A beam reduction method for wing aeroelastic design optimisation with detailed stress constraints

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Overview

- Motivation
  - Benefits of analysis-specific structural idealisations (hi-fidelity / low-fidelity)
  - Integration of the beam reduction method into an aeroelastic design optimisation
- Beam reduction method description
  - Overview
  - Stiffness reduction
- Examples
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  - University of Bristol Ultra-Green (BUG) aircraft wingbox
- Conclusions
Motivation
Benefits of analysis-specific structural idealisations

Why do we use different structural idealisations?

Hi-fidelity = Accuracy

Low-fidelity = Speed

Example:
- Flutter analysis
  \[10^2\,\text{DOF}^*\]

Example:
- GFEM** Internal loads analysis
  \[10^4\,\text{to}\,10^6\,\text{DOF}\]

DC3 wing section

* Degrees of freedom
** Global finite element model
How can we do MDO* with high and low fidelity structural idealisations?

Example:
Automatic beam reduction integration into a Multidisciplinary Feasible (MDF) architecture.

*Multidisciplinary design optimisation
Beam reduction method description
Beam reduction method - Overview

GFEM with variables $[v]$
- Thicknesses
- Ply percentages
- Stringer orientations …

Beam with properties $[\Omega]$ and $[M]$
**Beam reduction method - Overview**

**Stiffness reduction**
- Definition of a beam reference axis
  - Manual input
- Beam element flexibility matrix \([C]\) (numerical)
  - Auto-automated
- 13 physical isotropic beam element stiffness parameters \(\Omega\) (analytical)
  - Auto-automated

**Mass reduction**
- Definition of lumped mass element groups
  - Manual input
- Lumped mass and inertia matrix \([M]\) determination (numerical)
  - Auto-automated

\[
\frac{\partial C}{\partial v} \quad \frac{\partial \Omega}{\partial C} \quad \frac{\partial \Omega}{\partial v} \quad \frac{\partial M}{\partial v}
\]
Stiffness reduction

Example: BUG wing model GFEM

Manual input

Global model analysis coordinate system

Stringer datum
Rib datum

Beam Element Reference Axis

Fuselage/Wing Interface

Local beam reference axis coordinate system

Global model analysis coordinate system

Stringer (equivalent area and offset shown)
Multi-point Constraint
Upper Skin

Front Spar

Beam Node

Spar Cap

Rear Spar

1 Rib-bay

Section 1
Section 2
Section 3

Straight beam sections

Manual input
Stiffness reduction

Definition of a beam reference axis

Beam element flexibility matrix determination (numerical)

Calculation of 13 physical isotropic beam element stiffness parameters

1) GFEM analysis with 6 static tip load cases / section

2) Nodal deflection and rotation output

3) Post-process to find 6x6 \([C]\) matrix / beam element

Note:
This approach is equivalent to the ‘blade property extraction’ (BPE) method used for wind-turbine blades: Malcolm DJ, Laird DL. Extraction of equivalent beam properties from blade models. Wind Energy. 2007 Mar 1;10(2):135-57.
Stiffness reduction

→ \( \Omega \) defines the properties of an isotropic Timoshenko theory beam element.

→ \( \Omega \text{ is calculated analytically} \) from \([C]\) and assumed isotropic material properties \( E \) and \( G \).

→ Non-dimensional bend-twist coupling parameters \( \Psi = K/\sqrt{EI \cdot G} \) can be derived as functions of \( \Omega \).

Bend-twist coupling exists for any \( SC_A \neq SC_B \)

\[
\Omega = [SC_{AY}, SC_{AZ}, SC_{By}, SC_{Bz}, \bar{J}, \bar{I}_1, \bar{I}_2, \bar{I}_{12}, \bar{N}_y, \bar{N}_z, A, \bar{k}_y, \bar{k}_z]^T
\]

Effective shear centre offsets at nodes A and B = elastic axis definition

Bending and Torsion Stiffness parameters

Section centroid offsets from the elastic axis

Section Area

Timoshenko shear coefficients
Examples
Rectangular wingbox model

Constant-section rectangular wing-box GFEM:
16.8m span (28 rib bays), 1.68m chord and 1.0m height

Baseline model stiffness, with
- \( SC_A = SC_B = 0 \)
- \( N_Y = N_Z = 0 \)

- Stiffness increase at the root (\( Y=0m \)) >> **boundary constraint effect**
- Stiffness reduction at the tip (\( Y=16.8m \)) >> **load introduction effect**

due to the multipoint constraint (RBE3) assumption here resulting in equally distributed skin forces, not taking into account the section stiffness distribution or the skin/stiffener offsets.
Rectangular wingbox model

Effect of incremental stiffness changes on the elastic axis (locus of shear centres).

Baseline  + Thicker front spar  + Unbalanced skin laminate  + Rotated rib

$SC_A = 0$

$SC_B = 0$

Model 1

Model 2

Model 3
Gradients of the rectangular wingbox model

Stiffness parameter sensitivities to changes in the +45° fibre percentage in the upper skin.

Gradients are captured accurately.
University of Bristol Ultra-Green (BUG) aircraft wingbox (static & dynamic)
University of Bristol Ultra-Green (BUG) aircraft wingbox (static & dynamic)

Comparison of the GFEM and equivalent beam displacements and rotations for an applied tip force (linear analysis).

Static deflections captured accurately (tip displacements within 5% error).

*Twist due to wing sweep + bend-twist coupling
University of Bristol Ultra-Green (BUG) aircraft wingbox (static & dynamic)

Frequency response plots at the wing tip, for an applied wing tip excitation force of $10^4\text{N}$ in the Global Z-direction.

Dynamic behaviour captured accurately (first 10 modes natural frequencies within 2.1% error).

1.26 Hz (-0.1% Freq. error)  
First up/down bending mode

3.18 Hz (0.1% Freq. error)  
First FWD/AFT bending mode

14.78 Hz (0.5% Freq. error)  
Mode 8

16.3 Hz (2.1% Freq. error)  
Mode 9
Conclusions
Summary:

✓ Developed a numerical method for efficiently and accurately reducing a high-fidelity GFEM to a Timoshenko beam theory model with lumped masses.
✓ Suggested an approach for integrating the beam reduction method into a gradient-based aeroelastic design optimisation architecture.

Advantages:

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<thead>
<tr>
<th>Speed</th>
<th>or</th>
<th>Scope</th>
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<tbody>
<tr>
<td>➢ faster aeroelastic optimisation</td>
<td>➢ more aeroelastic load cases</td>
<td></td>
</tr>
<tr>
<td>➢ large deflection cases</td>
<td>➢ more refined GFEM</td>
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• **physical insight into the GFEM design optimization results** (e.g. quantify bend-twist coupling in terms of elastic axis rotation or $\Psi$ values)
• **information about the effects of design changes** on the overall wing stiffness and mass properties, in the vicinity of the current design
• Publication:

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