Double Diaphragm Forming of Continuous and Discontinuous Composite Layups Over Rigid and Active Tooling

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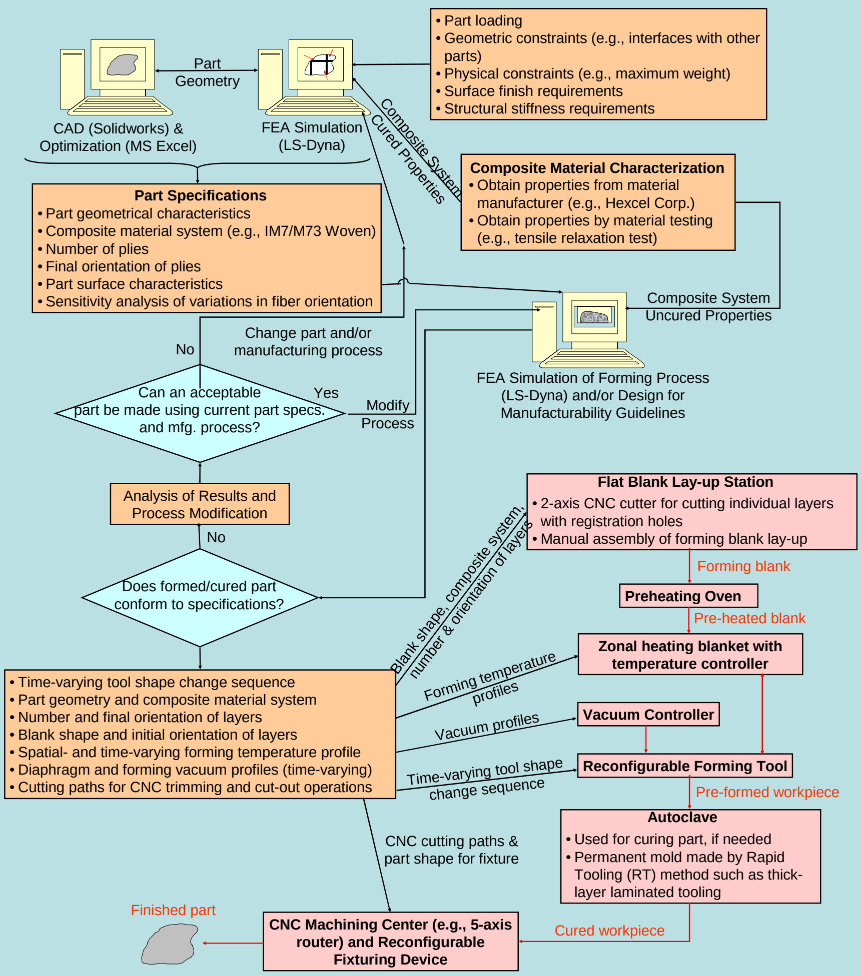
Composite Forming System Flowchart



Flexible Manufacturing Cell for Composites Forming

Hexcel Stretch Broken Carbon Fiber Material (SBCF)

- Continuous carbon fibers are intentionally broken into 5” lengths on average. (fibers break at approx. 10% strain)
- The breaks are done at random and the distribution can be considered normal.
- Currently, 7 micron AS4 and 5.4 micron IM7 fibers have been used to produce the material.
- The material is produced as either pre-impregnated uni-directional sheets or a as a pre-impregnated fabric.
- The matrix currently being used is an M73 formulation.
- The SBCF material is highly rate-, gauge length-, and temperature-dependent.
- Early tests have shown the material to have retained 95% of a comparable continuous materials strength after having been displaced (2% strain).

Material Modeling in LS-Dyna

- LS-Dyna from Livermore Software Technology Corporation is being used to do the FEA of the forming process
- An Orthotropic-Viscoelastic model will be used as a basis to model the SBCF and conventional materials
- The material law that relates stresses to strains is defined as:

$$C = T^T C_L T$$

where T is a transformation matrix containing direction cosines, and C_L is the constitutive matrix defined in terms of the material constants of the orthogonal matrix axis,a,b, and c. The inverse of C_L for the orthotropic case is:

$$C_L^{-1} = \begin{bmatrix} \frac{1}{E_a} & -\frac{\upsilon_{ba}}{E_b} & -\frac{\upsilon_{ca}}{E_c} & 0 & 0 & 0 \\ -\frac{\upsilon_{ab}}{E_a} & \frac{1}{E_b} & -\frac{\upsilon_{cb}}{E_c} & 0 & 0 & 0 \\ -\frac{\upsilon_{ac}}{E_a} & -\frac{\upsilon_{bc}}{E_b} & \frac{1}{E_c} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{ab}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{bc}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{ca}} \end{bmatrix}$$

Note That:

$$\frac{\upsilon_{ab}}{E_a} = \frac{\upsilon_{ba}}{E_b}, \frac{\upsilon_{ca}}{E_c} = \frac{\upsilon_{ac}}{E_a}, \frac{\upsilon_{cb}}{E_c} = \frac{\upsilon_{bc}}{E_b}$$

- For the viscoelastic part, linear viscoelasticity is assumed for the deviatoric stress tensor:

$$S_{ij} = 2\int_0^t \phi(t-\tau)\frac{\partial \varepsilon'_{ij}(\tau)}{\partial(\tau)} d\tau$$

where

$$\phi(t) = G_\infty - (G_0 - G_\infty)e^{-\beta t}$$

is the shear relaxation modulus.
- A recursion formula is used to compute the new value of the hereditary integral at time t_{n+1} from its value at time t_n. Elastic bulk behavior is assumed:

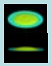
$$p = K \ln V$$

where pressure is integrated incrementally.
- The material constants needed for this model had to be experimentally determined for each material of interest
- An AS4/M73 SBCF uni-directional prepreg system was chosen for initial testing due to its common constituents and availability.
- Minimum and maximum forming temperatures for this material are 170F and 250F respectively.

Verification of Material Model

- Once material models are fully developed, they will be verified by comparison to test results
- The bulge test shown on the right will be used to further verify the material and to characterize the contact between the diaphragm and the material

Bulge test fixture designed and built by the Applied Research Laboratory at Penn State



First run model of bulge test from Pam-Form

Modeling of the Forming Process

- Preliminary FEA forming exercises were performed in Pam-Form and will resume using LS-Dyna as soon as the material models are done
- Both conventional and SBCF materials will be used in forming simulations

Virtual Design

- One of the long term goals for this project is to develop a design for manufacture tool for vacuum forming of complex double curvature composite parts using flat layups of pre-impregnated carbon/epoxy materials.
- This tool would reside in a solid modeling program such as Solid Works™ and would provide specific design criterion based on the users model of the desired part.
- The tool would automatically determine whether the part can be made, the appropriate material system to be used, the layup, number of ply's, pin heights for the incremental tool, strain rates, forming sequence, etc…

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