The use of elastomeric diaphragms in composites forming processes

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1. Introduction to Diaphragm forming

2. Diaphragm Characterisation

3. Finite Element Modelling

4. Conclusions and Future Work
Introduction

- Carbon fibre composites consist of a high strength and stiffness fibre embedded within a polymer matrix.
- Large automotive companies moving towards an RTM (Resin transfer moulding process) for composites manufacture.
  - High properties / Fast cycle times.
- RTM and other liquid forming processes rely on a separate preforming stage.
- Preforming stages are often labor intensive and difficult to automate.
- Diaphragm Forming is one solution to these problems.
  - Low capital investment
  - High flexibility

3D Preform creation
A diaphragm former with a bed size of $1.2 \times 1.6\text{m}$ has been developed at the university of Nottingham. Both double and single configurations are possible.

**Objectives**
- Understand forming limitations caused by features in component geometry
- Evaluate new material formats
- Evaluate the suitability of different diaphragm materials
- Estimate cycle times
- Support the design of a larger pre-production machines
Double Diaphragm Forming Process Steps

Stage 1
- Ply preparation
- Binder application
- Ply positioning

Stage 2
- Evacuate area between diaphragms
- Heat material
- Place tool in position

Stage 3
- Lower diaphragms and evacuate air beneath
- Cooling
- Demoulding
Diaphragm behavior is an important part of understanding the process.
- Friction
- Failure strain
- Fatigue behavior / Longevity of the bag
- Hole propagation
- Temperature resistance
- Thickness

It is also important be able to accurately model the behavior of the diaphragm in our FE model of the process.
Set-up similar to standard ASTM D 1894, ISO 8295:

- Aluminium table attached to Instron 5569 testing machine with 50N load cell
- Brick-shaped steel sled (100 × 50 × 25mm, mass 1.036kg)
- Connection to cross-head via angling line and pulley
- Measures both static and dynamic coefficients
- Can be used to measure material-material, material-aluminium and material-diaphragm coefficients
Fabric to Diaphragm

- Silicone diaphragms have different surface finishes on each side.
- Coefficient of friction for the silicon diaphragm is larger than Al-NCF (~0.25-0.3) and NCF-NCF (~0.4-0.5).
- Dynamic friction appears to be higher than the static friction.
- Aligning the stitches in the direction of travel reduces the coefficient of friction significantly.

![Graph showing static and dynamic friction](image)

**Silicone Top - FCIM359**

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<tr>
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<th>Static µ</th>
<th>Dynamic µ</th>
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**Silicone Bottom – FCIM359**

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Hole Propagation Testing
Diaphragm Failure

- Over 200 formings before first failure.
- Lower diaphragm failed due to large strains over the square edge at rear of tool.
- How do we measure fatigue? What properties are important?
Biaxial Testing

- 6 candidate materials tested – Stretchlon 350, Mosite, 3 silicones, 1 latex
- Two temperatures – RT, 85°C
- Three load cases – Uniaxial, Biaxial, Pure shear
- Two loading regimes – Monotonic, Cyclic

- Biaxial data shown (not taken to failure)
- Only Stretchlon 350 significantly affected by increase in temperature (polymeric material)
- Mosite and silicones all exhibit similar stress-strain behaviour
- Stiffness of latex is lower than silicones
- Silicones not always isotropic
• Three test configurations used: Uniaxial tension, biaxial tension, pure shear

• Non linear regression used to obtain fitting parameters from uniaxial and biaxial test data

• Pure shear load case used as validation

• Ogden Hyperelastic model (Abaqus)

• Non-linear stress-strain behaviour of rubbers

• $\lambda$ – principal strain

• $T$ – principal stress

• $N$, $\mu_i$, $\alpha_i$ – material constants

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<th>$N$</th>
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**Uniaxial mode**

$$\lambda_1 = \lambda_U, \quad \lambda_2 = \lambda_3 = \lambda_U^{-\frac{2}{3}}, \quad \lambda_U = 1 + \epsilon_U$$

$$T_U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i} (\lambda_U^{\alpha_i-1} - \lambda_U^{-\frac{2}{3}\alpha_i-1})$$

**Equibiaxial mode**

$$\lambda_1 = \lambda_2 = \lambda_B, \quad \lambda_3 = \lambda_B^{-2}, \quad \lambda_B = 1 + \epsilon_B$$

$$T_B = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i} (\lambda_B^{\alpha_i-1} - \lambda_B^{-2\alpha_i-1})$$

**Planar (pure shear) mode**

$$\lambda_1 = \lambda_S, \quad \lambda_2 = 1, \quad \lambda_3 = \lambda_S^{-1}, \quad \lambda_S = 1 + \epsilon_S$$

$$T_S = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i} (\lambda_S^{\alpha_i-1} - \lambda_S^{-\alpha_i-1})$$

**Silicone Diaphragm Characterisation**
Diaphragm Modelling

- Excellent fit for all three load cases
- Unit cell models pass all of the Abaqus stability checks
- Deformation modes are suitably captured by Ogden model
- Process can be repeated for other candidate materials as required

Fully Predicted
Diaphragm Forming FE Model

- An explicit finite element model has been developed in Abaqus.
- Diaphragm material uses Ogden Hyperelastic model.
- Uses data from picture frame testing to model behavior of carbon fiber.
  - Accounts for asymmetric behavior in NCF.
- Takes 1 hour to run on a standard office computer.
- Can be used with full scale automotive components.
Diaphragm Forming FE Model

- Colour coding used to identify problem areas according to excessive shear
- Wrinkles start to form in amber region, according to picture frame data
Comparison between simulation and experiment

- Very good agreement between simulation and experiment
- Yellow regions (simulation) agree well with wrinkles on real part
- Likely that some darting is required to overcome some of the major wrinkles
Ply shape optimisation

- Ply shape optimised using simulation to provide net-shape preform
- Perimeter shape is more rounded to conform to witness mark on tool

...... iterations

Initial

Optimum
Conclusions

- A diaphragm forming machine has been developed at the University of Nottingham.
- Material characterisation (diaphragm and fabric) has been performed to provide input data to the finite element simulation.
- A finite element model has been validated with experimental testing and can be used to reduce defects in components.

**Diaphragm challenges:**
- Long fatigue life
- Tear resistance
- Temperature + strain resistance
- Control of friction
- Allowing air evacuation
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Acknowledgements

The work was completed as part of the “Affordable Lightweighting through Pre-form Automation” (ALPA) project.

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