

CHARACTERIZATION AND MODELING OF THE TEMPERATURE AND RATE DEPENDENT SHEAR BEHAVIOR OF A NON-CONSOLIDATED POWDER IMPREGNATED FABRIC

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Introduction Shear characterization Modeling Forming tests Conclusion

Industrial context



Thermoplastic composite in crash-relevant structural parts for mass market cars: Cost efficiency + short cycle time (1000 parts/day \rightarrow 1' cycle time)









Introduction Shear characterization Modeling Forming tests Conclusion

Industrial context

• Thermoforming process:



- Short cycle times, complex shapes (double curvature) possible
- Organosheets expensive for high volume applications
- Thermoplastic semiproducts (semipregs):
 - Commingled fabrics
 - Powder towpreg
 - Powder-impregnated fabric
 - Easier to handle (stable)
 - Resin deposition posterior to weaving process
 - Not drapable at room temperature



with low viscosity resin: potential for direct forming of non-consolidated semipreg





Objectives

Introduction Shear characterization Modeling Forming tests Conclusion

- Forming of a non-consolidated prepreg stack:
 - Preheating step:
 - Thermo-optical properties
 - Ply/ply interfaces: thermal contact resistances
 - Forming step:
 - Shear behaviour vs. temperature/punch speed
 - Ply/ply friction at elevated temperatures
 - Consolidation/compaction
- Development of coupled simulation tools:
 - Infrared heating simulation:
 - Simulate the 3D temperature field evolution in the blank for a given oven configuration
 - Optimize an oven configuration for a required temperature field
 - Mechanical forming simulation:
 - Based on temperature/rate dependent material characterization
 - Predict the apparition of macroscale shape defects (wrinkles)





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Outline

- Introduction
 - Context
 - Project objectives
- Shear characterization
 - Material
 - Bias extension tests
 - Temperature/rate dependence
 - Sliding behaviour
- Modeling
 - Modeling scale
 - Non-orthogonal model
- Forming tests
- Conclusion





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Introduction Shear characterization Modeling Forming tests Conclusion

Material

Introduction Shear characterization Modeling Forming tests Conclusion

- Polyamide 6.6 powder impregnated glass fabric developed by Solvay
 - Powder impregnated on both faces
 - Balanced twill 2/2 weave, 2.6end/cm
 - 50% Vf, 960g/m²
- Low viscosity PA6.6
 - Melt viscosity: 30-50Pa.s
 - Melting temperature Tm: 260°C







PA66 surface coverage: 82-84% (S>100mm²)





Bias extension test

- Sample of aspect ratio >2 and fibers oriented at ±45° relative to the direction of sollicitation
- Pure shear in the central region
- Less prone to spurious tensions compared to picture frame





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Experimental setup

- Sample preparation:
 - I ply semipreg
 - I ply preconsolidated (ref)
 - 295°C, I.5bar
 - Dimensions: 250x100mm²
- Test conditions:
 - Full factorial plan
 - Temperature: 265/280°C
 - Crosshead speed:
 10/100/1000mm/min
 - 4+ repeats per condition
- Thermal cycle representative of the forming process:
 - Heating to 295°C
 - Cooling to test temperature





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SHEAR CHARACTERIZATION MODELING

Forming tests Conclusion

Bias extension test

- Realignment of the sample in the plane (sag)
- At small shear angles: rotation of the yarns around crossover points
- Compaction of the yarns at higher shear angles
- Inter-yarn sliding





Preconsolidated 265°C, 1000mm/min

Semipreg 265°C, 1000mm/min







SHEAR CHARACTERIZATION

Semipreg sample at 280°C, 1000mm/min



- •
- Local increase in flow distance to impregnate the yarns ٠



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Results

Introduction Shear characterization Modeling Forming tests Conclusion



Effect of temperature and speed coherent with literature:

- Temperature decrease \rightarrow increase of shear stress
- Speed increase \rightarrow increase of shear stress



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Results

INTRODUCTION

Shear characterization

MODELING FORMING TESTS CONCLUSION



- Both temperature and speed have significant effect on the shear behaviour
- Speed less significant for the semipreg material
- Different friction mechanisms at the crossover points: lubricated vs. dry



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Non-orthogonal model

• Modeling scale:







 $f_1^\circ = g_1^\circ$

Continuous approach: -less information than discrete / semi-discrete -more computationally efficient

- Non orthogonal model (VUMAT)
 - 'Tracks' the orientation of the yarns during deformation
 - Green-Naghdi stress derivative (Abaqus) not objective
 - Orientation of the GN axis follows the 'average' material rotation
 - Complex to express a constitutive law directly in this frame
 - A frame fixed with the yarns is updated from the deformation tensor
 - The strains are rotated from the Green-Naghdi frame to the material frame
 - The constitutive law is applied in the material frame
 - The stresses are rotated back to the Green-Naghdi frame

$$\underline{\boldsymbol{g}}_{\alpha} = \underline{\underline{\boldsymbol{R}}} \cdot \underline{\boldsymbol{g}}_{\alpha}^{0}$$

[M. Khan et al, 2010], [R. Pierce et al, 2014]



 $\underline{f}_{\alpha} = \frac{\underline{\underline{F}} \cdot \underline{g}_{\alpha}^{0}}{\left\|\underline{\underline{F}} \cdot \underline{g}_{\alpha}^{0}\right\|}$



 $f_2^\circ = g_2^\circ$ $g_1 f_1$

Undeformed configuration



configuration

Non-orthogonal model

Introduction Shear characterization **Modeling** Forming tests

- The fabric undergoes large, inelastic deformations
 - Hypoelastic framework
 - Constitutive relation expressed incrementally
- Constitutive law:
 - Two orthonormal frames built on the two fibre directions
 - In each frame, the stress components are expressed as:

$$d\sigma^{\alpha} = \begin{bmatrix} \delta_{\alpha 1} E_{11} & 0 & 0\\ 0 & \delta_{\alpha 2} E_{22} & 0\\ 0 & 0 & G_{12} \end{bmatrix} d\varepsilon^{\alpha} \quad \alpha = 1,2 \text{ fibre direction}$$
$$G_{12}(\gamma, \dot{\gamma}, T) = (a_1 + a_2\gamma + a_3\gamma^2) \left(1 + \left(\frac{\dot{\gamma}}{D}\right)^{\frac{1}{P}} \right) \left(e^{A\frac{T - T_0}{T_0}} \right)$$

- The stresses are integrated at each time increment and summed:

$$\left(\sigma_{ij}^{\alpha}\right)^{n+1} = \left(\sigma_{ij}^{\alpha}\right)^n + \left(d\sigma_{ij}^{\alpha}\right)^{n+1/2}$$
$$\sigma_{ij}^{n+1} = \left(\sigma_{ij}^{1}\right)^{n+1} + \left(\sigma_{ij}^{2}\right)^{n+1}$$



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[M. Machado 2016]

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Model fit

Introduction Shear characterization

Hodeling Forming tests





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Forming tests

FORMING TESTS

- Forming setup:
 - IRC oven (I bank of I0 lamps) •
 - 60kN Promess press .
 - Hemispherical punch .
 - Spring actuated blankholder
- Initial forming simulations:
 - Blank assumed isothermal at 280°C
 - I ply modelled
 - Coulomb friction between blank and tool











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Conclusions & future work

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- Bias extension tests conducted at various speeds and temperatures on unconsolidated and preconsolidated material
- Intra-ply sliding leads to characteristic pattern of apparent dry fibres/resin rich regions in unconsolidated samples
- Decreasing temperature/increasing test speed increases shear stiffness
- Speed effect less important for unconsolidated semipreg: differences in friction mechanisms at the yarn crossover
- Multiplicative decoupling model accurately represents the shear behaviour

- Hemispheric forming test campaign ongoing
- Experimental study on semipreg compaction



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Thank you for your attention

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