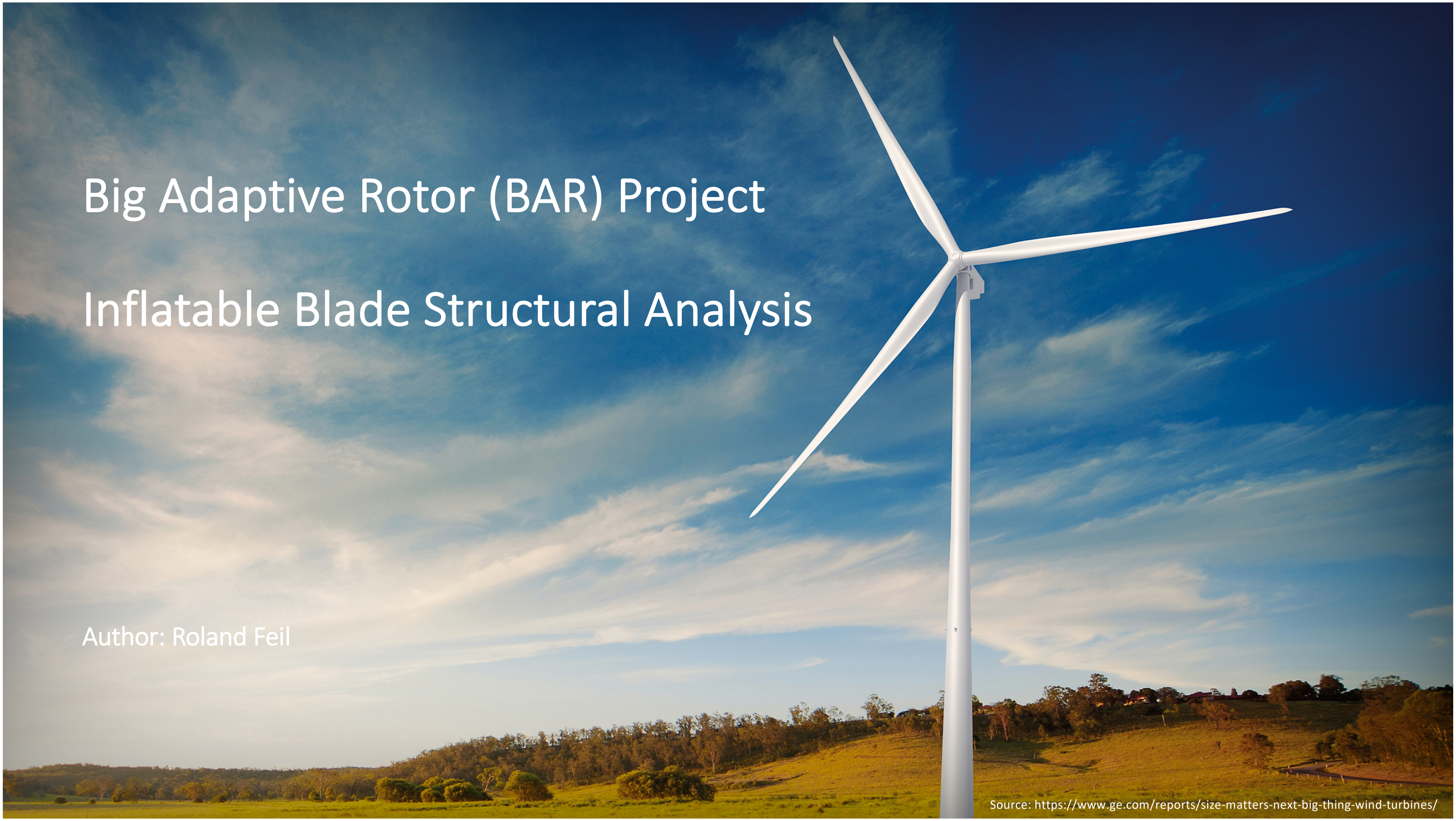


Big Adaptive Rotor (BAR) Project

Inflatable Blade Structural Analysis

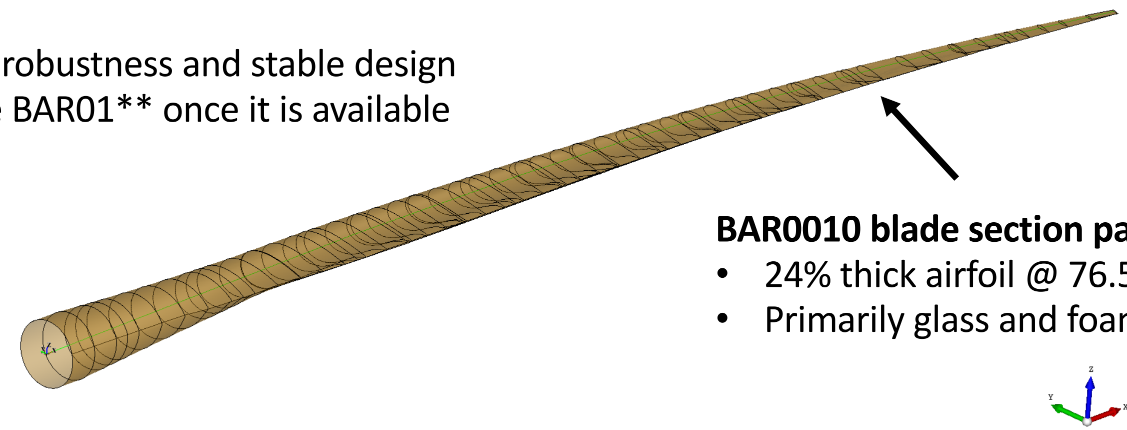
Author: Roland Feil

Source: https://www.ge.com/reports/size-matters-next-big-thing-wind-turbines/

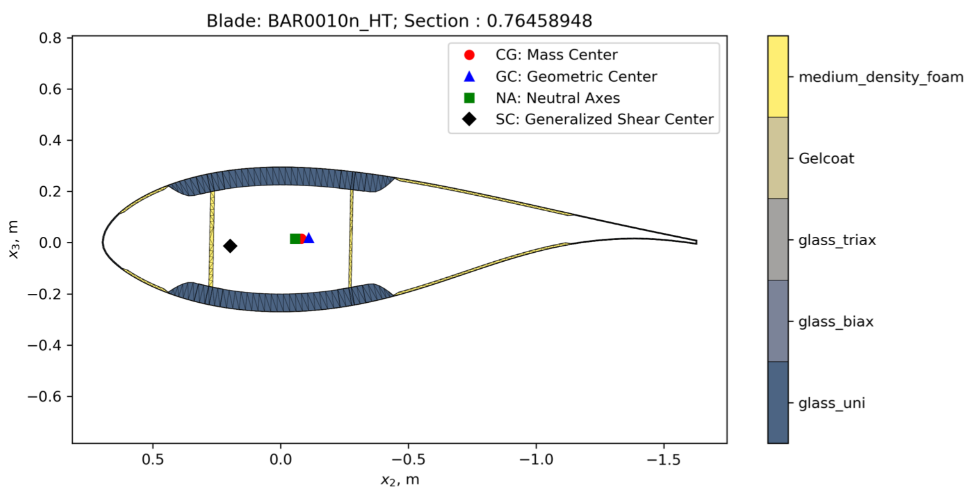
Content

Inflatable Blade Structural Analysis – Baseline (0)

BAR baseline blade:
- Currently using BAR0010 for robustness and stable design
- Will convert to slender blade BAR01** once it is available



BAR0010 blade section parameters:
- 24% thick airfoil @ 76.5% span
- Primarily glass and foam



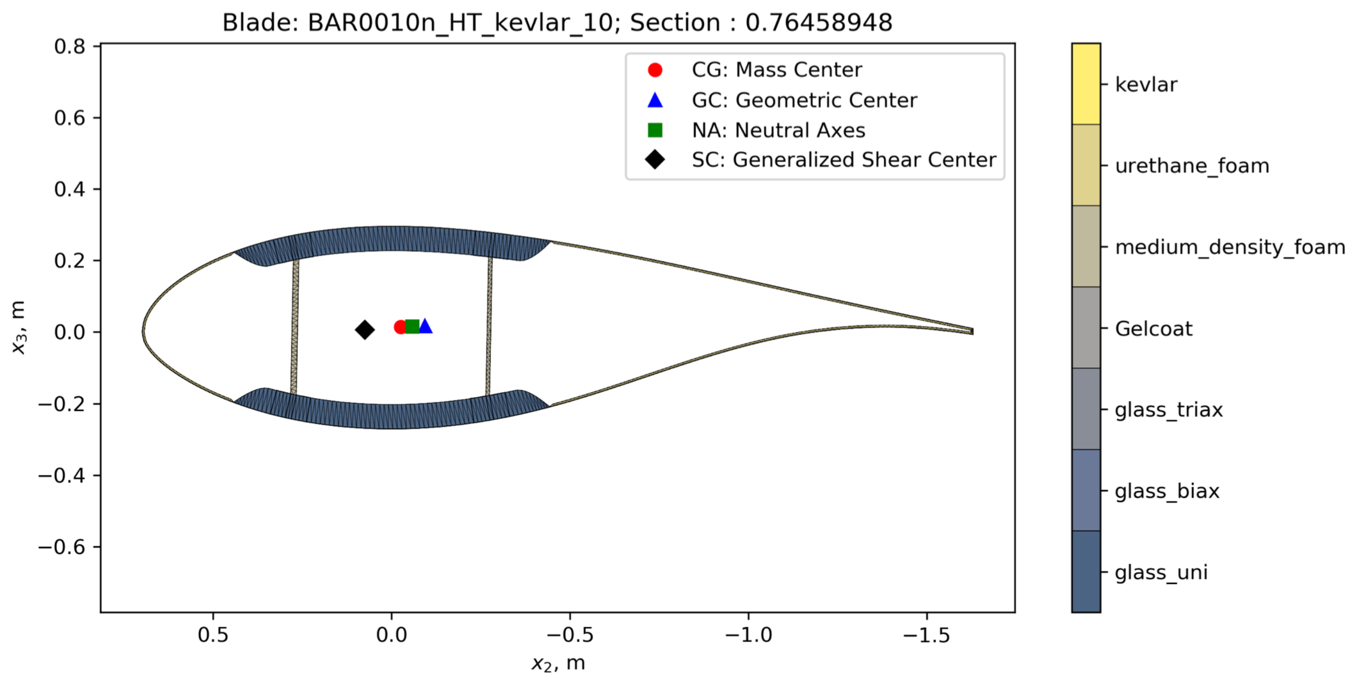
Parameter	Value	Description
EI_{flap}	2.86 E+08 Nm^2	Flap stiffness
EI_{lag}	7.64 E+08 Nm^2	Lag/Edge stiffness
GJ	1.39 E+07 Nm^2	Torsion stiffness
m	264.5 kg/m	Section mass

Inflatable Blade Structural Analysis – Kevlar Skin (10)

- Optimized shell only, kept identical beams and webs
- Removed LE & TE reinforcements
- Glass skin adapted to → Kevlar
  medium density foam → injectable foam (thickness = 0.5 mm)

Design Var	Opt. Value
t_{Kevlar}	0.487 mm *

*Value for each the outer and the inner skin layer

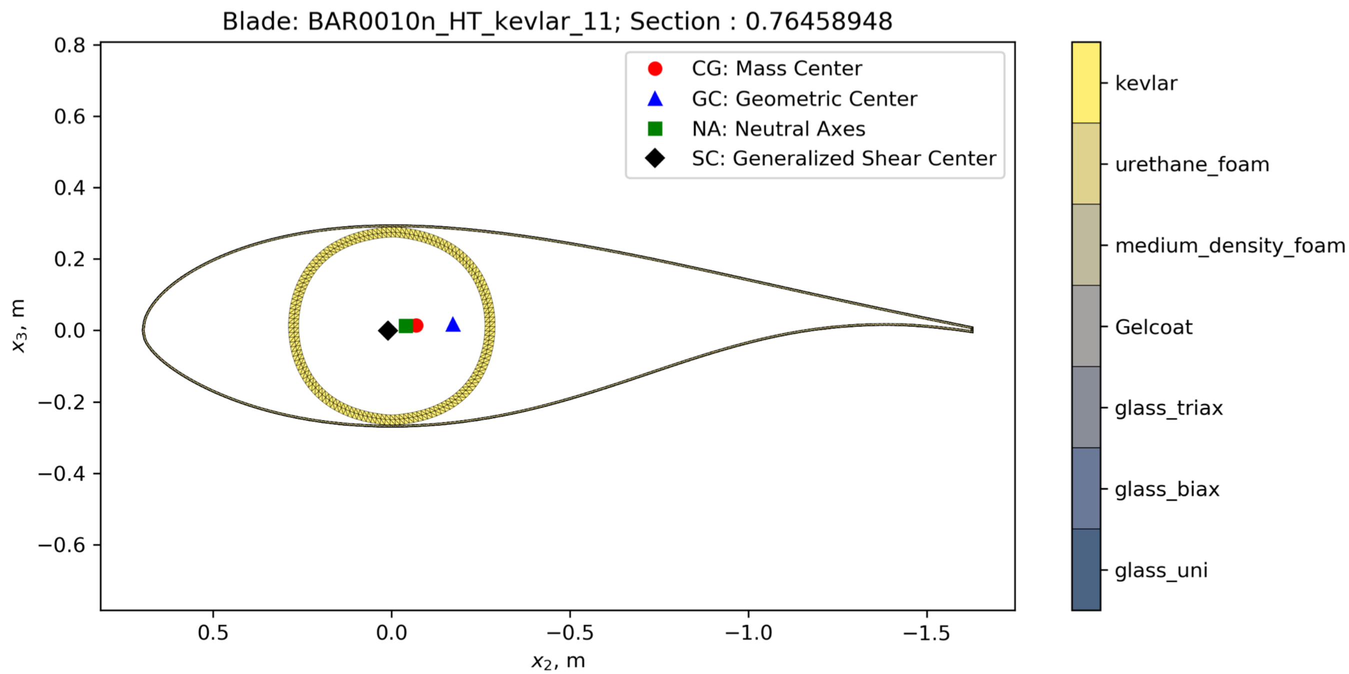


Para.	Value	Diff to (0)
EI_{flap}	2.95 E+08 Nm^2	3.183 %
EI_{lag}	7.62 E+08 Nm^2	-0.281 %
GJ	4.42 E+06 Nm^2	-68.133 %
m	231.2 kg/m	-12.601 %

Inflatable Blade Structural Analysis – Kevlar (11a)

- Uses Kevlar skin (10)
- Replaced spar caps and webs from with filament wounded Kevlar
- Optimization variables: Ellipse curvature (a) & wall thickness ($t_{ellipsis}$)
- Optimization objectives: Flap & Lag/Edge stiffness
- Monitor: Torsional stiffness & section mass
- 0 deg filament wound material orientation angle

Design Var	Opt. Value
a	0.3183 m
$t_{ellipsis}$	28.47 mm

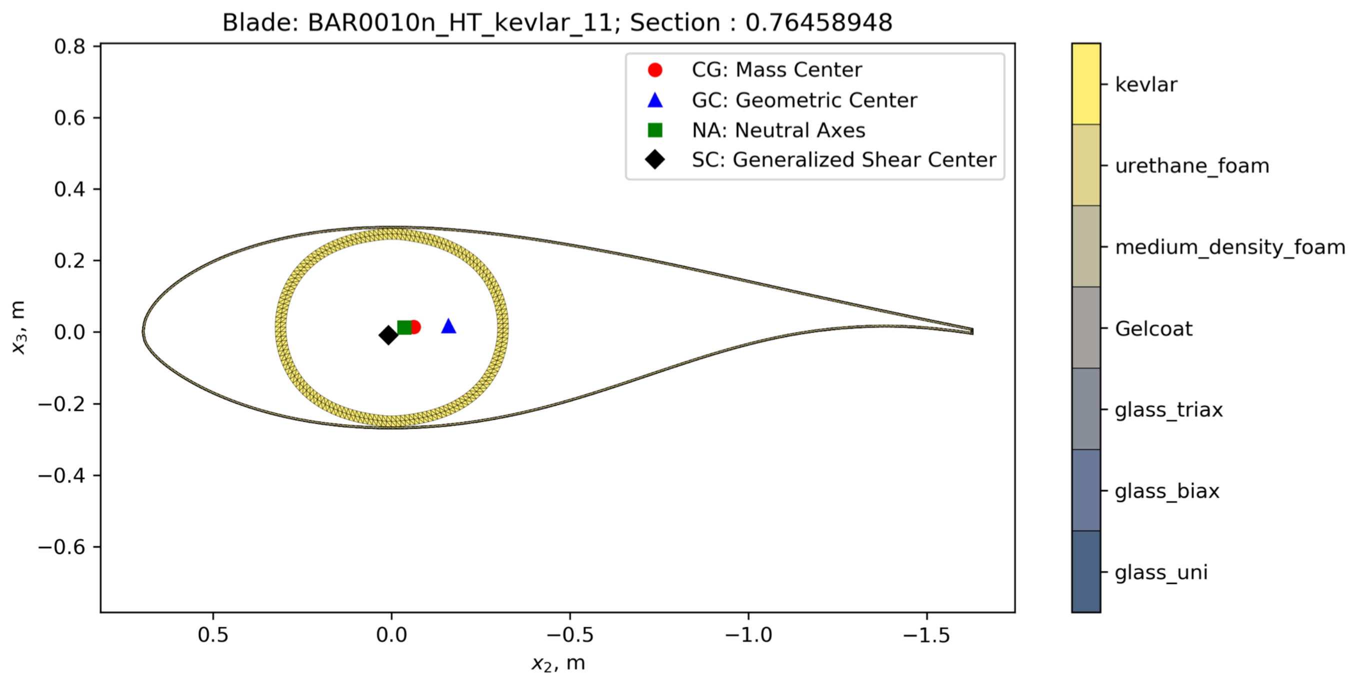


Para.	Value	Diff to (0)
EI_{flap}	2.89 E+08 Nm^2	1.009 %
EI_{lag}	7.53 E+08 Nm^2	-1.558 %
GJ	5.58 E+06 Nm^2	-59.777 %
m	84.6 kg/m	-68.038 %

Inflatable Blade Structural Analysis – Kevlar (11b)

- Uses Kevlar skin (10)
- Replaced spar caps and webs from with filament wounded Kevlar
- Optimization variables: Ellipse curvature (a) & wall thickness ($t_{ellipsis}$)
- Optimization objectives: Flap, Lag/Edge, and torsional stiffness
- Monitor: Section mass
- 0 deg filament wound material orientation angle

Design Var	Opt. Value
a	0.3611 m
$t_{ellipsis}$	30.31 mm

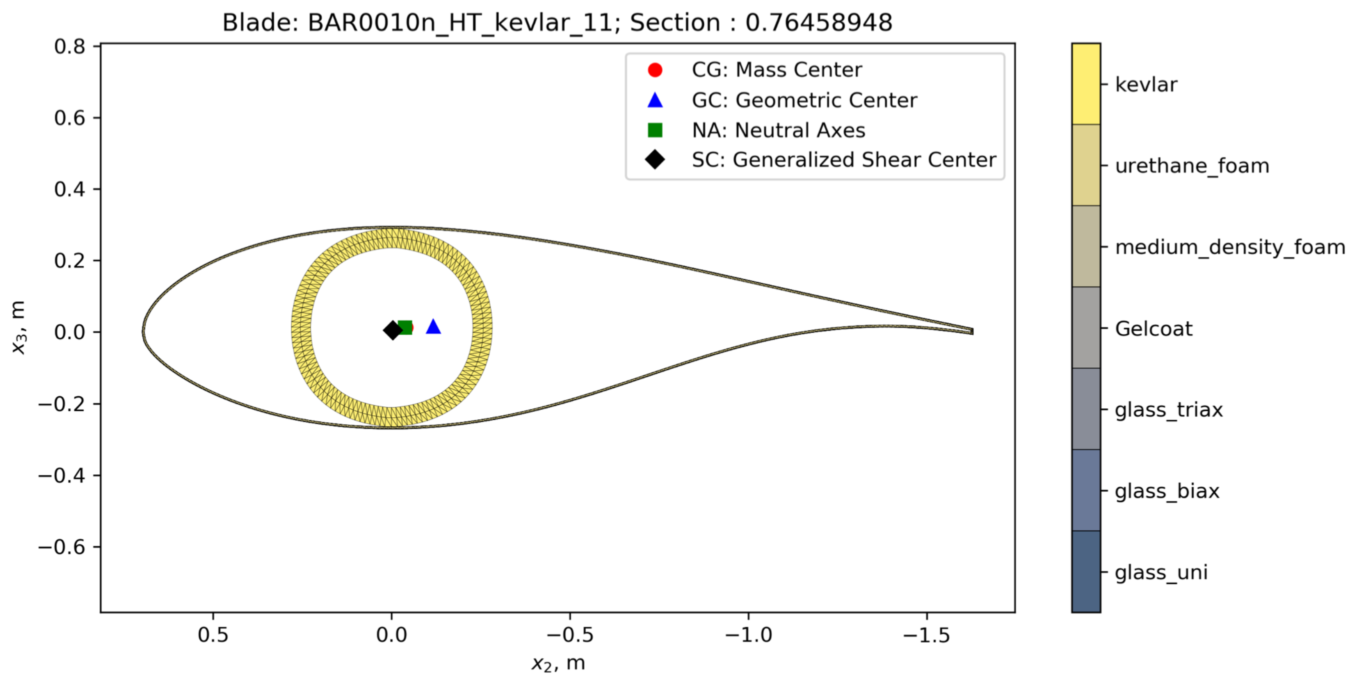


Para.	Value	Diff to (0)
EI_{flap}	3.31 E+08 Nm^2	15.978 %
EI_{lag}	8.58 E+08 Nm^2	12.242 %
GJ	6.80 E+06 Nm^2	-50.935 %
m	94.3 kg/m	-64.360 %

Inflatable Blade Structural Analysis – Kevlar (11c)

- Uses Kevlar skin (10)
- Replaced spar caps and webs from with filament wounded Kevlar
- Optimization variables: Ellipse curvature (a), wall thickness ($t_{ellipsis}$), and material orientation angle (Θ_3)
- Optimization objectives: Flap, Lag/Edge, and torsional stiffness
- Monitor: Section mass

Design Var	Opt. Value
a	0.3091 m
$t_{ellipsis}$	53.87 mm
Θ_3	4.5744 deg

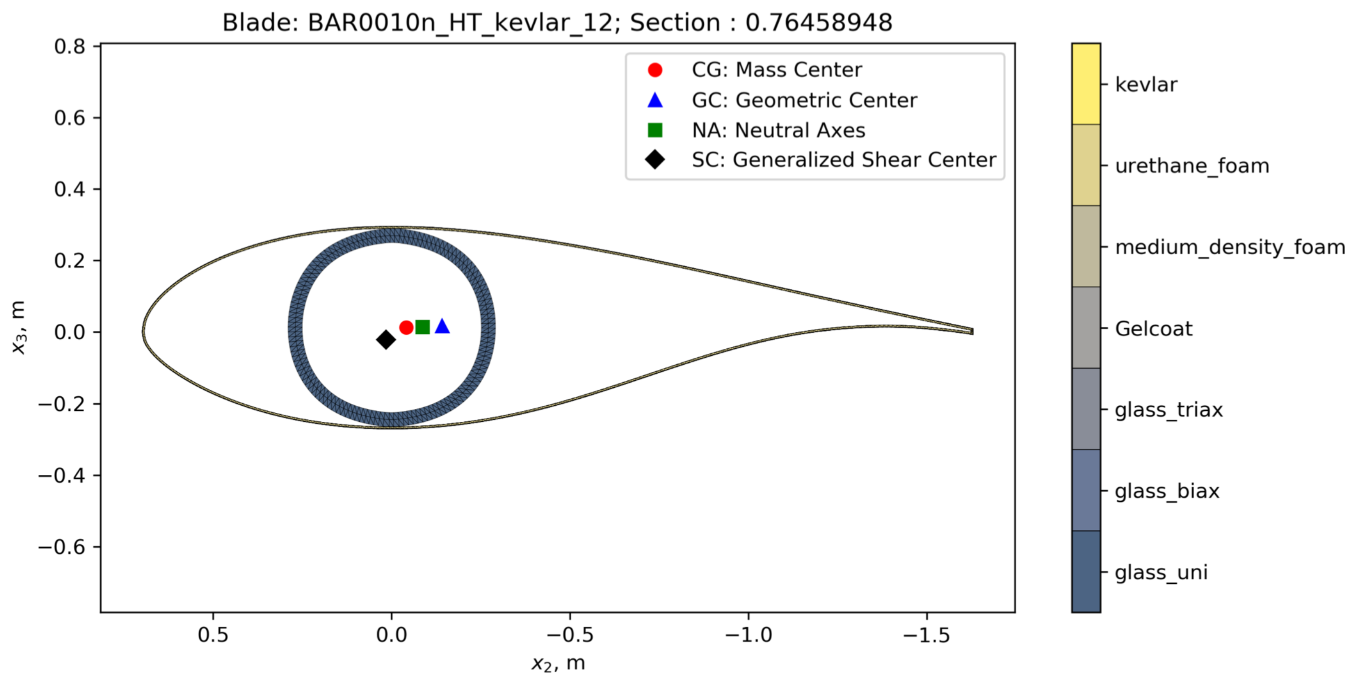


Para.	Value	Diff to (0)
EI_{flap}	2.77 E+08 Nm^2	-2.919 %
EI_{lag}	8.05 E+08 Nm^2	5.286 %
GJ	1.37 E+06 Nm^2	-1.022 %
m	139.8 kg/m	-47.144 %

Inflatable Blade Structural Analysis – Glass Uni (12a)

- Uses Kevlar skin (10)
- Replaced spar caps and webs from with filament wounded unidirectional glass
- Optimization variables: Ellipse curvature (a), wall thickness ($t_{ellipsis}$), and material orientation angle (Θ_3)
- Optimization objectives: Flap, Lag/Edge, and torsional stiffness
- Monitor: Section mass

Design Var	Opt. Value
a	0.3197 m
$t_{ellipsis}$	39.58 mm
Θ_3	0.2302 deg

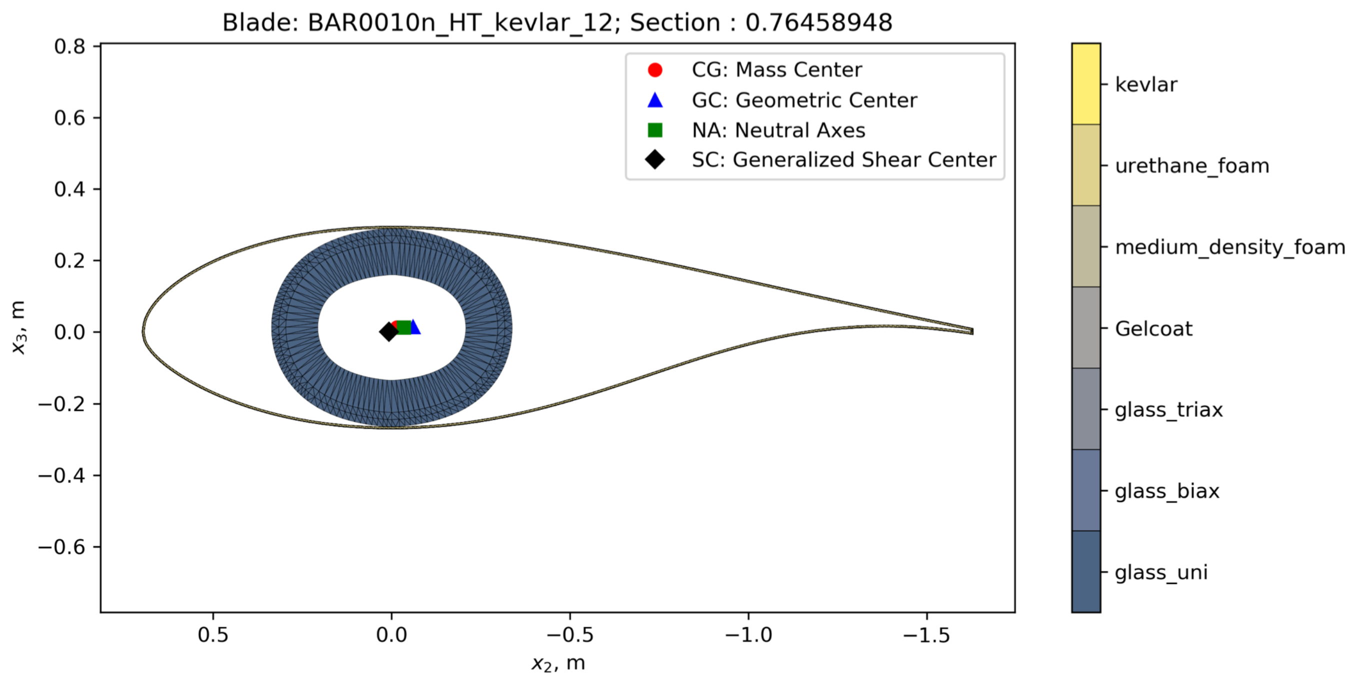


Para.	Value	Diff to (0)
EI_{flap}	1.27 E+08 Nm^2	-55.467 %
EI_{lag}	5.85 E+08 Nm^2	-23.530 %
GJ	16.5 E+06 Nm^2	18.637 %
m	141.9 kg/m	-46.347 %

Inflatable Blade Structural Analysis – Glass Uni (12b)

- Uses Kevlar skin (10)
- Replaced spar caps and webs from with filament wounded unidirectional glass
- Optimization variables: Ellipse curvature (a), wall thickness ($t_{ellipsis}$), and material orientation angle (Θ_3)
- Optimization objectives: Flap and Lag/Edge stiffness
- Monitor: Torsional stiffness & section mass

Design Var	Opt. Value
a	0.373 m
$t_{ellipsis}$	129.7 mm
Θ_3	-0.144 deg



Para.	Value	Diff to (0)
EI_{flap}	2.61 E+08 Nm^2	-8.586 %
EI_{lag}	8.04 E+08 Nm^2	5.17 %
GJ	41.5 E+06 Nm^2	199.332 %
m	401.7 kg/m	51.850 %

Material Properties

Property	Description	Unit	Kevlar-49 aramid fibres with Polyimide thermosetting plastic as matrix	Glass_uni	Glass_triax
	Source		**JES2014 - Yeung_Rao - Mechanical Properties of Boron and Kevlar-49 Reinforced Thermosetting Composites and Economic Implications** http://web.usm.my/jes/10_2014/JES%20Vol.%2010%202014-Art.%203-(19-29).pdf Tables 1 & 2	SANDIA (Exact source?)	SANDIA (Exact source?)
rho	Density	kg/m^3	1467.0	1940.0	1940.0
E_1	0° Tensile Modulus	N/m^2	151.70 E+09	44.6 E+09	28.7 E+09
E_2	90° Tensile Modulus	N/m^2	4.10 E+09	17.0 E+09	16.6 E+09
E_3	90° Tensile Modulus ($E_3 = E_2$)	N/m^2	4.10 E+09	16.7 E+09	16.7 E+09
G_{12}	Secondary shear modulus	N/m^2	1.28 E+09	3.27 E+09	3.49 E+09
G_{13}	$G_{13} = G_{12}$	N/m^2	1.28 E+09	3.48 E+09	3.49 E+09
G_{23}	*G_{ij}, is the shear modulus in direction j on the plane whose normal is in direction I; primary shear modulus*	N/m^2	2.90 E+09	3.50 E+09	8.40 E+09
ν_{12}	Secondary poisson's ratio	-	0.350	0.262	0.170
ν_{13}	$\nu_{13} = \nu_{12}$	-	0.350	0.350	0.170
ν_{23}	*ν_{ij} is the Poisson's ratio that corresponds to a contraction in direction j when an extension is applied in direction i.*	-	0.350	0.264	0.500
X_t	*0° tensile strengh*	N/m^2	2.75790 E+09	0.6092 E+09	0. 396 E+09
X_c	*0° compressive strenght*	N/m^2	0.51712 E+09	0.47471 E+09	0.4489 E+09
Y_t	*90° tensile strenght*	N/m^2	0.1034 E+09	0.0381 E+09	0.0764 E+09
Y_c	*90° compressive strenght*	N/m^2	0.2068 E+09	0.11264 E+09	0. 1747 E+09
S_{21}	*in-/out of plane shear strength*	N/m^2	0.0896E+09	0.01724 E+09	0.0172 E+09

Summary

General

- Lag/Edge stiffness not a problem because of edgewise oriented UD fibers in the elliptical structure

Kevlar Filament Wound

- Drop in GJ when adapting to the Kevlar skin. This drop can be recuperated with filament wound Kevlar at an approx. 4.5 deg wounded angle.
- High 0deg tensile modules compared to 90deg tensile modulus advantageous to match stiffness prop.
- Weight reduction by 47 % when using filament wound Kevlar at similar structural characteristics compared to baseline architecture with spar caps and webs.

Unidirectional Glass Filament Wound

- Not possible to achieve the same stiffness characteristics compared to the baseline design. Optimizing results in a trade-off between greater GJ and reduced $\mathrm{EI_{flap}}$ and $\mathrm{EI_{lag}}$.
- Most challenging to match $\mathrm{EI_{flap}}$
- Optimizing on $\mathrm{EI_{flap}}$ and $\mathrm{EI_{lag}}$ only works to achieve baseline characteristics, resulting in 200 % increase of GJ and 52 % increase of mass.
- Apply different structure to enhance $\mathrm{EI_{flap}}$?

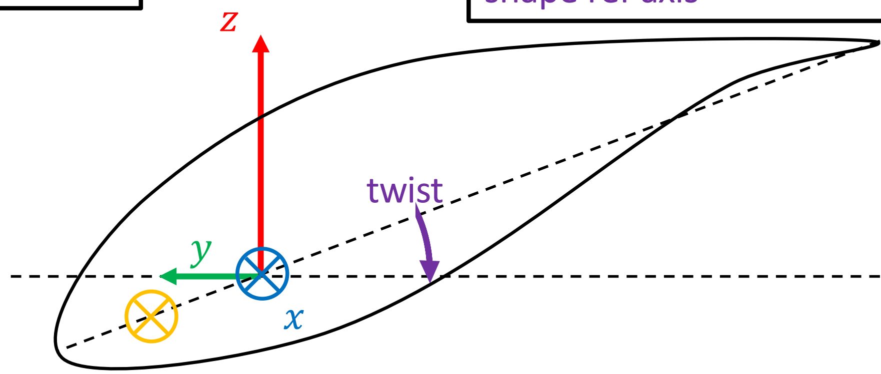
Outlook & Ongoing Work

- Add carbon composite for filament wound
- Reduce material properties due to smaller fvf in filament wound primary structure? By what quantity?
- (Potentially) exclude the shell and create new baseline from most realistic & promising result based on step 1 studies
- (Potentially) add central straight web if insufficient stiffness
- How to handle loads’ transmission from shell to primary structure? Add additional supporting structures?
- How to preserve airfoil geometric shape with applied loads?

Coordinate System – SONATA & VABS

Ref axis defined with x, y, and z

Twist is defined along the outer shape ref axis



Pitch axis defined in relative to chord length, starting at the leading edge

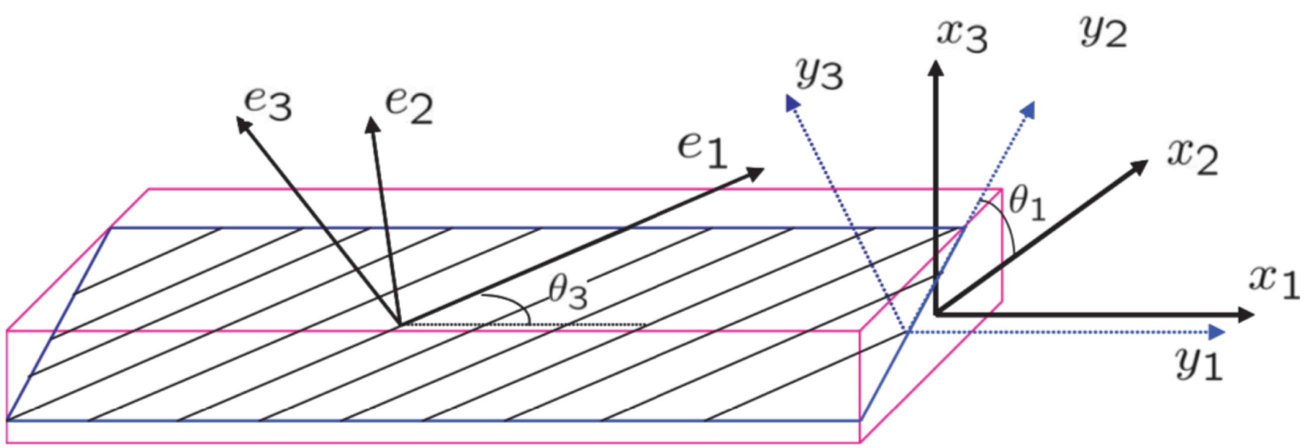
INPUT EXAMPLE

```
Outer_shape_bem:
    twist:
        grid: [0.0, 1.0]
        values: [0.2, 0.1]

    pitch_axis:
        grid: [0.0, 1.0]
        values: [0.5, 0.3]

    reference_axis:
        x:
            grid: [0.0, 1.0]
            values: [0.0, 50.0]
        y:
            grid:  [0.00, 1.00]
            values: [0.0, 0.0]
        z:
            grid:  [0.0, 1.0]
            values:  [0.0, 0.0]
```

Layup Convention – VABS



x1, x2, x3	beam coordinate system
y1, y2, y3	ply plane coordinate system (beam system rotated along x1)
e1, e2, e3	material coordinate system (ply plane system rotated along y3)
Θ_1	ply plane orientation angle
Θ_3	material orientation angle