Viewgraph for the Third ACC Energy Management Research Meeting

Damage and Constitutive Modeling for Impact Simulation of Random Fiber Composites

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Outline

- Fundamental issues on progressive crushing in RFPCs under impact loading
- Micromechanical material models
- Damage evolution
- Numerical simulations and experimental comparison
- Finite element implementation for impact simulation
- Future efforts

Fundamental issues on progressive crushing in RFPCs under impact loading

- Damage evolution under impact
- Failure mechanisms
- Energy dissipation
- Failure prediction and damage constitutive modeling for composite structures

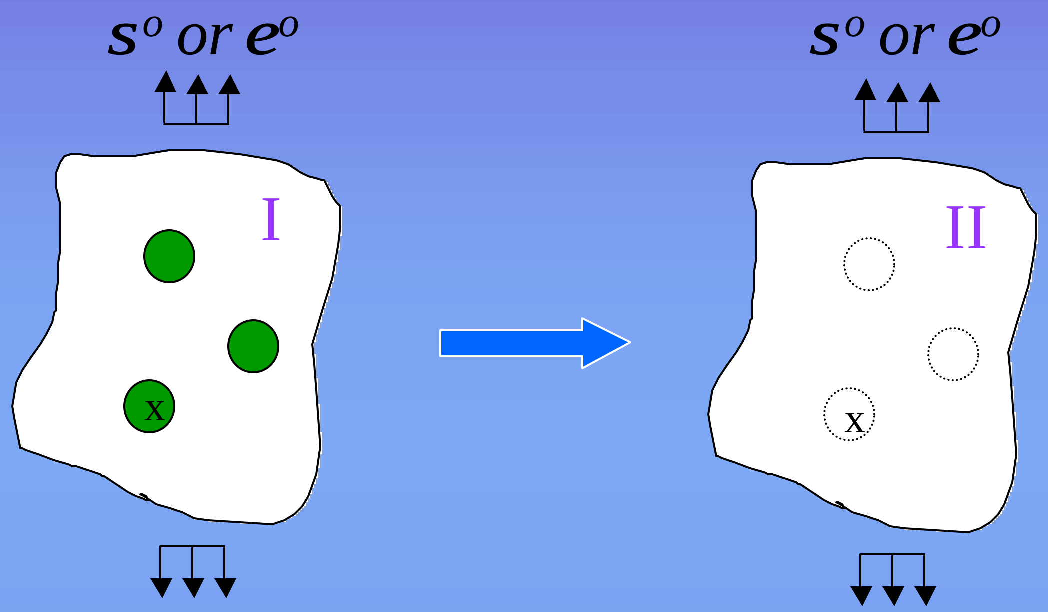
Damage constitutive models

- Based on micromechanical formulation and combination of micro- and macro-mechanical damage criteria
- Ensemble volume averaging process and effects of eigenstrains
- Two- and three-dimensional damage constitutive models
- Implemented into finite element code DYNA3D to simulate crashworthiness of composites

Micromechanical material models

- Allow for prediction of local stress and strain fields in each constituents
- Used for rigorous analysis of composite structures on a fine scale
- Applicable for composite materials with *randomly oriented discontinuous fibers*
- Incorporate probabilistic micromechanics for evolutionary damage in composite materials

Eshelby's equivalence principle



Strain at x: $e^o + e'(x)$ $\qquad$ $e^o + e'(x) + a$

Stress at x: $C_1 : e(x) = C_1 : [e^o + e'(x)] = C_o : [e^o + e'(x) + a]$

$\alpha = -e^*(x)$ = nonzero, x in fibers

= zero, x in matrix

where $e'(x) = Int\_v\ G(x - x') : e^*(x) dx'$

Effective elastoplastic behavior of composites with aligned discontinuous fibers

- Effective elastic moduli of multi-phase composites containing randomly located, aligned elastic ellipsoids

$$\mathbf{C}_* = \mathbf{C}_0 \cdot \left\{ \mathbf{I} + \mathbf{B} \cdot (\mathbf{I} - \mathbf{S} \cdot \mathbf{B})^{-1} \right\}$$

- Total stress at any point **x** in the matrix

$$\boldsymbol{\sigma}(\mathbf{x}) = \boldsymbol{\sigma}^o + \boldsymbol{\sigma}'(\mathbf{x})$$

in which $\boldsymbol{\sigma}^o$ and $\boldsymbol{\sigma}'$ are defined as

$$\boldsymbol{\sigma}^o \equiv \mathbf{C}_0 : \boldsymbol{\epsilon}^o$$

$$\boldsymbol{\sigma}'(\mathbf{x}) \equiv \mathbf{C}_0 : \int_V \mathbf{G}(\mathbf{x} - \mathbf{x}') : \boldsymbol{\epsilon}_1^*(\mathbf{x}')\, d\mathbf{x}' + \mathbf{C}_0 : \int_V \mathbf{G}(\mathbf{x} - \mathbf{x}') : \boldsymbol{\epsilon}_2^*(\mathbf{x}')\, d\mathbf{x}'$$

Effective elastoplastic behavior of composites with aligned discontinuous fibers

- Ensemble-averaged stress norm for any matrix point **x**

$$\langle H \rangle_m(\mathbf{x}) \cong H^o + \int_{|\mathbf{x}-\mathbf{x}_1^{(1)}|>a} \left\{ H(\mathbf{x}|\mathbf{x}_1^{(1)}) - H^o \right\} P(\mathbf{x}_1^{(1)})\, d\mathbf{x}_1^{(1)} + \int_{|\mathbf{x}-\mathbf{x}_2^{(1)}|>a} \left\{ H(\mathbf{x}|\mathbf{x}_2^{(1)}) - H^o \right\} P(\mathbf{x}_2^{(1)})\, d\mathbf{x}_2^{(1)} + \ldots\ldots$$

- Effective yield function for fiber-reinforced composites

$$\bar{F} = (1-\phi_1)^2 \bar{\boldsymbol{\sigma}} : \bar{\mathbf{T}} : \bar{\boldsymbol{\sigma}} - K^2(\bar{e}^p)$$

where the isotropic hardening function $K(\bar{e}^p)$ is defined as

$$K(\bar{e}^p) = \sqrt{\frac{2}{3}} \left\{ \sigma_y + h(\bar{e}^p)^{\bar{q}} \right\}$$

Effective elastoplastic behavior of composites with randomly oriented, discontinuous fibers

- Orientational averaging process

$$\subset \cdot \supset \equiv \int_0^{2\pi} \int_0^{\pi/2} (\cdot) P(\theta, \phi) sin\theta d\theta d\phi$$

- Governing equations for randomly oriented fiber-reinforced composites

$$\subset \bar{\boldsymbol{\sigma}} \supset = \mathbf{C}_0 : [\subset \bar{\boldsymbol{\epsilon}} \supset - \sum_{r=1}^{2} \phi_r \subset \boldsymbol{\epsilon}_r^* \supset]$$

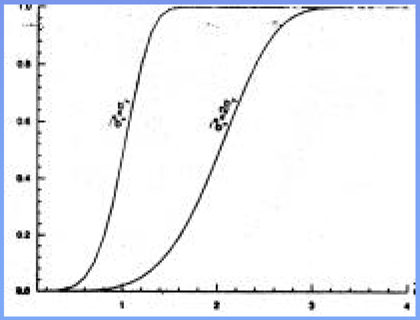
$$\subset \bar{\boldsymbol{\epsilon}} \supset = \boldsymbol{\Upsilon} : \boldsymbol{\epsilon}^o$$

$$\subset \boldsymbol{\epsilon}_r^* \supset = -\boldsymbol{\Omega}_r : \boldsymbol{\epsilon}^o$$

Evolutionary interfacial debonding: Probabilistic micromechanics

- Weibull probabilistic distribution function for fiber debonding (damage)

$$P_d[(\bar{\boldsymbol{\sigma}}_m)_1] = 1 - exp\left[-\left(\frac{(\bar{\boldsymbol{\sigma}}_m)_1}{S_o}\right)^M\right]$$



- Current debonded (damaged) fiber volume fraction

$$\phi_2 = \phi P_d[(\bar{\boldsymbol{\sigma}}_m)_1] = \phi\left\{1 - exp\left[-\left(\frac{(\bar{\boldsymbol{\sigma}}_m)_1}{S_o}\right)^M\right]\right\}$$

- Average internal stresses of fibers

$$\bar{\boldsymbol{\sigma}}_1 = \mathbf{C}_1 \cdot \left[\mathbf{I} - \mathbf{S}\cdot(\mathbf{A}_1 + \mathbf{S})^{-1}\right] \cdot \left[\mathbf{I} - \sum_{m=1}^{2} \phi_m \mathbf{S}\cdot(\mathbf{A}_m + \mathbf{S})^{-1}\right]^{-1} : \bar{\boldsymbol{\epsilon}} \equiv \mathbf{U} : \bar{\boldsymbol{\epsilon}}$$

Numerical simulation

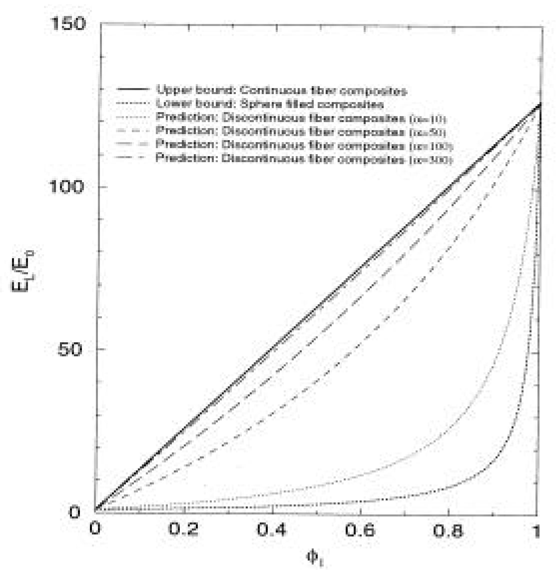
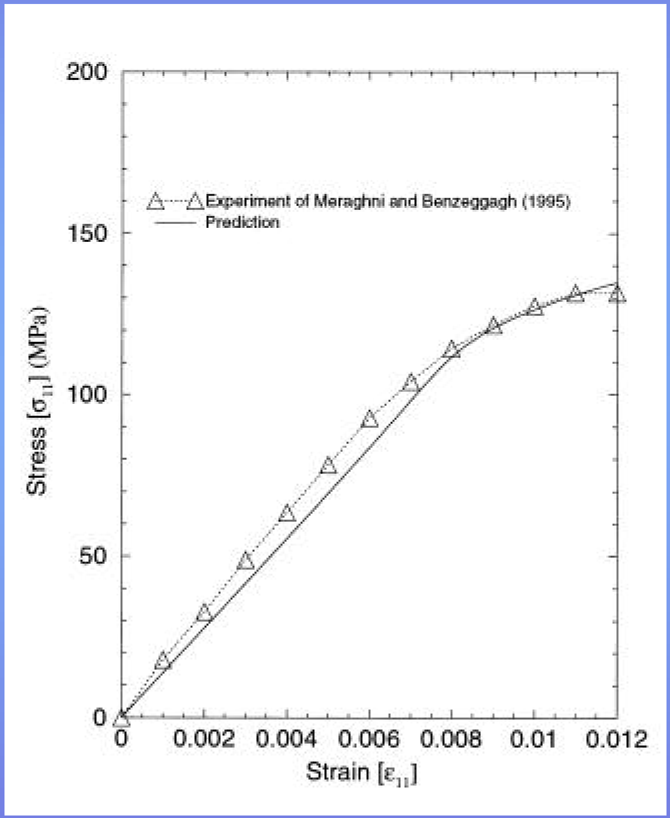
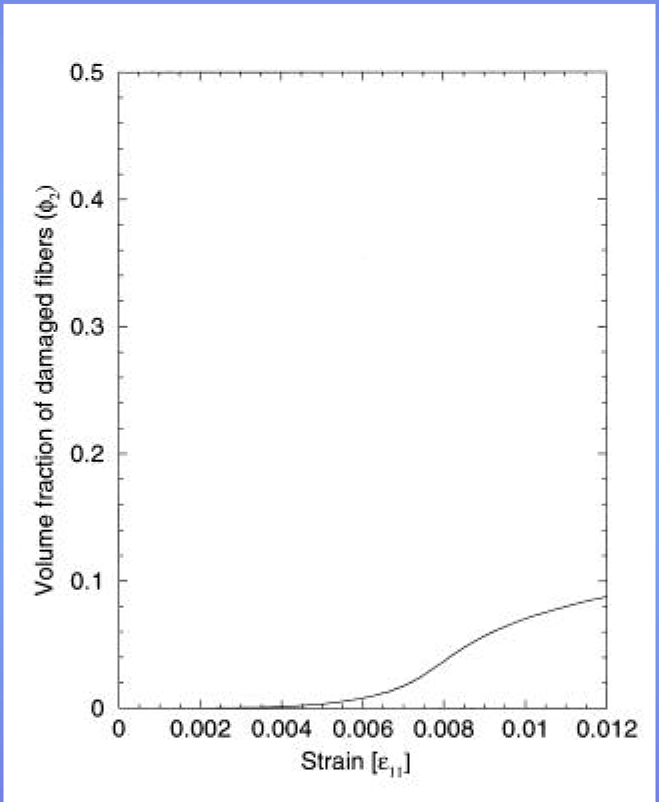


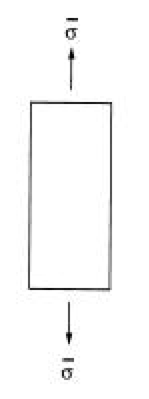
Figure 1. The comparison between the proposed predictions with various fiber aspect ratios and Halpin–Tsai's bounds for effective Young's modulus in the fiber direction vs. fiber volume fraction.

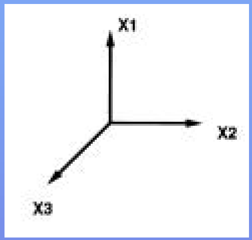
- Comparison between proposed predictions and Halpin-Tsai's bounds

Experimental comparison







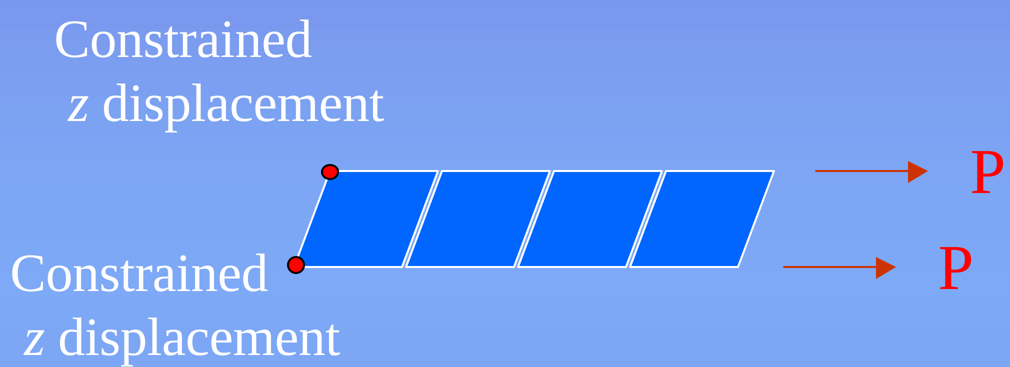


- Effects of fiber-interaction and other damage mechanisms

Finite element implementation for impact simulation

- Implementation into explicit finite element code DYNA3D, since impact simulation requires a very small time step integration
- Strain driven algorithm to implement into displacement based finite element code DYNA3D
- Micromechanical iterative algorithm for progressive damage model
- Prediction of dynamic response of composite structures and elimination of need for expensive large-scale experiments

Uniaxial loading



MODEL: 400x100x10 mm^3 beam is modeled by 4 Belytschko-Tsay shell elements.

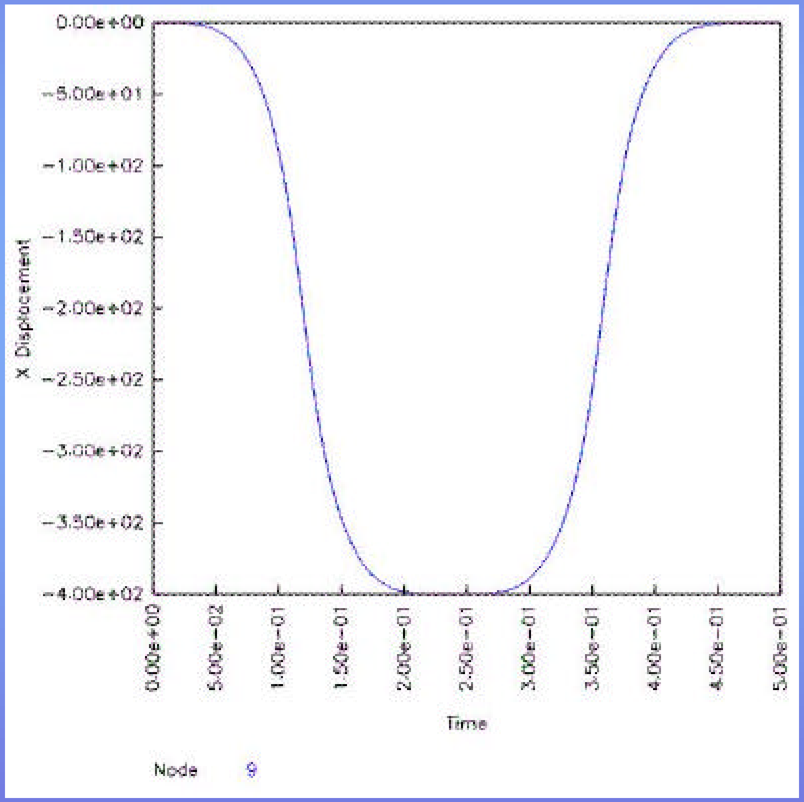
MATERIAL: steel fiber, steel matrix composite.

FORCE: 1,000 N is applied at the free edge.

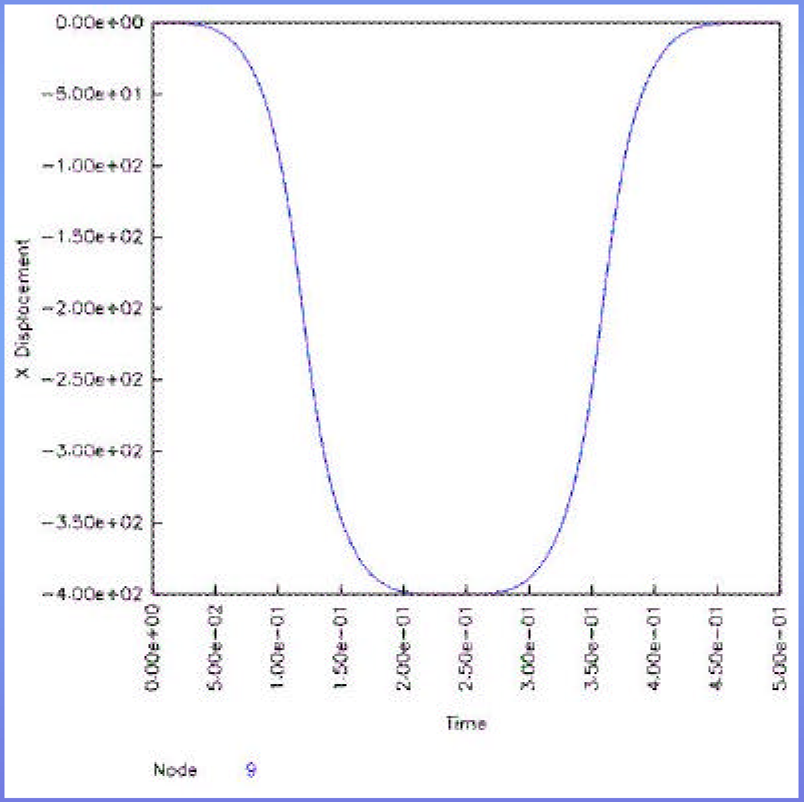
TIME: calculation ends at 0.5 sec.

Impact simulation

User material



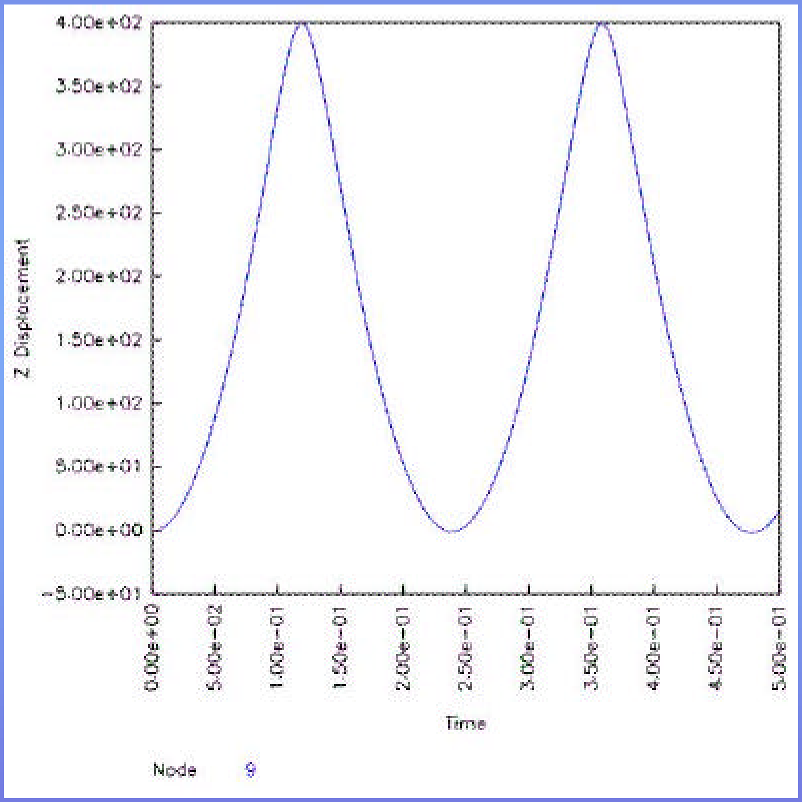
Material # 1 (elastic)



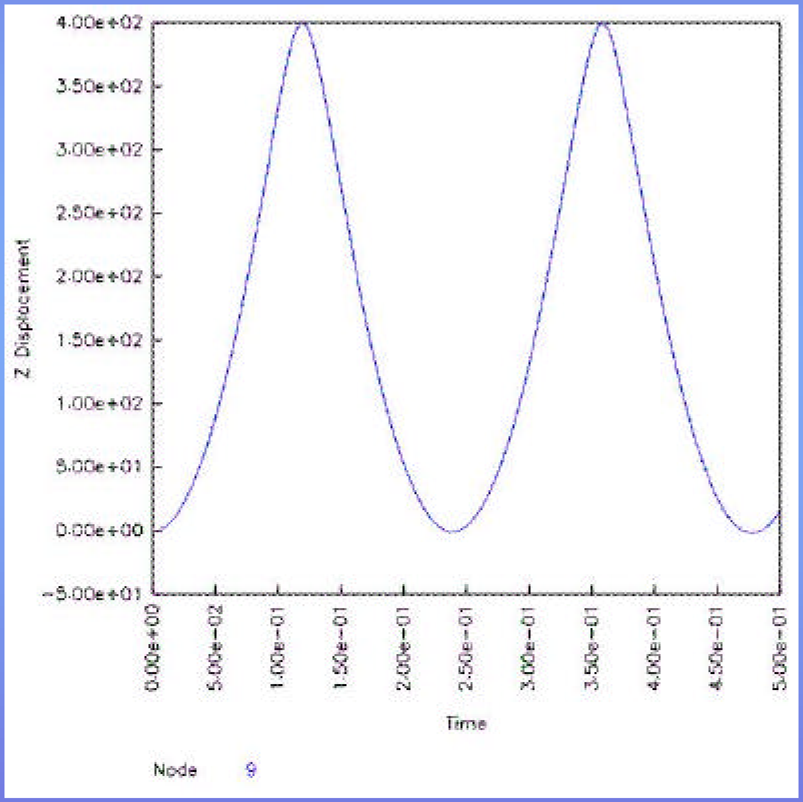
- Displacement in the x-direction during impact

Impact simulation

User material



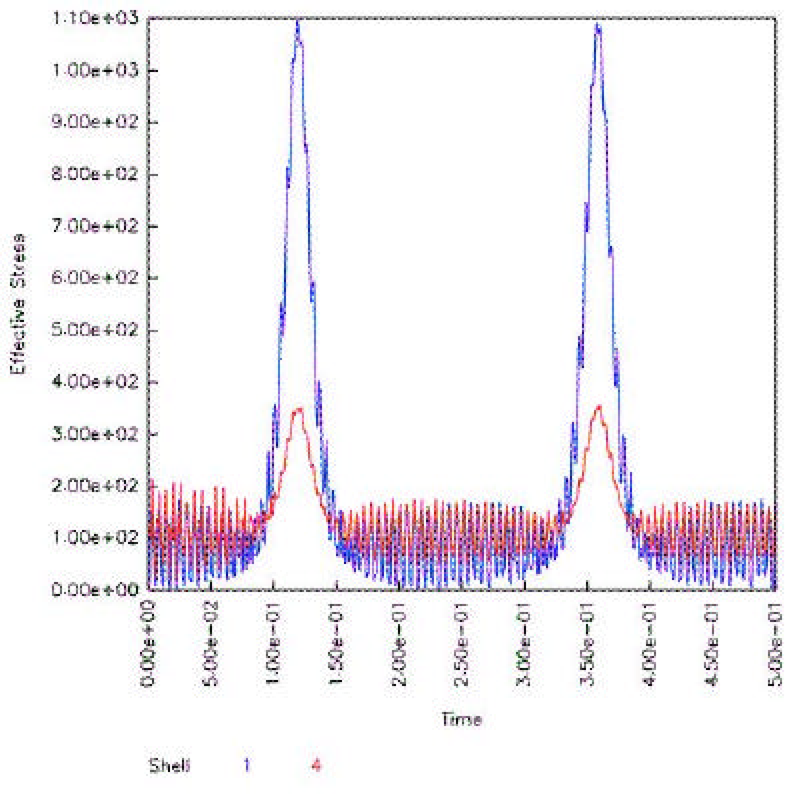
Material # 1 (elastic)



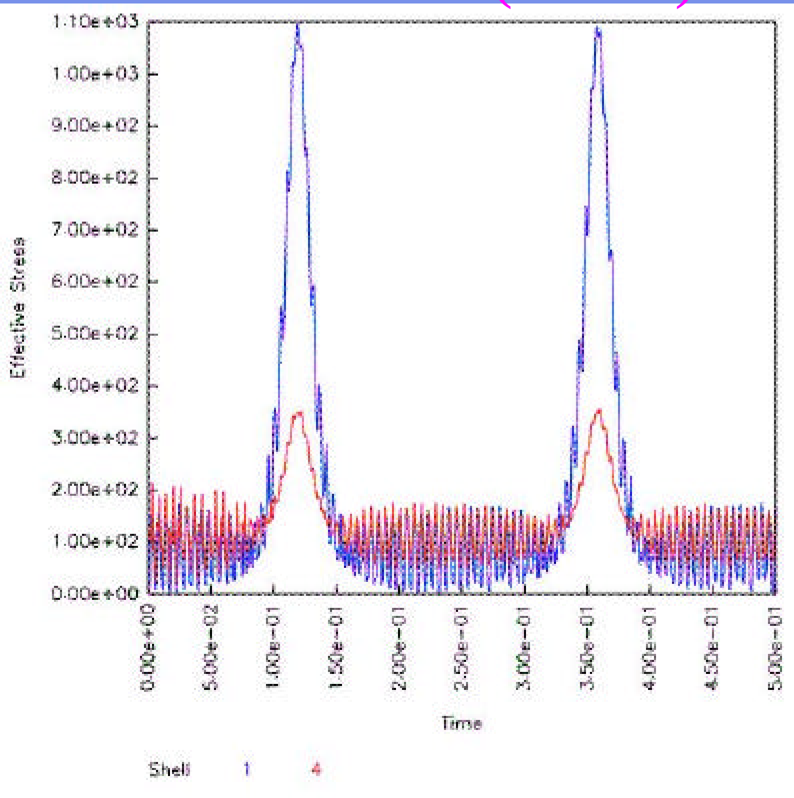
- Displacement in the z-direction during impact

Impact simulation

User material

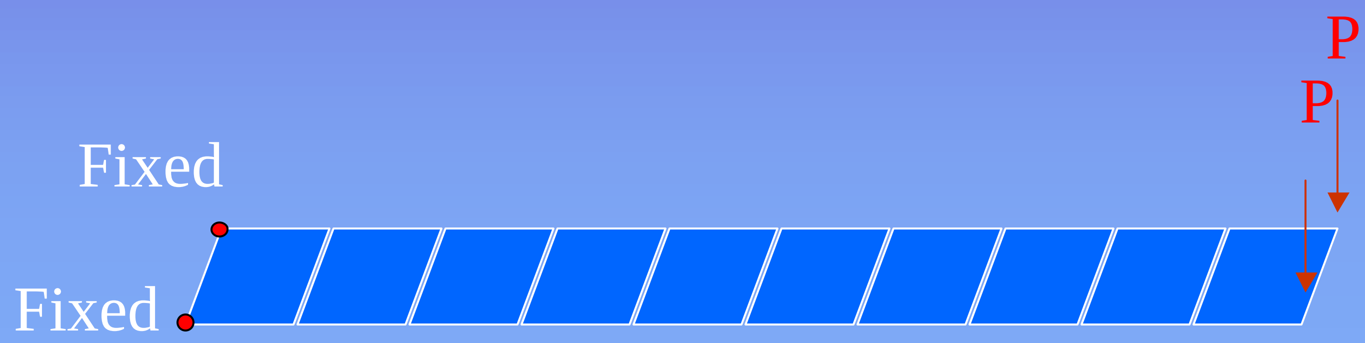


Material # 1 (elastic)



- von-Mises effective stress during impact

Cantilever Beam



MODEL: 1000x100x10 mm^3 beam is modeled by
10 Belytschko-Tsay shell elements.

MATERIAL: glass fiber epoxy resin composite.
(c.f. carbon fiber polyurethane resin composite)

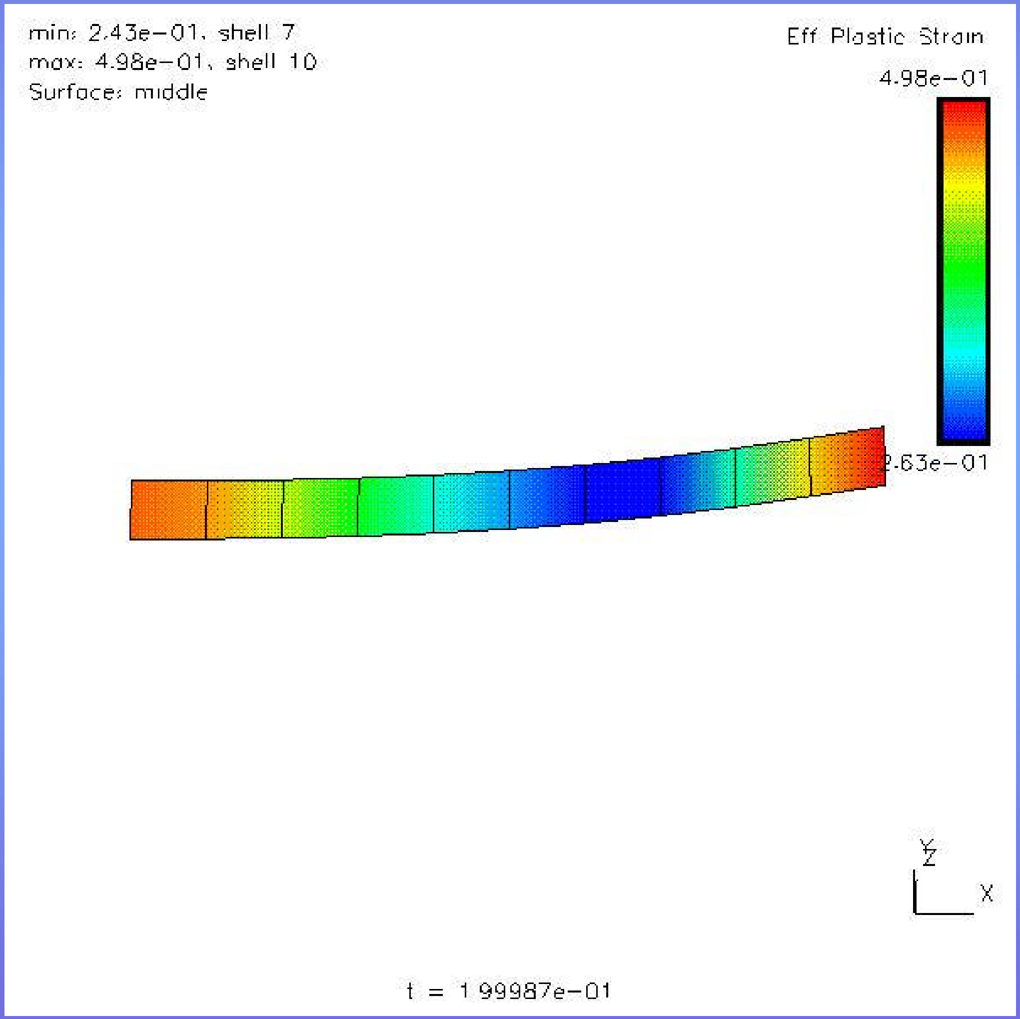
FORCE: 1,000 N is applied at the free edge.

TIME: calculation ends at 0.5 sec.

Material properties and model parameters of RFPCs for impact simulation

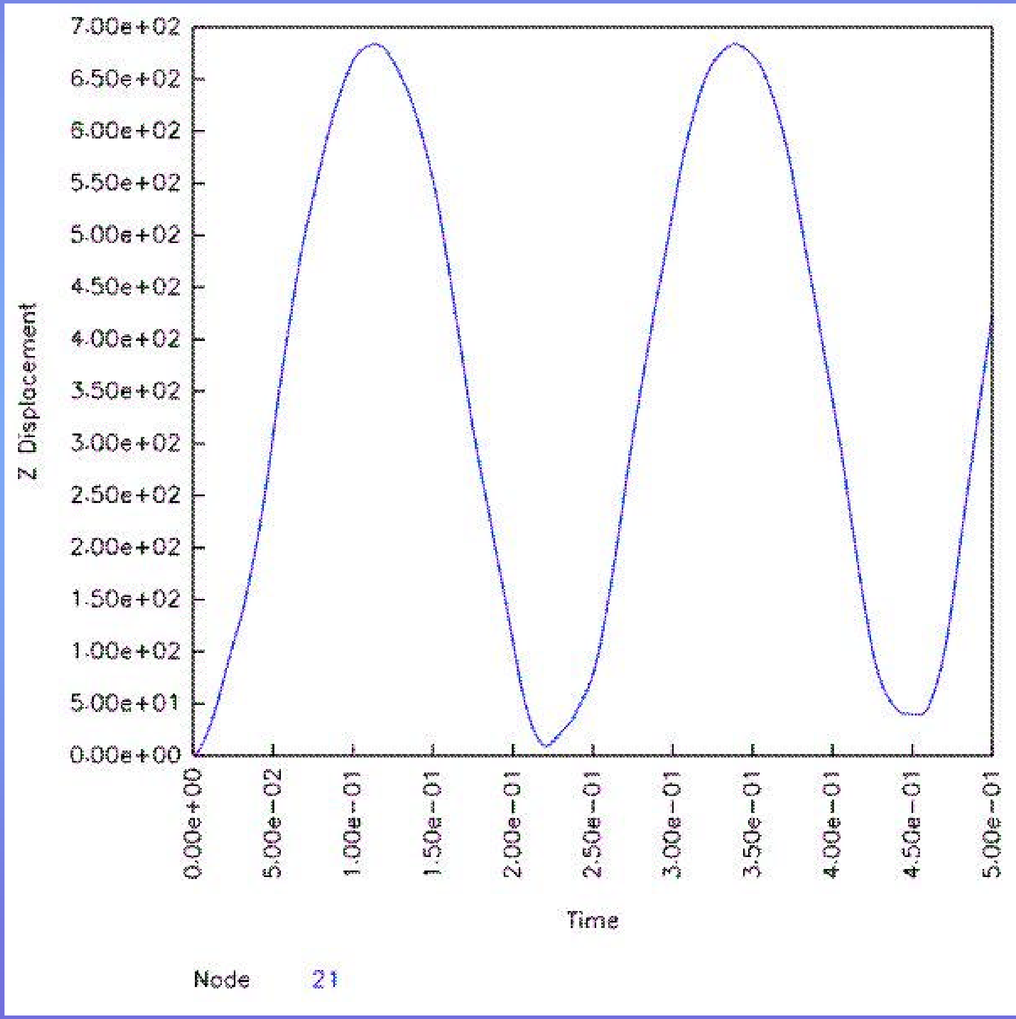
NO.	DESCRIPTION	VALUE
Cm(1)	Macroscopic Young's modulus in the xy plane	33,000.0 Mpa
Cm(2)	Macroscopic Poisson's ratio in the xy plane	0.30
Cm(3)	Young's modulus of phase 1	3,000.0 Mpa
Cm(4)	Young's modulus of phase 2	72,000.0 Mpa
Cm(5)	Poisson's ratio of phase 1	0.35
Cm(6)	Poisson's ratio of phase 2	0.17
Cm(7)	Yield stress of the composite	150.0 Mpa
Cm(8)	Linear hardening parameter	400.0 Mpa (estimated)
Cm(11)	Exponential hardening parameter	0.5 (estimated)
Cm(12)	Weibull parameter related to shape of function	4000.0 Mpa (assumed)
Cm(13)	Weibull parameter related to length of function	4.0 (assumed)
Cm(14)	Initial volume fraction of phase 1	0.5
Cm(15)	Aspect ratio of fibers	20.0

Impact simulation



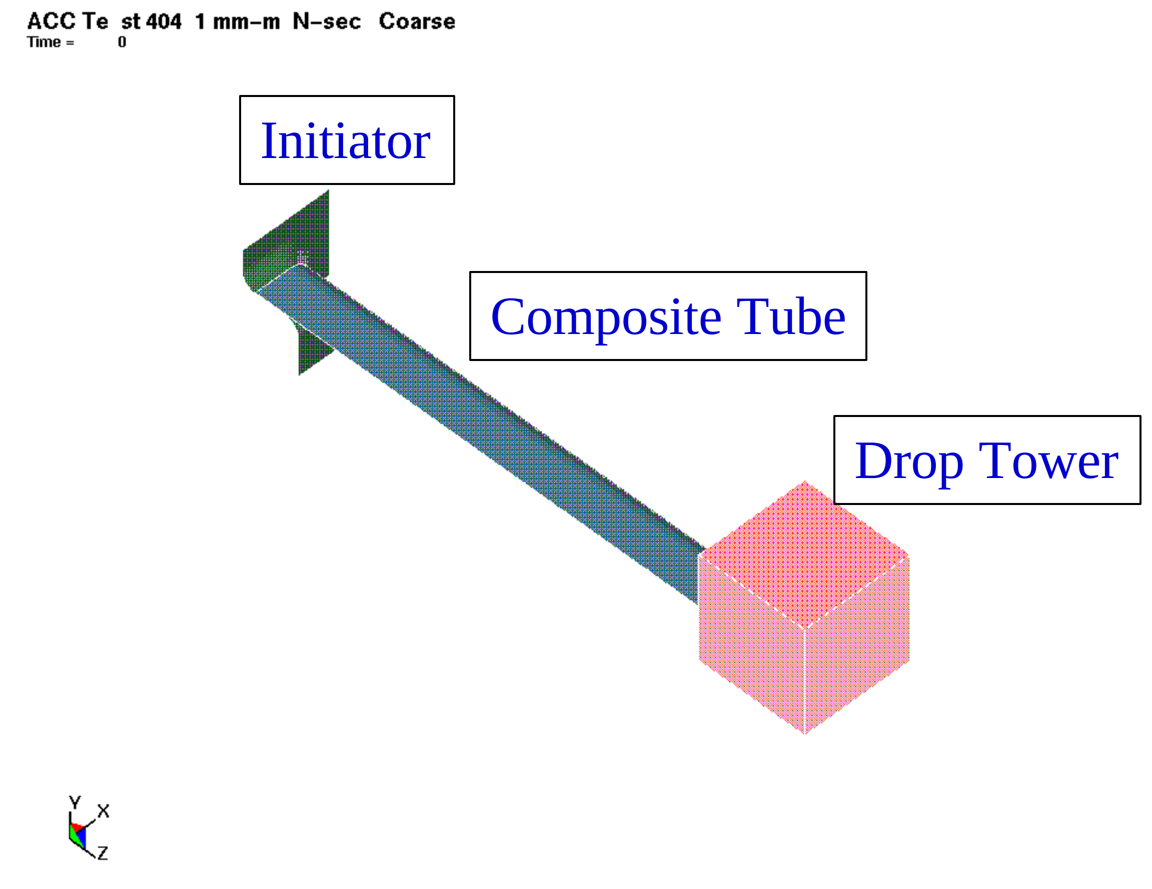
- Damage index during impact simulation

Impact simulation



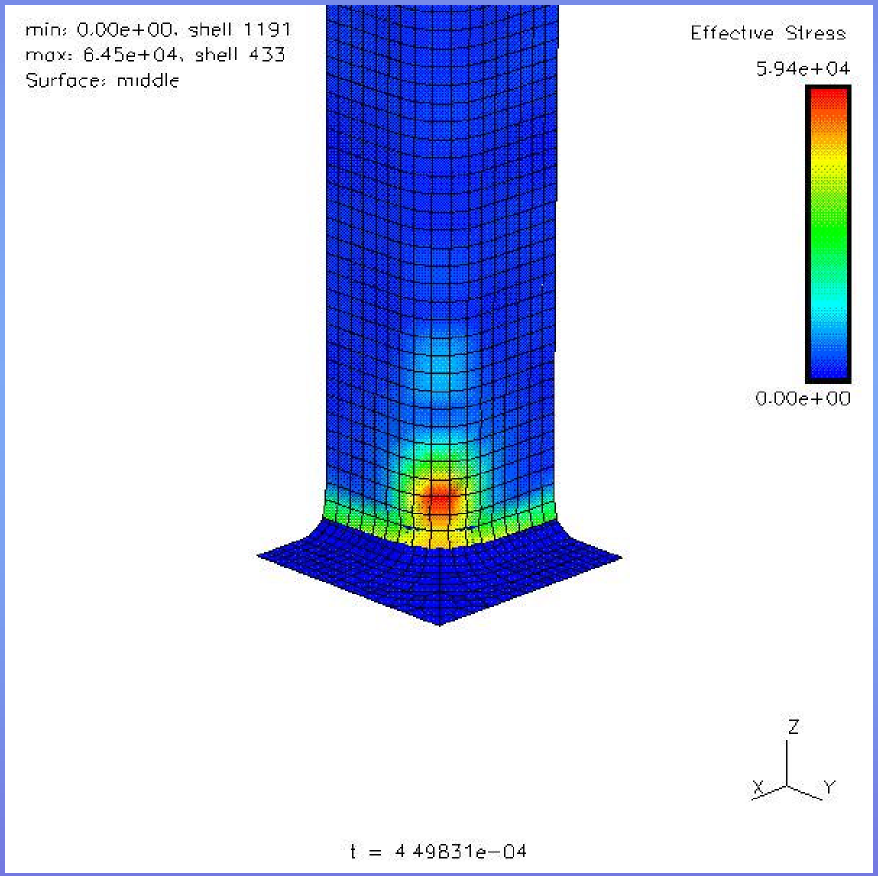
- Vibration relative to equilibrium position

Impact simulation



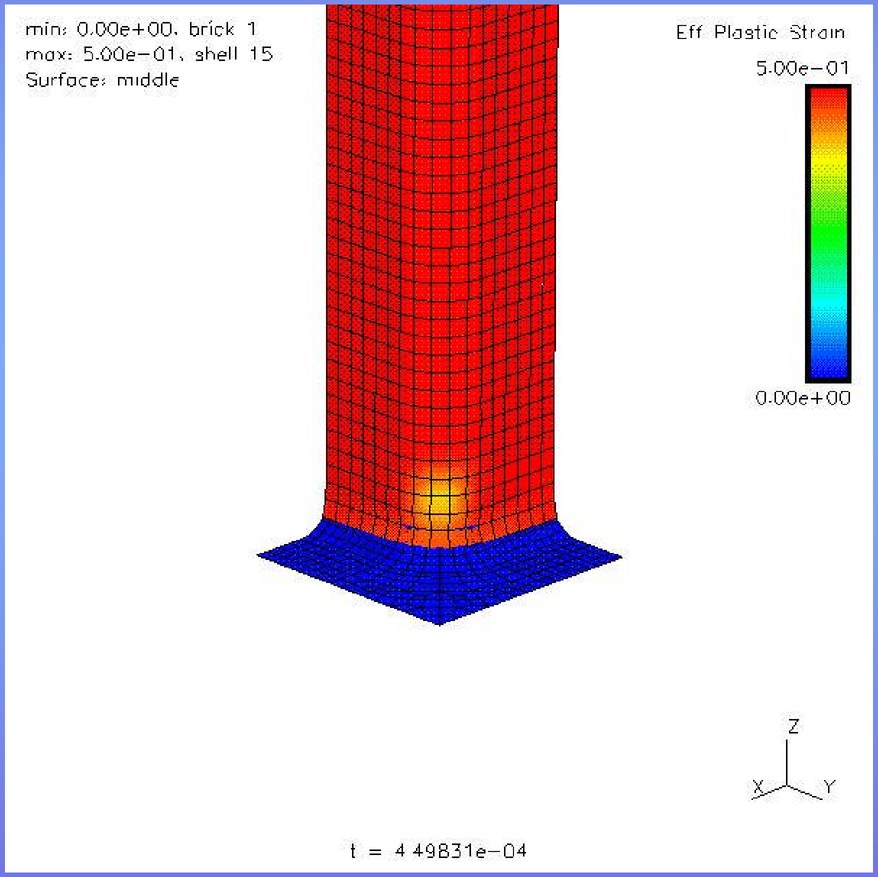
- Drop tower test for composite tube

Impact simulation (drop tower test simulation)



- von-Mises effective stress during impact

Impact simulation (drop tower test simulation)



- Damage contour during impact

Chances of success of the chosen micro-mechanics approach for RFPCs

- Damage constitutive model based on micro-mechnical framework and micro- and macro-mechanical damage criteria to predict damage behavior of RFPCs
- Composite materials reinforced with randomly oriented discontinuous fibers
- Analytical bounds and experimental data
- Experimental work for determining model parameters and damage variables

Chances of success of the chosen micro-mechanics approach for RFPCs

- Large deformation formulation for dealing with negative stiffness zone
- Examples of uniaxial, biaxial and triaxial tensions and compressions
- Interaction effects among constituents and effect of matrix microcracks on overall stiffness
- Evolutions of microcrack density and volume fraction of damaged fibers

Nondestructive testing to validate micro-mechanics model

- Acoustic emission (AE) analysis for monitoring damage initiation and evolution under static and dynamic loads
- Impact damage characterization using drop weight test frame and NDE technique
- Correlation between received acoustic wave and damage models in monitoring damage evolution

Future efforts

- Applying two-dimensional/distributive orientational averaging process for transversely isotropic composites with randomly oriented fibers in the 1-2 plane
- Modeling of microcrack-weakened composites
- Development of new failure criteria for randomly oriented, discontinuous fiber composites under impact loading

Future efforts

- Extending the present damage to be able to account for fiber interactions for the composite with high fiber volume fraction
- Employing large deformation theory for high ductility of organic matrix composite materials
- Modeling of tube crush tests to determine the validity of the current damage constitutive models
- Nondestructive testing to validate micromechanics model