Embeddable Variable Stiffness Elements for Load Alleviation in Morphing Lift Generating Structures

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Introduction to morphing: shape adaptation

Conventional devices:
- Discontinuities in the surface
- High performance for a limited set of flight conditions

Benefits of Morphing:
- Hinge- and gap-less surface
- High performance for a wider range of flight conditions

(Joshi 2004)

Bio-inspired

ng:
less surface for a wider onditions
Morphing with complaint systems

Integration of different functions:

- Structural
- Actuation
- Sensing

Reduced complexity:

- Joints
- Fixing elements
- No moving parts

Smart-adaptation

Robustness
Wing morphing for load alleviation

Spanwise morphing: Optimal operation
- Morphing wings can adapt to perform optimally at various flight states

Performance gains
- Control $c_L$ can be achieved along the entire wingspan

Load alleviation:
- Higher structural efficiency
- Less fuel, materials required
Variable stiffness components for morphing

- Morphing challenge: conflicting stiffness Vs. compliance trade off

<table>
<thead>
<tr>
<th>Reference</th>
<th>Material</th>
<th>Stiffness variability</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>[50]</td>
<td>Shape memory alloys</td>
<td>$E_{\text{hot}} / E_{\text{cold}} \approx 4$</td>
<td>82–38 °C</td>
</tr>
<tr>
<td>[51]</td>
<td>Polyurethane of polyester polyole series</td>
<td>$E_{\text{cold}} / E_{\text{hot}} \approx 100$</td>
<td>Below and above $T_g = 55$ °C</td>
</tr>
<tr>
<td>[52]</td>
<td>Polystyrene-based</td>
<td>$G_{\text{cold}} / G_{\text{hot}} \approx 326–517$</td>
<td>at $T_{\text{room}}$ and $T = 95$ °C</td>
</tr>
<tr>
<td>[53,54]</td>
<td>CTD-DP-5.1 bulk thermoset resin</td>
<td>$E_{\text{cold}} / E_{\text{hot}} \approx 100$</td>
<td>20–80 °C</td>
</tr>
<tr>
<td>[55]</td>
<td>Elastomeric memory composites</td>
<td>$E_{\text{cold}} / E_{\text{hot}} \approx 79$</td>
<td>23–90 °C</td>
</tr>
<tr>
<td>[56–58]</td>
<td>Shape memory composite topology concepts</td>
<td>$E_{\text{cold}} / E_{\text{hot}} \approx 15–77$</td>
<td>35–75 °C</td>
</tr>
<tr>
<td>[59]</td>
<td>Fluidic flexible matrix composites</td>
<td>$E_{\text{closed}} / E_{\text{open}} \approx 25.1$</td>
<td>Discrete: closed/open-valve</td>
</tr>
</tbody>
</table>

Kuder et al. Variable stiffness material and structural concepts for morphing applications, Progress in Aerospace Sciences, 2013
Presentation outline

- Multi-stable composites
- Embeddable multi-stable composites: novel lay-out
- Stable configurations
- Parameter study
- Variable stiffness of multi-stable: longitudinal stiffness
- Integration into a wider structure
- Conclusion and discussion
Multi-stable composites

- Multi-stability arises due to a residual stress field in the laminates
  - Pre-stress
  - Unsymmetrical lamination
  - Complex lay-out

- For unsymmetric laminated composites residual stresses caused by a mismatch of CTE

\[[0,0,90,90]\]
Multi-stable components in morphing

- Multi-stability is been exploited for achieving large deformations
- Multi-stable structures
  - Reduced actuator systems weight and complexity due to bi-stability

![Configuration morphing](Daynes et al. 2009)
Structural response variability

- Stable states exhibit different structural directional response

- Ratio between:

\[
\frac{k_S}{k_C}
\]

\[\text{Obtained stiffness variability}\]
Previous embeddable configurations: cantilevered plates

- Thermally introduced multi-stable with simple cantilever lay-outs as shown below are already investigated:

  ![Diagram showing symmetric and unsymmetric lay-outs](image)

  - **Can be clamped**
  - **Symmetric**
  - **Unsymmetric**
  - **Lay-out**
  - **Curved**
  - **Straight**

- Symmetric part causes smooth reduction of curvature

  ![Graph showing first and second stable shapes](image)

  **Fig. 11. Numerical equilibrium shapes.**

  *Analysis of thermally induced multistable composites, F. Mattioni, 2007*
Embedding multi-stable components

- For the cantilevered configuration:
  - Simply clamping the other edge results in loss of multi-stability

- New lay-out required
Novel lay-out design

- Introduction of an elastic boundary condition on either side of a main central unsymmetric section

- Transition regions allow for:
  - Maintaining multi-stability when embedded by clamping both short edges
Stable configurations: straight state

- All produced specimens showed a multi-stable behaviour
- Moisture expansion (time dependent) has a significant influence to the shape and can be considered with a reduction of the thermal expansion coefficient in the FEA
- For the further FEA validation the $\alpha_2$ is chosen according to this data
Stable configurations: curved state

- Curled EXP 3 h after curing
- Curled EXP 16 d after curing
- Curled FEM, moisture ($\alpha_2 = 2.5 \times 10^{-5} 1/K$)
- Curled FEM, moisture ($\alpha_2 = 2.25 \times 10^{-5} 1/K$)
- Curled EXP 4 d after curing

- Good agreement achieved for shape prediction for both stable states

$w$ [mm] vs $x$ [mm]

$z$ $y$ $x$
Longitudinal stiffness tests

- Show variability in structural response between states

- Objective - ratio between:\n  \[
  \frac{k_S}{k_C}
  \]

- Lay-out design
  - Region length
  - Region lay-up

Diagram showing:
- Straight state, $k_S$
- Curved state, $k_C$
- Unsymmetric central region
- Transition regions
Parameter study: stiffness variability

- Lay-out designs are studied:
  - Two ply
  - Three ply

- 4 different shapes are found:
The longitudinal stiffness is investigated with a simulated compression test.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>6</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>19</th>
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<tr>
<td>Chart</td>
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<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Plies</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
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<tr>
<td>$k_{\text{straight}}$ [N/mm]</td>
<td>19.97</td>
<td>11.53</td>
<td>3.81</td>
<td>89.00</td>
<td>159.20</td>
<td>84.35</td>
<td>117.83</td>
<td>180.96</td>
<td>166.30</td>
<td>9.83</td>
<td>7.57</td>
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<tr>
<td>$k_{\text{curved}}$ [N/mm]</td>
<td>0.36</td>
<td>0.24</td>
<td>0.12</td>
<td>2.25</td>
<td>1.44</td>
<td>2.26</td>
<td>3.59</td>
<td>2.30</td>
<td>1.14</td>
<td>4.83</td>
<td>6.77</td>
</tr>
<tr>
<td>$k_{\text{straight}}/k_{\text{curved}}$ [-]</td>
<td>55.57</td>
<td>47.77</td>
<td>31.27</td>
<td>39.60</td>
<td>110.4</td>
<td>37.36</td>
<td>32.80</td>
<td>94.12</td>
<td>145.52</td>
<td>2.03</td>
<td>1.12</td>
</tr>
<tr>
<td>L [mm]</td>
<td>450.0</td>
<td>450.0</td>
<td>450.0</td>
<td>300.0</td>
<td>300.0</td>
<td>300.0</td>
<td>280.0</td>
<td>280.0</td>
<td>280.0</td>
<td>450.0</td>
<td>400.0</td>
</tr>
<tr>
<td>width [mm]</td>
<td>225.0</td>
<td>150.0</td>
<td>75.0</td>
<td>225.0</td>
<td>150.0</td>
<td>225.0</td>
<td>225.0</td>
<td>225.0</td>
<td>150.0</td>
<td>75.0</td>
<td>225.0</td>
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<tr>
<td>L4/L2 [-]</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

A significant change in stiffness can be seen in each case, best results for 2 ply
Experimental validation – Longitudinal stiffness (1)

- Experiment Curled
  - FEM Curled ($\alpha_2 = 2.5e-05 \text{ J/K}$)
  - FEM Straight ($\alpha_2 = 2.5e-05 \text{ J/K}$)

- Experiment Straight
  - FEM Straight ($\alpha_2 = 2.5e-05 \text{ J/K}$, $\delta = 2e-07$)

$u$ [mm]

- The experimental data are in good agreement to the FE simulation
- STABILIZED option is need to simulate the post-buckling behaviour
Experimental validation – Longitudinal stiffness (2)

- Snaps from straight into curled state by introducing in-plane loads
- Snap instead of buckling → “Fail Safe”
Load alleviation mechanism

- **GOAL:** passive load alleviation for wing structures: wind turbine blades
  - Protection for rapidly changing aerodynamic: gusts

- **Requirement for bending stiffness and strength can be reduced**
  - Save costs and weight, an increased fatigue life

- **IDEA:** reducing the thrust by decreasing the camber of the airfoil (maintain low drag)

\[ F_x = L \cos(\Phi) + D \sin(\Phi) \]
Integration into wider structure - 1st Demonstrator

Passive load alleviation aerofoil: inextensible skin

- NACA 0012, chord length 500 mm
- Skin and conventional rib
  - GFRP
  - 0.5 mm thickness
- Front reinforced with foam
  - Assumed to be rigid
- Reaction force of a pressure load of the compliant part is assumed to be acting at the second web at the bottom skin
Integration into wider structure - 1st Demonstrator

- Experimental Testing

**Straight**

6 N

0.64 mm

**Curved**

6 N

20.0 mm

**Stiffness variability:**

- Small displacements
  \[ \frac{k_s}{k_c} \Big|_{\text{small}} = 5 \]

- Large displacements
  \[ \frac{k_s}{k_c} \Big|_{\text{large}} = 5.5 \]
Integration into wider structure - 2\textsuperscript{nd} Demonstrator

- Improved demonstrator

Corrugation [2] for proper aerodynamic shape:

\textit{Extensible skin}

Restriction of 2\textsuperscript{nd} mode:

\textit{Increased stiffness}

Cambered aerofoil in 1\textsuperscript{st} mode

Integration into wider structure - 2\(^{nd}\) Demonstrator

RF\(_{v}\) Restoring Force [N]

\(RF_{v} = 5.14u_{v}\)

\(RF_{v} = 0.13u_{v} - 0.92\)

\(RF_{v} = 0.18u_{v} - 1.70\)

\(k_{s}/k_{c}\) \(_{small} \approx 40\)
Conclusions

- Embeddable variable stiffness elements exploiting multi-stability are realised through a novel lay-out featuring symmetric unsymmetric regions are presented

- Parameter study:
  - Adequate lay-out design shows multi-stability with a significant change in stiffness in different states
  - The stiffness can be tailored
Conclusions

- Experimental validation show good agreement to FE results:
  - Shape
  - Compression test
  - Snap-through

- Two demonstrator proving feasibility of using bi-stable variable stiffness elements for load alleviation in lift generating structures
Thank you for your attention

Questions?

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