BladeBeam Verification Examples

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- Self-weight of beam not included in analysis
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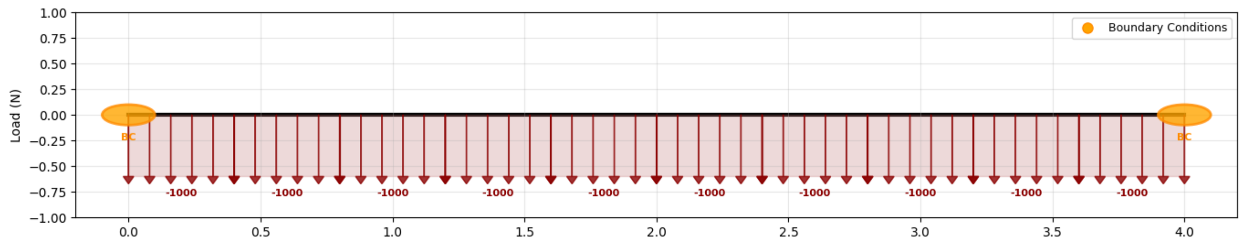
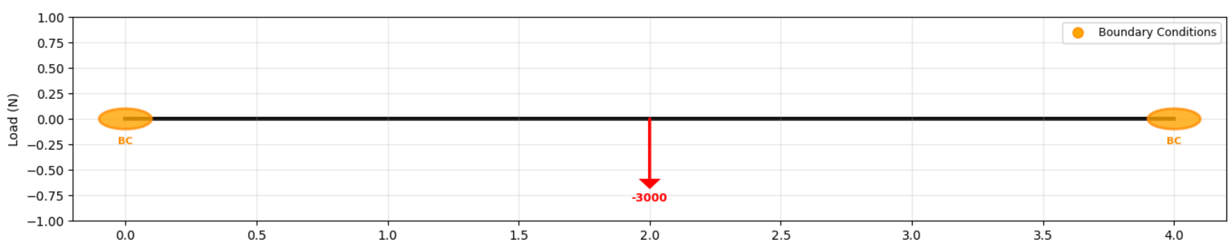


Analysis	EI (N-m^2)	Deflection @ Midspan (m)	Rotation @ Ends (rads)	End Shear (N)	Midspan Moment (N-m)
SkyCiv	45000000	-0.00007407	-0.000059	2000	2000
BladeBeam v2.3.3	45000000	-0.00007407	-0.000059	2000	-2000

1.1.2 300x100 steel beam point load

- Self-weight of beam not included in analysis
- 4 meter long beam

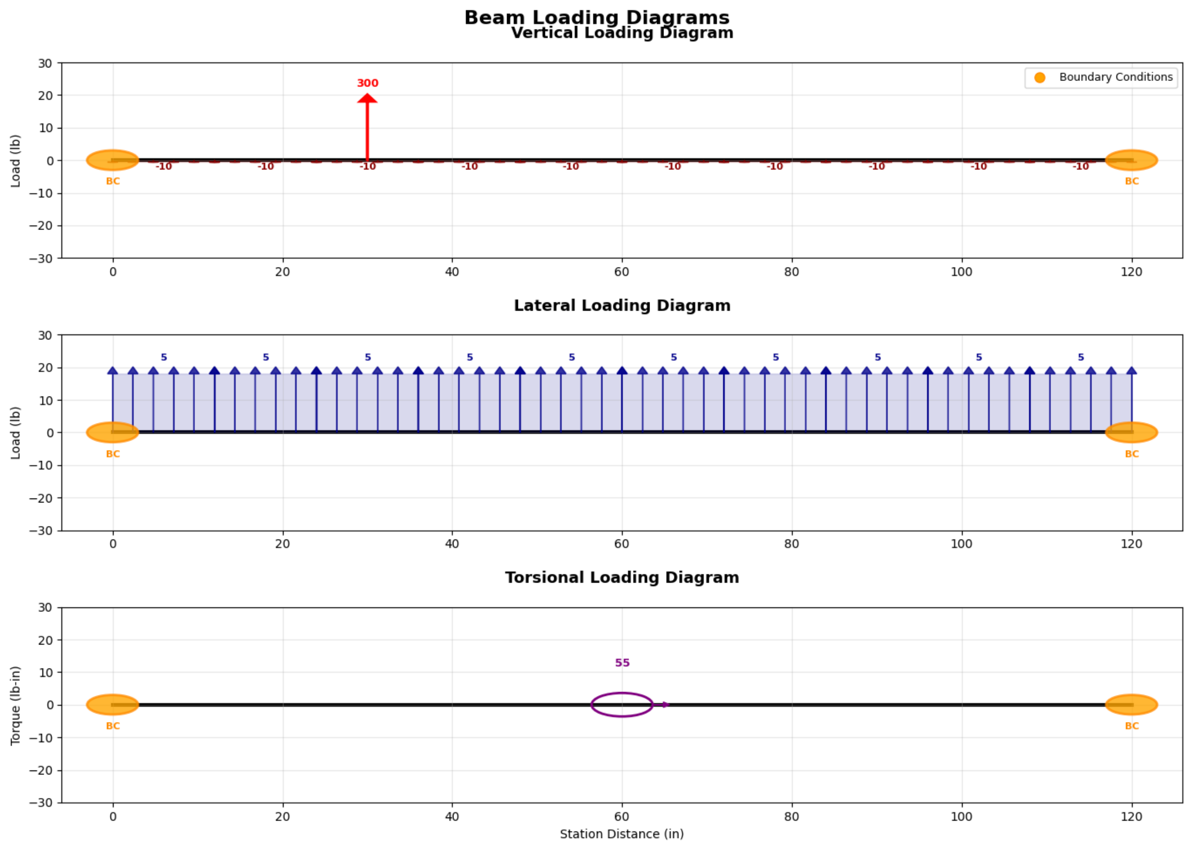


Analysis	EI (N-m^2)	Deflection @ Midspan (m)	Rotation @ Ends (rads)	End Shear (N)	Midspan Moment (N-m)
SkyCiv	45000000	-0.0000889	-0.000067	1500	3000
BladeBeam v2.3	45000000	-0.0000889	-0.000067	1500	-3000

1.2 Fixed Boundary Conditions

1.2.1 2x4 steel beam fixed-fixed

- Self-weight of beam included in analysis
- 10 ft long span

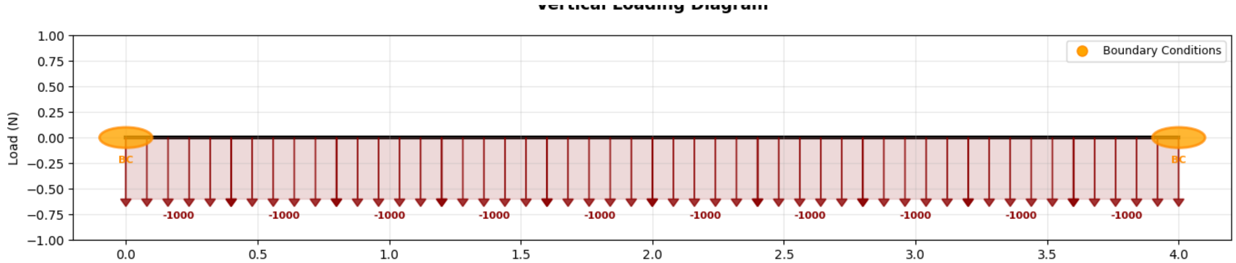


Analysis	EI (lbf-in^2)	m (lb-mass/in)	Vertical Deflection @ Midspan (in)	Lateral Deflection @ Midspan (in)	Torsional Rotation @ Midspan (rads)	Moment @ Ends (lb-in) left side *right side*
SkyCiv	309430000	2.272	-0.01705	0.0349	0.00002	-9663 *-13038*
BladeBeam v2.3.3	309430000	2.272	-0.01834	0.0349	0.0000197	10118 *13574*

1.3 Semi-Fixed Boundary Conditions

1.3.1 300x100 steel beam, 25% stiffness

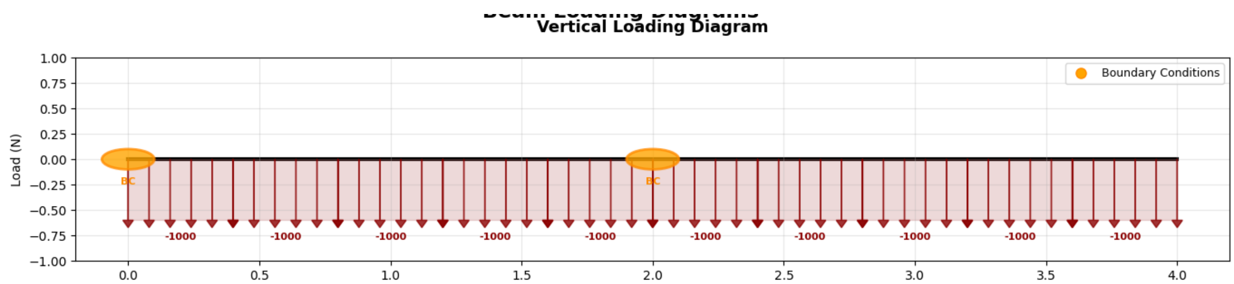
- Self-weight of beam not included in analysis
- 4 meter long beam



Analysis	EI (N-m^2)	BC Stiffness (N-m/rad)	Deflection @ Midspan (m)	Rotation @ Ends (rads)	End Moment (N-m)	Midspan Moment (N-m)
SkyCiv	45000000	11250000	-0.000054	-0.00004	-444	1556
BladeBeam v2.3	45000000	11250000	-0.0000543	-0.0000395	444	-1556

1.3.2 300x100 steel beam, 25% stiffness, with overhang

- Self-weight of beam not included in analysis
- 4 meter long beam with 2 meters overhanging



Analysis	EI (N-m^2)	BC Stiffness (N-m/rad)	Deflection @ End (m)	Rotation @ End (rads)	Midspan Shear (N)	Midspan Moment (N-m)
SkyCiv	45000000	11250000	-0.0000813	-0.000048	-2000	-2000
BladeBeam v2.3.3	45000000	11250000	-0.0000818	-0.000048	2000	2000

1.4 Natural Frequency Calculation

1.4.1 300x100 steel beam simply supported

- Only self-weight of beam used in analysis
- 4 meter long beam

Analysis	EI (N-m^2)	m (kg/m)	Vertical Mode (Hz)	Lateral Mode (Hz)
Analytical Solution	45000000	235.5	42.92	14.31

BladeBeam v2.3.3	45000000	235.5	43.18	14.39

1.4.2 2x4 steel beam simply supported

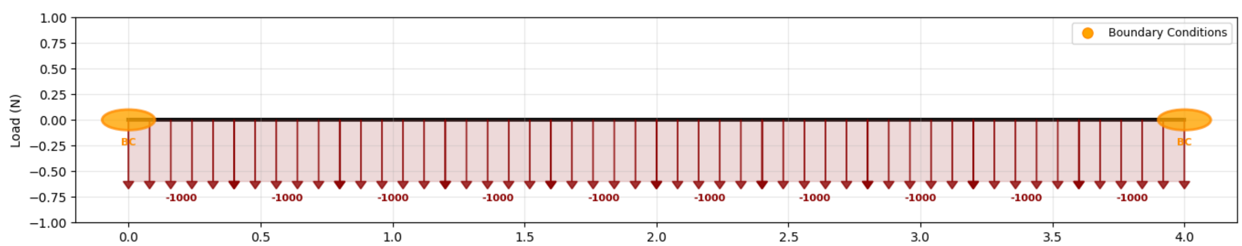
- Only self-weight of beam used in analysis
- 10 ft long span

Analysis	EI (lbf-in^2)	m (lb-mass/in)	Vertical Mode (Hz)	Lateral Mode (Hz)
Analytical Solution	309430000	2.272	25.02	12.52
BladeBeam v2.3	309430000	2.272	25.17	12.59

1.5 Shear Deformation

1.5.1 300x100 steel beam simply supported with distributed load

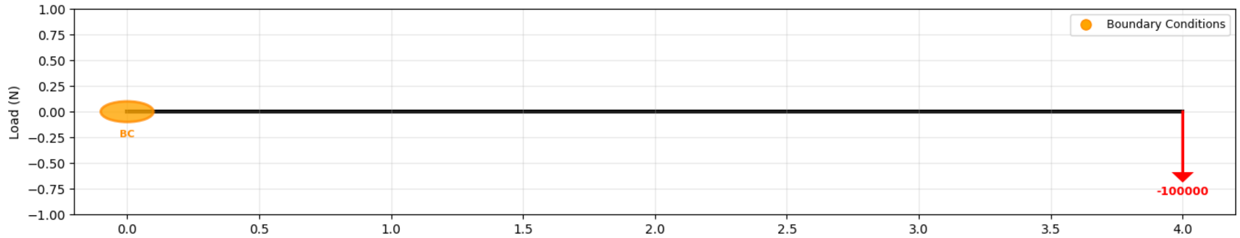
- Self-weight of beam not included in analysis
- 4 meter long beam



Analysis	EI (N-m^2)	kGA (N)	Deflection @ Midspan (m)
Hand Calculation	45000000	1.97E+09	-0.0000751
BladeBeam v2.3.2	45000000	1.97E+09	-0.0000751

1.5.2 300x100 steel beam cantilever with point load

- Self-weight of beam not included in analysis
- 4 meter long beam



Analysis	EI (N-m^2)	kGA (N)	Deflection @ End (m)
Hand Calculation	45000000	1.97E+09	-0.0476
BladeBeam v2.3.2	45000000	1.97E+09	-0.0476

2 Section properties validation of *abdbeam*

2.1 Section Stiffnesses

2.1.1 Example 6.3 from Kollar and Springer Mechanics of Composites

- Example taken from: Kollar, L. P., & Springer, G. S. (2003). *Mechanics of composite structures*. Cambridge university press.
- All laminates in the section are identical with a $[\pm 45^{f}_{2}/0_{12}/\pm 45^{f}_{2}]$ layup
  - Note, material properties for $\pm 45^{f}_{2}$ given by Kollar and Springer are not in fiber coordinates, but are in laminate coordinates and can be derived by calculating the properties for a laminate with two plies of the [0] material at +45 and -45 degree orientation.

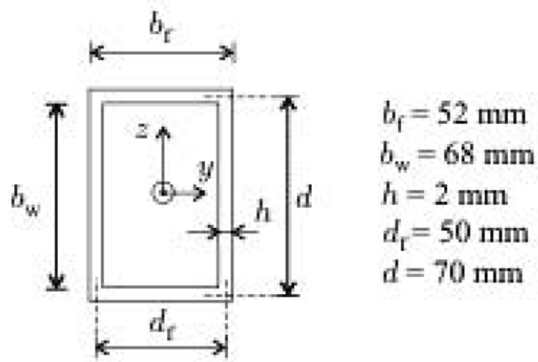


Table 3.6. Properties of the material used in the examples

		[0]	$\pm 45^{f}$
Longitudinal Young's modulus (GPa)	E_1	148	16.39
Transverse Young's modulus (GPa)	E_2	9.65	16.39
Longitudinal shear modulus (GPa)	G_{12}	4.55	38.19
Longitudinal Poission's ratio	ν_{12}	0.3	0.801
Thickness (mm)	h_0	0.1	0.2

Analysis	EI_{yy} (N-m^2)	EI_{zz} (N-m^2)	GJ (N-m^2)
Kollar and Springer	34692	20924	7352
BladeBeam v2.3.2	34665	20904	7372

2.1.2 Comparison with PreComp

- Wind turbine blade material properties and geometry from the NuMAD SNLWindPact3 example blade are used to calculate blade section properties in BladeBeam and PreComp. These properties are compared for NREL circular (at the root of the blade), S818, and S825_24 airfoil shapes at blade spans 0 m, 7 m, and 15.75 m respectively. The later two airfoil shapes each have two shear webs with varying composite laminate layups and thicknesses throughout the section, making it a difficult torsion problem.
- Due to a difference in how flapwise bending is defined compared to minor axis bending in BladeBeam (due to different applications), these values cannot be directly compared and as such are not displayed below. However, since the methodologies for calculating major and minor axis bending are the same, minor axis stiffness calculations can be assumed to behave similarly as the compared major axis bending stiffnesses.

Analysis	EI_{yy} (N-m^2)	GJ (N-m^2)	EA (N)	Mass (kg)	Airfoil
PreComp	1.14E+09	4.06E+08	2.59E+09	171.5	circular
BladeBeam v2.3.3	1.16E+09	4.16E+08	2.6E+09	171.6251	
Percent Difference	2.5%	2.5%	0.1%	0.1%	
PreComp	7.50E+08	4.27E+07	4.34E+09	283.6	S818
BladeBeam v2.3.3	7.55E+08	4.21E+07	4.33E+09	282.866	
Percent Difference	0.6%	-1.5%	-0.2%	-0.3%	
PreComp	2.63E+08	1.04E+07	2.25E+09	149.2	S825_24
BladeBeam v2.3.3	2.66E+08	1.25E+07	2.21E+09	146.3493	
Percent Difference	1.3%	20.7%	-1.9%	-1.9%	

2.2 Shear Flow

2.2.1 Example 19.1 from Megson's Design of Aircraft Structures

- Example taken from: Megson, T. H. G. (2007). *Aircraft structures for engineering students, 4th Edition*. Elsevier.
- This example uses an isotropic material with uniform thickness throughout all of the sections.

Analysis	I_{yy} (mm^4)	Max N_{xy} for Seg 3-4 (N/mm)	Max N_{xy} for Seg 2-3 (N/mm)	Max N_{xy} for Seg 1-2 (N/mm)	Min N_{xy} for Seg 3-4 (N/mm)
Megson's	14.5e6	281.7	138.5	34.5	172.5
abdbeam incorporated within BladeBeam	14.5e6	280.2	137.9	34.5	172.4

Megson's

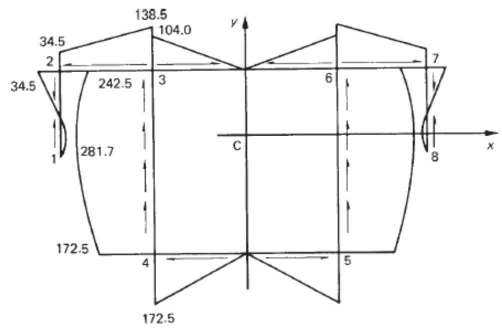
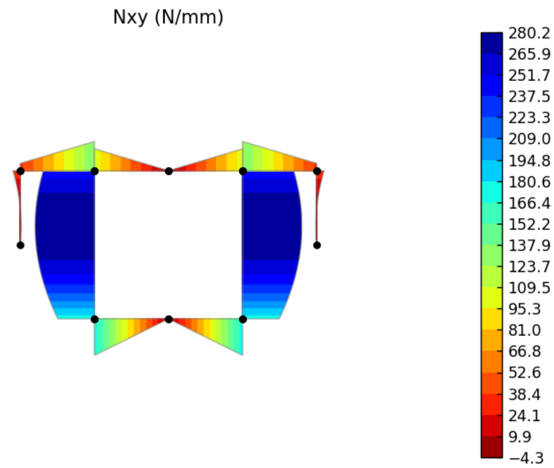


Fig. 19.3 Shear flow distribution in beam of Example 19.1 (all shear flows in N/mm).

abdbeam incorporated in BladeBeam



2.3 Beam Compliance Matrix

2.3.1 Example 6.5 from Kollar and Springer Mechanics of Composites

- Example taken from: Kollar, L. P., & Springer, G. S. (2003). *Mechanics of composite structures*. Cambridge university press.
- All laminates in the section are identical with an asymmetric $[0_{10}/45_{10}]$ layup.

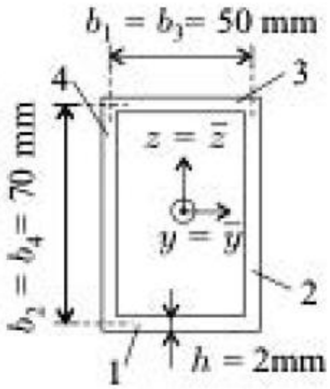


Table 3.6. Properties of the material used in the examples

		[0]
Longitudinal Young's modulus (GPa)	E_1	148
Transverse Young's modulus (GPa)	E_2	9.65
Longitudinal shear modulus (GPa)	G_{12}	4.55
Longitudinal Poission's ratio	ν_{12}	0.3
Thickness (mm)	h_0	0.1

Kollar and Springer

$$\begin{bmatrix} 0.2576 & 0 & 0 & -0.0042 \\ 0 & 0.0004 & 0 & 0 \\ 0 & 0 & 0.0006 & 0 \\ -0.0042 & 0 & 0 & 0.0025 \end{bmatrix} \times 10^{-7}$$

abdbeam incorporated in BladeBeam

$$\begin{bmatrix} 0.2576 & 0 & 0 & -0.0042 \\ 0 & 0.00034 & 0 & 0 \\ 0 & 0 & 0.00056 & 0 \\ -0.0042 & 0 & 0 & 0.00251 \end{bmatrix} \times 10^{-7}$$

3 Stress/Strain Validation

3.1 Single Cell Shapes

3.1.1 Example 6.5 from Kollar and Springer Mechanics of Composites

In this case, strains and stresses are calculated for Example 6.5 from Kollar and Springer previously shown above. The following 1D beam strains are reported in Example 6.5 with a 24 kN axial load applied to the centroid.

$$\begin{Bmatrix} \epsilon_x^o \\ \frac{1}{\rho_y} \\ \frac{1}{\rho_z} \\ \vartheta \end{Bmatrix} = \begin{Bmatrix} 0.0006182 \\ 0 \\ 0 \\ -0.01017 \end{Bmatrix}$$

Using the equation below, derived from the Bredt-Batho theory and simplified as to relate laminate shear strain at the mid-surface to the beam twist rate, shear strains, γ_{xy}, can be found.

$$\gamma_{xy} = \frac{2 \cdot A_m \cdot \vartheta}{P_m}$$

Where A_m is the area enclosed by the median line and P_m is the perimeter of the median line.

Thus, using this method to calculate laminate shear strains, and since axial strains are constant throughout the beam section due to the nature of the loading, the theoretical stresses using the Bredt-Batho theory and Springer and Kollar methods can be compared with the results from BladeBeam.

Analysis	ϵ_x	γ_{xy}
Kollar and Springer	0.000618	-0.0002966
BladeBeam v2.3.2	0.000618	-0.0002965