Tool-part interaction

Project done by:
UBC and CMT

Summary:
Mechanical tool-part interaction can cause substantial residual stress build-up in composite part. The study examines the mechanisms of tool-part interactions and develops an analytical model that predicts the observed behaviour. It is also shown how the phenomena can be simulated using COMPRO 2D.

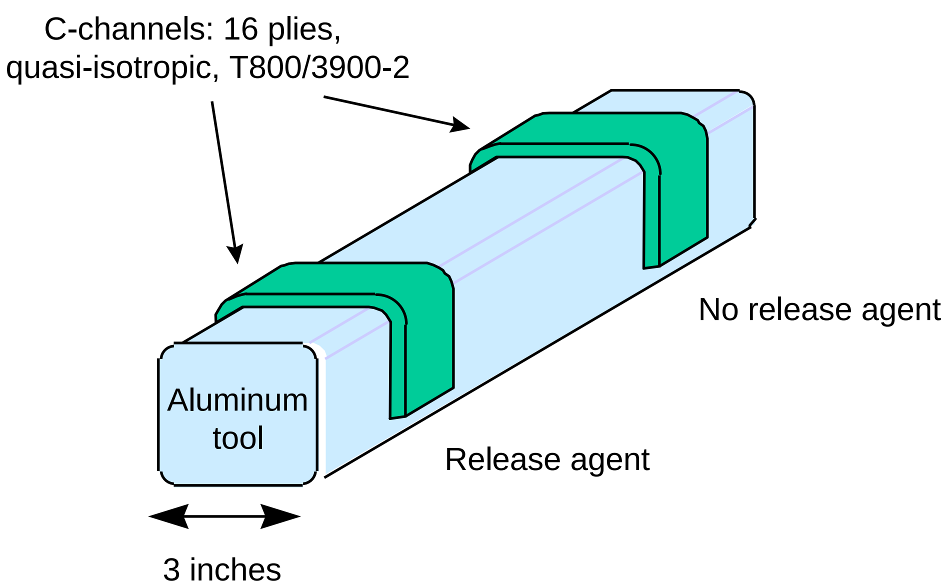
References:

*Twigg G, Poursartip A, Fernlund G. An Experimental Method for Quantifying Tool-Part Shear Interaction Duing Composites Processing. Comp Sci Tech 2003: 63; 1985-2000.

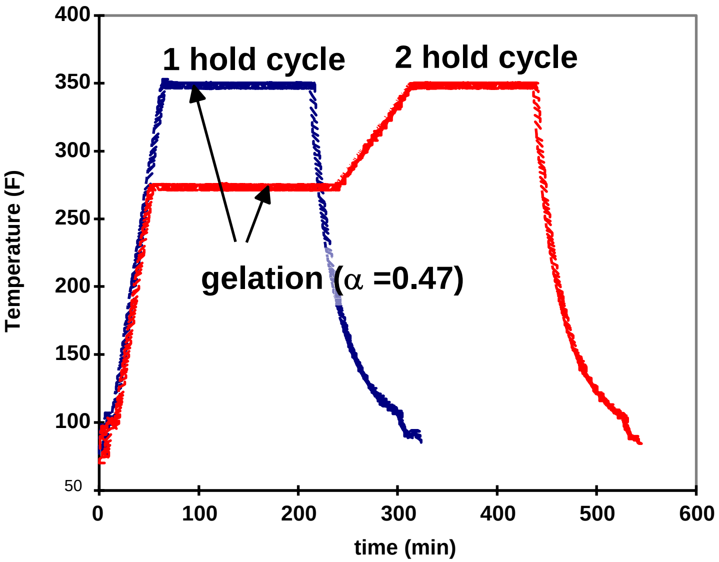
Predictive example

Effect of tool-part interaction and cure cycle on spring-in

Tool and parts

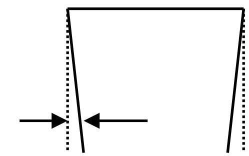


Cure cycles

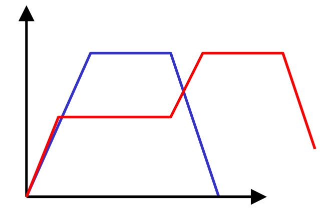


Final degree of cure is the same in all cases, but history is very different

Measured and predicted flange spring-in

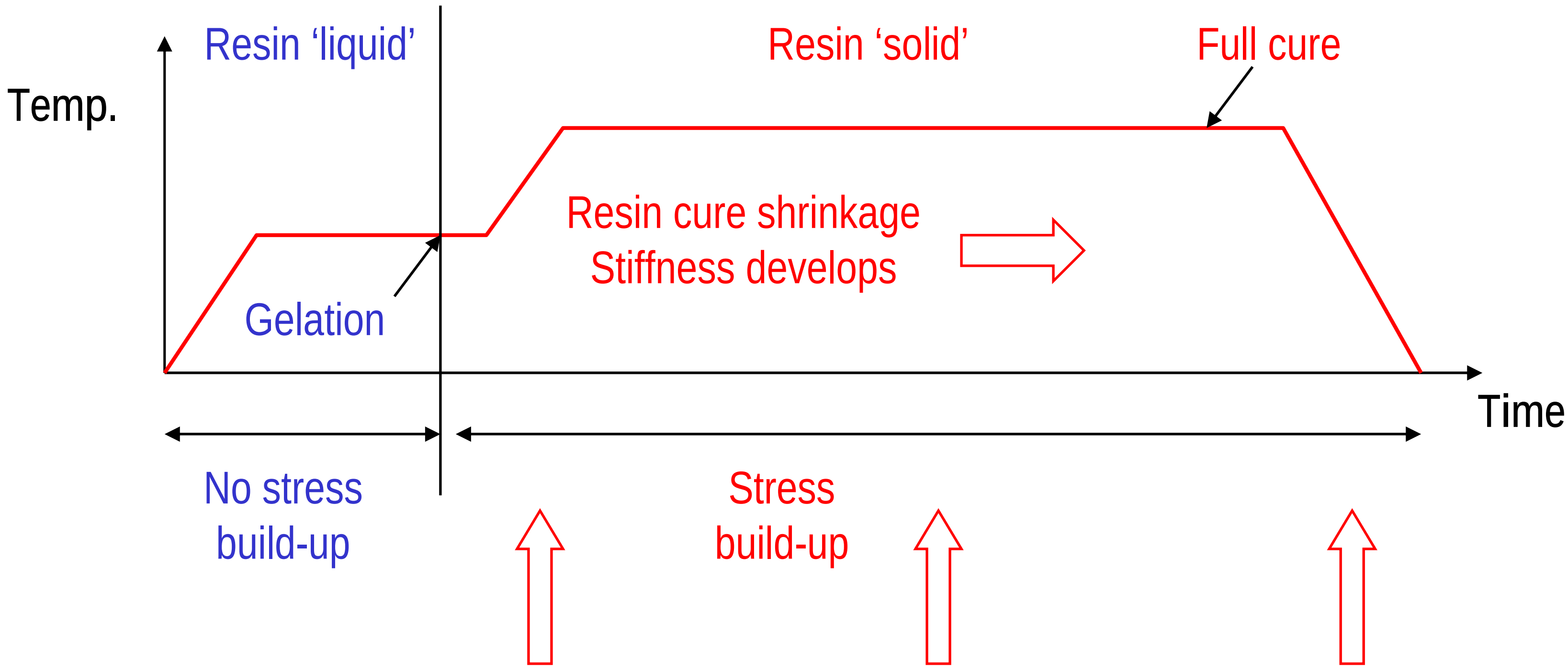


Closed-form prediction ~ 1.25º



Final degree of cure is the same in all cases, but history is different

Interpretation of the experiment



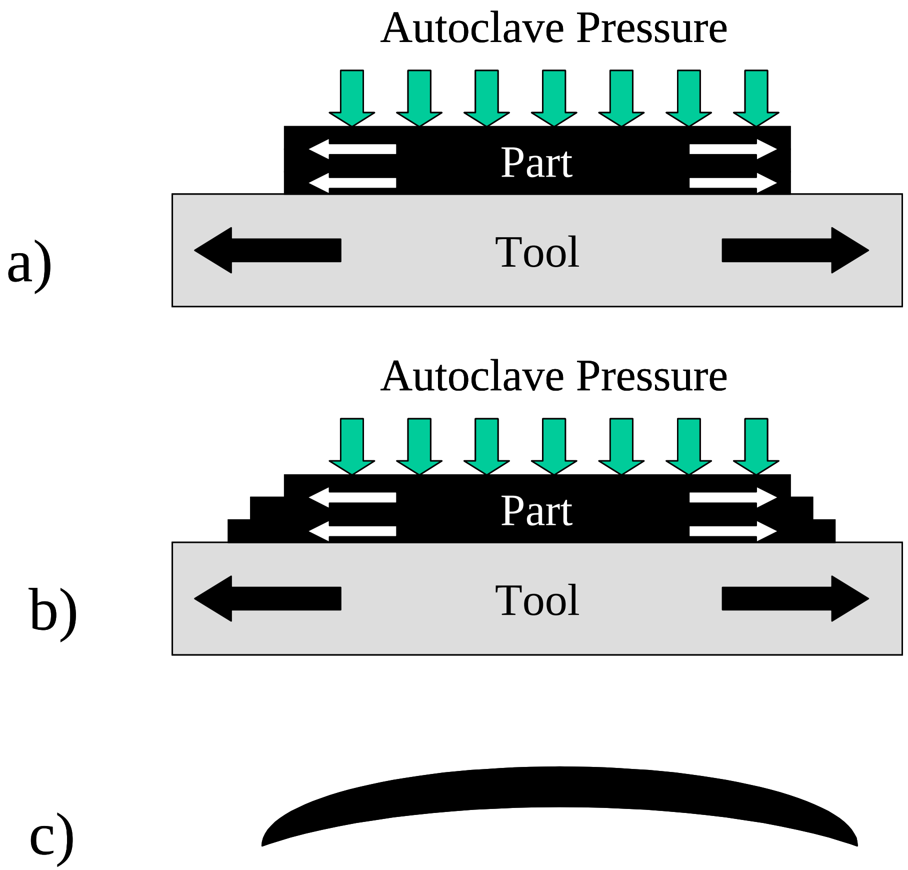
Main mechanisms:

1. Tool-part interaction

2. Cure shrinkage

3. Thermal contraction

Tool-part interaction induced warpage



Mechanism:

- Low CTE part is stretched by higher CTE tooling due to interfacial shear stress.
- Shear deformation within the part results in non-uniform stress distribution through part thickness. Upon curing this is locked in a residual stress.
- Residual stress distribution causes a net bending moment warping part.

Warpage parametric study

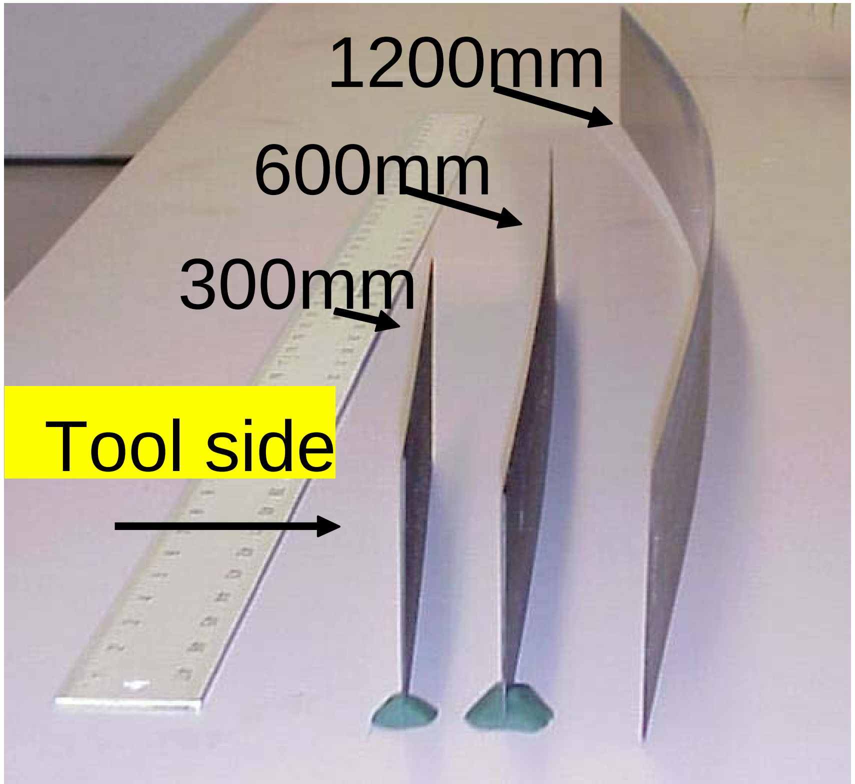
- A parametric study was performed to examine the effect of part geometry and process conditions on warpage.
- Laminate material - T-800 / 3900-2
- Tooling Material – Aluminum (6061-T6)

Parameters Studied

- Part Thickness – $[0]_4$, $[0]_8$ and $[0]_{16}$ ply lay-ups
- Part Length – 300 mm, 600 mm , 1200 mm nominal part lengths
- Autoclave Pressure – 103 kPa (15 psig) and 586 kPa (85 psig)
- Tool Surface Condition – 2 plies of FEP and Freekote 700NC release agent

Warpage parametric study

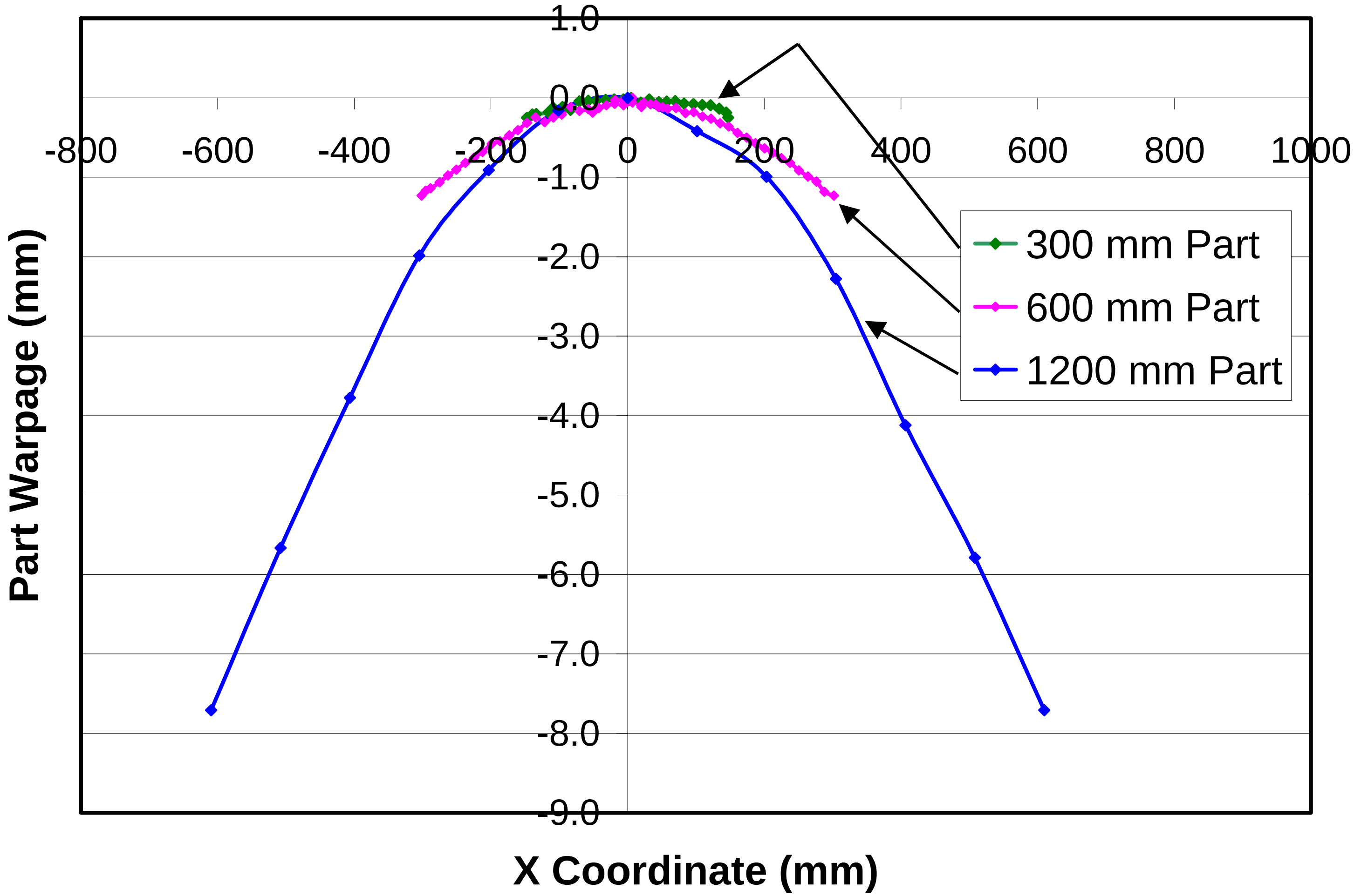
deformed shapes



Warpage resulting from tool-part interaction for $[0]_4$ parts. (85 psig / FEP interface)

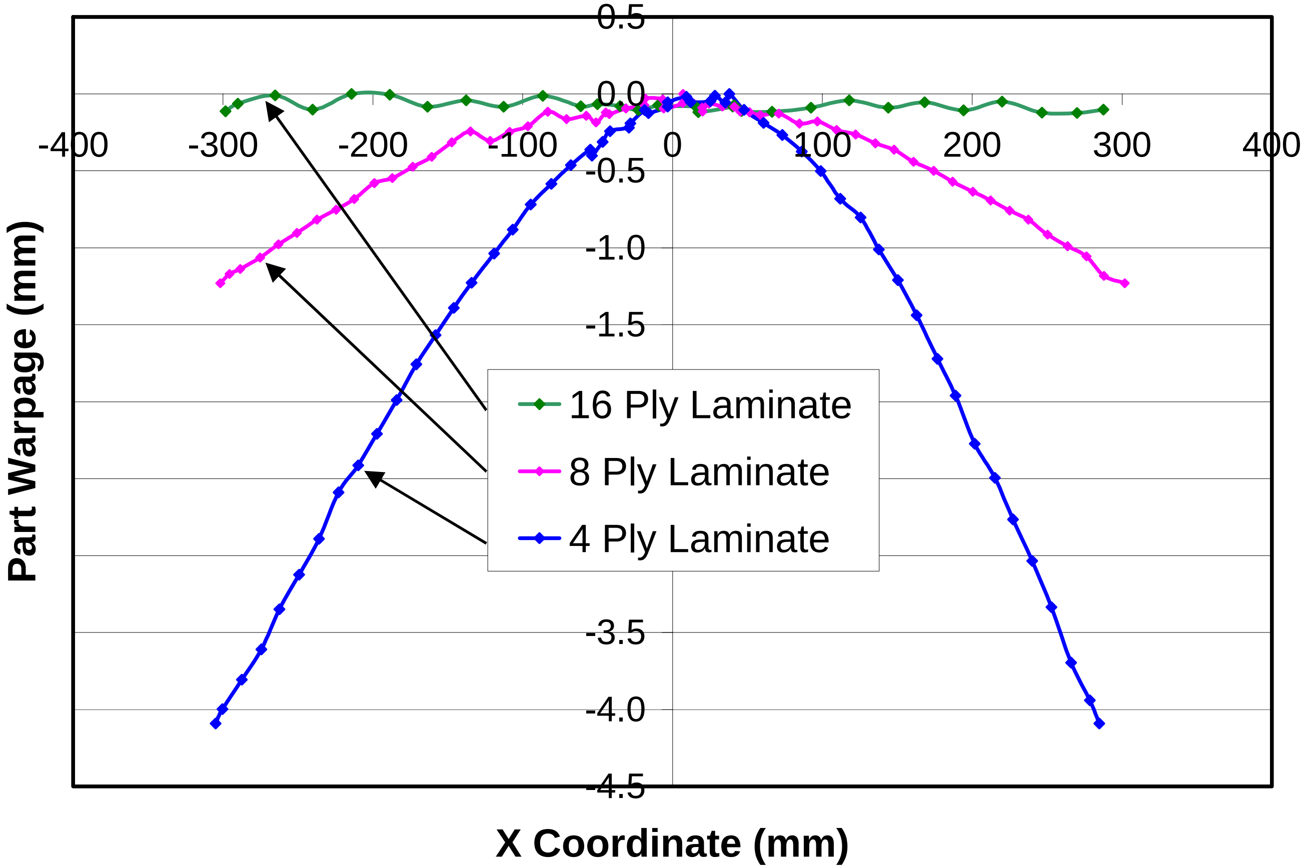
Warpage parametric study

part length effect



Warpage parametric study

part thickness effect



Warpage parametric study

empirical warpage relation

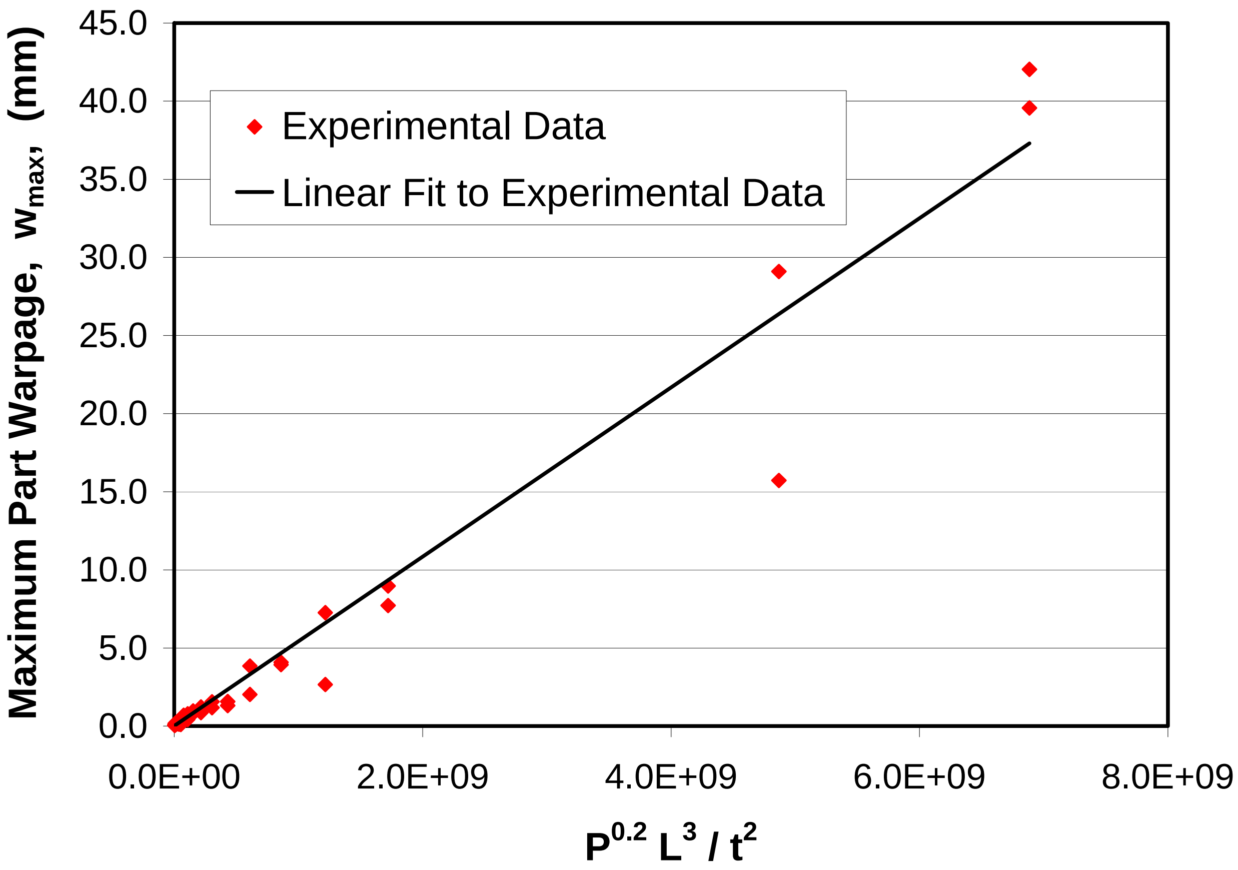
The observed effects of part geometry and process conditions on part warpage can be summarized in the following empirical relation:

$$\textit{Maximum Part Warpage} \propto \frac{P^{0.2} \cdot L^3}{t^2}$$

where *P* is the autoclave pressure, *L* is the part length and *t* is the part thickness

Warpage parametric study

empirical warpage relation

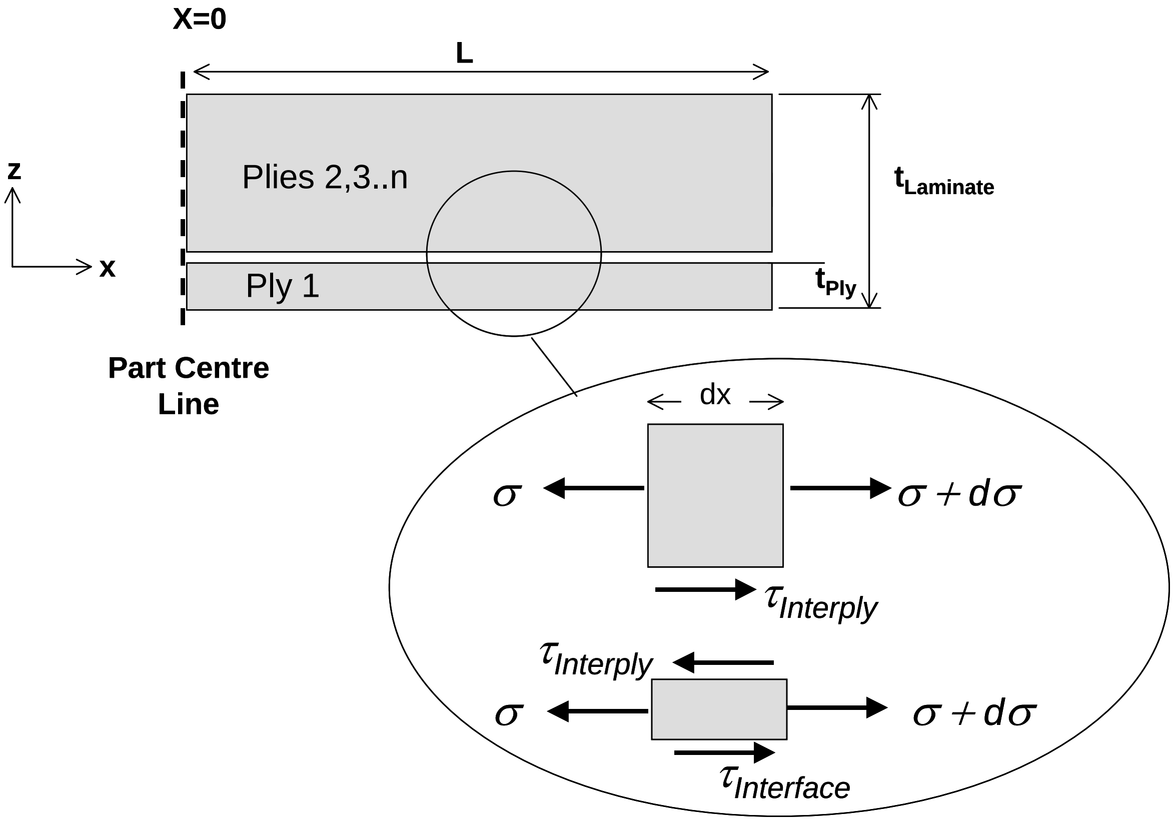


Analytical warpage modeling
model assumptions

- A very simple analytical model ha been developed to predict the warpage arising from tool-part interaction.
- Assumptions:
  - The interply sliding friction coefficient is smaller than the interface sliding friction coefficient.
  - There is no through thickness stress gradient in the upper plies.
  - The effect of part degree of cure on part modulus and interface friction coefficients is neglected.

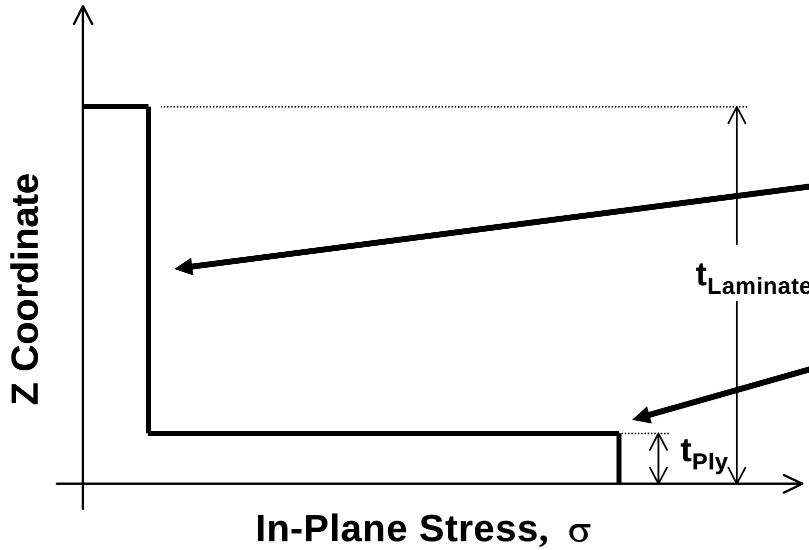
Analytical warpage modeling

model development



Analytical warpage modeling

model development



$$\sigma_{Ply2,3..n} = \frac{\tau_{Interply} \cdot (L - x)}{t_{Lam} - t_{Ply}}$$

$$\sigma_{Ply1} = \frac{(\tau_{Interface} - \tau_{Interply}) \cdot (L - x)}{t_{Ply}}$$

• The assumptions lead to a non-uniform stress distribution through the part thickness.

Analytical warpage modeling

model results

- The warpage predicted by the analytical model is as follows:

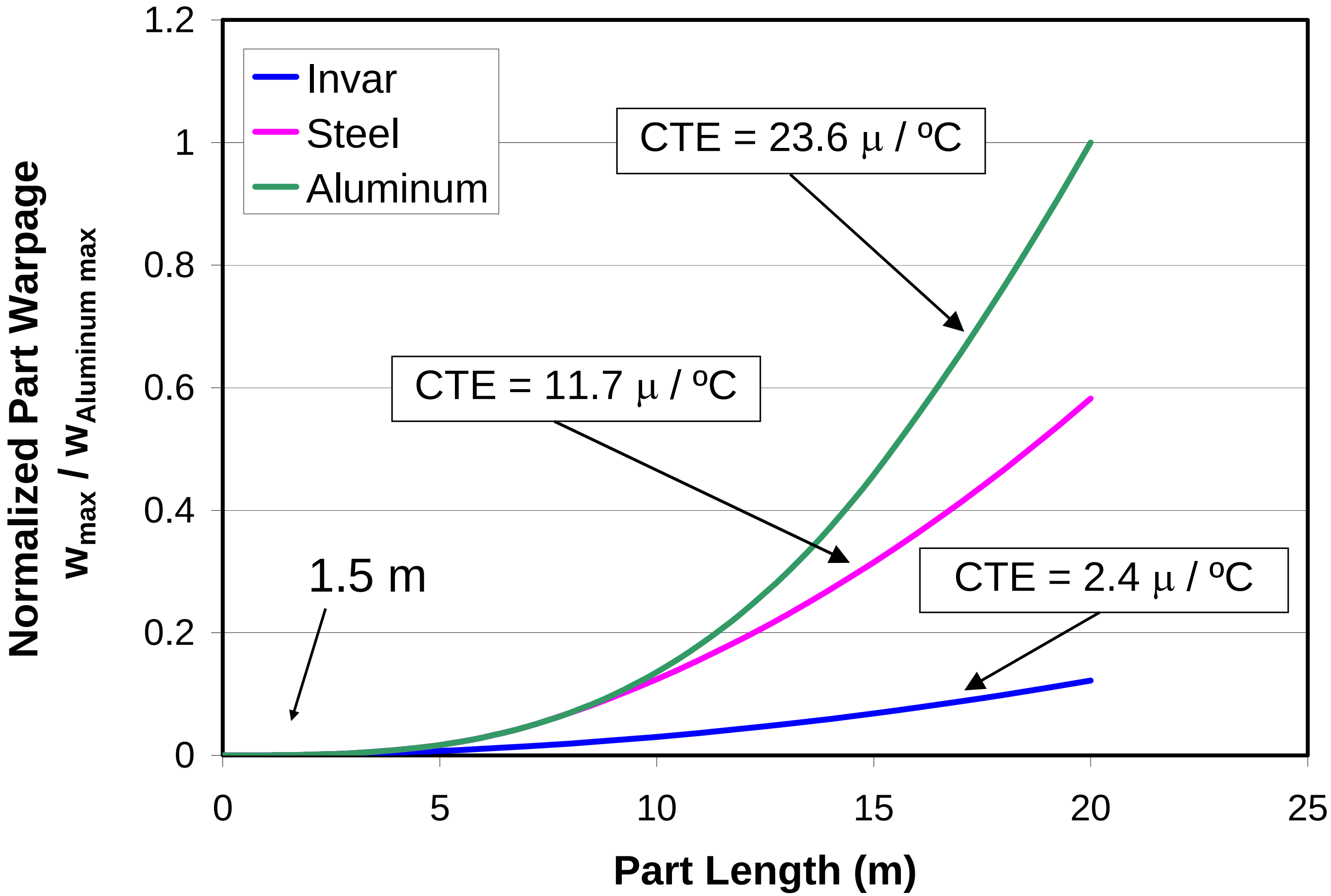
$$Maximum\ Part\ Warpage \propto \frac{\tau_{Net} \cdot L^3}{t^2}$$

Comparing this with the empirical relation:

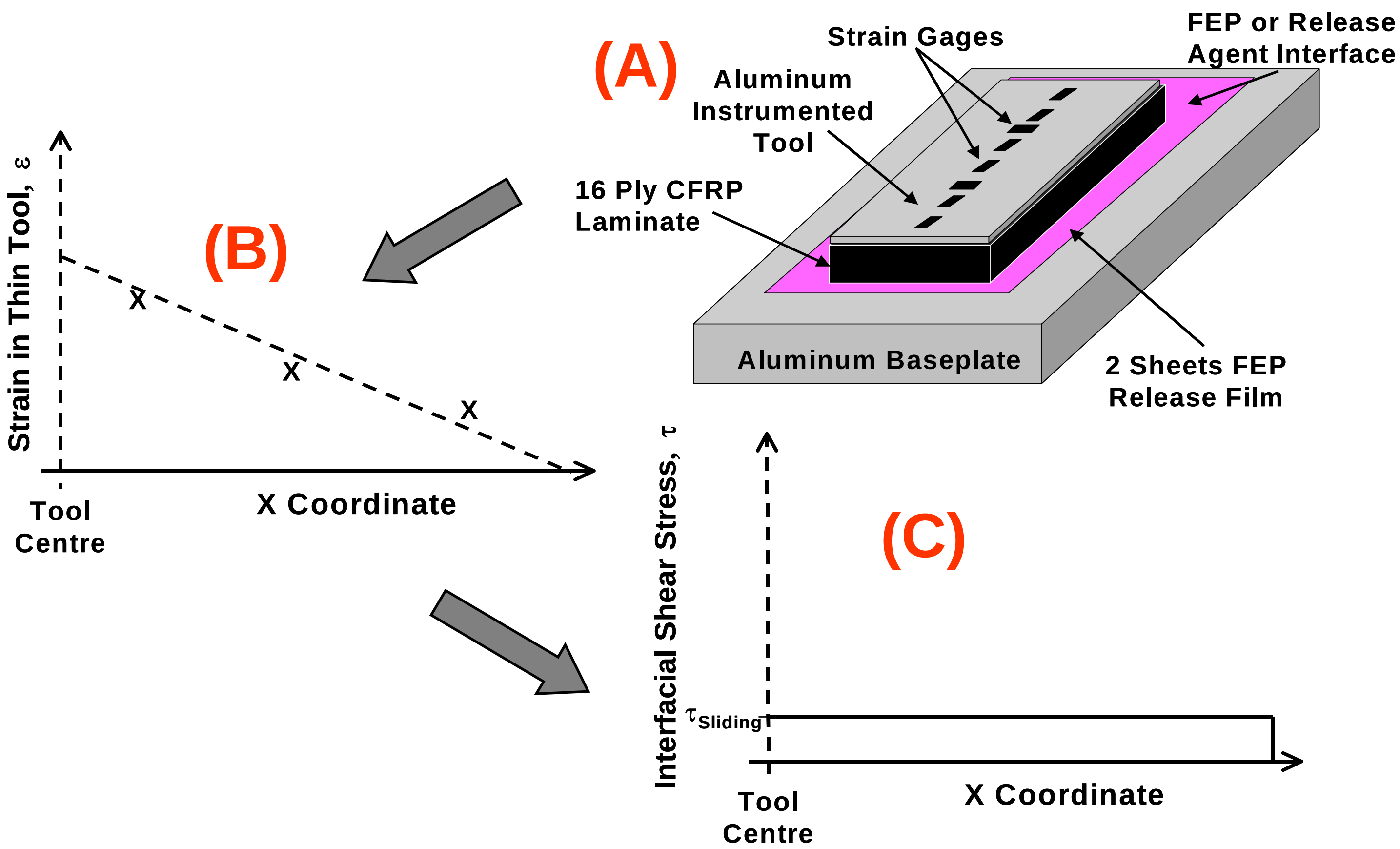
$$Maximum\ Part\ Warpage \propto \frac{P^{0.2} \cdot L^3}{t^2}$$

Analytical warpage modeling

tooling CTE effect for 0º laminate on different tools

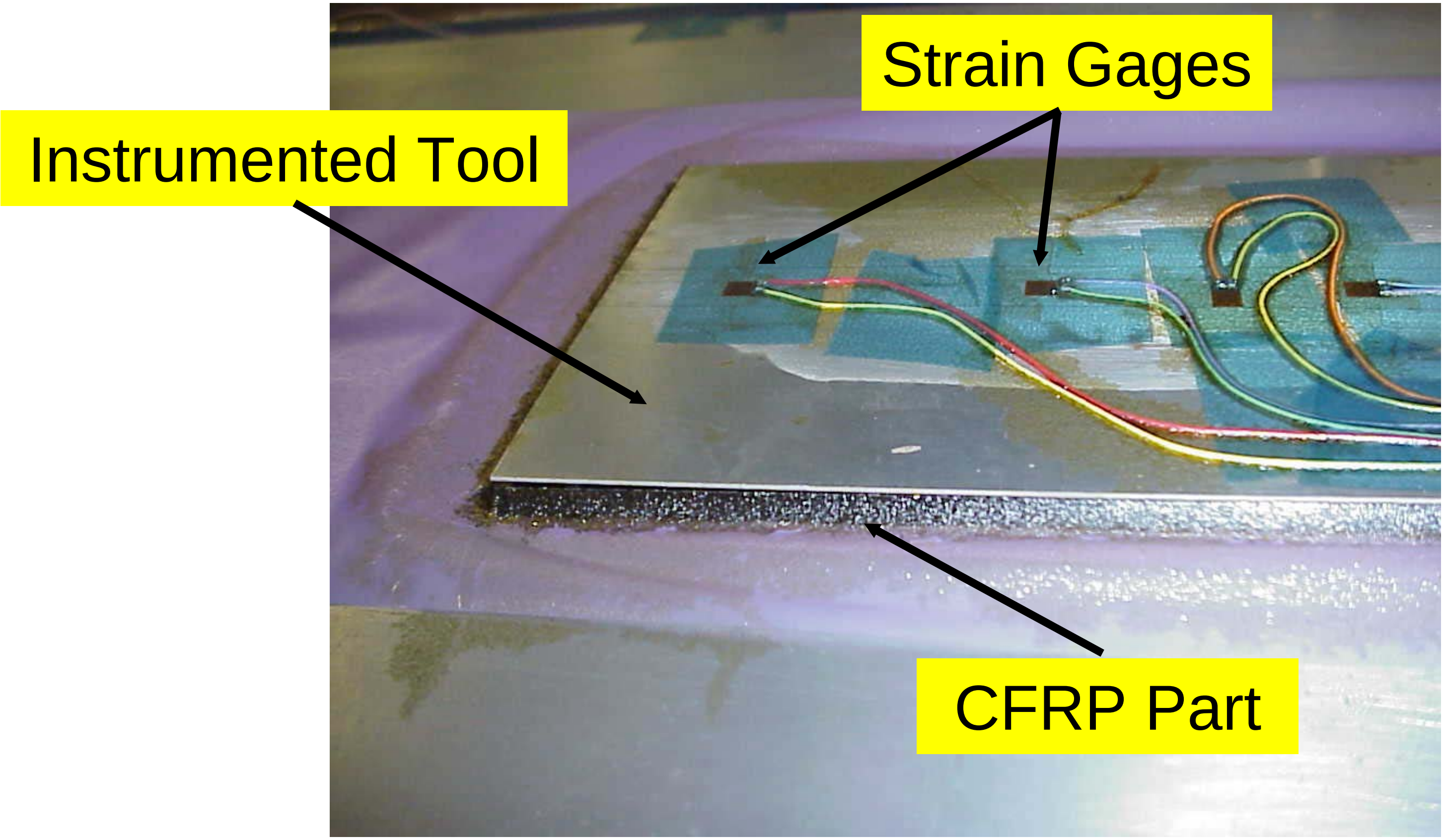


Instrumented tool experiments



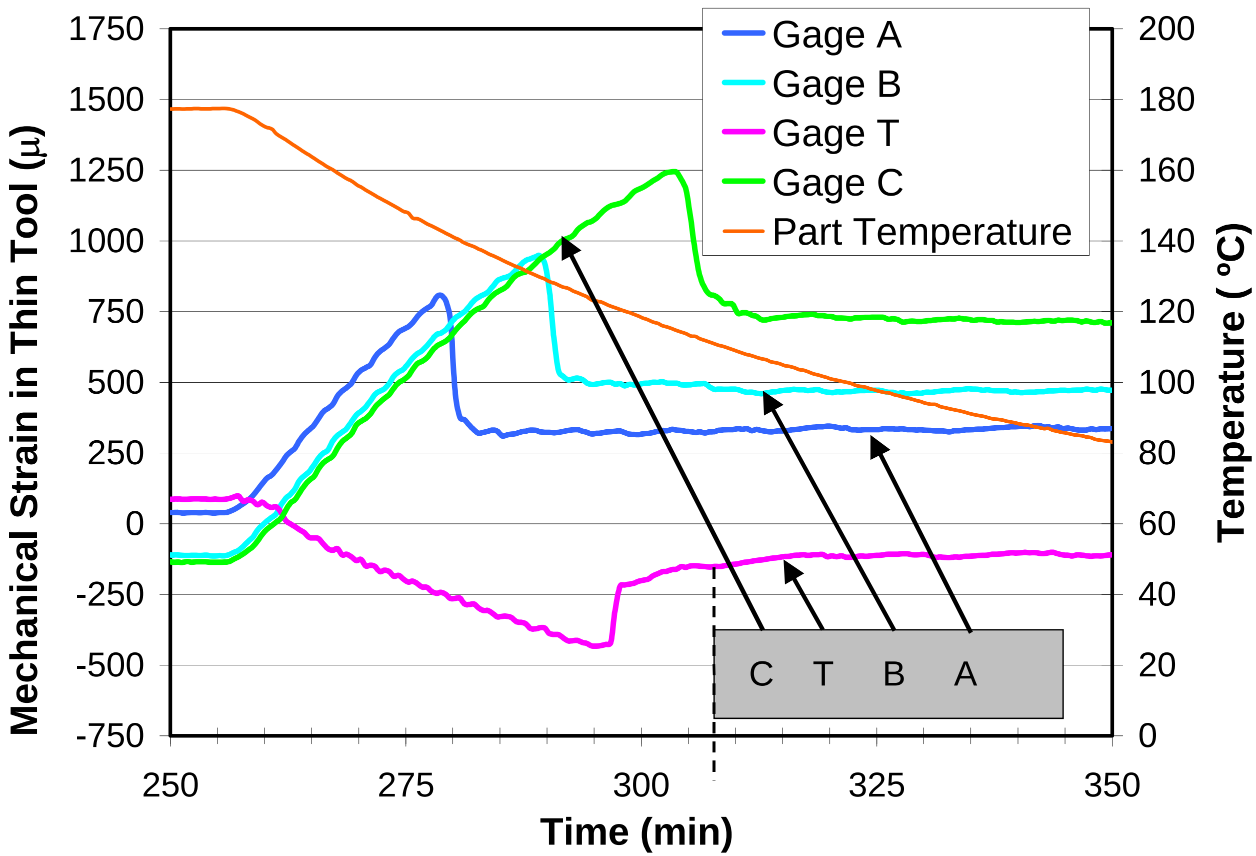
Instrumented tool experiments

instrumented tool setup



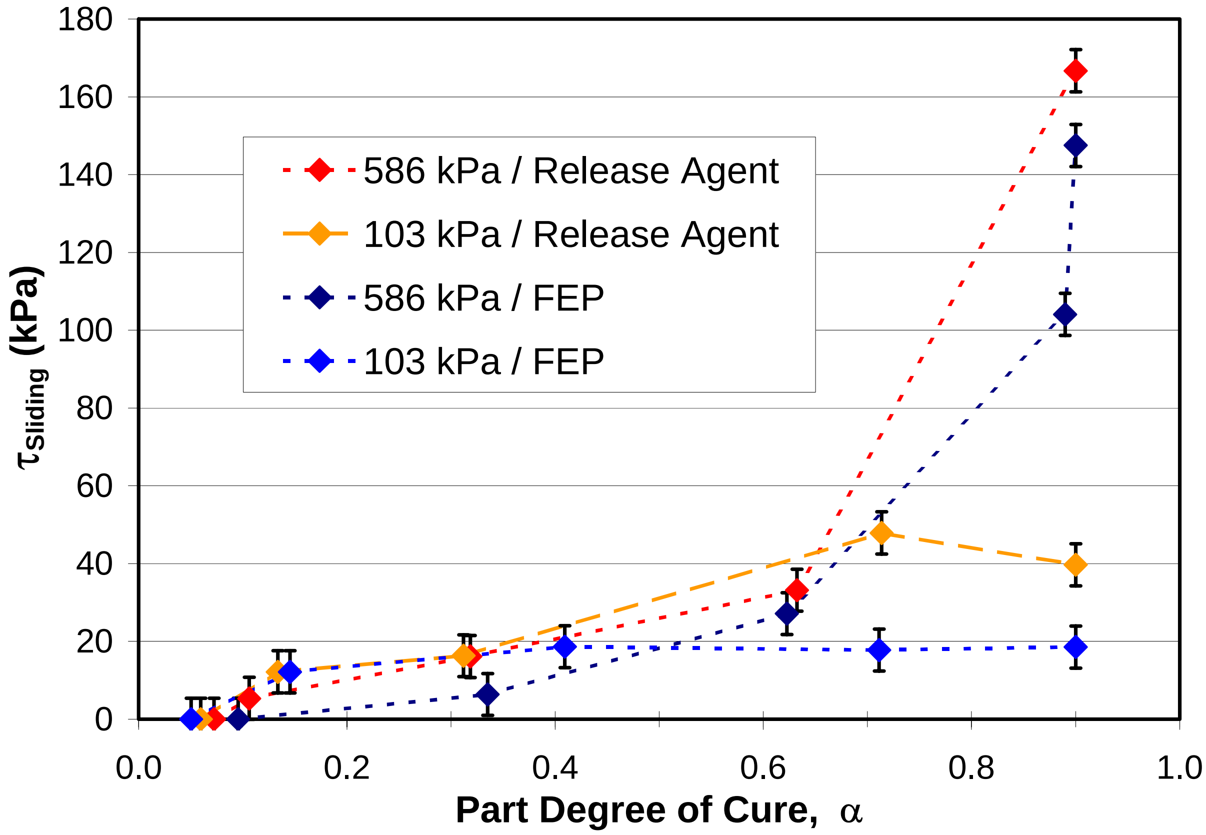
Instrumented tool experiments

typical experimental output

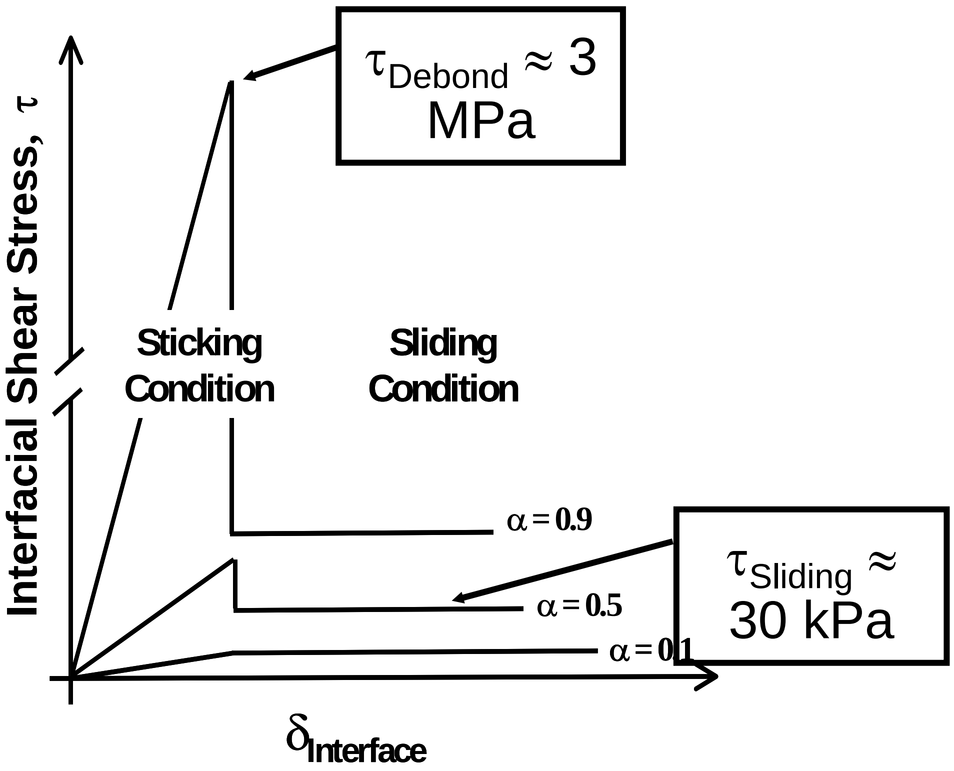


Instrumented tool experiments

development of interfacial shear stress

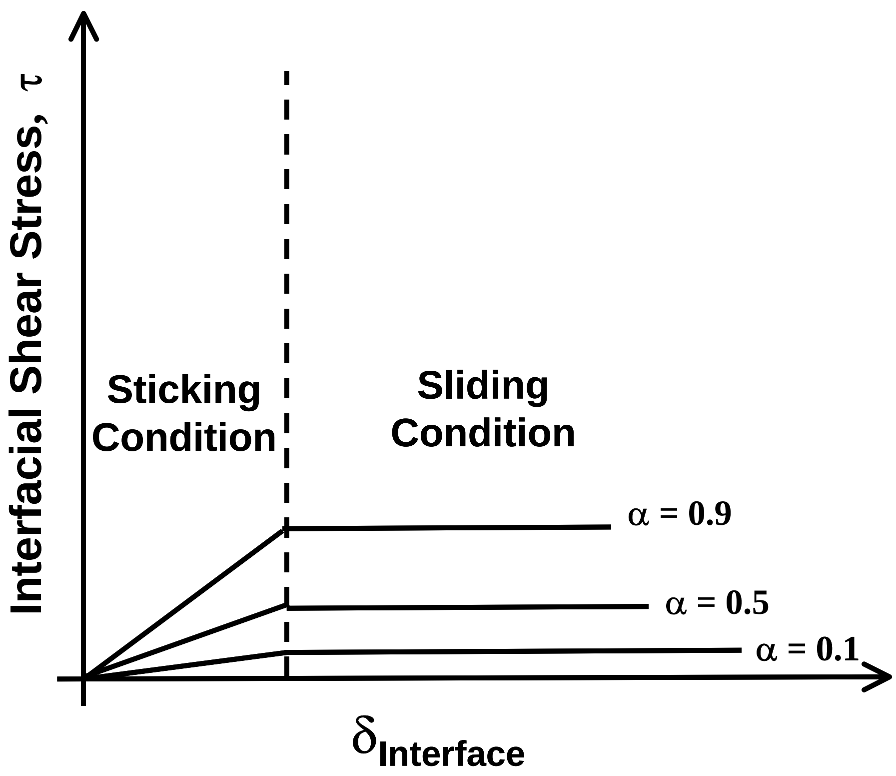


Instrumented tool experiments
development of interfacial shear stress – release agent



Instrumented tool experiments

development of interfacial shear stress – FEP Interface



Instrumented tool experiments
key findings

- During the heat-up portion of the cure cycle when residual stresses are building in the part, a sliding friction condition was prevalent at the tool-part interface.
- At times a sticking interface condition can occur, particularly after isothermal dwells.
- Adhesive bonding can occur between the tool and part despite the use of a release agent.
- The use of FEP at the interface prevents any adhesive bonding.

Numerical warpage modeling

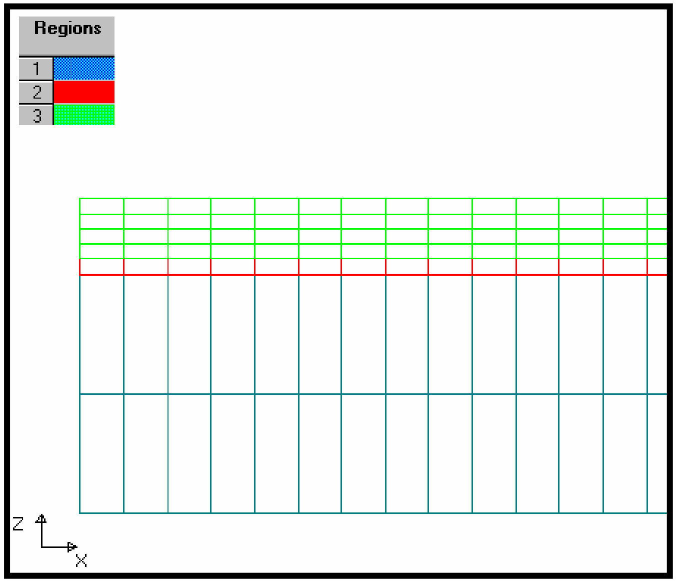
COMPRO: A 2-dimensional, plane-strain FE code for modelling composites processing

Thermochemical Module
- Tool and part temperature
- Degree of cure/cure kinetics

Flow Module
- Resin flow

Stress Module
- Stress build-up during processing
- Final part shape

Numerical warpage modeling
COMPRO shear layer



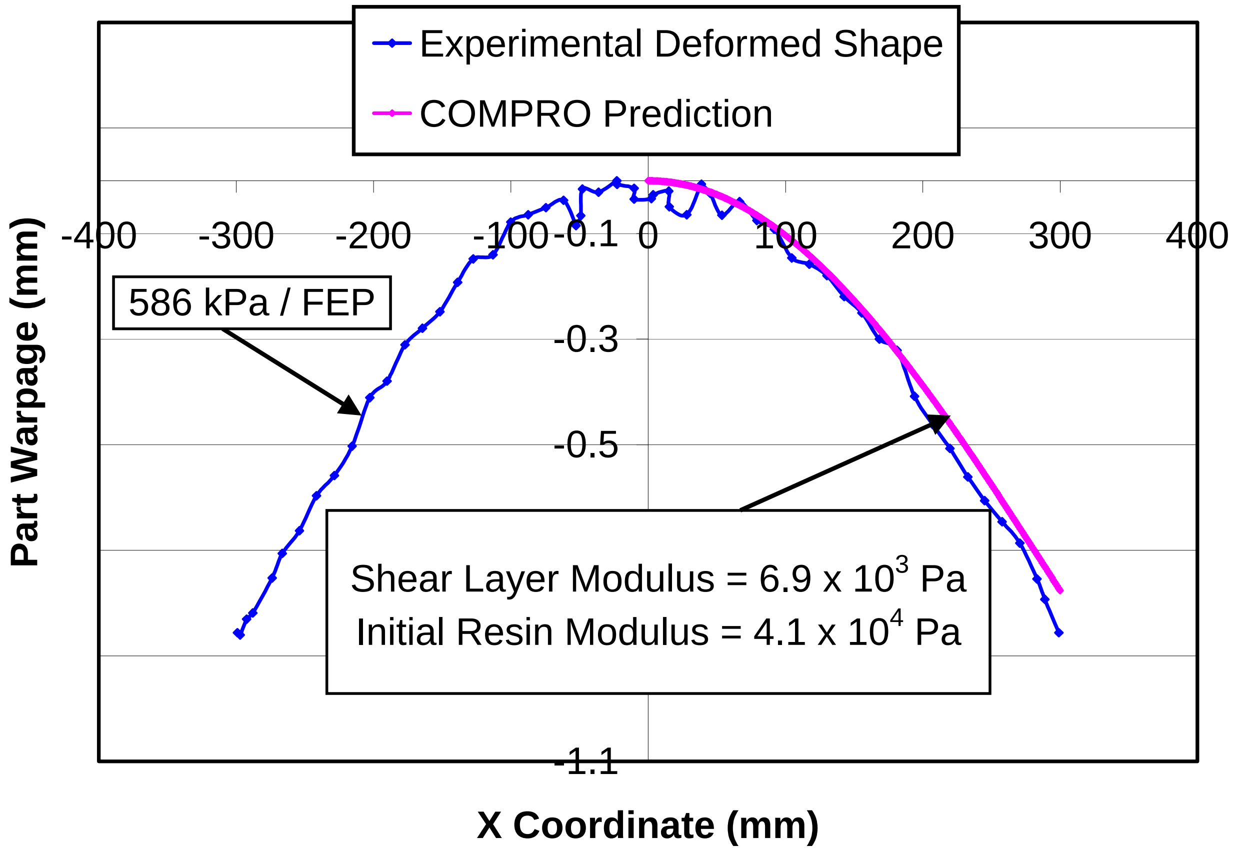
- Stress transfer between tool and part can be tailored by adjusting the properties of the elastic Shear Layer

Numerical warpage modeling
COMPRO parametric study

- A parametric study was performed to examine the effect varying shear layer and part properties over the range of part geometries examined experimentally

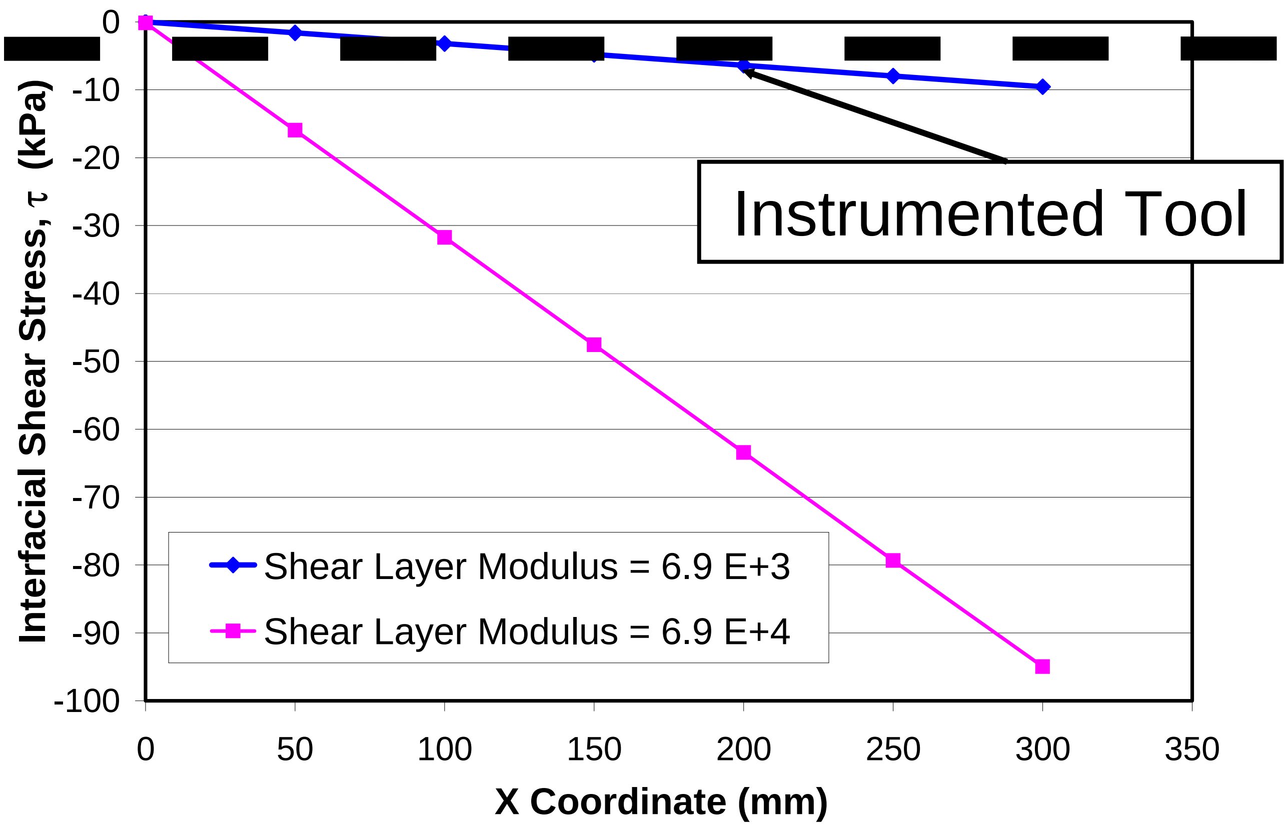
- Parameters Studied
- Part Thickness – [0]4, [0]8 and [0]16 ply lay-ups
- Part Length – 300 mm, 600 mm , 1200 mm nominal part lengths
- Shear Layer Stiffness – 6.9 x 103 Pa, 6.9 x 104 Pa
- Initial Resin Modulus – 4.1 x 103 Pa – 4.1 x 107 Pa

Numerical warpage modelling
COMPRO deformed shape



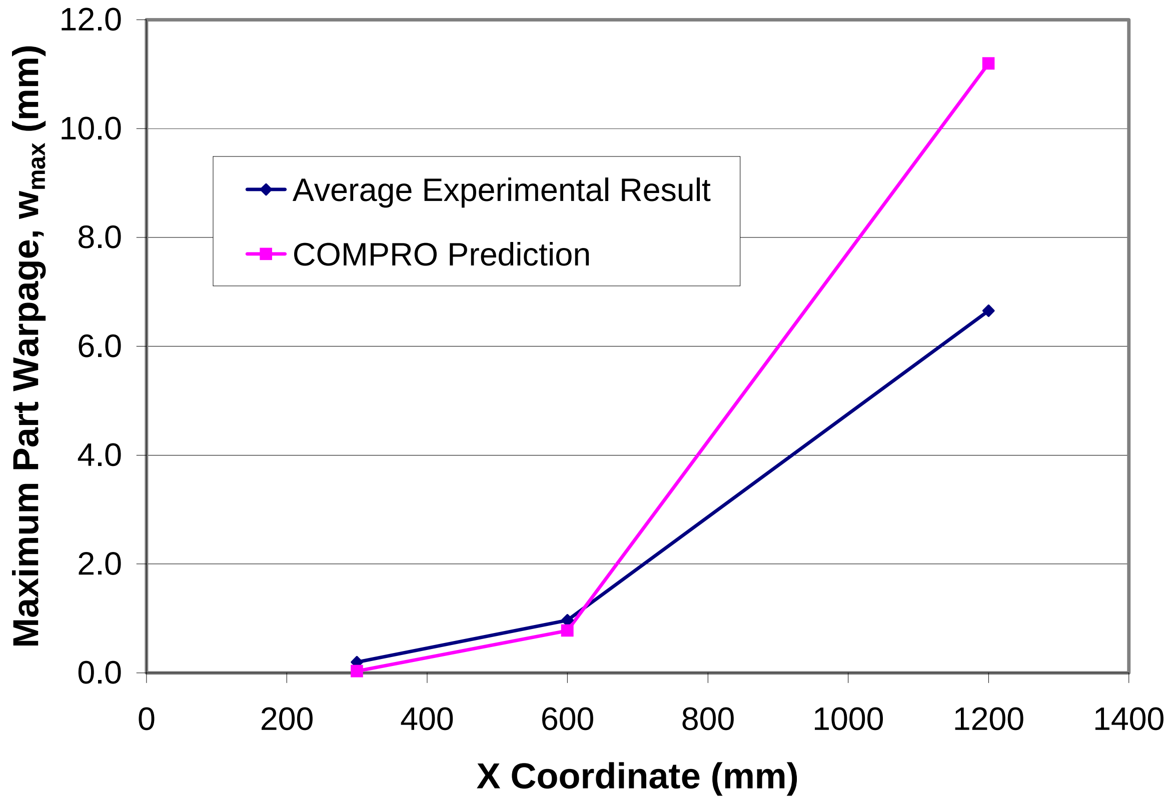
Numerical warpage modeling

COMPRO interfacial shear stress distribution



Numerical warpage modelling

COMPRO prediction versus experimental result



Conclusions

- The key parameters influencing warpage due to tool-part interaction have been identified.
  - Laminate geometry plays the largest role
- A simple analytical relation to predict this tool-part interaction induced warpage has been developed.
- A technique to measure the magnitude and distribution of tool-part interfacial shear stress during processing has been developed.
  - A sliding interface condition is in effect for most of the cycle
  - The interfacial shear stress increases with degree of cure
- An existing numerical process model has been exercised, and strengths and weaknesses of its tool-part interaction representation identified.
  - The current soft elastic shear layer does not reflect the true behaviour
  - However, if the observed interfacial shear stresses in the instrumented tests are matched, the warpage experiments are predicted well

Summary:

Mechanical tool-part interaction can cause substantial residual stress build-up in composite part. The study examines the mechanisms of tool-part interactions and develops an analytical model that predicts the observed behaviour. It is also shown how the phenomena can be simulated using COMPRO 2D.

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