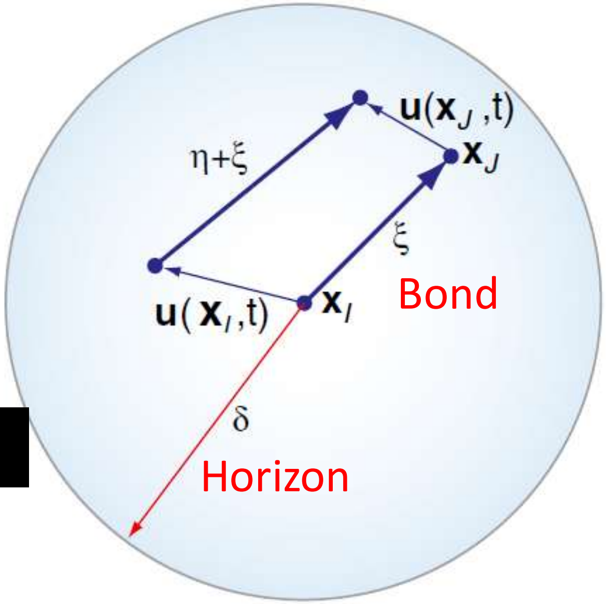
1. Peridynamic Theory

$\rho\ddot{u}_i(X_I) = \sigma_{ij,j} + b_i(X_I)$ *Classical local theory*

$$\rho\ddot{u}_i(X_I) = \int_{H_X} f_i < \eta_i, \xi_I > dV_{X'} + b_i(X_I)$$

$$\xi_I = X_I' - X_I$$

$$\eta_i = u_i^P - u_i$$

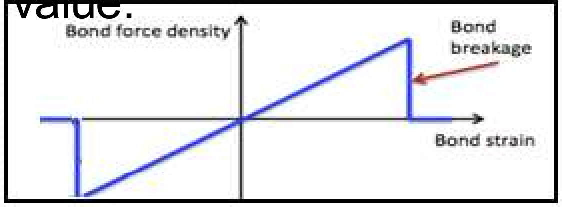


[redacted]

$$f = cs\frac{\eta + \xi}{|\eta + \xi|}, \quad s = \frac{|\xi + \eta| - |\xi|}{|\xi|}, c = \frac{18K}{\pi\delta^4}$$

Here s is the bond stretch with micro modulus c. A bond will break permanently when its bond compression or tension over a critical value:

$$s \leq s_t \ or \ s \geq s_c$$



3. The Keywords for Peridynamics

- *SECTION_SOLID_PERI (Available in R10., MPP, SMP)
  - Card 1

Variable	SECID	ELFORM
Type	I	I
Default		

ELFORM EQ.48: Peridynamic formulation for TET, PENT, HEX solid elements

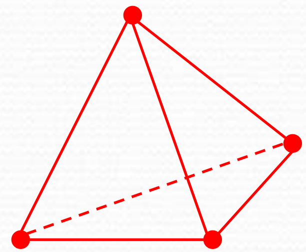
  - Card 2

Variable	DR	PTYPE
Type	F	I
Default	1.01	1

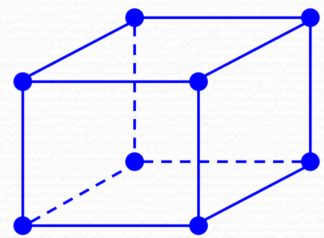
DR: normalized horizon size, **0.6~1.2** is recommended

PTYPE EQ.1: bond based formulation

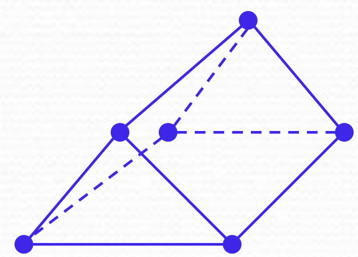
EQ.2: state based formulation



Tetrahedron (TET)



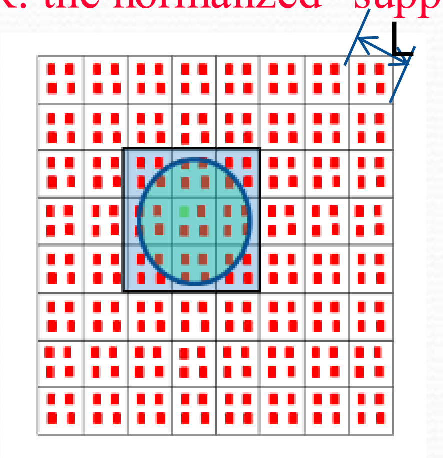
Hexahedron (HEX)



Pentahedron (PENT)

3. The Keywords for Peridynamics

- DR: the normalized support zone size

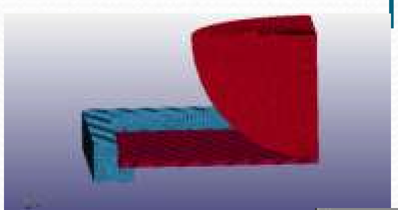


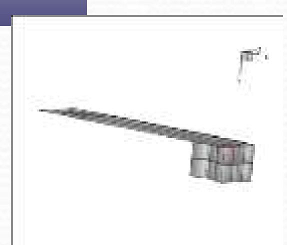
$$R = DR * L$$

DR is the user defined reference support size LSDYNA will adjust DR automatically to make sure the neighbors of a point is

$$10 \leq n_g \leq 136$$

Warning. The maximum neighbor number is 36
the minimum neighbor number: 9
which violates the threshold: 10~136 (Min~Max).
The horizon size will be tuned, and new search starts





Don't support the extremely poor mesh

3. The Keywords for Peridynamics

- *MAT_ELASTIC_PERI (available in R10.0, MPP, SMP)
  - Card 1

Variable	MID	RO	E	G_T	G_S
Type	I	I	F	F	F
Default				1.0E20	1.0e20

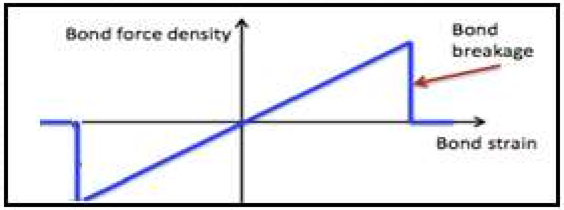
The only material type can be used for peridynamics.

RO: density

E: Young's modulus $\boldsymbol{E \rightarrow c}$

G_T: fracture energy release rate $\mathbf{G} \rightarrow \boldsymbol{s_c}$

G_S: fracture energy release rate for compression



Comments

G_S=2.0*G_T For compression problems

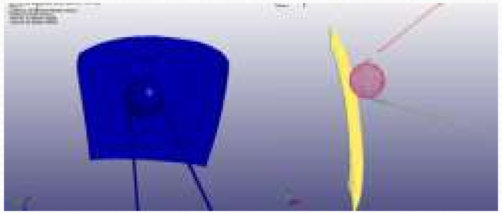
Nonconforming mesh leads to wrong results

3. The Keywords for Peridynamics

Four ways to deal with peridynamic and FEM interface:

1) ***CONTACT_AUTOMATIC_*.**

Peridynamic parts can interact with other parts through regular contact.
*CONTACT_AUTOMATIC_NODES_TO_SUFRACE is recommended as peridynamic part is the slave part.



2) **Sharing nodes at the interfaces**

Merging all the nodes on the FEM-Peridynamic interfaces
Advantage: efficient
Disadvantage: the interface can not be separated.

3) ***CONTACT_TIED_SURFACE_TO_SURFACE_OFFSET**

Advantage: easy to use, the tie can break.
Disadvantage: expensive, sometimes unstable.

4) ***CONTACT_FEM_PERI_TIE_opts**

Advantage: efficient, the tie can break.
Disadvantage: require coincide nodes on the interface.

3. The Keywords for Peridynamics

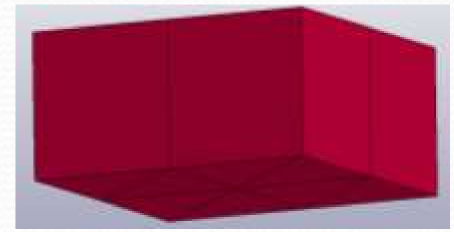
This key word requires coincide nodes on the interface.

*CONTACT_FEM_PERI_TIE_opt (beta version, SMP)

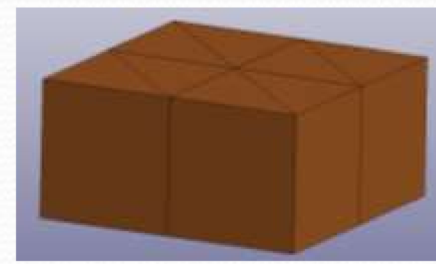
This keyword will be changed to: *CONSTRAINED_FEM_PERI_TIE_opt

- Card 1

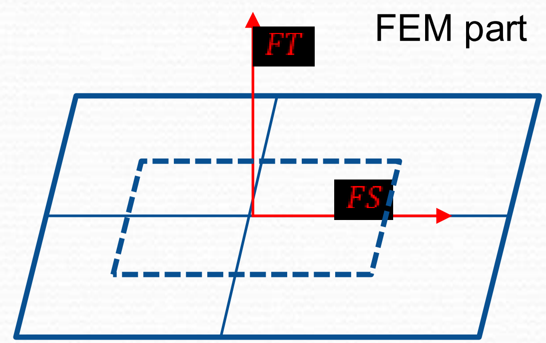
Variable	CID	MSID	SSID	*FT*	*FS*
Type	I	I	F	F	F
Default				1.0E20	1.0E20



Peridynamic part



CID: Contact ID
MSID: The FEM part ID
SSID: The peridynamic part ID



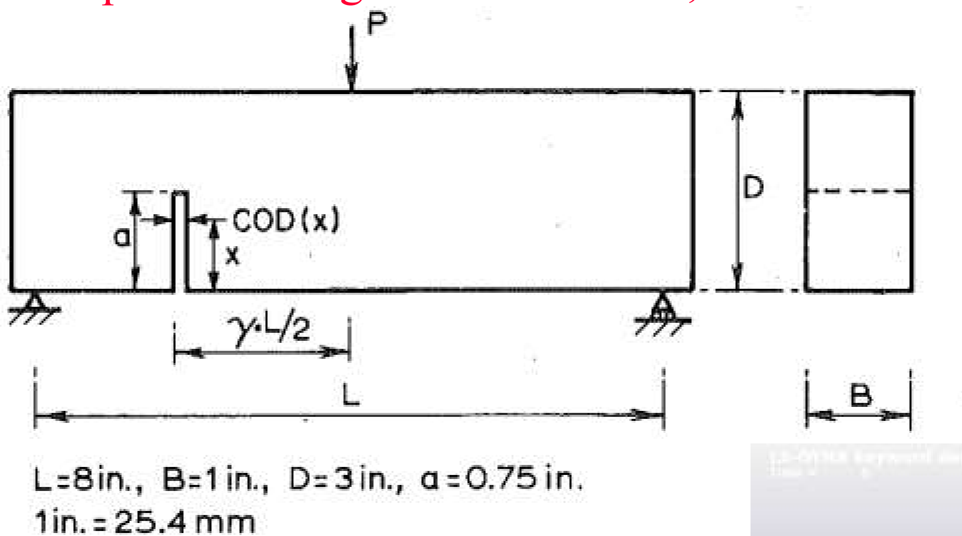
FEM part

opt: BREAK

FT: The tensile stress to break the tie
Fs: The shear stress to break the tie

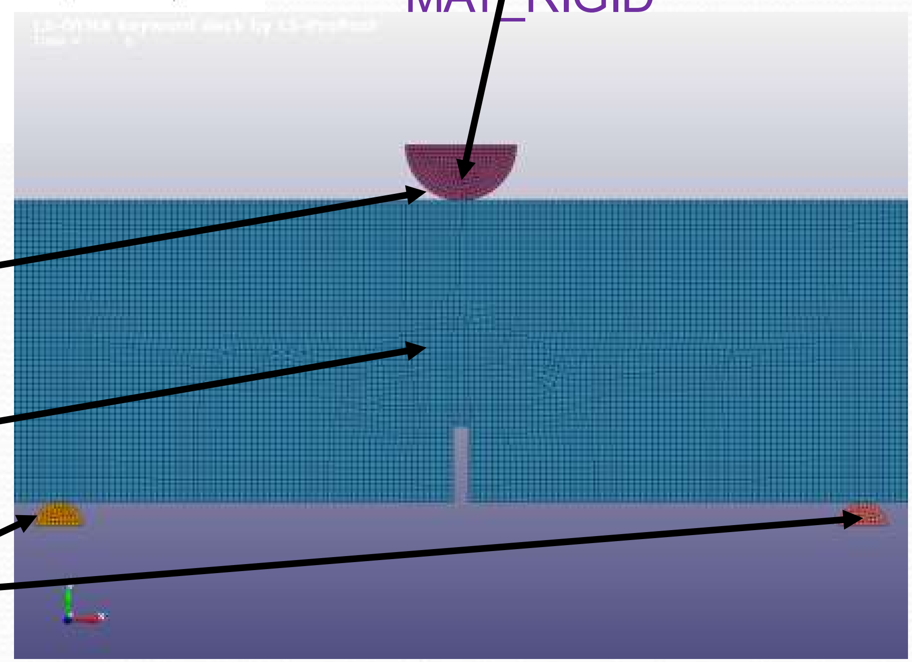
4. Application Examples

- Three-point bending of cement beam, validation



A dynamic mixed mode fracture problem, Solid to peridynamic contact

*SECTION_SOLID
*MAT_RIGID



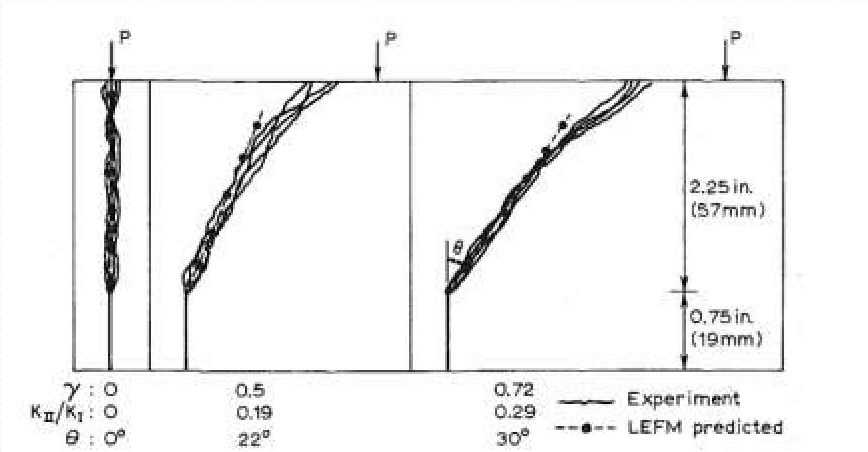
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE

*SECTION_SOLID_PERI
*MAT_ELASTIC_PERI

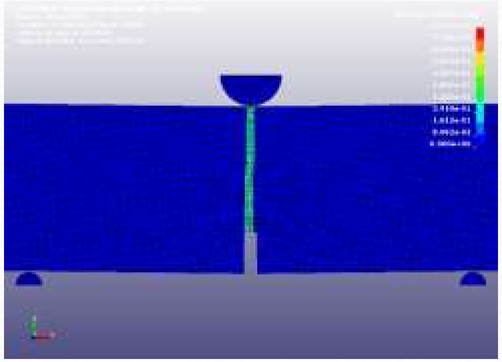
Velocity boundary

4. Application Examples

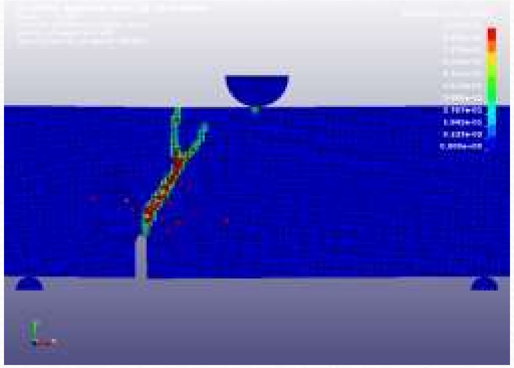
- Three-point bending of cement beam, validation



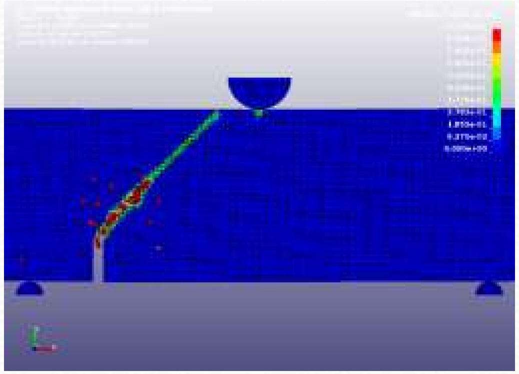
Experimental crack path from tension to mixture mode



γ=0
Θ=0^0



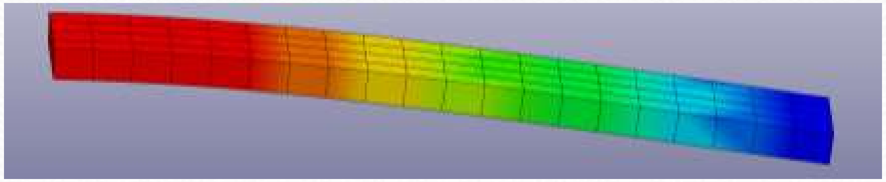
γ=0.5
Θ=21^0



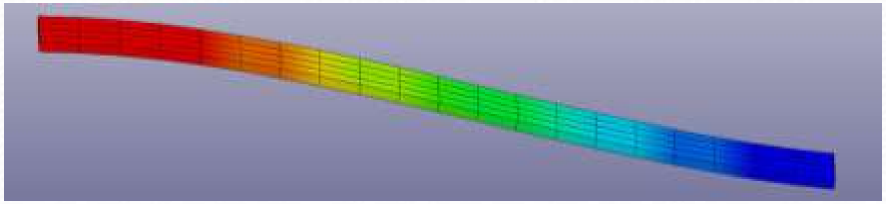
γ=0.7
Θ=29^0

4. Application Examples

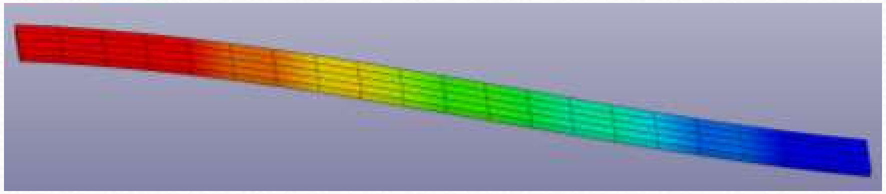
- Cantilever beam-High aspect ratio elements



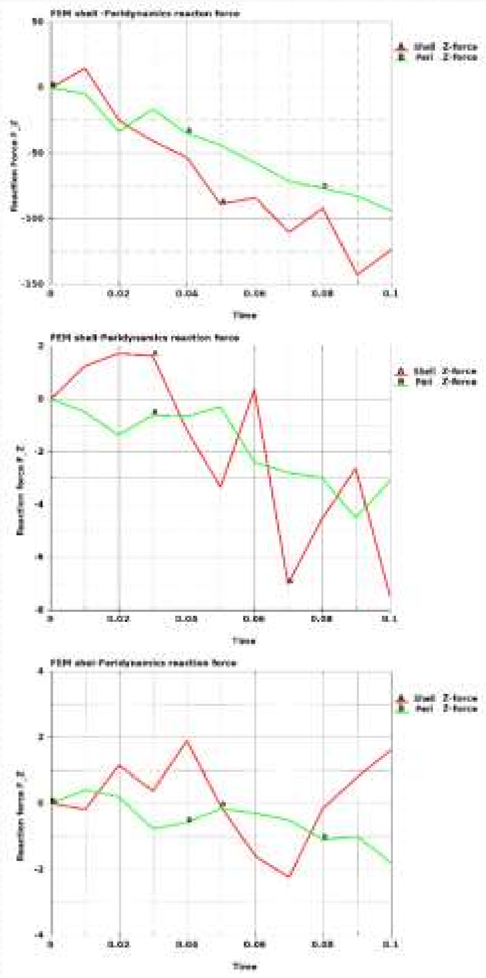
•Thickness: 1.0



•Thickness: 0.3



•Thickness: 0.2

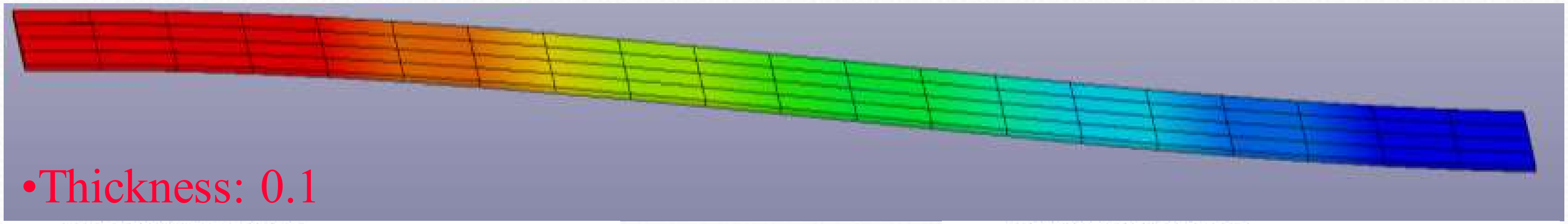


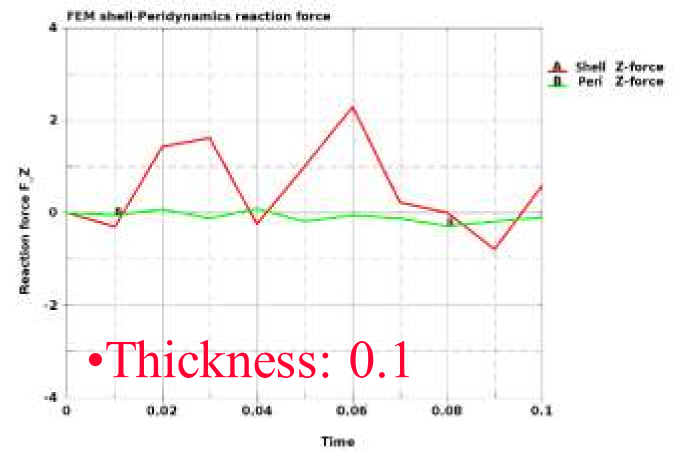
*SECTION_SOLID_PERI
*MAT_ELASTIC_PERI

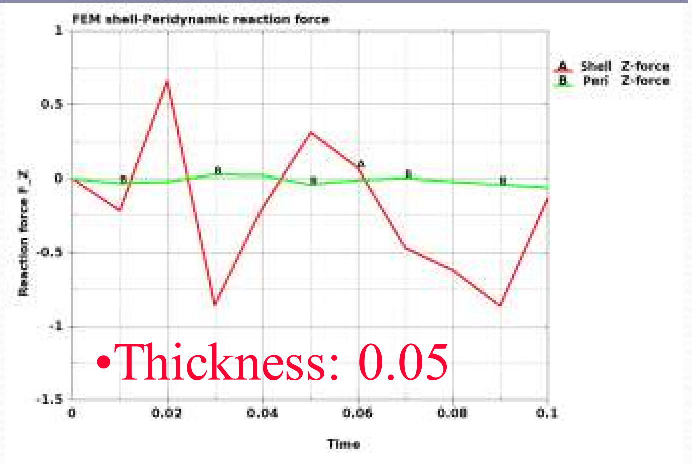
A example for shear locking problem

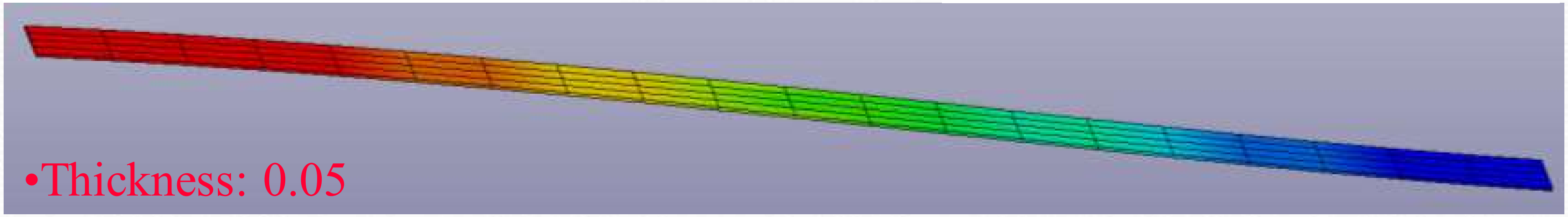
4. Application Examples

- Cantilever beam-High aspect ratio elements









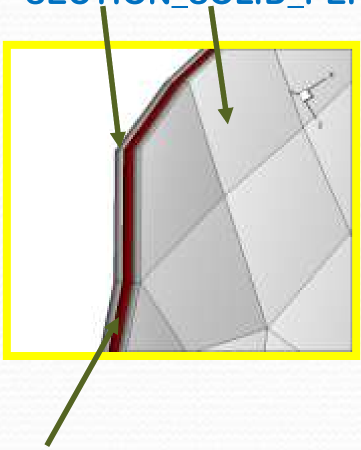
A sample for shear locking problem

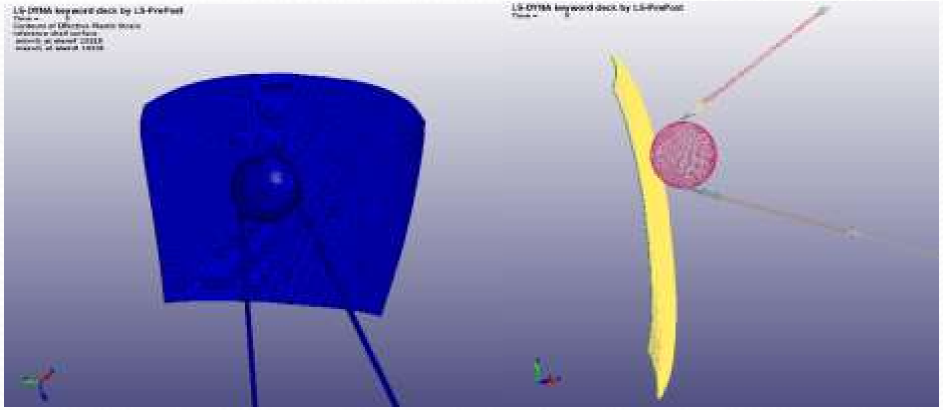
4. Application Examples

- Windshield impact

Impact/penetration,
FEM-Peridynamic parts tie

Glass layers: Peridynamic solid
*SECTION_SOLID_PERI, *MAT_ELASTIC_PERI



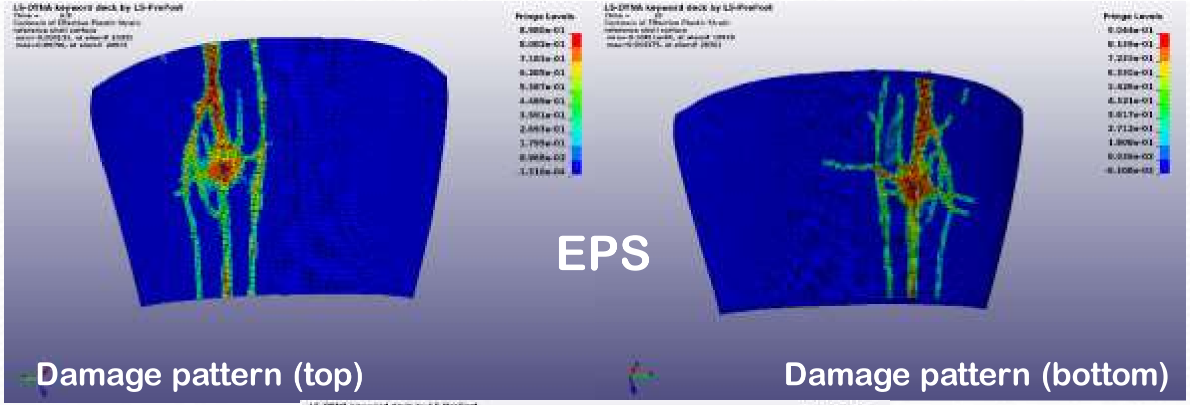


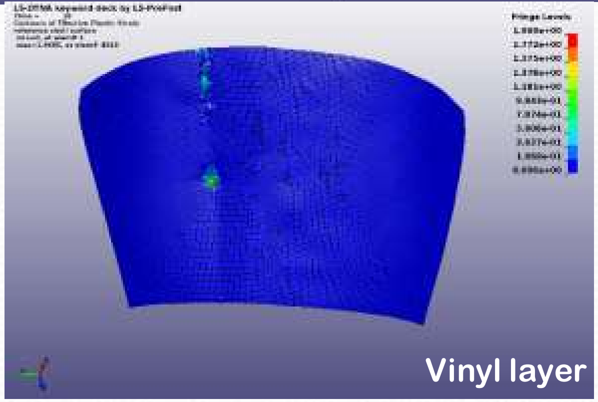
Vinyl layer: FEM solid
*MAT_PIECEWISE_LINEAR_PLASTICITY

Interface of vinyl and glasses:
*CONTACT_TIED_SURFACE_TO_SURFACE_OFFSET

4. Application Examples

- Windshield impact

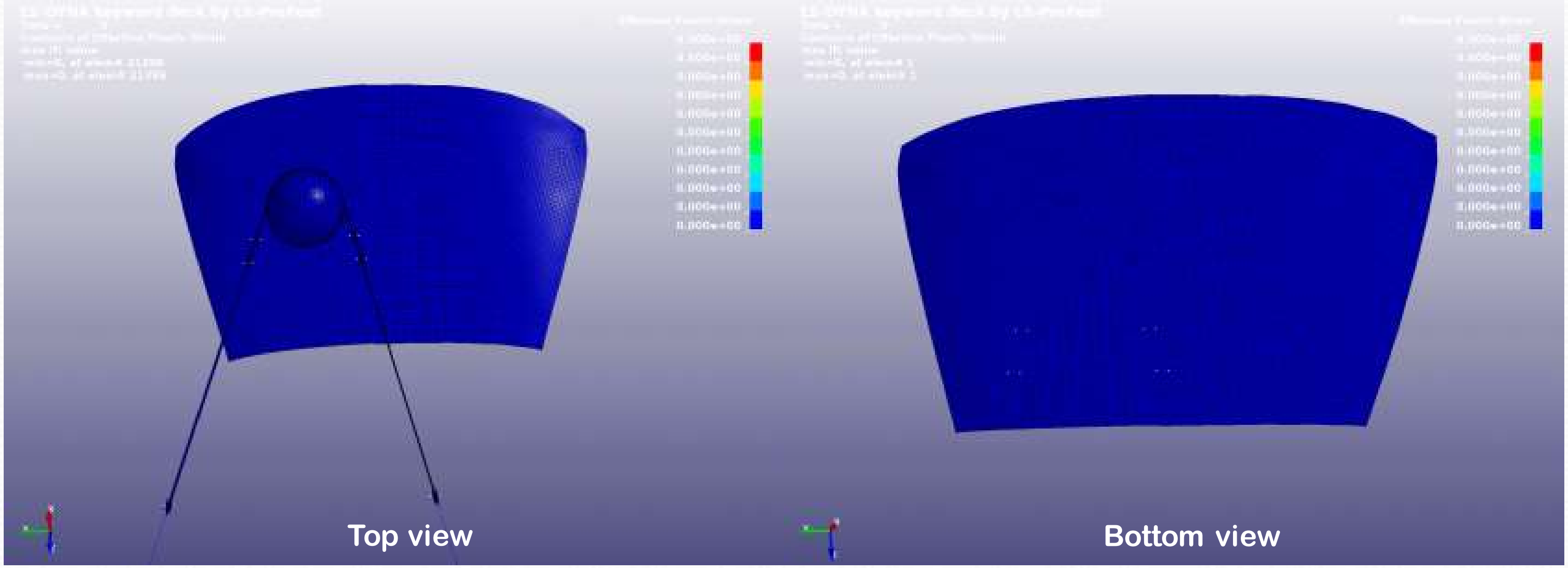




4. Application Examples

- Windshield impact

von Mises stress on vinyl interlayer

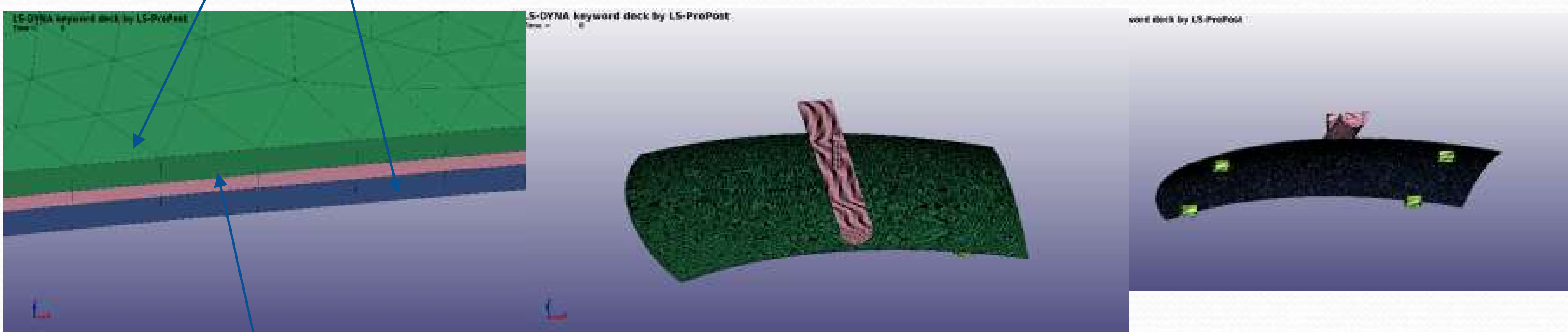


4. Application Examples

- Windshield: 3-point bending

Indentation failure,
FEM-Peridynamic parts tie

Glass layers: Peridynamic solid
*SECTION_SOLID_PERI, *MAT_ELASTIC_PERI: GC=2.*GT



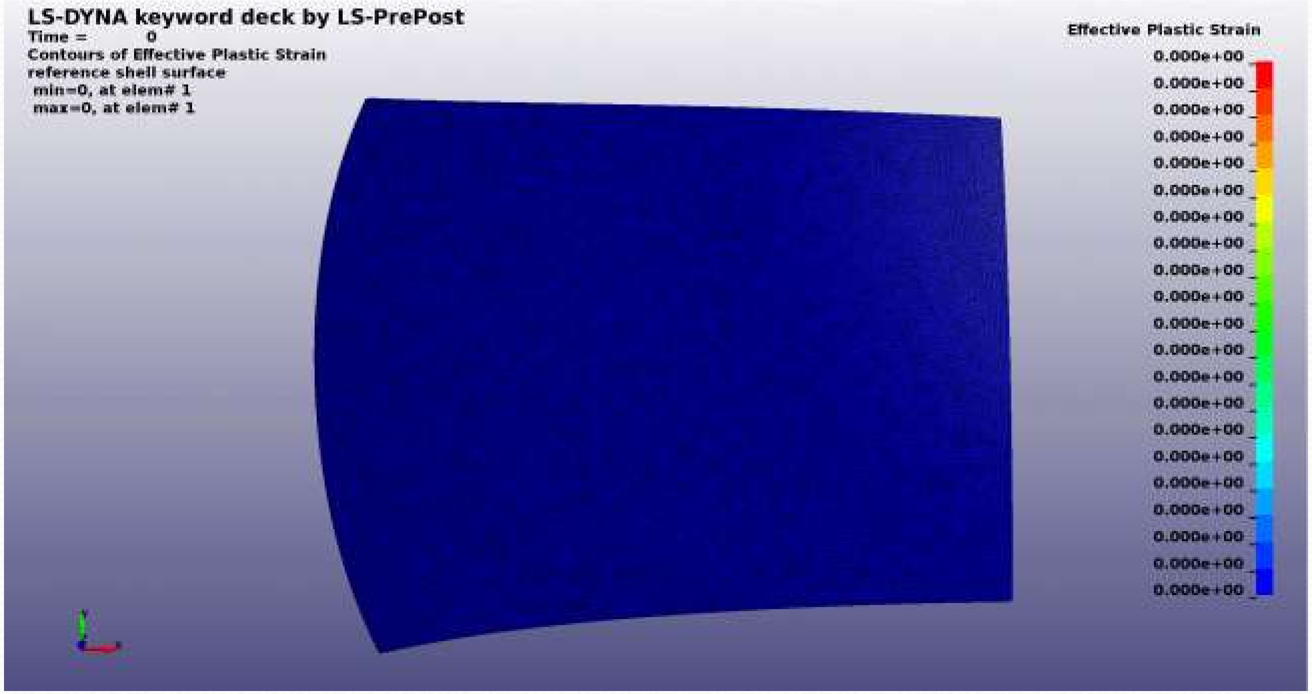
Vinyl layer: FEM solid
*MAT_PIECEWISE_LINEAR_PLASTICITY, fail EPS: 0.05, sigy:12.0

Interface of vinyl and glasses:
*CONTACT_FEM_PERI_TIE_BREAK, FT, FS=10.5

Contact between Impactor and glass layers:
*CONTACT_AUTOMATIC_NODES_TO_SURFACE

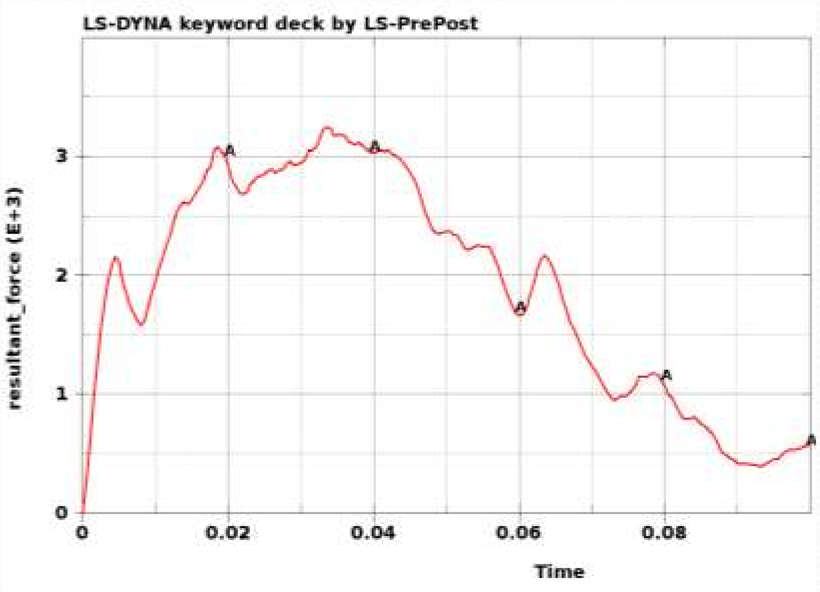
Contact between Supports and glass layers:
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE

4. Application Examples

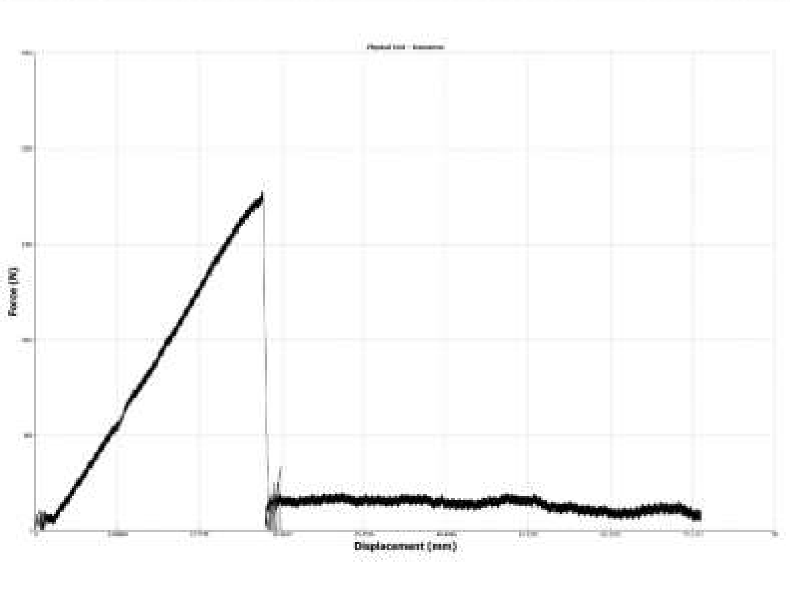


Damage evolution

4. Application Examples



Numerical dynamic reaction force history

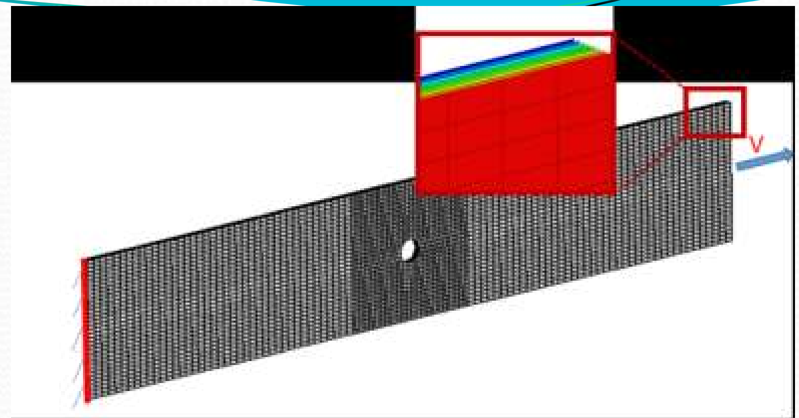


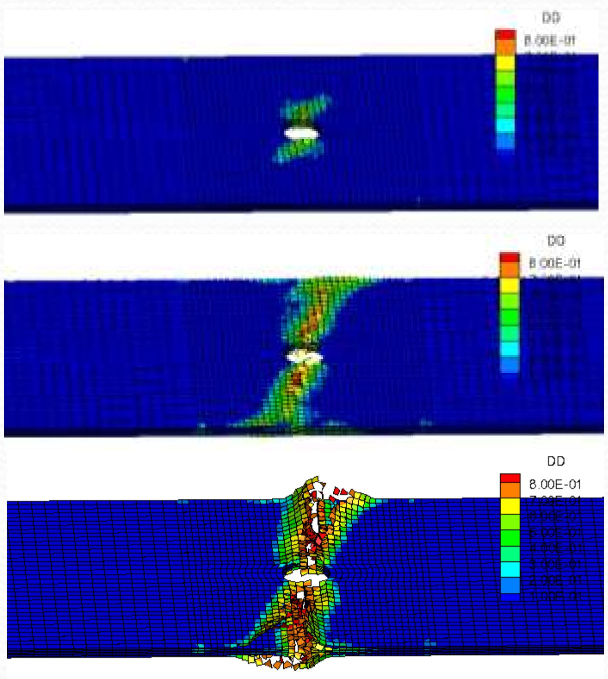
Experimental static reaction force history

Maximum Force (N)		Displacement (mm)	
Exp.	Num.	Exp.	Num.
2841	3250	24.6	16.7

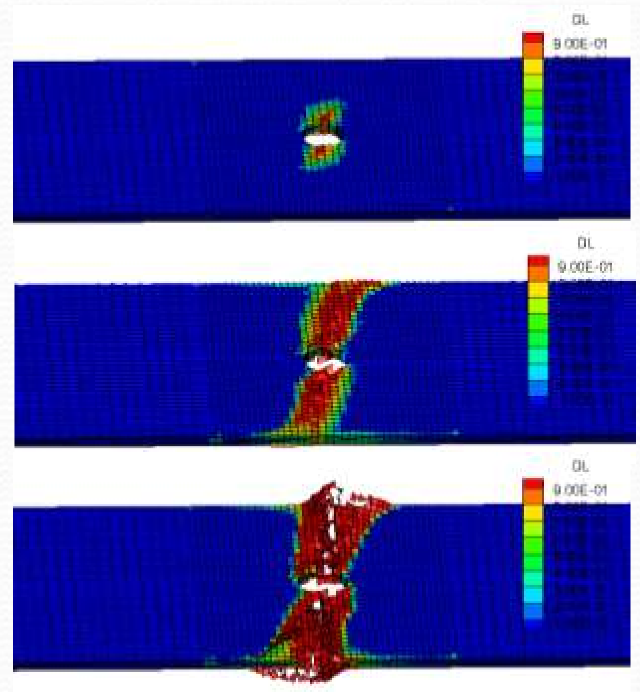
5. Future Work

- Fiber reinforced composite laminate
  - T700 carbon/epoxy material
  - Eight laminate $[45/0/-45/90]_s$ layers
  - 229504 nodes





Inner-layer failure



Delamination

Conclusion Remarks on the Peridynamics

- Current explicit dynamics version is mainly for brittle failure analysis.
- Is a discontinuous Galerkin (DG) approach with bond-based peridynamic theory.
- Failure is based on critical energy released rate. No element deletion is needed to advance the cracks.
- Branching of the cracks is an outcome of the DG approach. Self-contact between cracks is possible but CPU time consuming.
- Accommodates for non-uniform mesh and allow the direct enforcement of essential boundary conditions and constraints.
- A trial executable is available upon request. R10.0 support *SEC.._PERI and *MAT.._PERI
- In crashworthiness simulation, it is mainly for windshield and brittle panels damage analysis.

Thanks for your attention !