Experimental modal analysis of aeroelastic tailored rotor blades in different boundary conditions

Dipl.-Ing. Janto Gundlach
Dr.-Ing. Yves Govers
Institute of Aeroelasticity
German Aerospace Center (DLR), Göttingen

Trondheim – EERA DeepWind'19

January 17, 2019

Experimental modal analysis of aeroelastic tailored rotor blades in different boundary conditions

Content

Context of test campaign

SmartBlades2 T1 rotor blades

Rotor blade properties

- built by DLR
- geometric coupling induced by prebend and sweep
- demo length scale of 20m
- intended to reduce overall loading

Main project goals

- demonstration of technology in operational tests
- validation of numerical tools

pictures: NREL

project partners

Forschungsverbund Windenergie

Deutsches Zentrum für Luft- und Raumfahrt

ForWind Zentrum für Windenergieforschung

Fraunhofer IWES

Henkel

Nidec All for dreams

SSB Wind Systems Be consistent.

NORDEX We've got the power.

SENVION wind energy solutions

SUZLON POWERING A GREENER TOMORROW

ENERCON ENERGIE FÜR DIE WELT

Context of test campaign

SmartBlades2 T1 rotor blades

Rotor blade properties

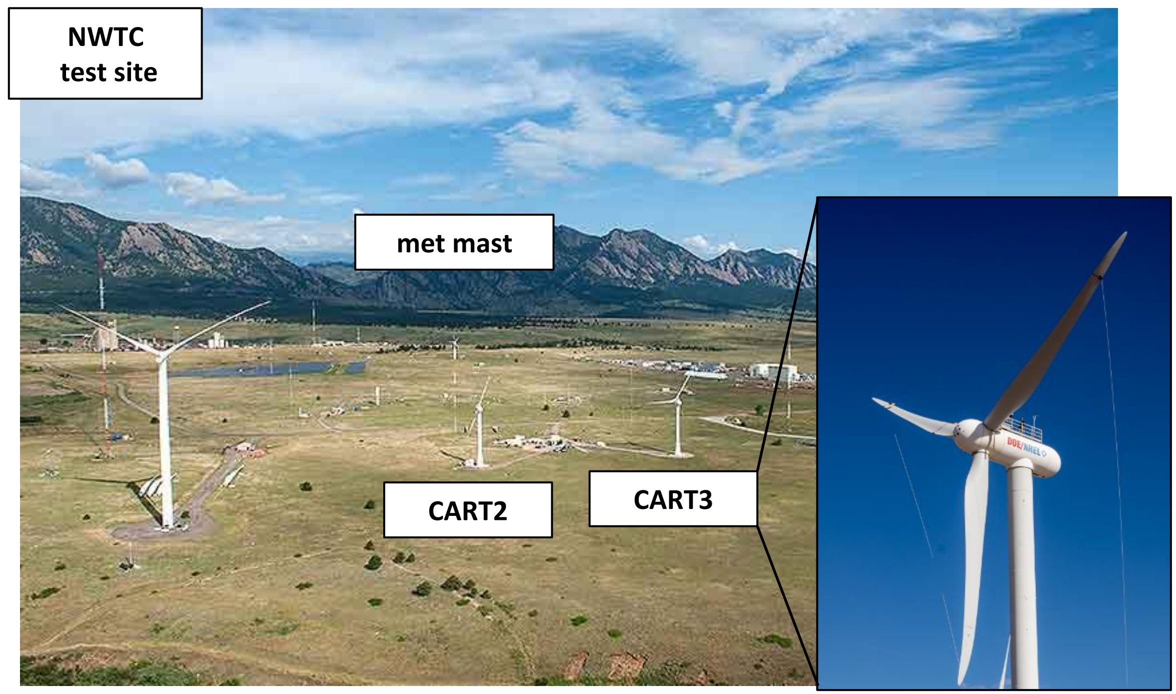
- built by DLR
- geometric coupling induced by prebend and sweep
- demo length scale of 20m
- intended to reduce overall loading

Main project goals

- demonstration of technology in operational tests
- validation of numerical tools

Operational tests on CART3, Boulder, Colorado (blade #2-blade #4)

- varying test conditions (cross wind, start-up, shutdown)
- multitude of measurements
  - met mast
  - aero probes
  - Lidar on nacelle
  - SSB BladeVision
  - strain gauges
  - DIC



Context of test campaign

pictures: IWES Bremerhaven

Related structural testing

Certification of blade #1 according to IEC61400-23
- static extreme loads
  - flapwise bending, edgewise bending, torsion; before and after fatigue test
- dynamic high-cycle fatigue test

Bend-twist coupled blades
- coupled mode-shapes are predicted with uncertainty
- affects power production, loading, flutter stability

➢ structural dynamic validation of FE shell and beam models

modal tests
- free-free boundary condition (4 blades)
  - deviations from manufacturing
- at the test rig (blade #1)
  - very high sensor density
  - larger deformations

ideal database for FE model update

Context of test campaign

Process of finishing

unfinished blade

Finish of rotor blades

- Removal of remains from previous manufacturing steps
- installing blade root connection
- additional layers of lay-up laminate
- colouring the blade
- approximated mass increase: 103kg

Mass of individual rotor blades

	mass in kg
blade #1 w/o finish	1793
blade #2	1971
blade #3	1892
blade #4	1917

Overview of test campaign

	blade #1	blade #2	blade #3	blade #4
free (DLR)	x	x	x	
free w/ finish (NREL)		x	x	x
test rig (IWES)	x			

Experimental modal analysis of aeroelastic tailored rotor blades in different boundary conditions

Content

Test setups and realisation

Comparison of test scenarios

	feasibility	aspects of validation
free-free	• instrumentation and excitation on ground • suspension system replaces hub connection • low test site requirements	• fewest mass loading • "blade only"
	➢ less than two days of testing	
test rig	• instrumentation and excitation in heights • effort of blade attachment	• resemblance to hub connection • compliance of test rig • higher force input possible
	➢ testing of non-linear behaviour	

Test setups and realisation

Sensor distribution

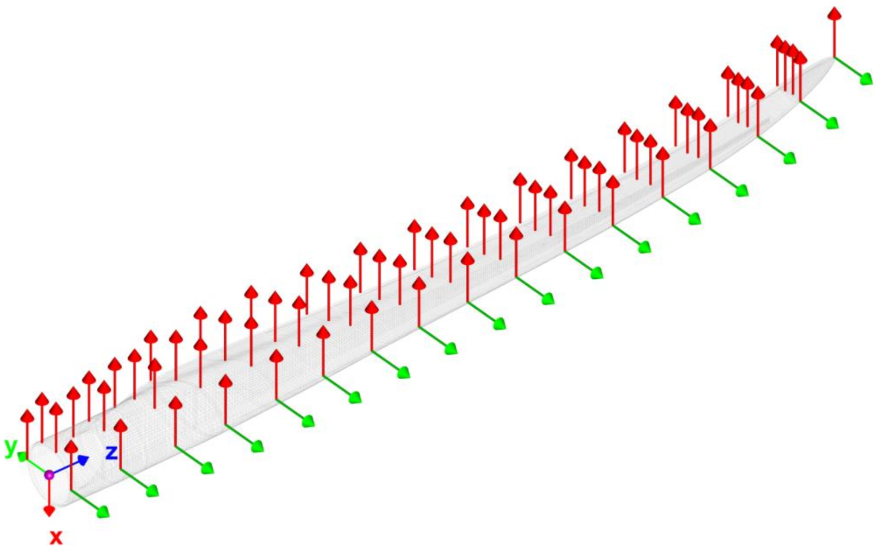
free-free

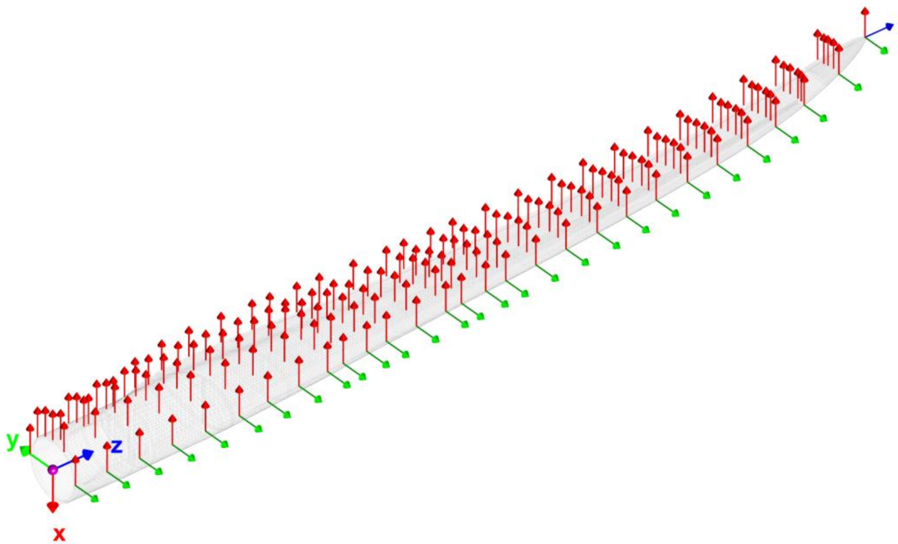
- equidistant spacing along length and chord axis
- edgewise motion captured by sensors on leading edge
- 3-4 instrumented cross-sections on suction side

clamped to test rig

- equidistant spacing along length on girder, equidistantly to leading and trailing edge
- 15 instrumented cross-sections on suction side
- in total 288 acceleration signals

➢ high sensor density for validation purpose





Test setups and realisation

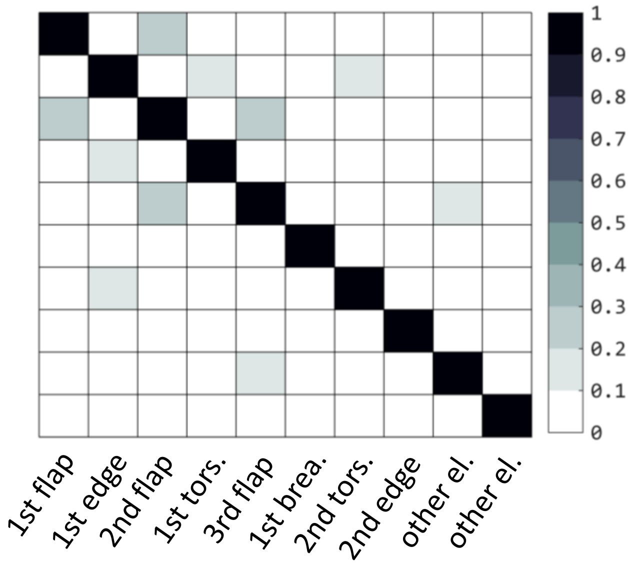
Sensor distribution

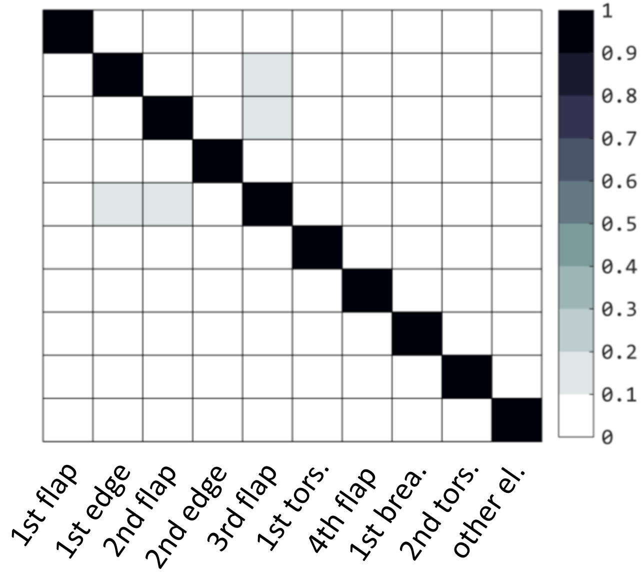
free-free
- equidistant spacing along length and chord axis
- edgewise motion captured by sensors on leading edge
- 3-4 instrumented cross-sections on suction side

clamped to test rig
- equidistant spacing along length on girder, equidistantly to leading and trailing edge
- 15 instrumented cross-sections on suction side
- in total 288 acceleration signals

➢ high sensor density for validation purpose

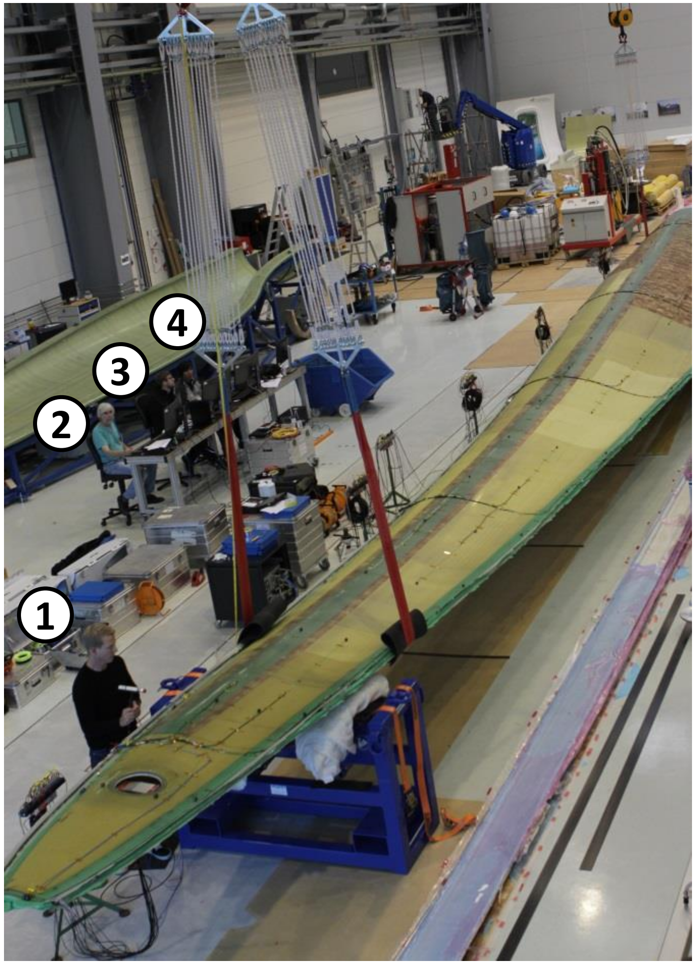
AutoMAC from FE model





Test setups and realisation

Modal testing procedure



Sequence of operations

1. **hammer/shaker excitation**
2. data acquisition and signal generation
3. signal processing
4. modal analysis and correlation

impact hammer (free-free)

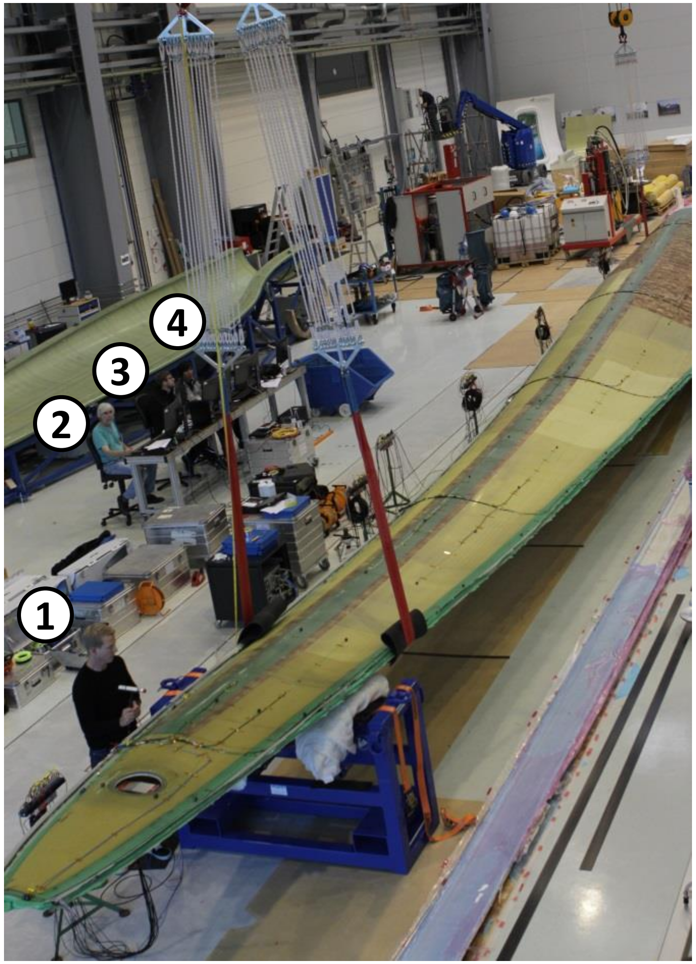
- soft tip, 10 averages
- 8 excitation points on leading edge, trailing edge, girder, blade shell
- huge windows (rigid body modes)

electrodynamic shaker (test rig)

- slow-paced logarithmic sine upsweeps (0.5 oct/min)
- different amplitude levels up to 800N
- multi-point excitation flapwise
- attachment built from mixed adhesive

Test setups and realisation

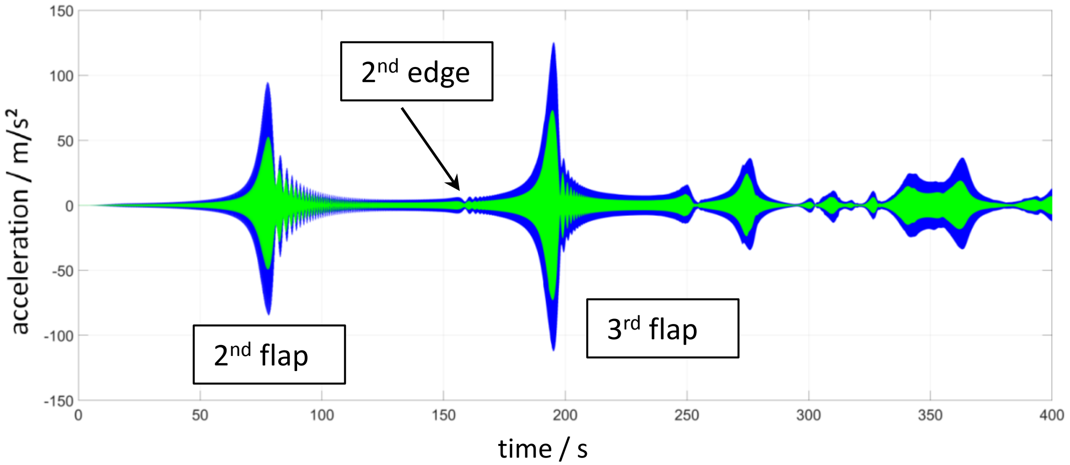
Modal testing procedure



Sequence of operations

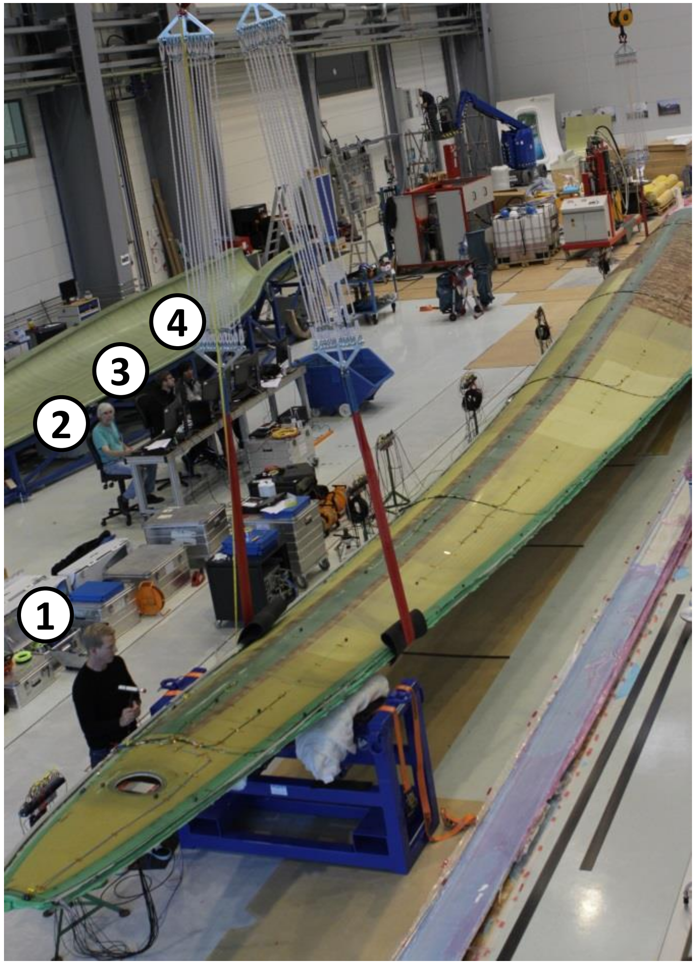
1. hammer/shaker excitation
2. data acquisition and signal generation
3. signal processing
4. modal analysis and correlation

time data of sine sweep



Test setups and realisation

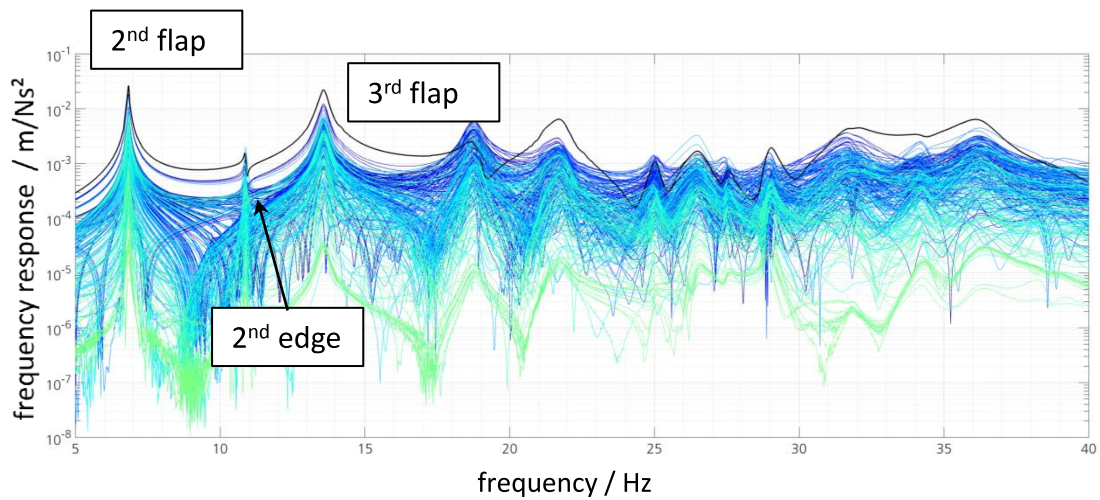
Modal testing procedure



Sequence of operations

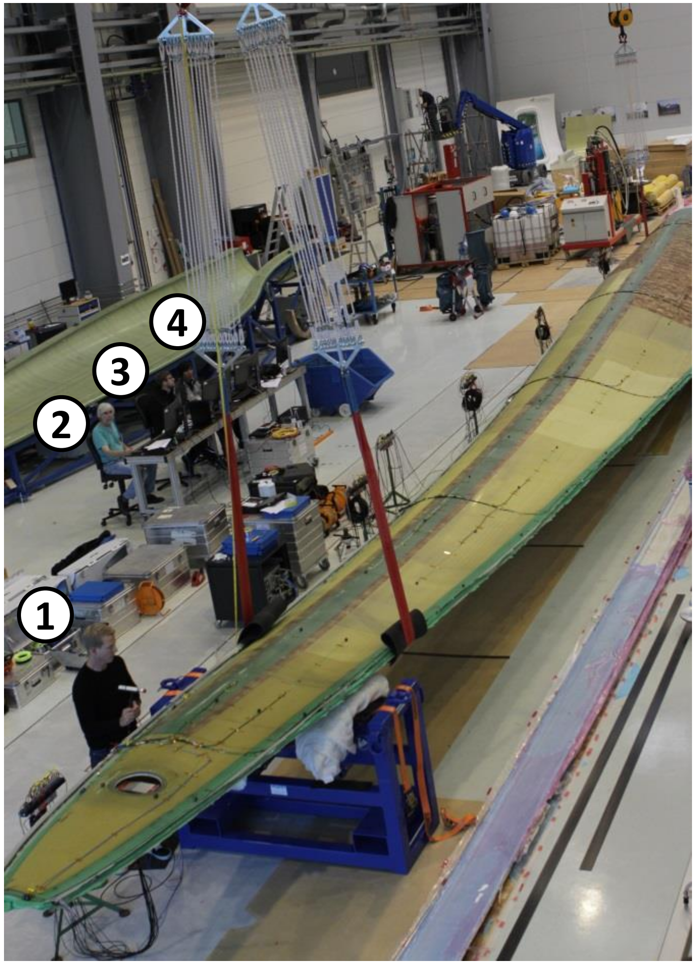
1. hammer/shaker excitation
2. data acquisition and signal generation
3. **signal processing**
4. modal analysis and correlation

frequency response functions



Test setups and realisation

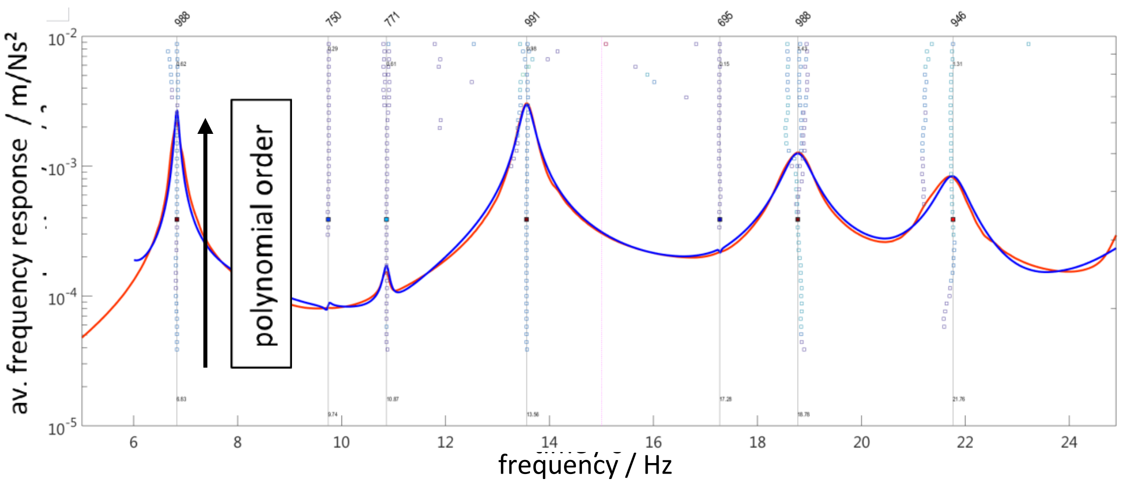
Modal testing procedure



Sequence of operations

1. hammer/shaker excitation
2. data acquisition and signal generation
3. signal processing
4. **modal analysis and correlation**

stabilisation diagram from identification algorithm



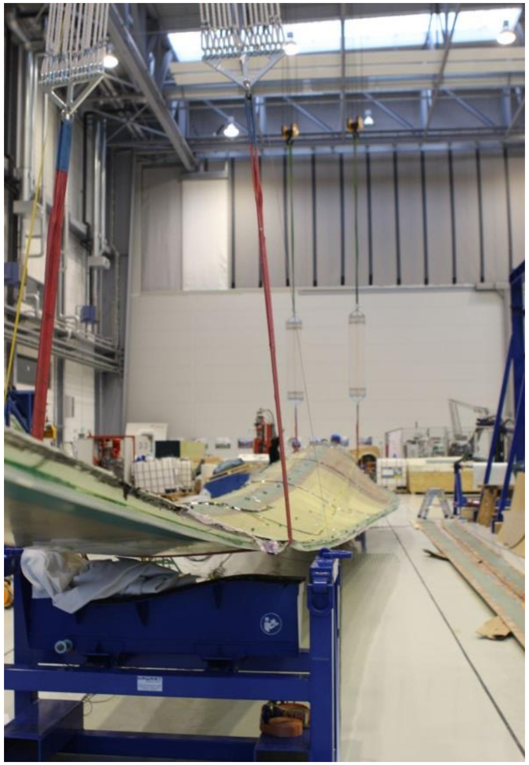
Experimental modal analysis of aeroelastic tailored rotor blades in different boundary conditions

Content

Assorted results

Overview of mode shapes from free-free test (blade #1)

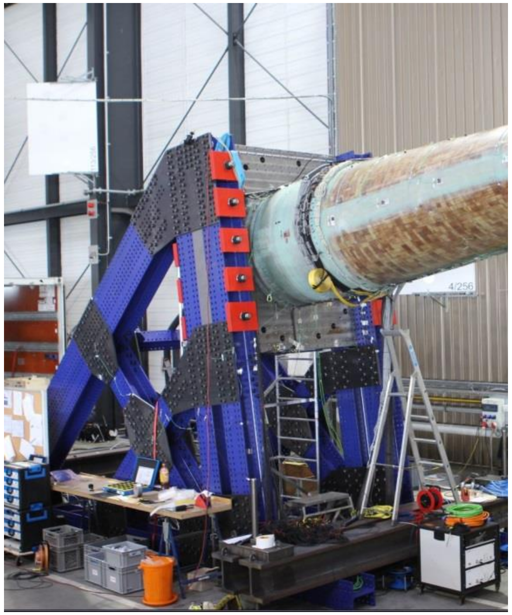
no.	mode shape	f in Hz	D in %
1	rigid body heave	0.74	3.62
2	rigid body roll	0.86	2.42
3	rigid body pitch	0.99	4.03
4	1. bending flapwise	4.80	0.23
5	1. breathing mode	7.74	0.61
6	1. bending edgewise	10.13	0.43
7	2. bending flapwise	11.99	0.43
8	2. breathing mode	14.48	0.56
9	1. torsion	16.85	1.25
10	3. bending flapwise	20.90	0.66
11	3. breathing mode	22.20	0.50
12	2. bending edgewise	27.15	0.57
13	2. torsion	27.98	0.97



Assorted results

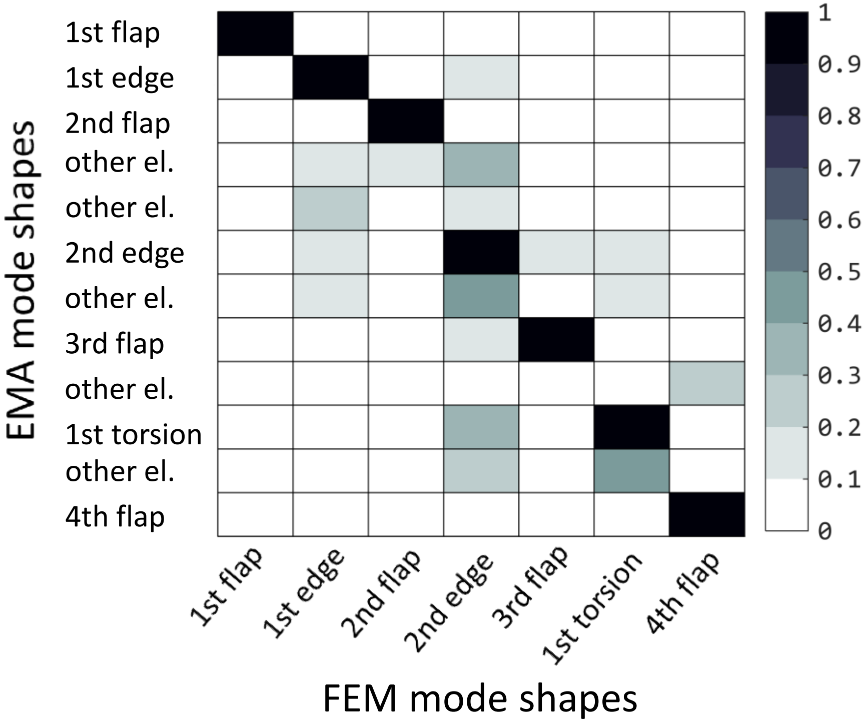
Overview of mode shapes from blade #1 being clamped

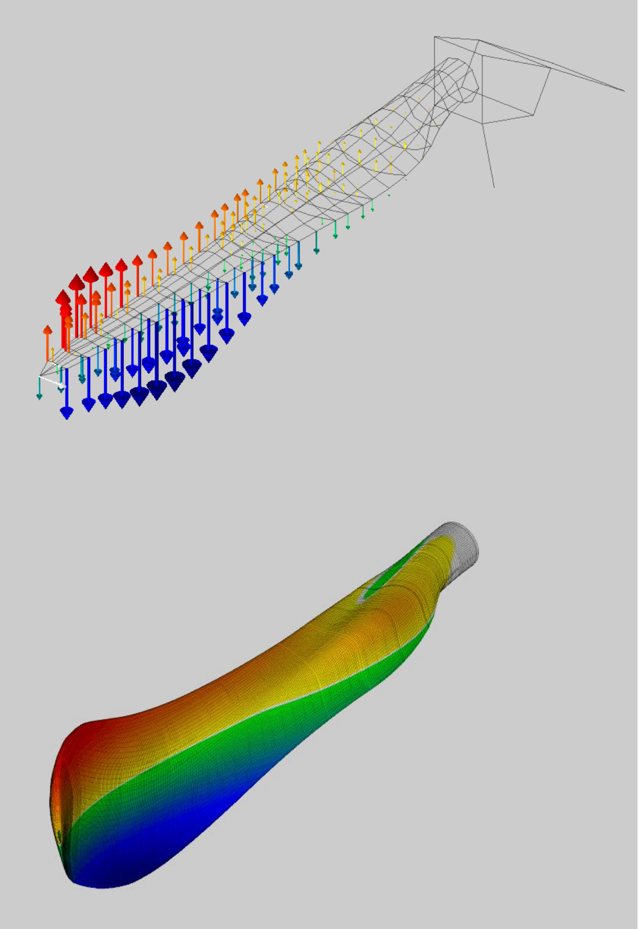
no.	mode shape	f in Hz	D in %
1	1. bending flapwise	2.20	0.35
2	1. bending edgewise	3.07	0.31
3	2. bending flapwise	6.85	0.28
4	lateral test rig mode	7.26	0.58
5	2. bending edgewise + 1. breathing	9.74	0.40
6	2. bending edgewise	10.88	0.31
7	2. bending edgewise + 2. breathing	11.95	0.63
8	3. bending flapwise	13.58	0.34
9	1. breathing mode	17.27	0.44
10	1. torsion	18.73	0.46



Assorted results

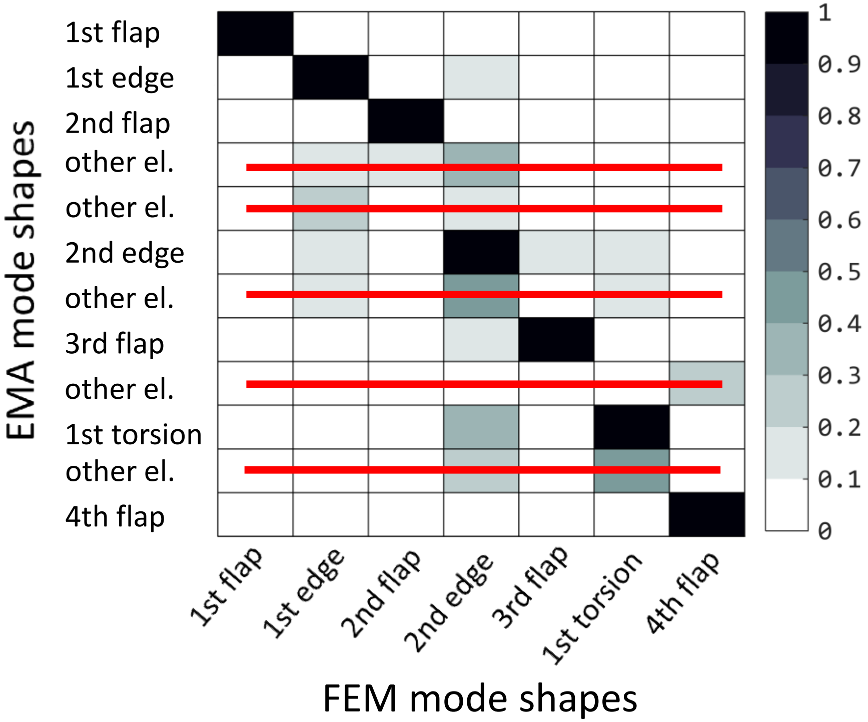
Correlation with FE model (test rig)

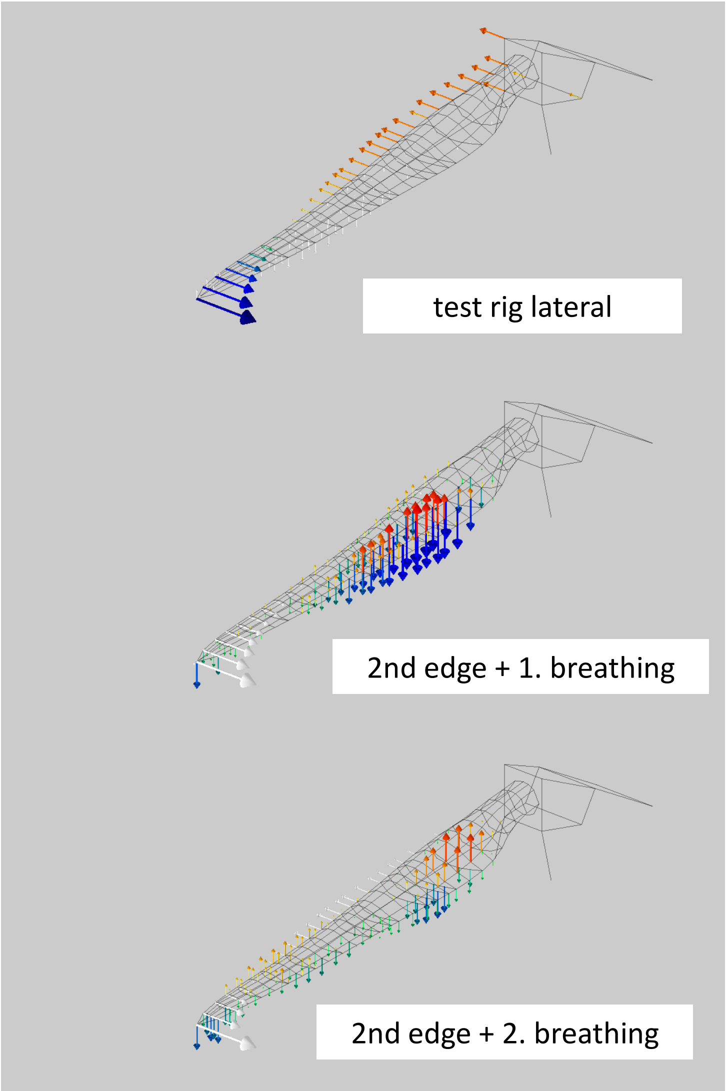




Assorted results

Correlation with FE model (test rig)





Assorted results

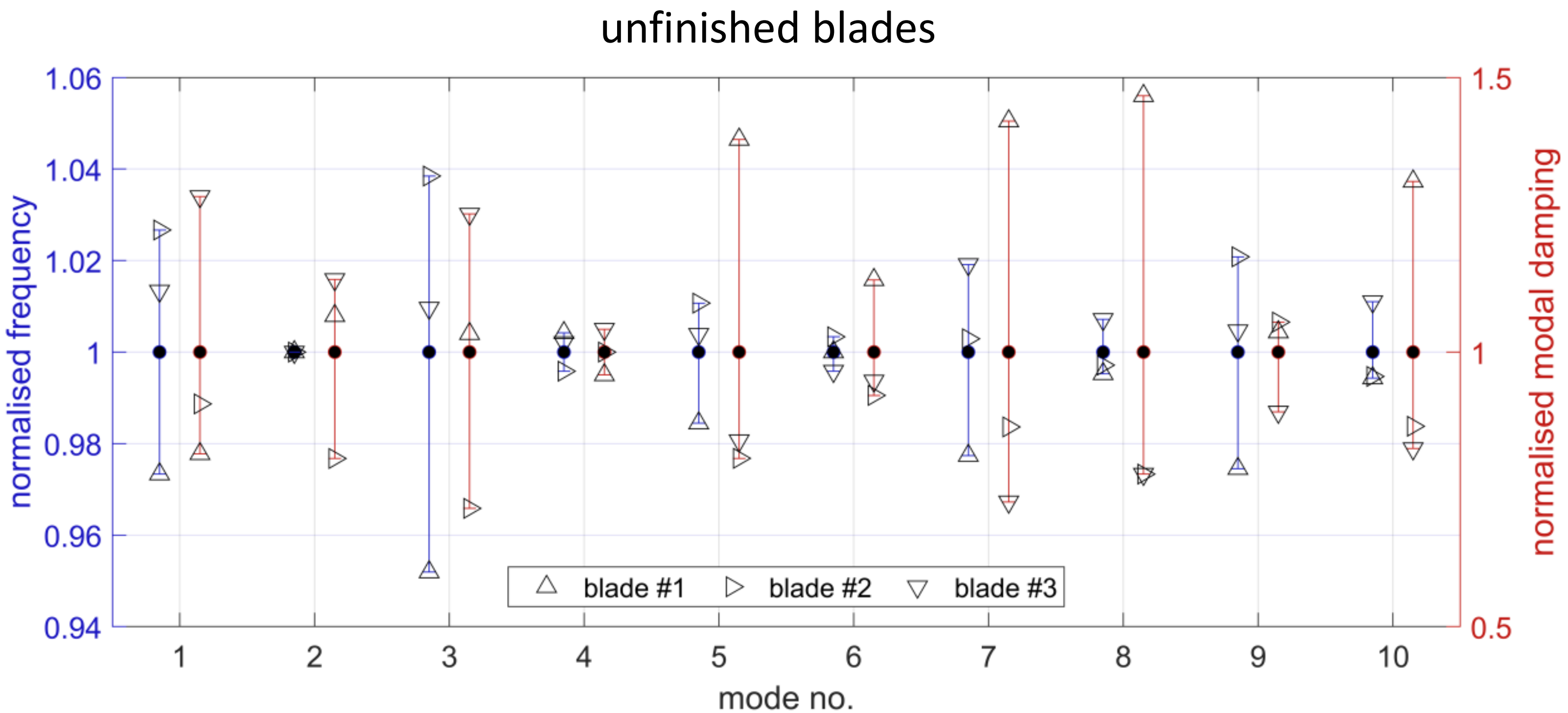
Impact of finishing process

averaged eigenfrequencies and damping

mode no.	mode description	eigenfrequency in Hz		diff. in %	modal damping in %		diff. in %
		w/o finish	w/ finish		w/o finish	w/ finish	
1	rigid body heave	0.75	0.70	-6.7	2.86	2.53	-11.5
2	rigid body roll	0.86	0.84	-1.7	2.27	2.51	10.6
3	rigid body pitch	1.04	0.98	-5.8	3.90	3.19	-18.2
4	1st bend. flapwise	4.78	4.72	-1.3	0.24	0.26	8.3
5	1st bend. edgewise	10.29	9.81	-4.7	0.31	0.38	22.6
6	2nd bend. flapwise	11.99	11.87	-1.0	0.38	0.23	-39.5
7	1st torsion	17.24	17.14	-0.6	0.88	0.56	-36.4
8	3rd bend. flapwise	21.00	20.58	-2.0	0.45	0.36	-20.0
9	2nd bend. edgewise	27.86	26.67	-4.3	0.55	0.45	-18.2
10	2nd torsion	28.14	28.69	2.0	0.74	0.47	-36.5

Assorted results

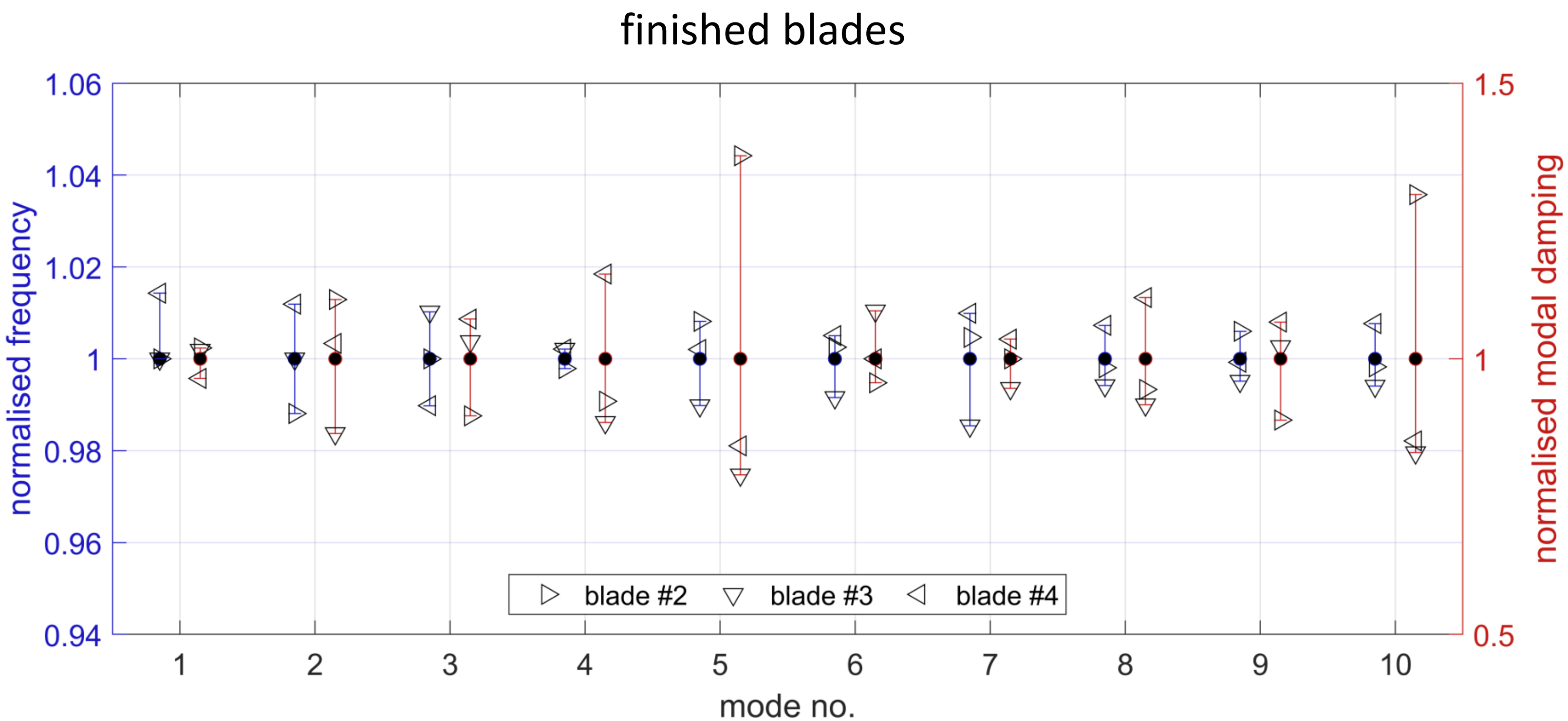
Impact of finishing process



- blade #1: high damping and low frequencies
- flap modes (no. 4,6,8) insensitive to frequency variations

Assorted results

Impact of finishing process

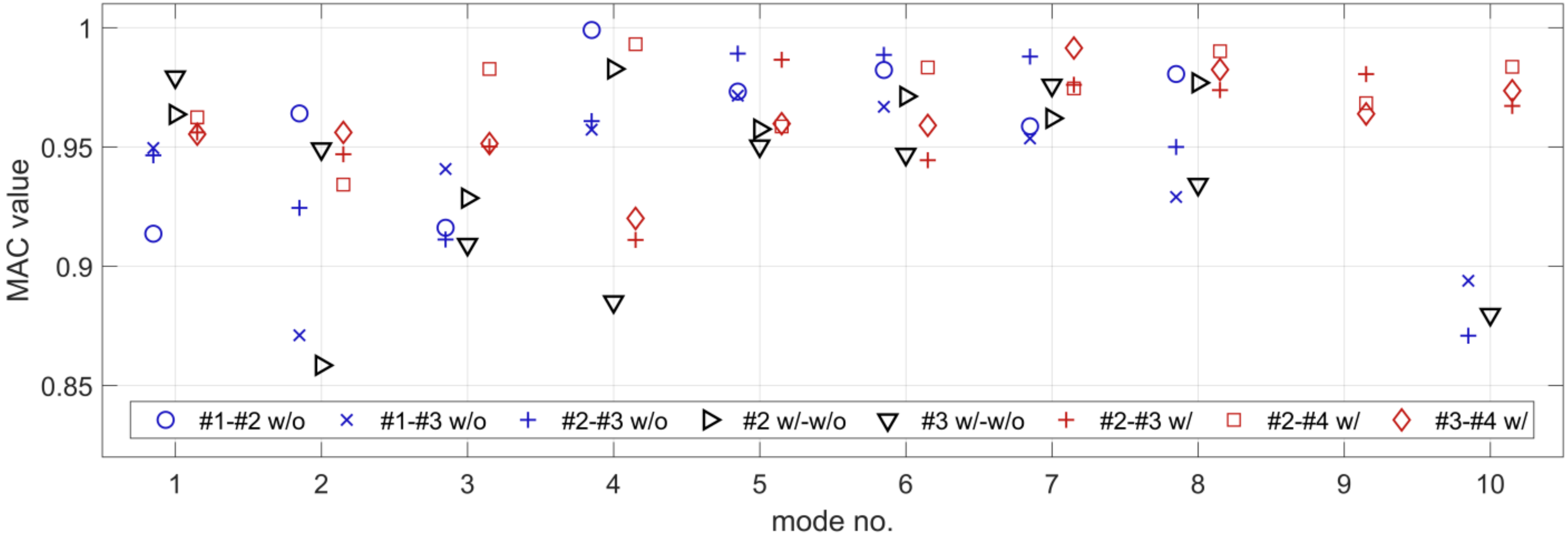


- smaller deviations in both frequency and damping
- some major changes in damping for blade #2 (no. 5,10)

Assorted results

Impact of finishing process

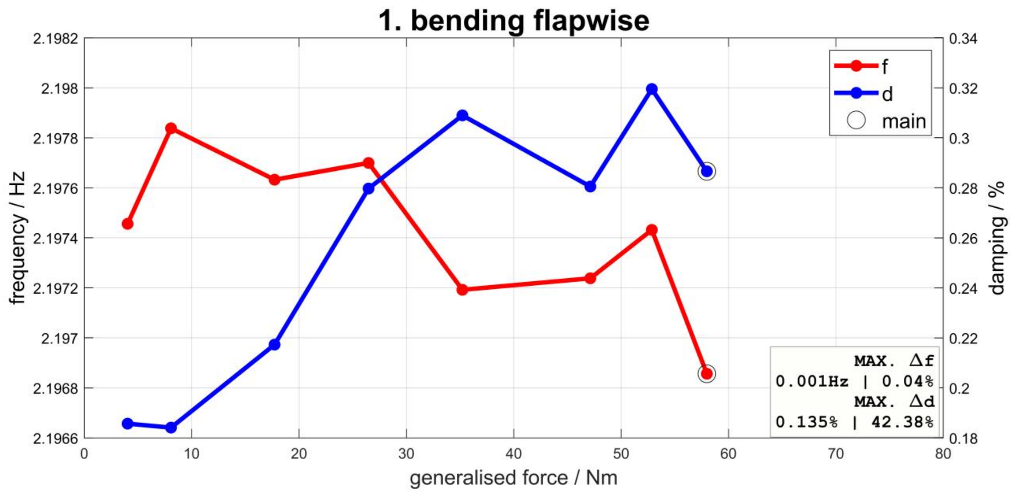
comparison of mode shapes

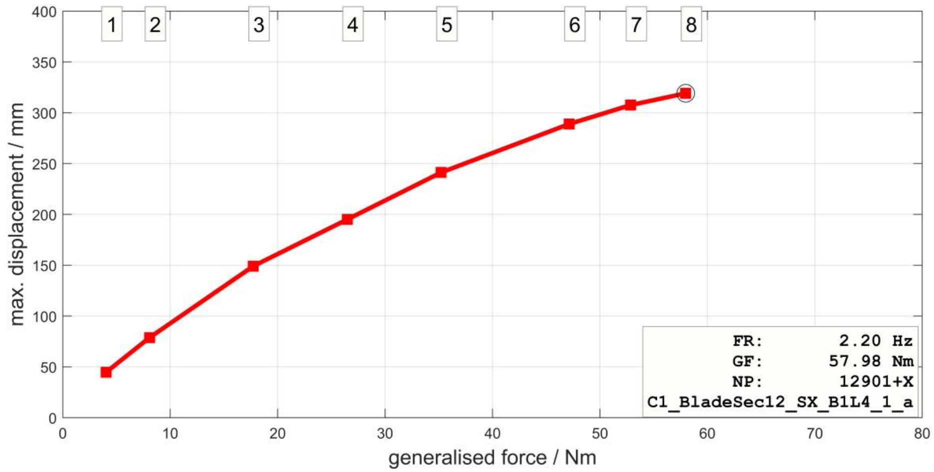


- correlation in higher modes only for finished data set
- mode shapes are affected significantly

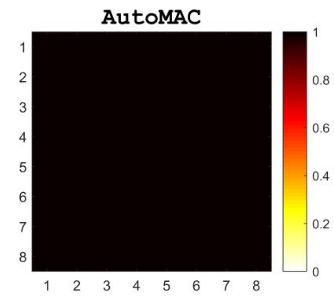
Assorted results

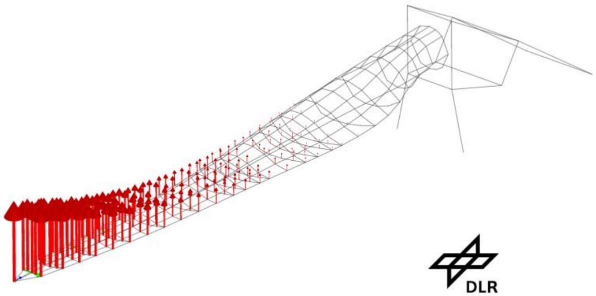
Non-linearity study






```
1: C1_BladeSec12_UX_B1L1_5_a  MIF: 997
2: C1_BladeSec12_SX_B1L1_3_a  MIF: 997
3: C1_BladeSec12_UX_B1L2_3_a  MIF: 997
4: C1_BladeSec12_SX_B1L2_2_a  MIF: 997
5: C1_BladeSec12_UX_B1L3_7_a  MIF: 997
6: C1_BladeSec12_SX_B1L3_1_a  MIF: 997
7: C1_BladeSec12_UX_B1L4_8_a  MIF: 997
8: C1_BladeSec12_SX_B1L4_1_a  MIF: 997
```

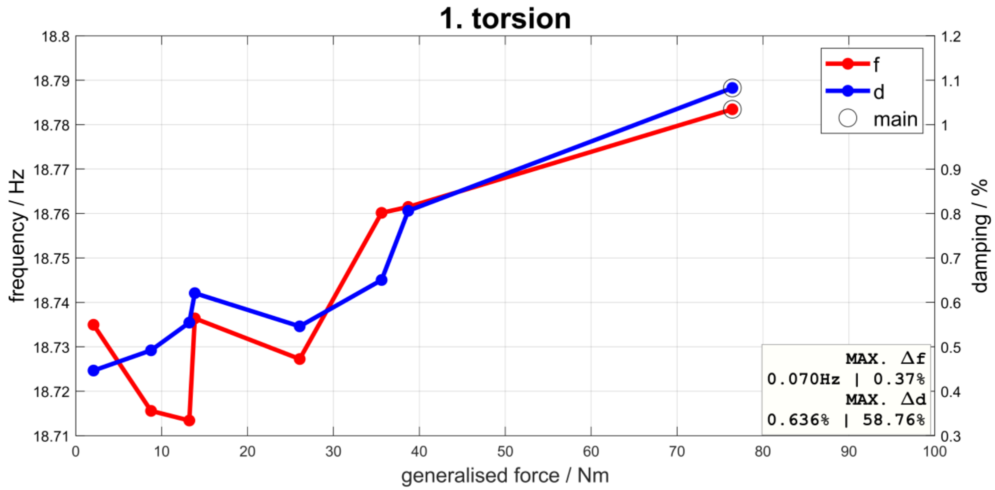


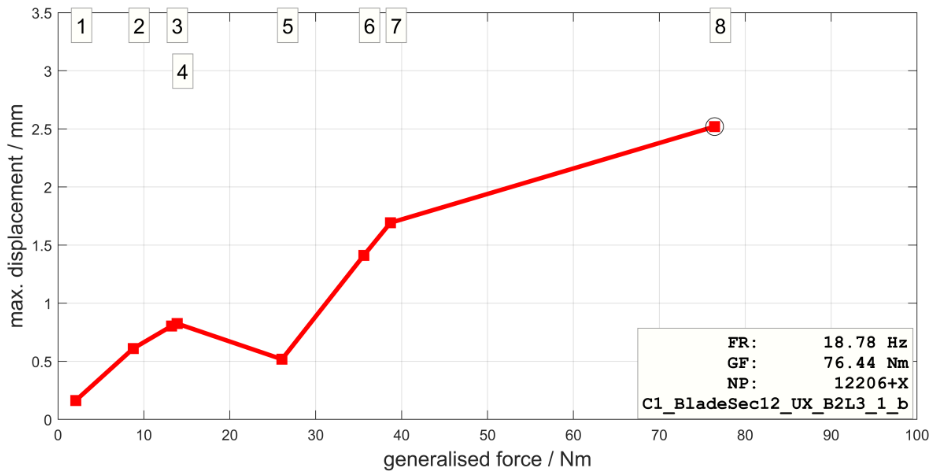


DLR

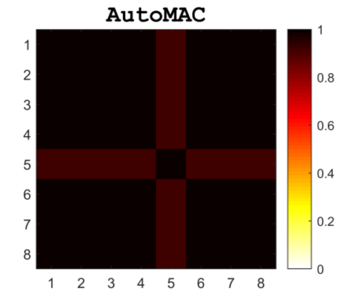
Assorted results

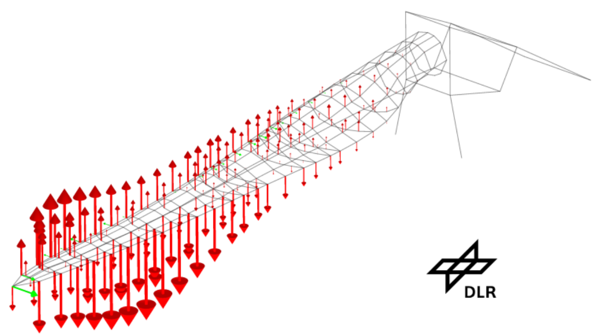
Non-linearity study






```
1: C1_BladeSec19_UY_B1L1_1_c  MIF: 983
2: C1_BladeSec19_UY_B1L3_1_b  MIF: 988
3: C1_BladeSec19_UY_B1L2_1_b  MIF: 987
4: C1_BladeSec12_UX_B2L1_1_a  MIF: 989
5: C1_BladeSec12_SX_B2L1_1_b  MIF: 954
6: C1_BladeSec12_AX_B2L1_2_b  MIF: 971
7: C1_BladeSec12_UX_B2L2_3_b  MIF: 990
8: C1_BladeSec12_UX_B2L3_1_b  MIF: 989
```





Experimental modal analysis of aeroelastic tailored rotor blades in different boundary conditions

Content

Summary and future work

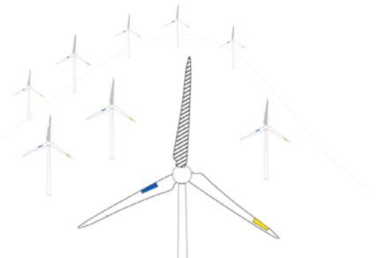
Design and realisation of high-resolution modal tests in different boundary conditions

- free-free
  - time-efficient test option
  - finished vs. unfinished blades
    - reduction of eigenfrequencies
    - notable impact on mode shapes

- clamped to test rig
  - costly test option with resemblance to operation
  - realisation of larger flapwise deformations
    - insensitive eigenfrequencies but increase of damping
    - beneficial for critical load cases and aeroelastic stability

Summary and future work

- methodology for computational model updating of rotor blades
- modal identification incorporating load frames
- modal identification by using strain data



Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

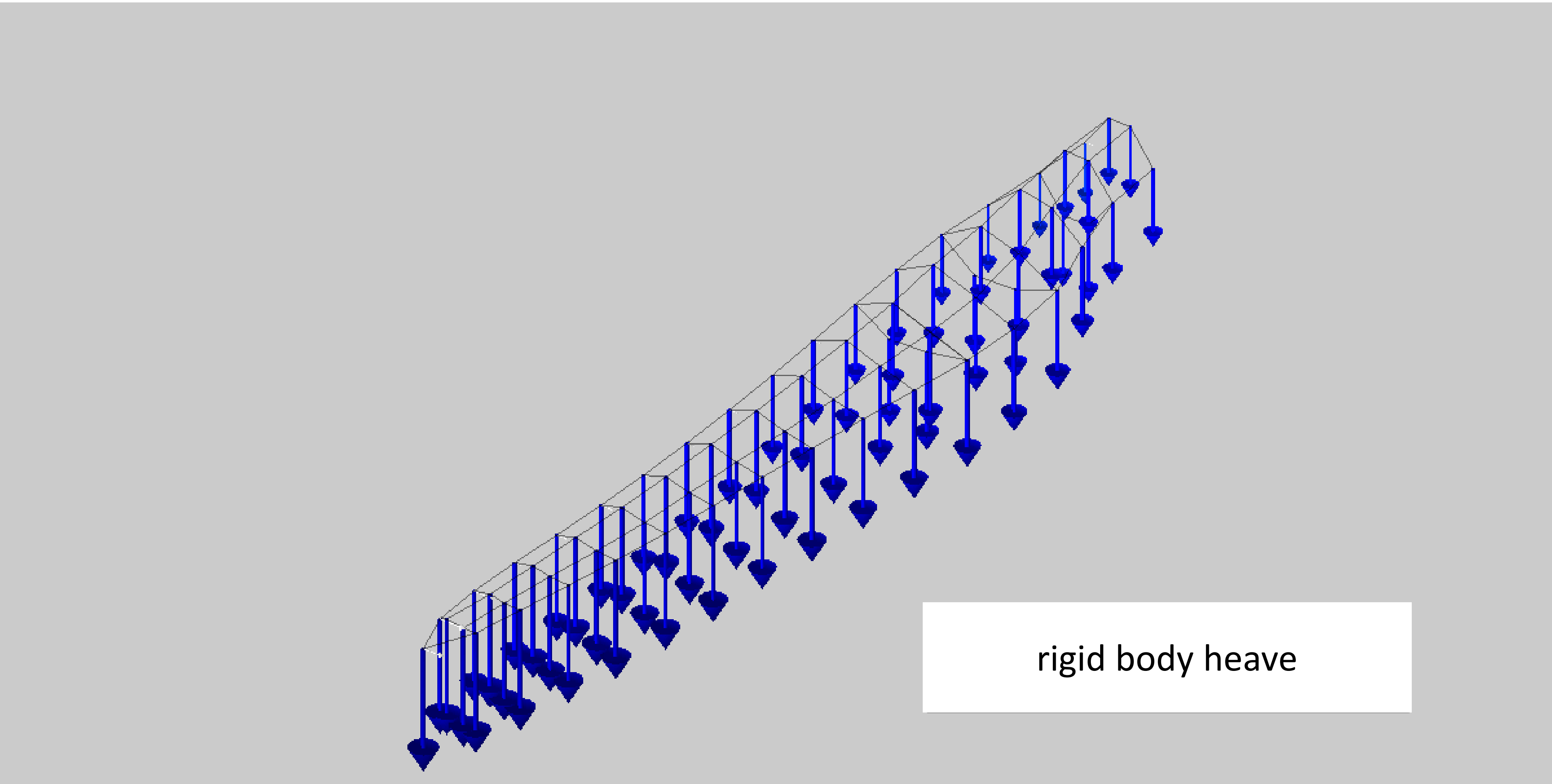
Thank you for your attention!

Janto Gundlach
janto.gundlach@dlr.de
Tel.: +49 551 709-2172

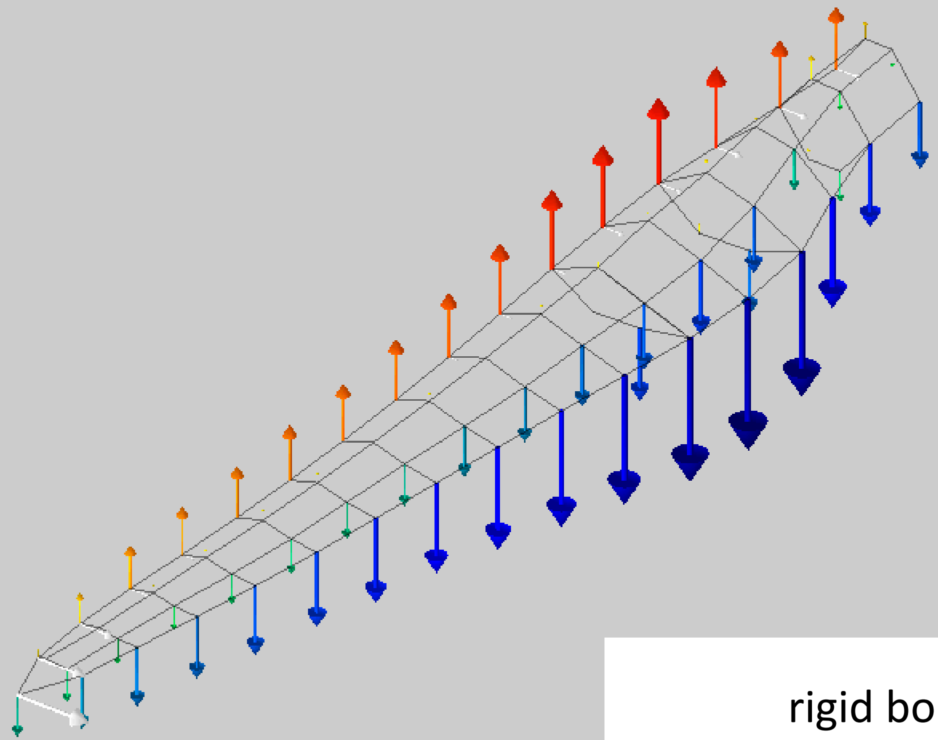
Yves Govers
yves.govers@dlr.de
Tel.: +49 551 709-2288

DLR

back

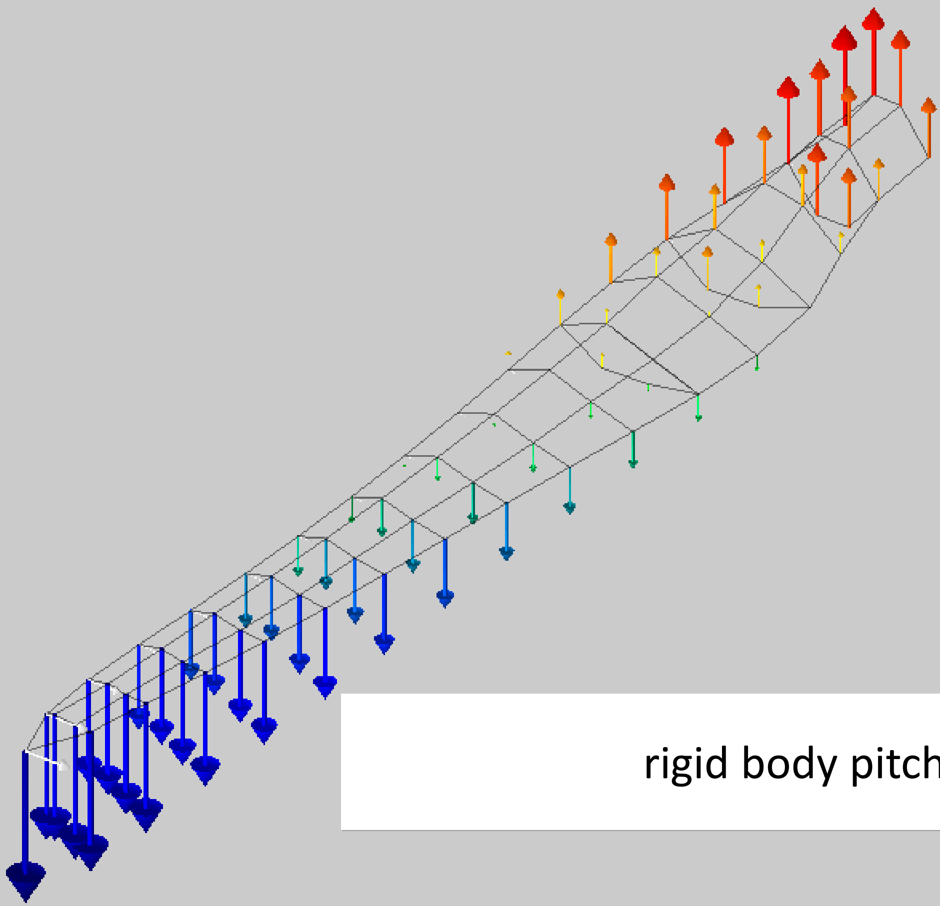


back



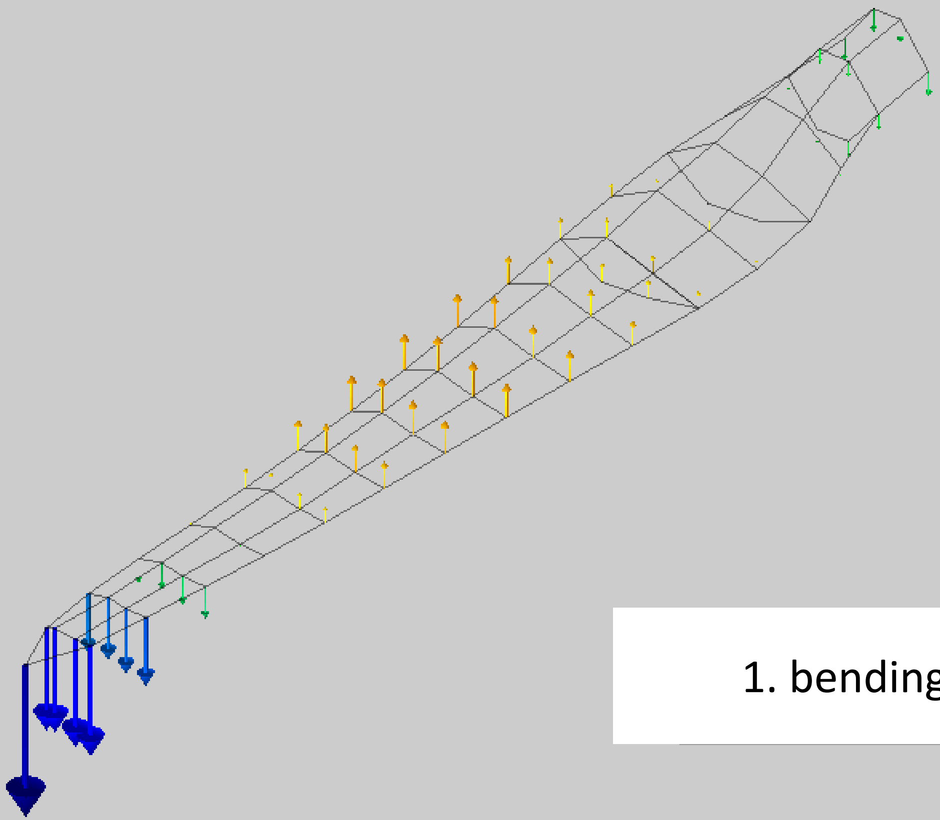
rigid body roll

back



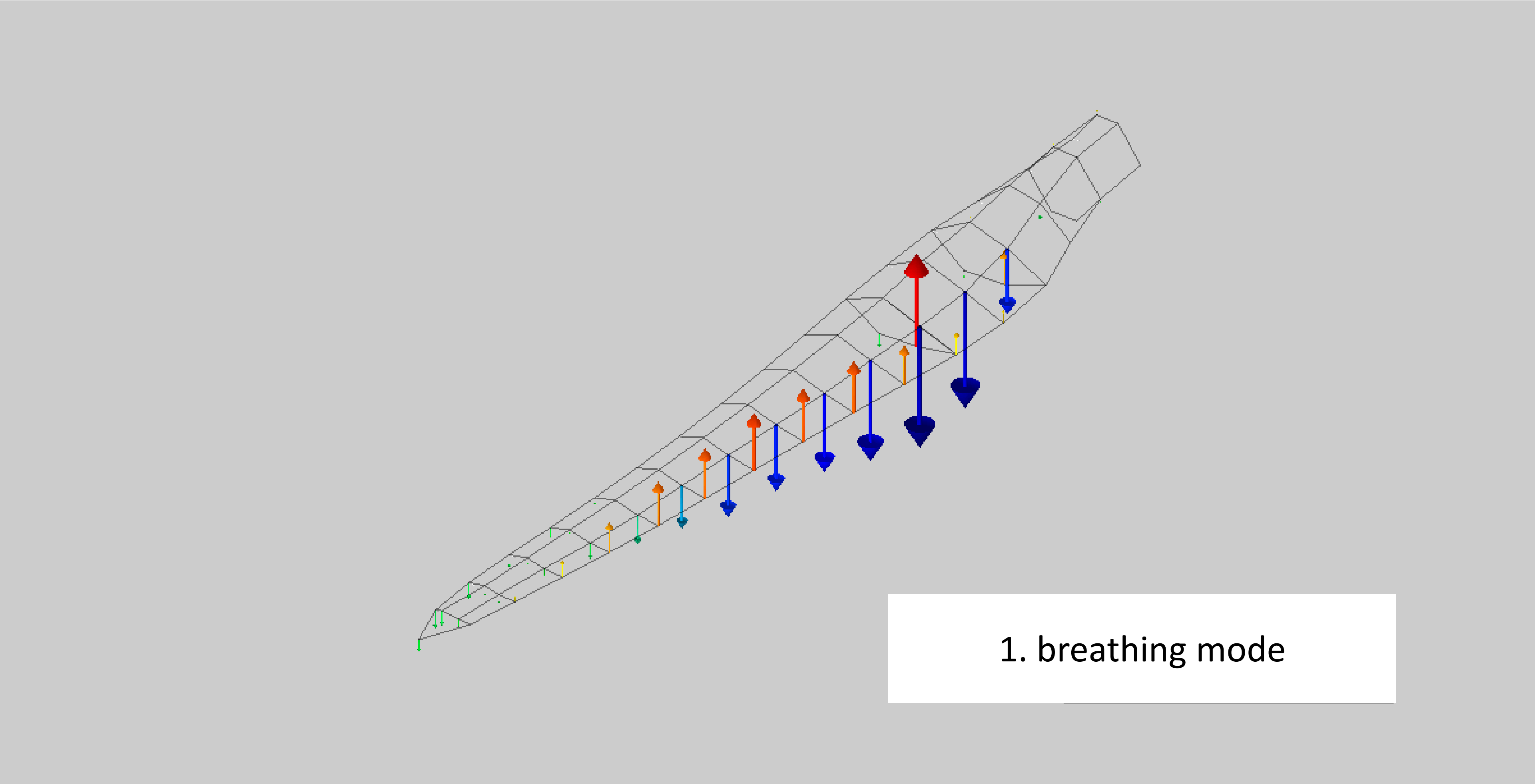
rigid body pitch

back

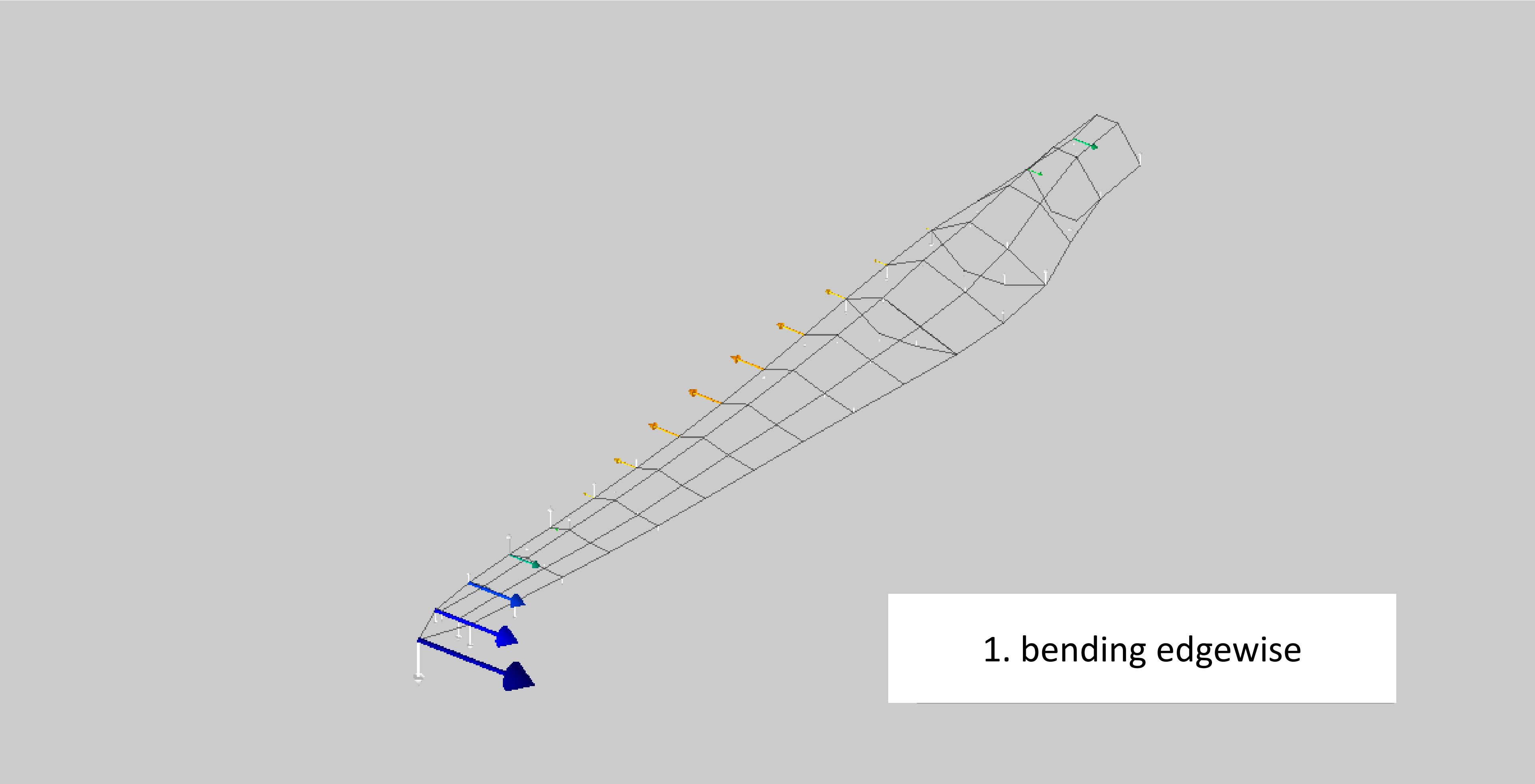


1. bending flapwise

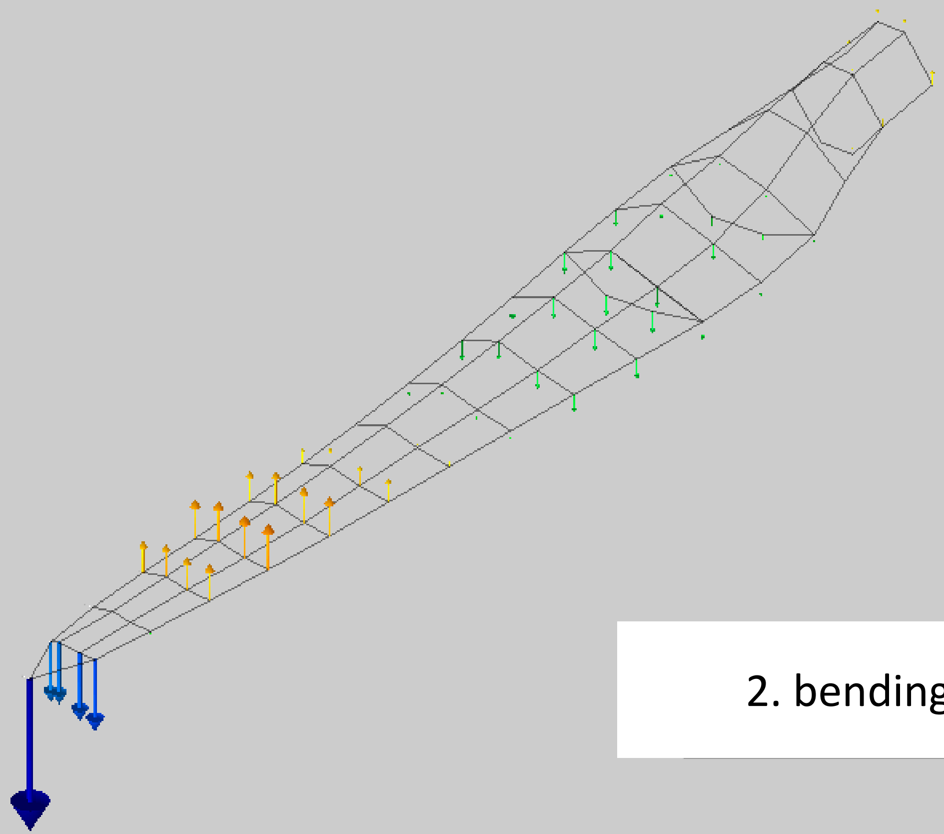
back



back

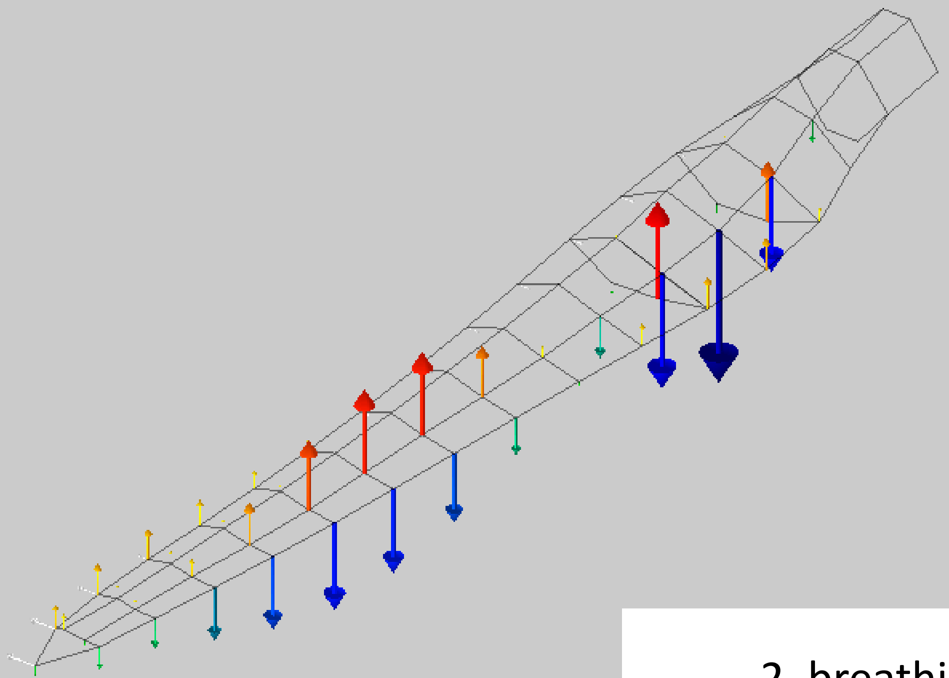


back



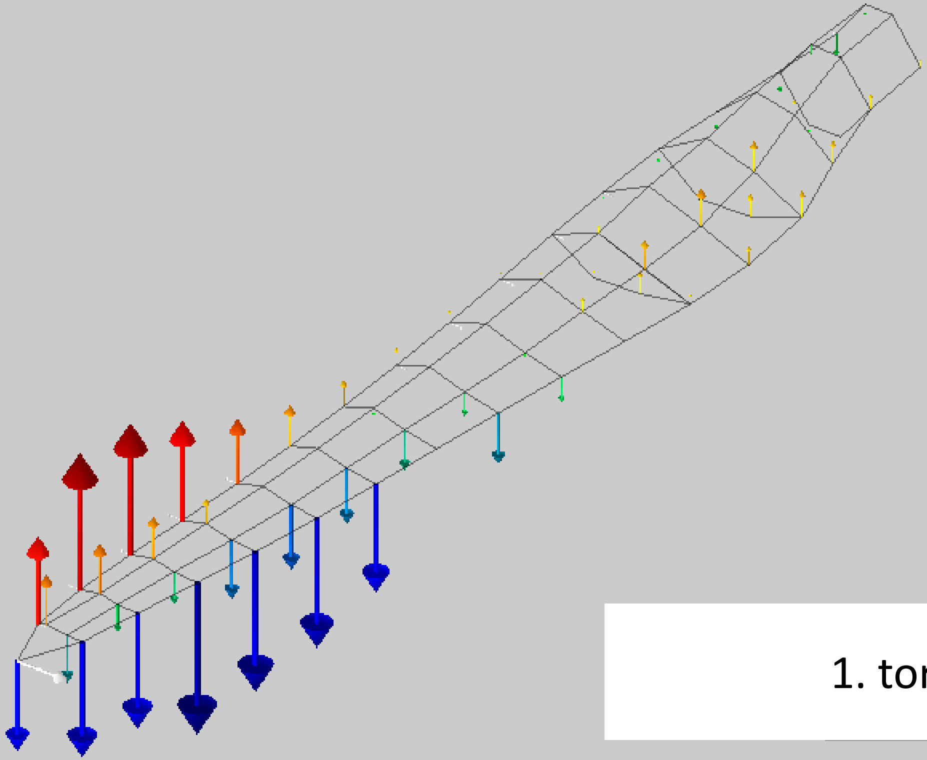
2. bending flapwise

back



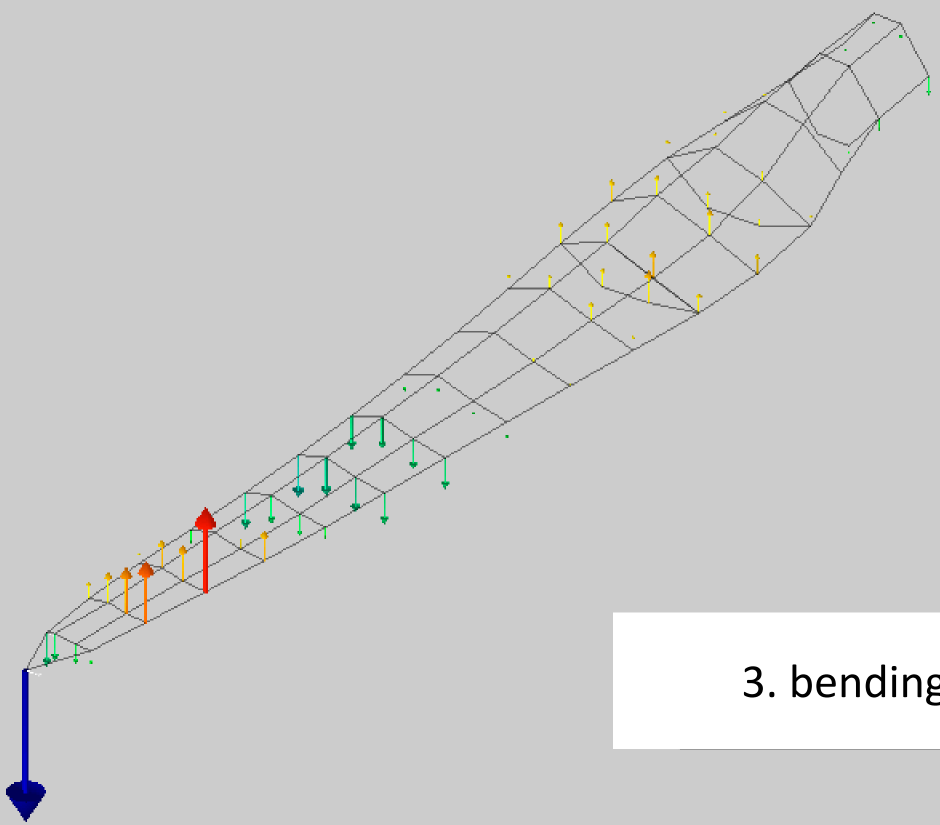
2. breathing mode

back



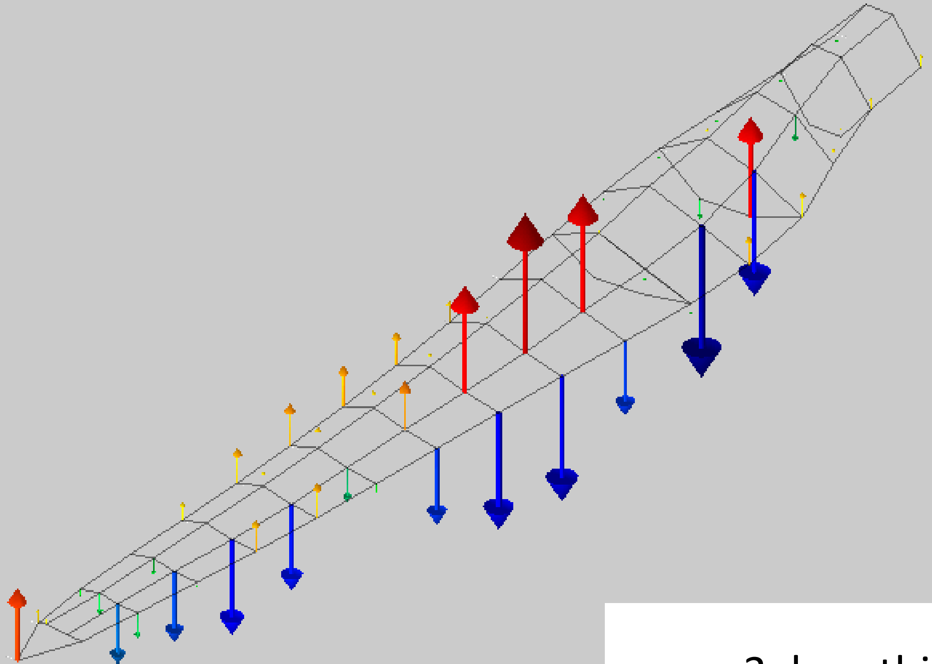
1. torsion

back



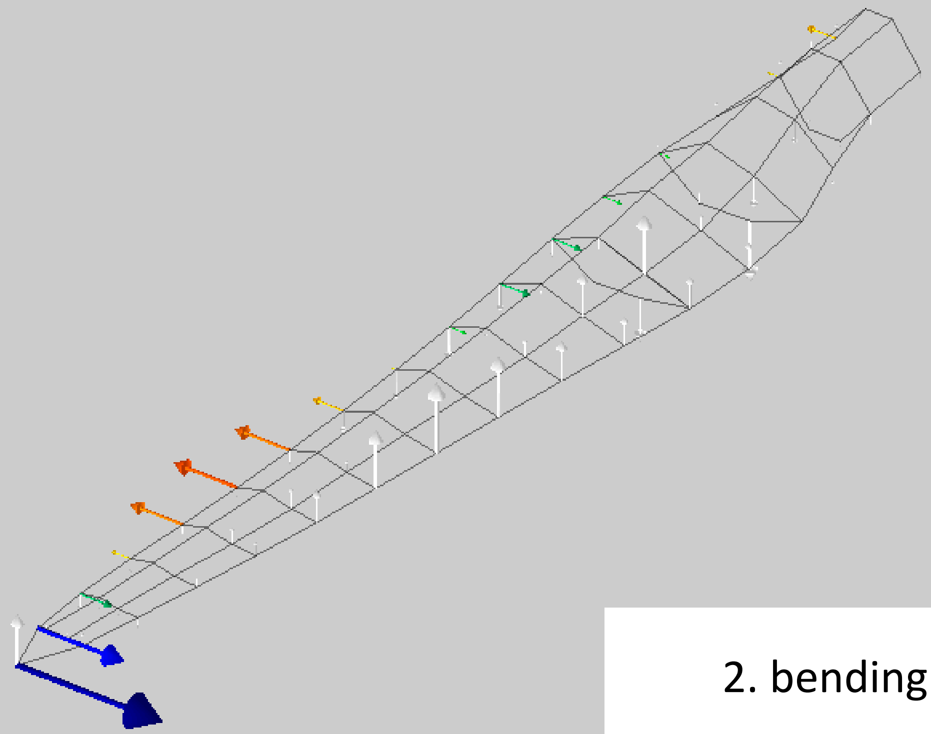
3. bending flapwise

back



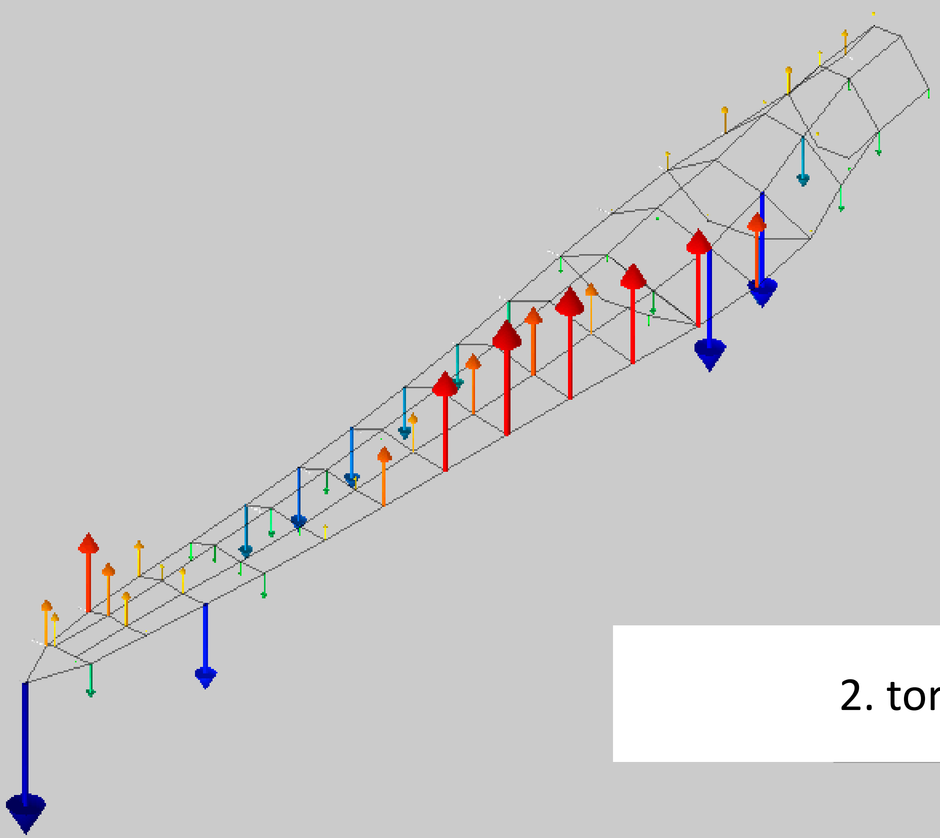
3. breathing mode

back



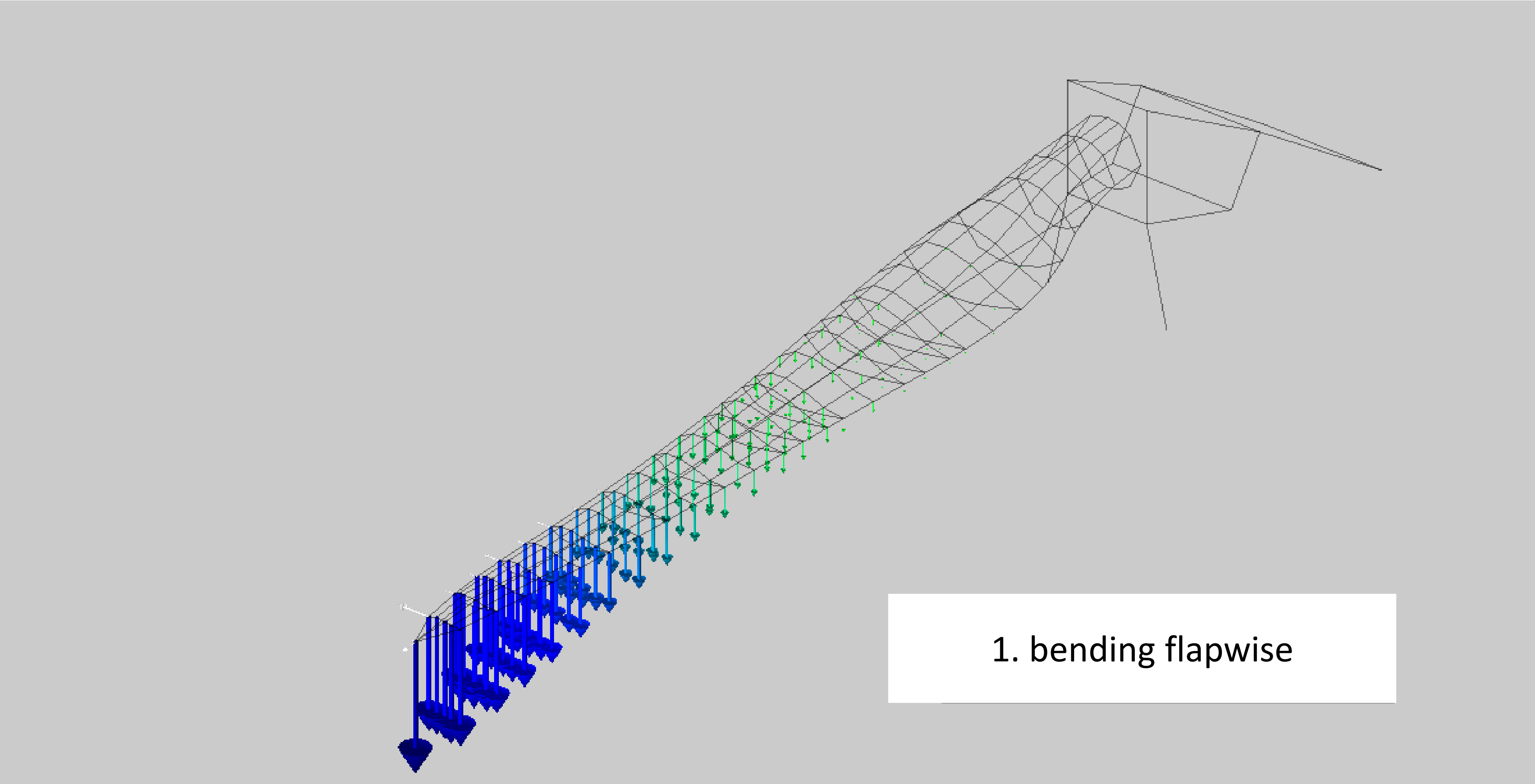
2. bending edgewise

back



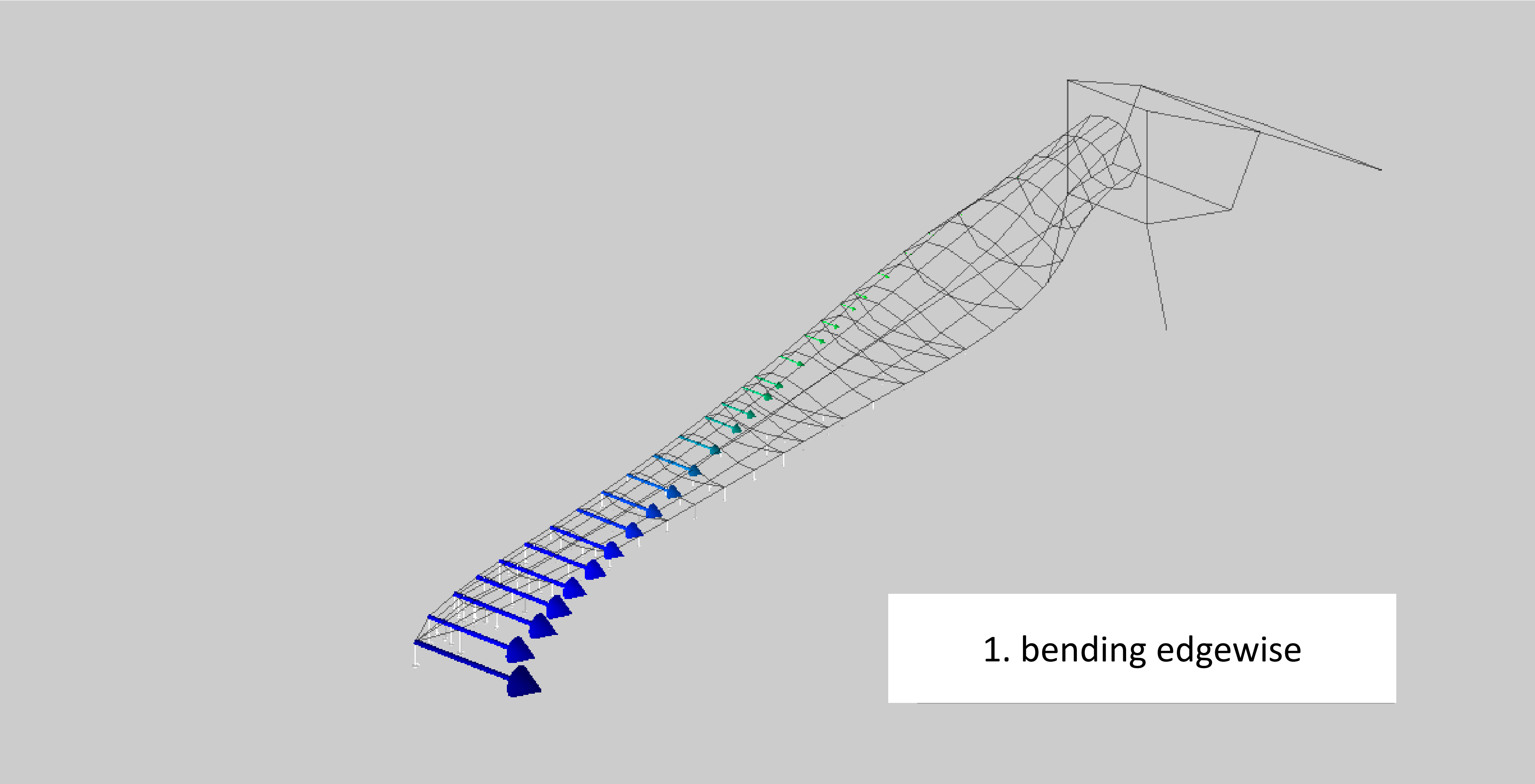
2. torsion

back

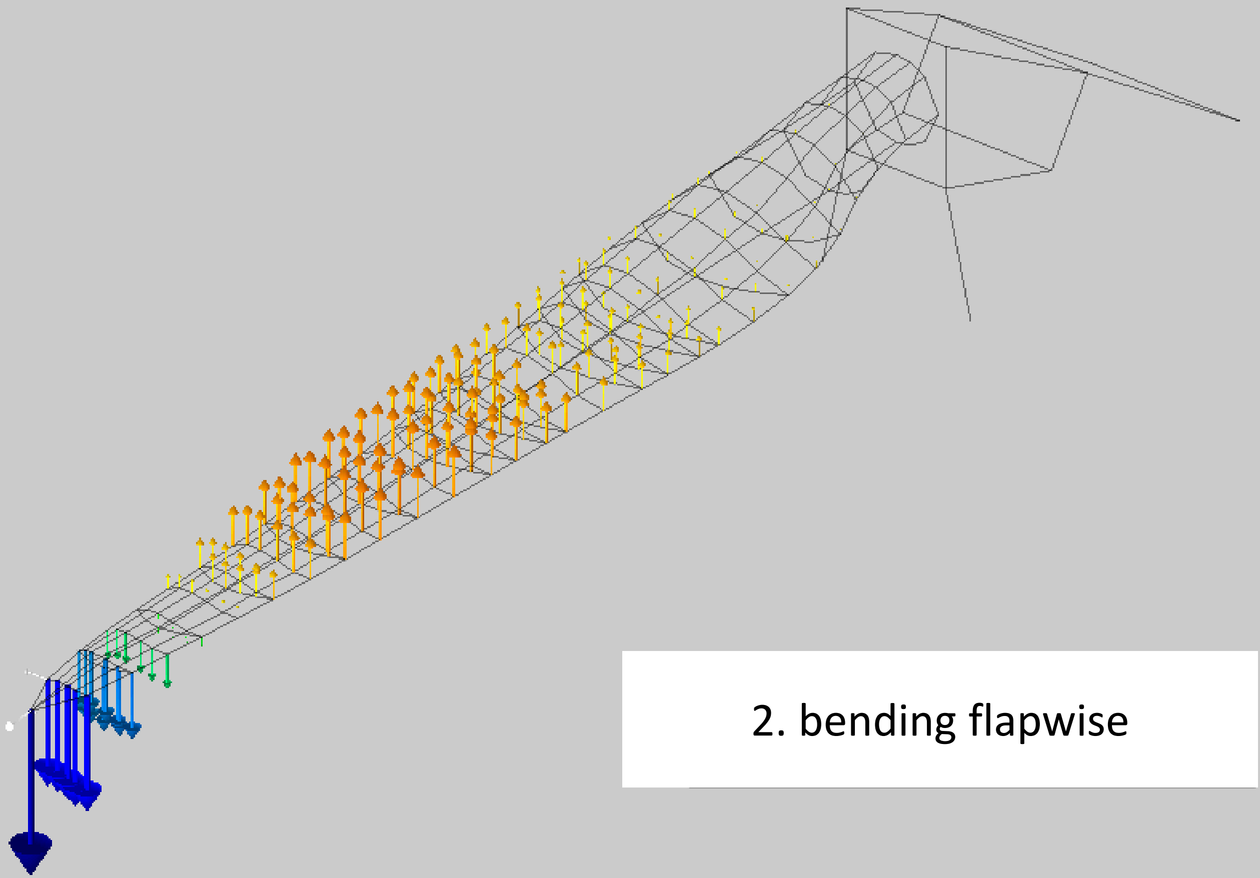


1. bending flapwise

back

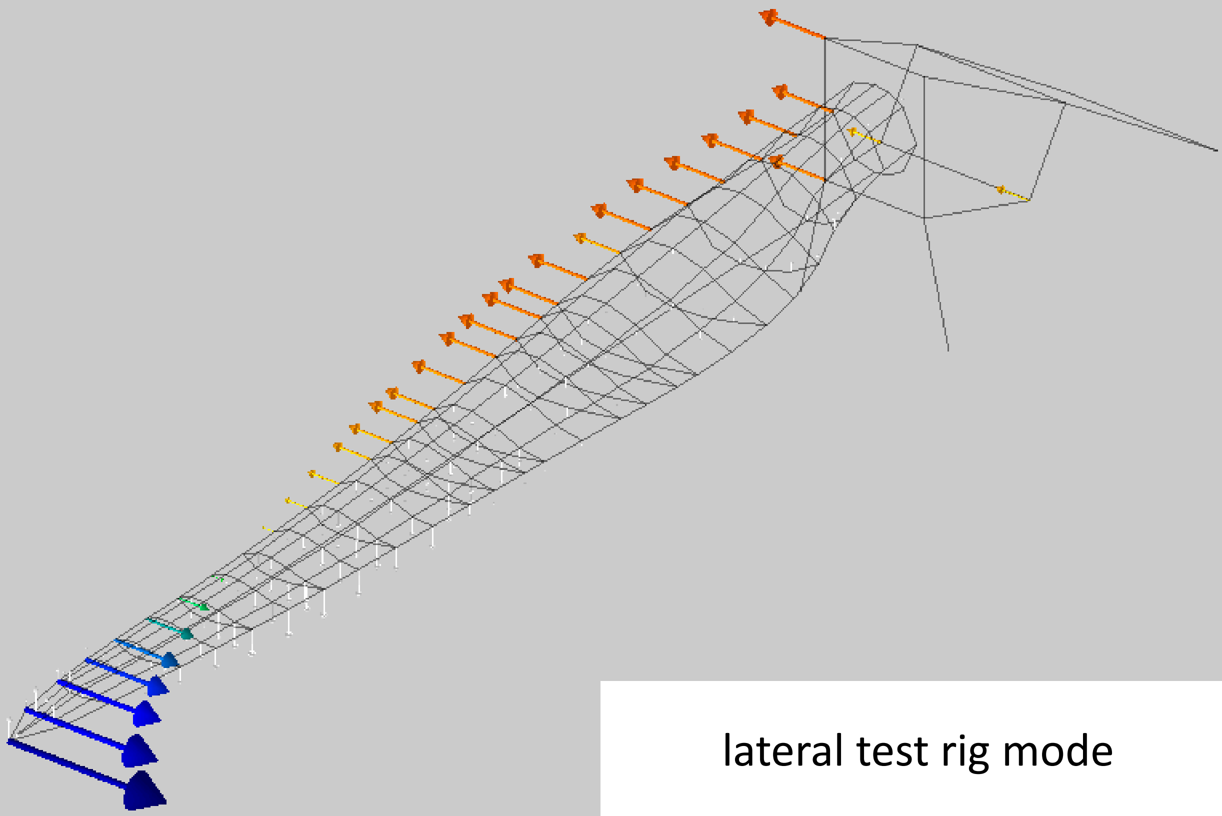


back



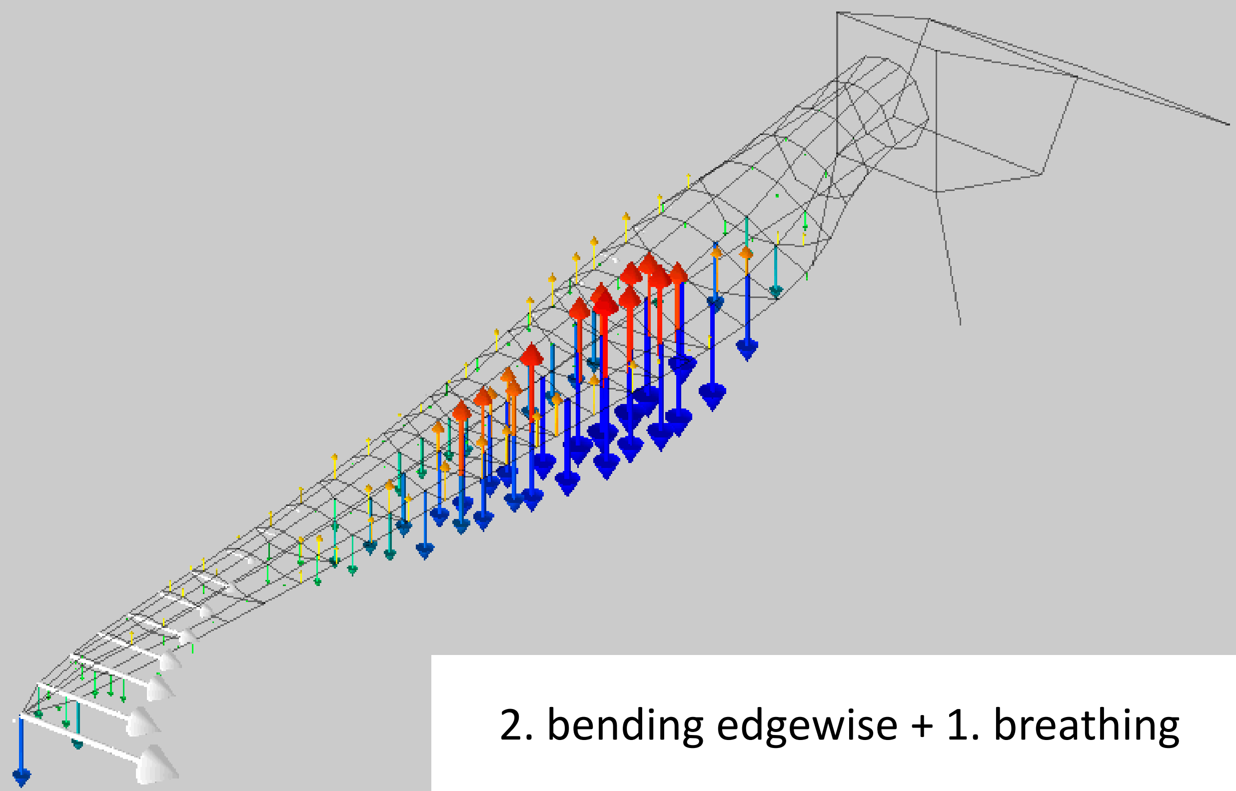
2. bending flapwise

back



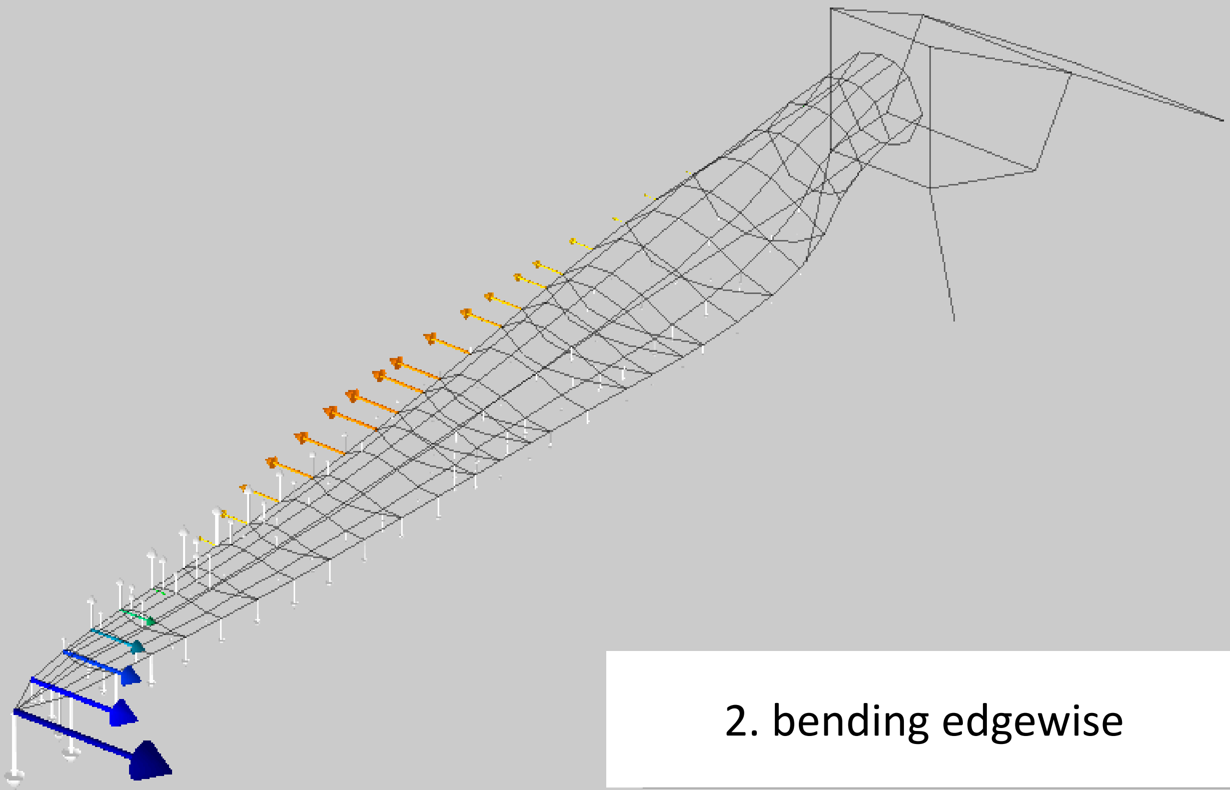
lateral test rig mode

back



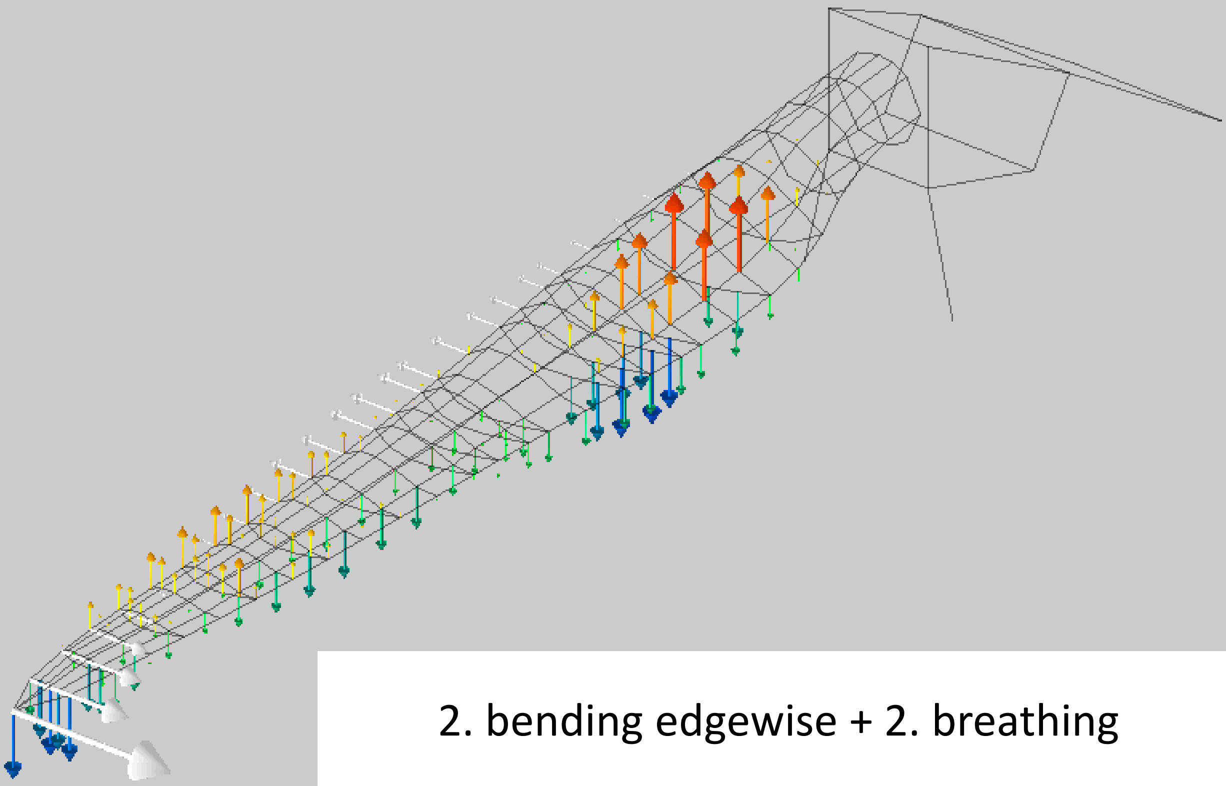
2. bending edgewise + 1. breathing

back



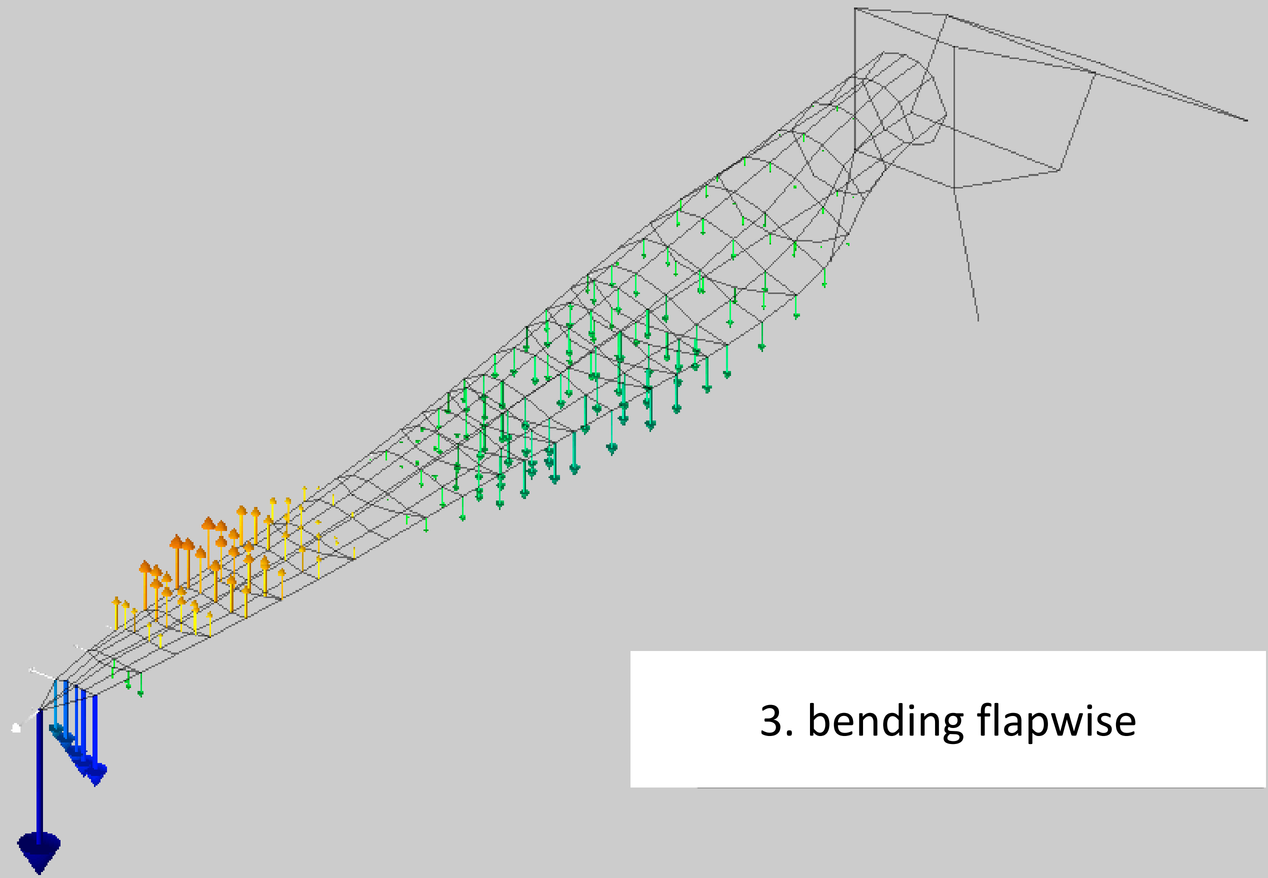
2. bending edgewise

back



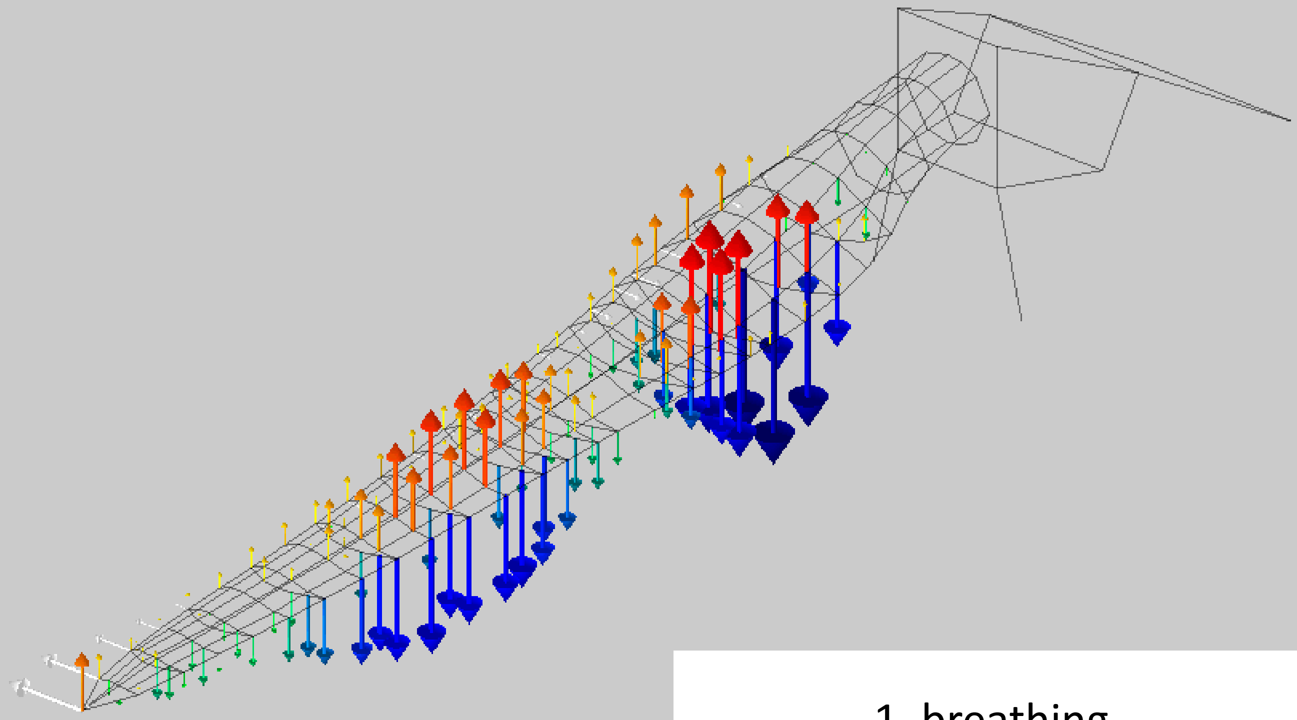
2. bending edgewise + 2. breathing

back



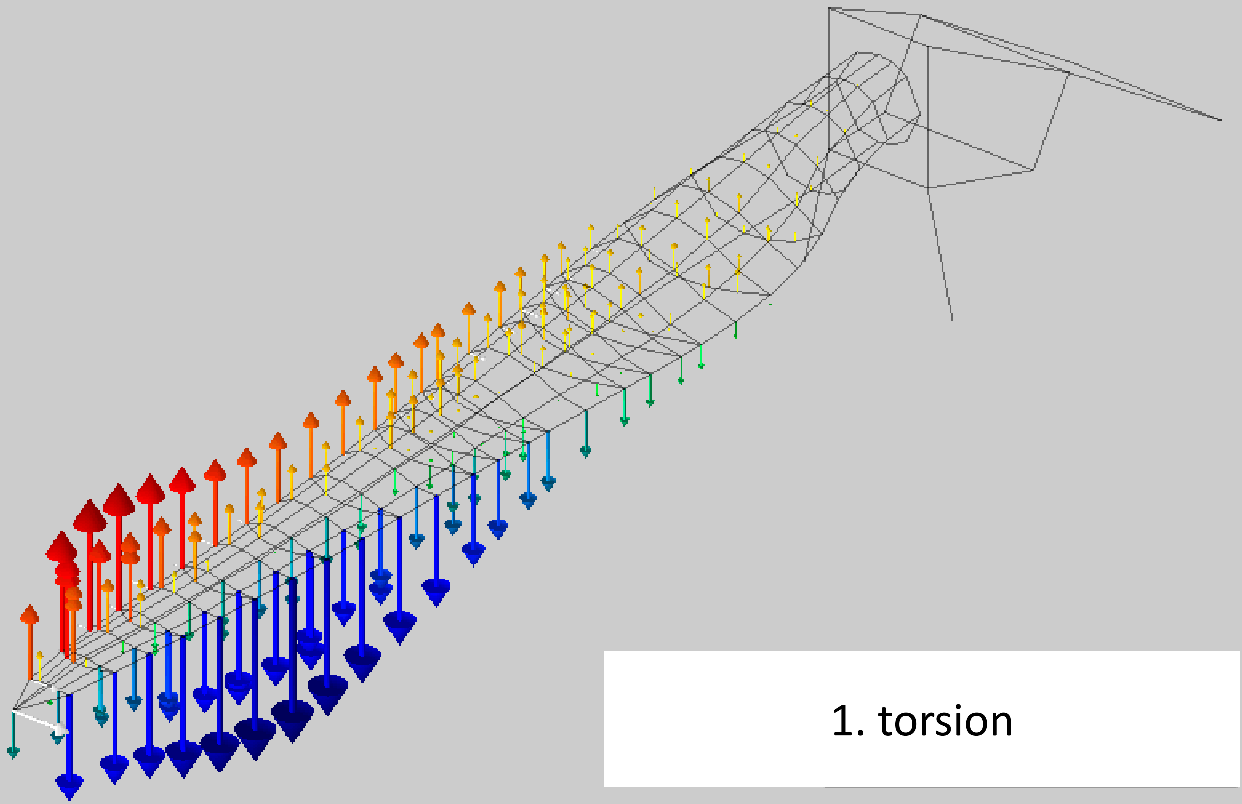
3. bending flapwise

back



1. breathing

back



1. torsion