AEROSPACE TECHNOLOGY CONGRESS 2016

Prediction of post-cure residual stresses and distortions in the fabrication of composite structures

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OVERVIEW

- Objectives
- Fundamentals
- FE modeling
- Preliminary results
- New element proposal
- Way forward

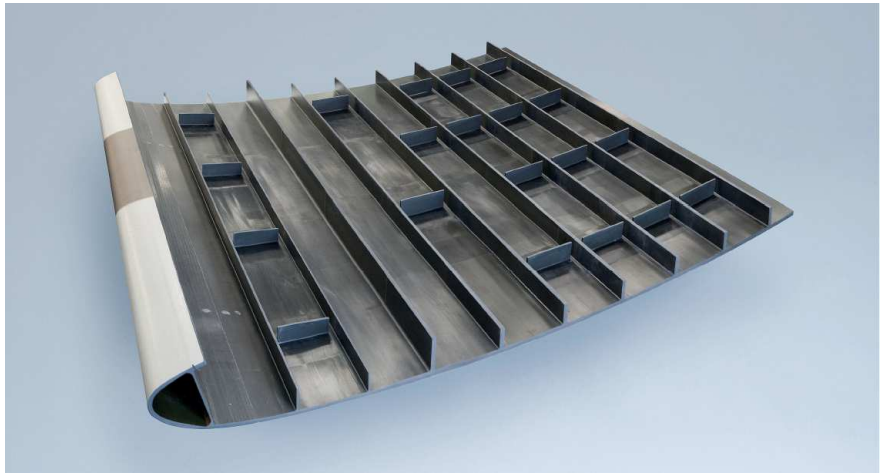
OBJECTIVES

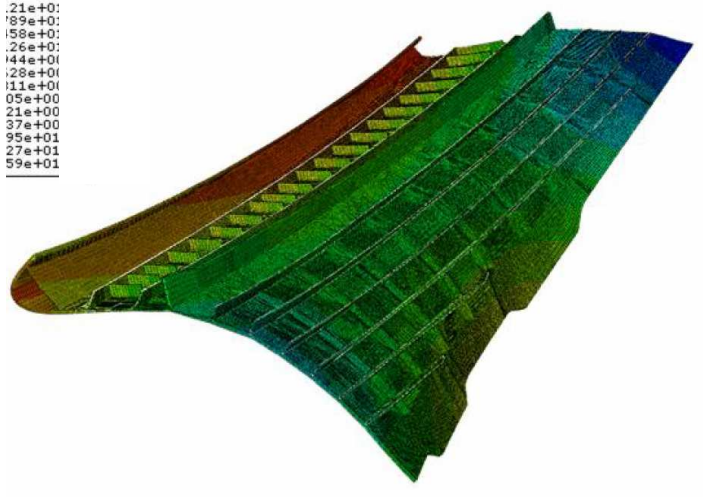
Develop numerical model to predict of distortions and residual stresses present in cured composite structures

Assess spring-in effects

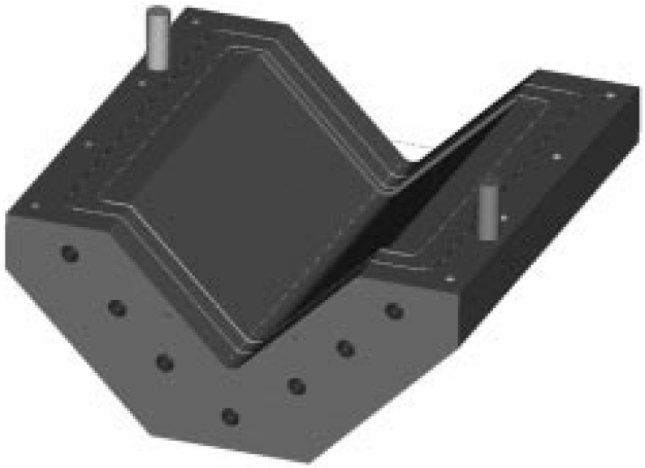
Compute residual stresses that may crucially impair stiffness and strength of cure composite structures

Propose highly efficient elements specially designed

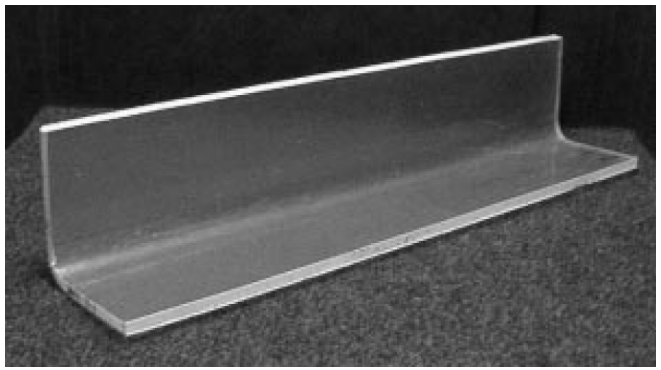




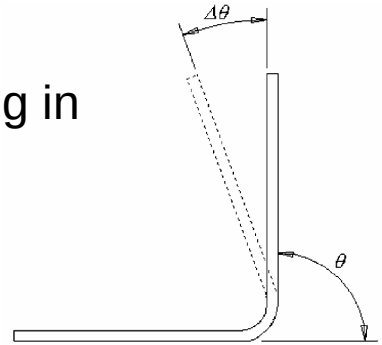
FUNDAMENTALS



demo ld



spring in



Distortions and residual stresses are always present in cured composite structures

Mechanical + thermal + chemical shrinkage stresses

FE code under development that considers cure cycle

FUNDAMENTALS

Separation of strains:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{e} + \boldsymbol{\varepsilon}^{t} + \boldsymbol{\varepsilon}^{c} = \boldsymbol{\varepsilon}^{e} + \boldsymbol{\alpha}\Delta T + \boldsymbol{\beta}\Delta X$$

$$\alpha_{ij} = \begin{cases} \alpha_{ij}^{l}, & X < X_{gel}, \quad T \geq T_g(X) \\ \alpha_{ij}^{r}, & X \geq X_{gel}, \quad T \geq T_g(X) \\ \alpha_{ij}^{g}, & T < T_g(X) \end{cases}, \quad \beta_{ij} = \begin{cases} \beta_{ij}^{l}, & X < X_{gel}, \quad T \geq T_g(X) \\ \beta_{ij}^{r}, & X \geq X_{gel}, \quad T \geq T_g(X) \\ \beta_{ij}^{g}, & T < T_g(X) \end{cases}$$

DiBenedetto equation:

$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda X}{1 - (1-\lambda)X}$$

Constitutive models:

$$\begin{cases} \Delta\boldsymbol{\sigma} = \begin{cases} \mathbf{C}_r \Delta(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_t - \boldsymbol{\varepsilon}_c) - \mathbf{s} & , \quad T \geq T_g(X) \\ \mathbf{C}_g \Delta(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_t - \boldsymbol{\varepsilon}_c) & , \quad T < T_g(X) \end{cases} \\ \mathbf{s}(t + \Delta t) = \begin{cases} 0 & , \quad T \geq T_g(X) \\ \mathbf{s}(t) + (\mathbf{C}_g - \mathbf{C}_r)\Delta(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_t - \boldsymbol{\varepsilon}_c) & , \quad T < T_g(X) \end{cases} \end{cases}$$

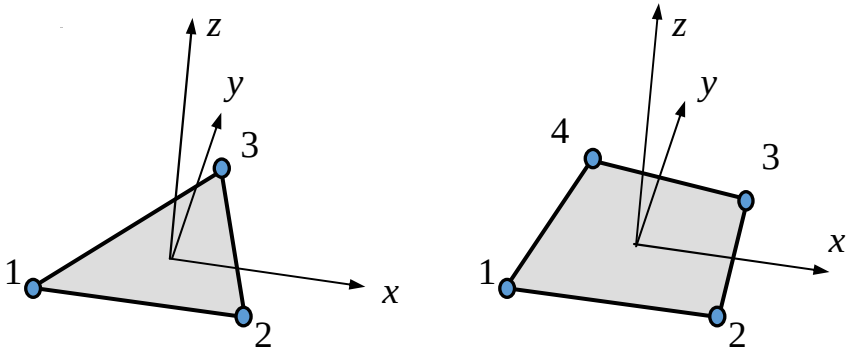
FE MODELING

FE modeling

$$\bar{u}(x,y,z)=u(x,y)+z\theta_y(x,y)$$

$$\bar{v}(x,y,z)=v(x,y)-z\theta_x(x,y)$$

$$\bar{w}(x,y,z)=w(x,y)$$



Incremental solution to the FE model

$$\sum_{e=1}^{N_e}\left[\int_{V_e}[(\mathbf{B}_m^T+z\mathbf{B}_b^T)(\mathbf{Q}-\mathbf{Q}_{gr})(\mathbf{B}_m+z\mathbf{B}_b)+\mathbf{B}_s^T(\mathbf{Q}_s-\mathbf{Q}_{sgr})\mathbf{B}_s]dV_e\right]\Delta\mathbf{q}_e=$$

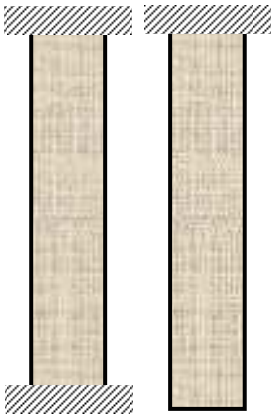
$$\mathbf{f}_{ext}^{n+1}-\mathbf{f}_{ext}^{n}+\sum_{e=1}^{N_e}\int_{V_e}(\mathbf{B}_m^T+z\mathbf{B}_b^T)(\mathbf{Q}-\mathbf{Q}_{gr})(\boldsymbol{\alpha}\Delta T+\boldsymbol{\beta}\Delta X)dV_e+$$

$$\sum_{e=1}^{N_e}\int_{V_e}(\mathbf{B}_m^T+z\mathbf{B}_b^T)(\mathbf{Q}-\mathbf{Q}_{gr})(\mathbf{s}_{\sigma e}^n+z\mathbf{s}_{\sigma\kappa}^n)dV_e+\sum_{e=1}^{N_e}\int_{V_e}\mathbf{B}_s^T(\mathbf{Q}_s-\mathbf{Q}_{sgr})\mathbf{s}_{\gamma e}^n dV_e$$

$$\sum_{e=1}^{N_e}\mathbf{K}_e\Delta\mathbf{q}_e=$$

$$\mathbf{f}_{ext}^{n+1}-\mathbf{f}_{ext}^{n}+\Delta\mathbf{f}_t+\Delta\mathbf{f}_c+\Delta\mathbf{f}_s$$

PRELIMINARY RESULTS

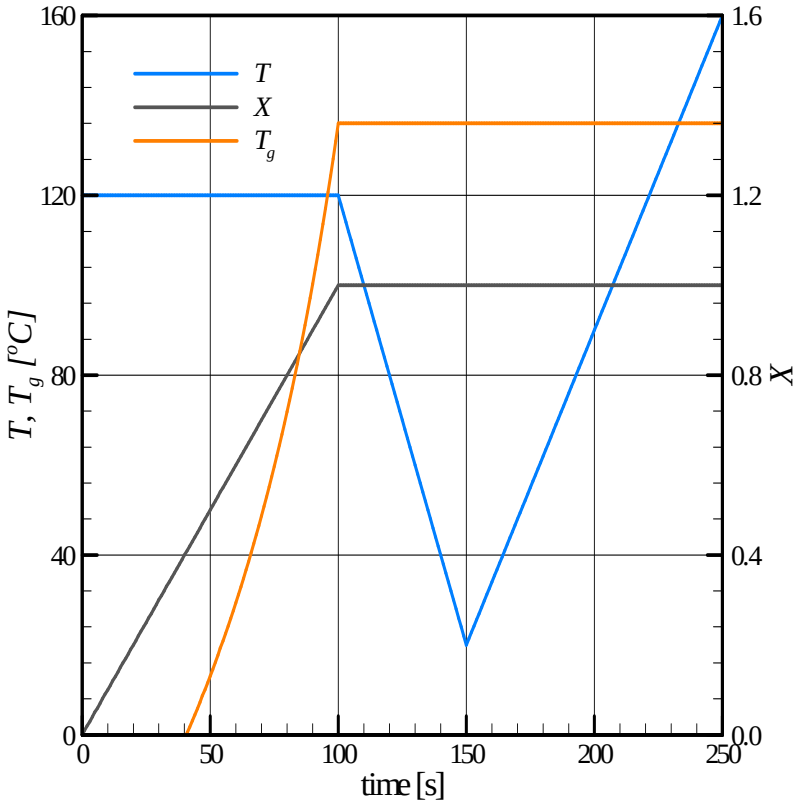


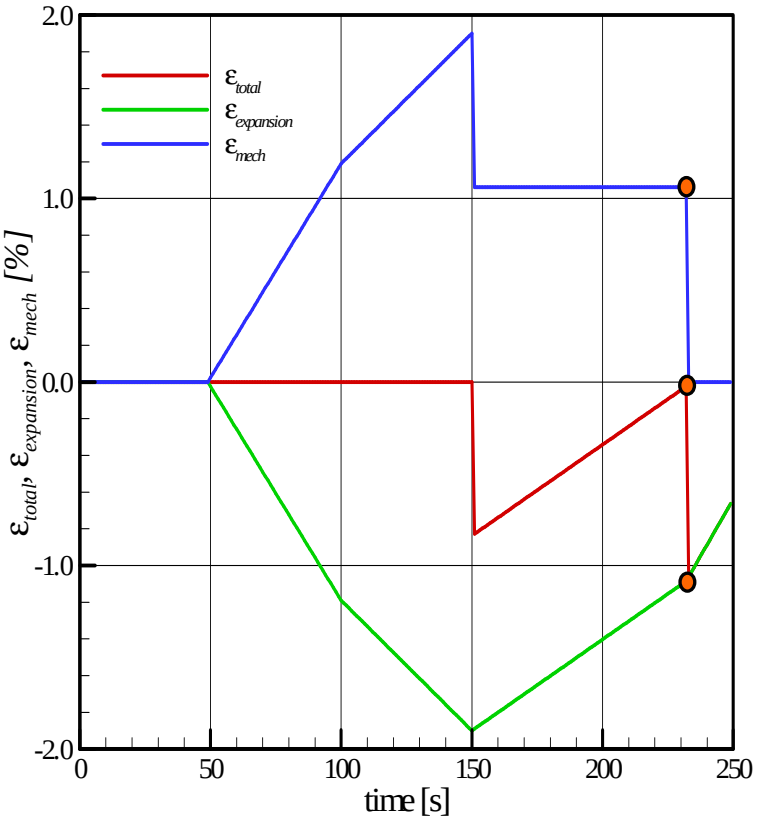
cure

120º C

demo ld

Demoulding simulation

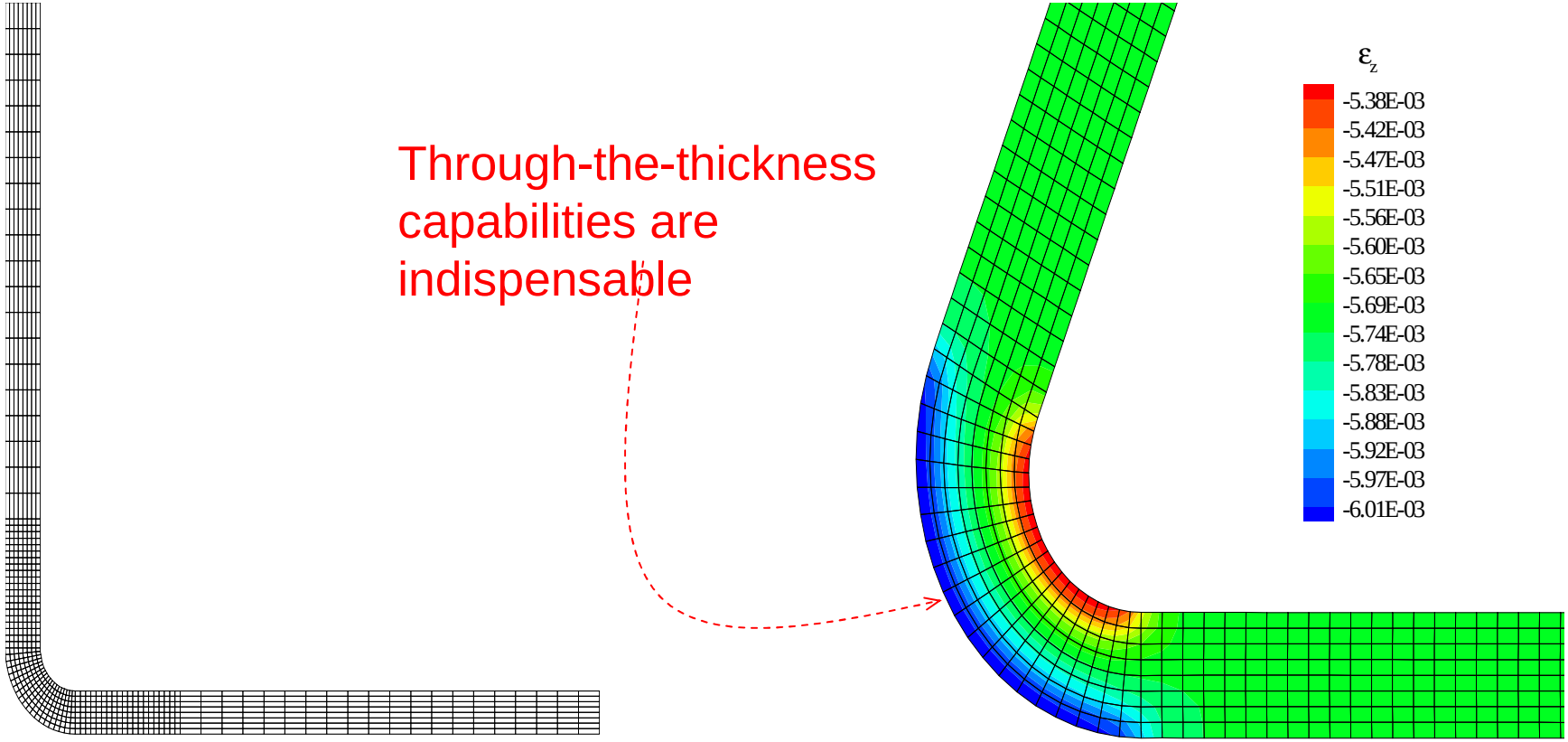




PRELIMINARY RESULTS

Bracket modeling: membrane elements

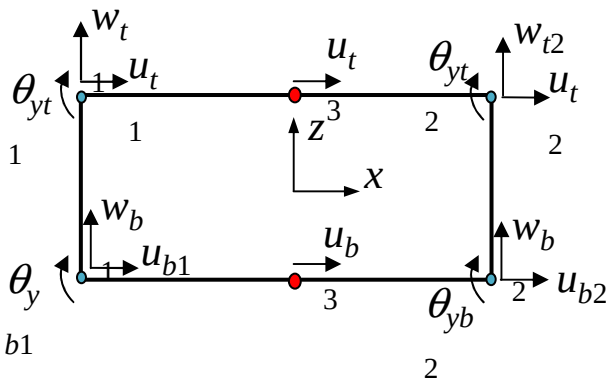
Halpin-Tsai rules of mixture used to compute laminae mechanical properties



NEW ELEMENT PROPOSAL

Bracket modeling: enhanced beam element (solid-like)

- σ_z and transverse shear stresses (τ_{xz}) are obtained without the need of postprocessing
- Only displacements and rotations DOF's
- Nonhomogeneous boundary conditions on top and bottom surfaces are applicable (contact is tractable)
- Analytical solution is achieved for the classical cantilever beam problem



$$u = u_b H_1(\zeta) + u_t H_3(\zeta) - \frac{h}{2}\left[(w_{b,x} - \gamma_{xzb}) H_2(\zeta) + (w_{t,x} - \gamma_{xzt}) H_4(\zeta)\right]$$

$$w = w_b H_1(\zeta) + \frac{h}{2\bar{Q}_{33}^1}(\sigma_{zb} + \sigma_{zT}^1 - \bar{Q}_{13}^1 u_{b,x}) H_2(\zeta) + w_t H_3(\zeta) + \frac{h}{2\bar{Q}_{33}^N}(\sigma_{zt} + \sigma_{zT}^N - \bar{Q}_{13}^N u_{t,x}) H_4(\zeta)$$

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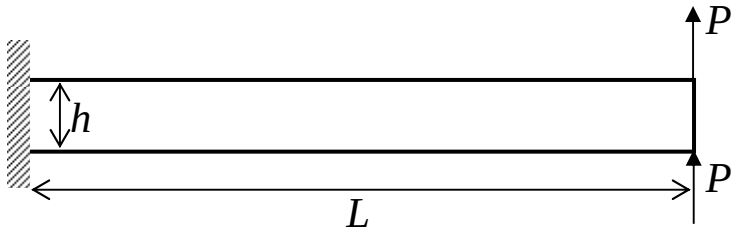

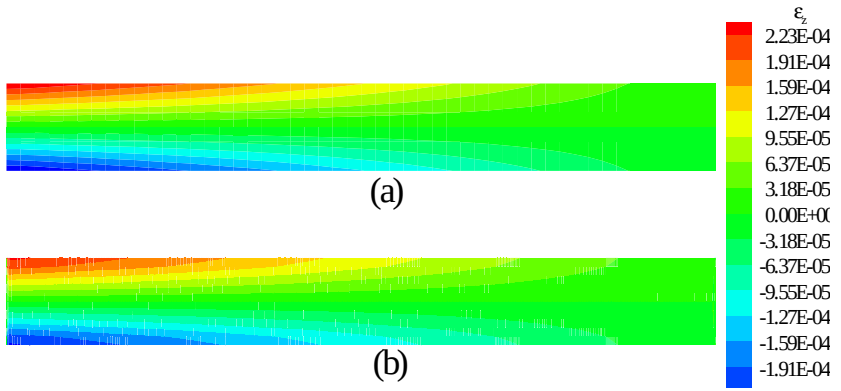

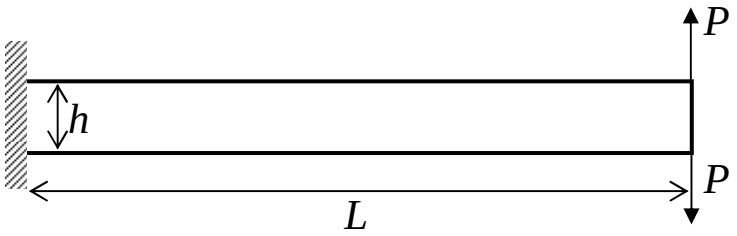

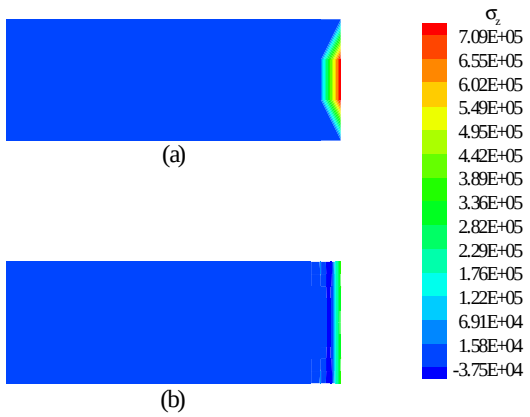

NEW ELEMENT PROPOSAL

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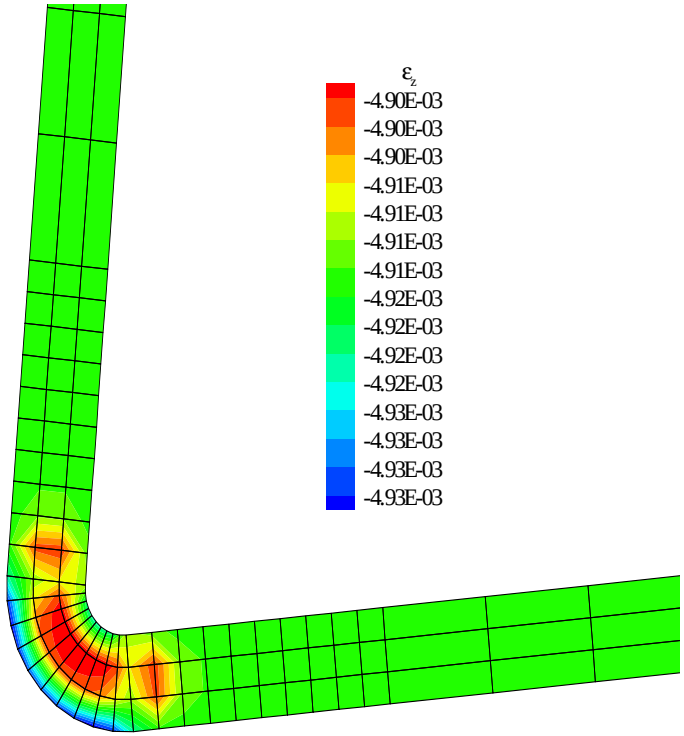

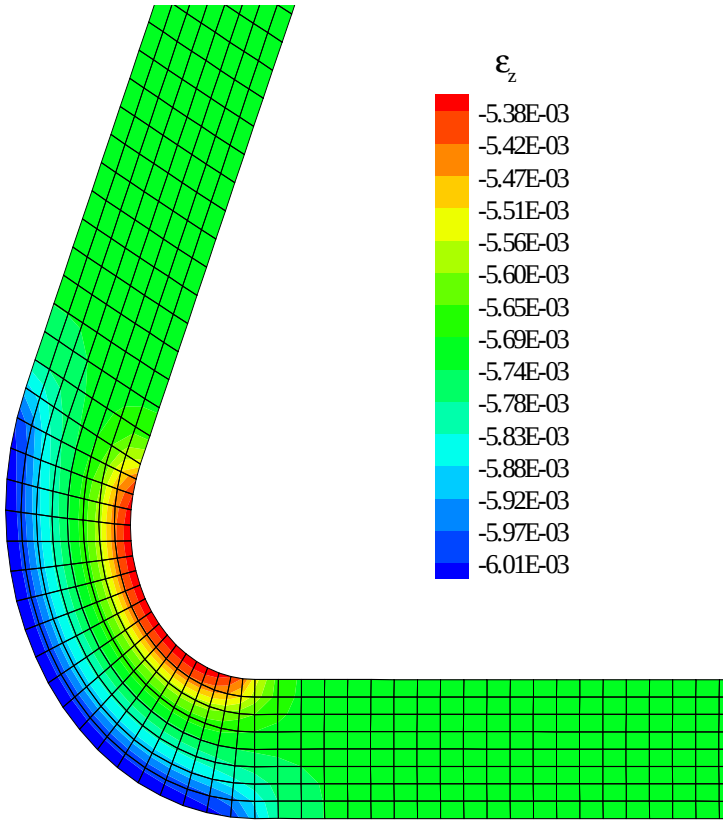

WAY FORWARD

Implement element with through the thickness capabilities for composite beams and plates

Develop strategy to handle contact including possible flexibility of molds

Expand formulation to consider cure kinetics of laminates