Aeroelastic tailoring

Comp-Eco workshop

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This is a team effort in Delft …

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  - Tito Bordogna
  - Samuel Ijsselmuiden
- And many others

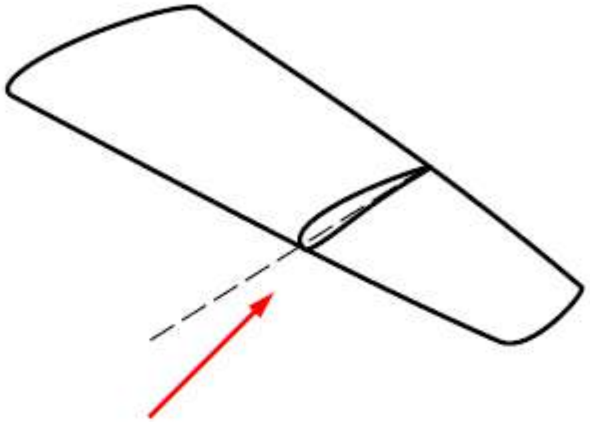
What are we going to discuss?

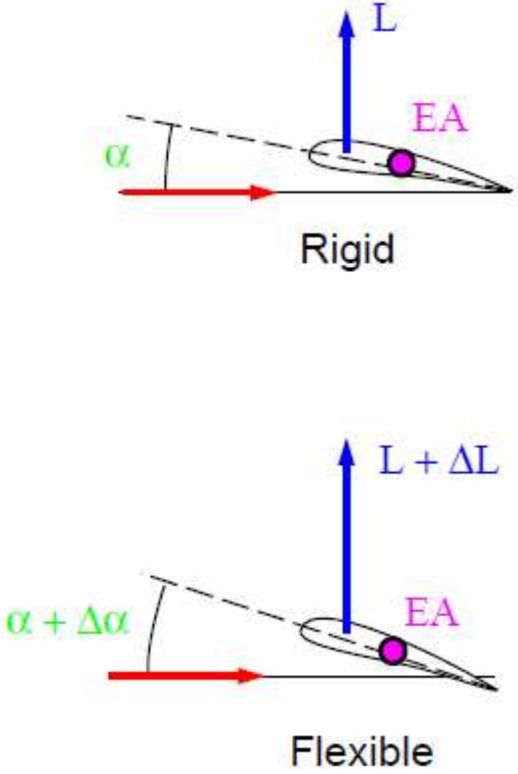
- Introduction to aeroelasticity and aeroelastic tailoring
- Modelling aspects
- Optimisation formulation
- Aeroelastically tailored results
- Experiments

What is aeroelasticity?

Aeroelasticity deals with the behaviour of an **elastic** structure in an **air**flow where there is signification **interaction** between the two

What is aeroelasticity?

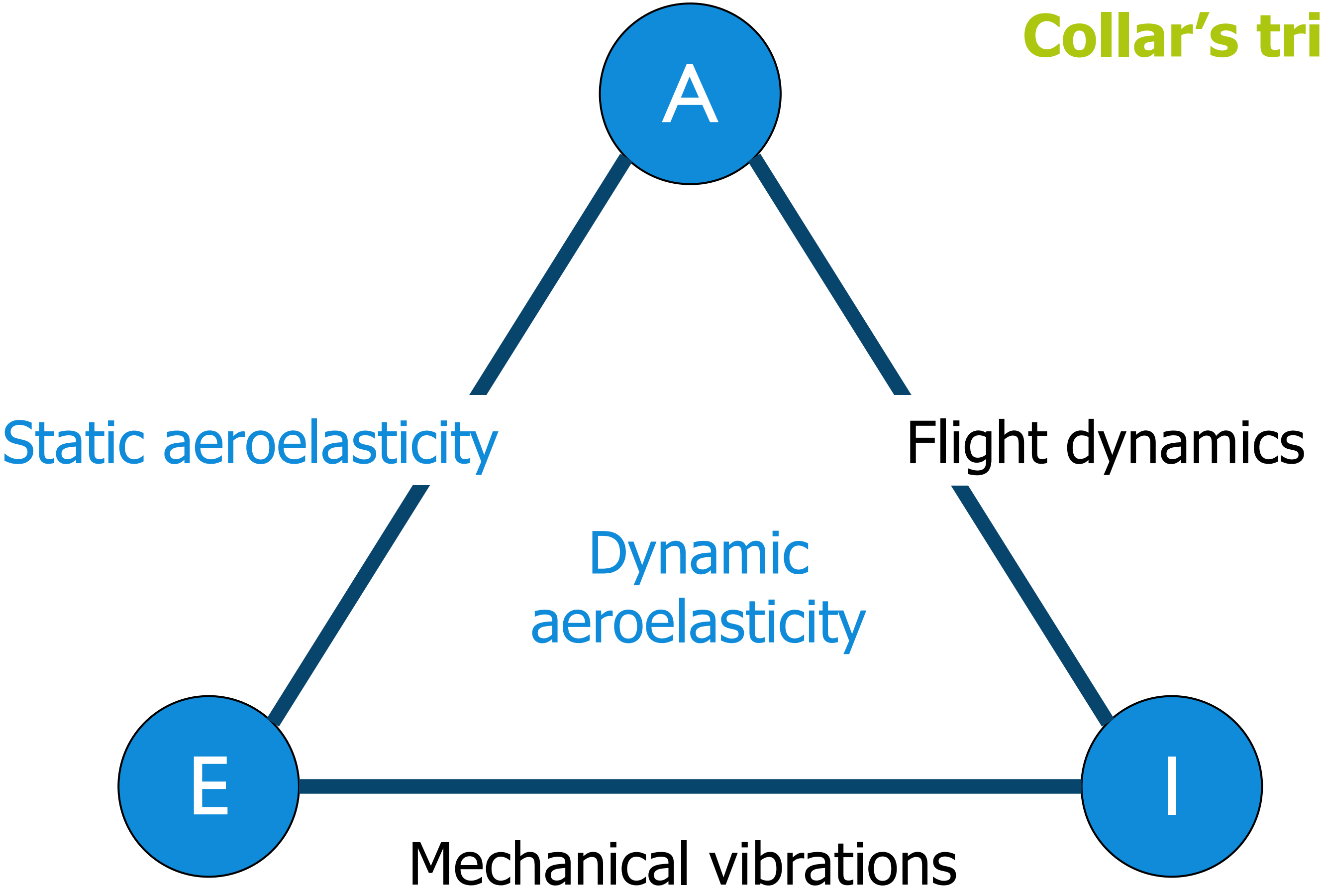




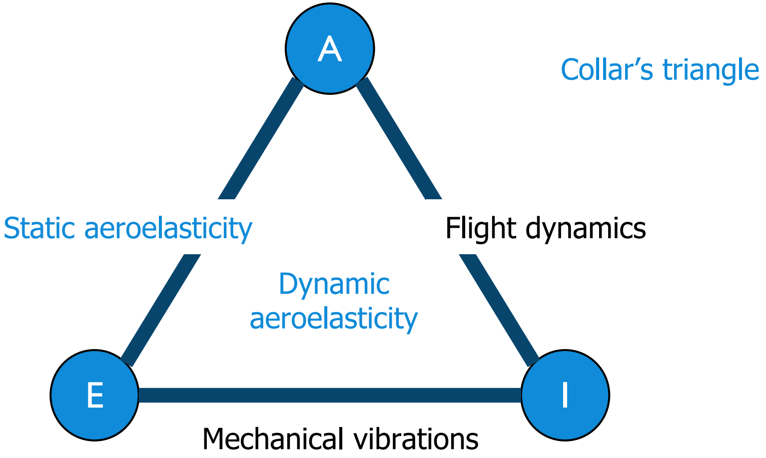
L: total lift
α: original angle of attack
$\Delta\alpha$: structural twist
EA: elastic axis

Aeroelastic interaction

Collar's triangle



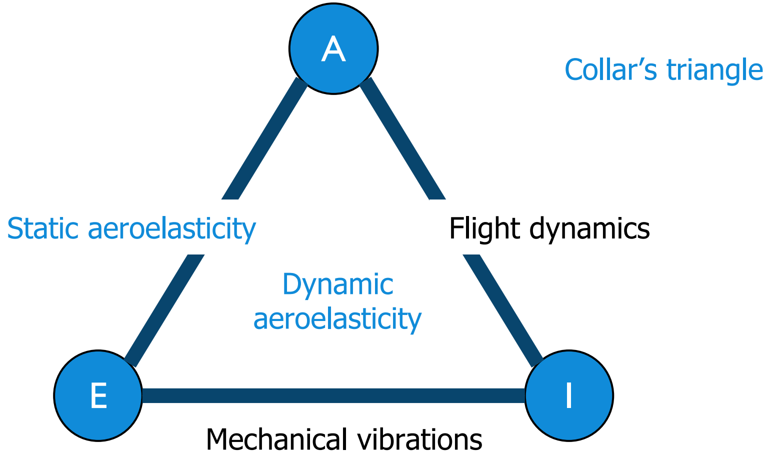
Static aeroelasticity



- Divergence
- Control reversal/effectiveness
- Trim
- Manoeuvre loads

Dynamic aeroelasticity

- Flutter
- Dynamic loads
  - Gust loads
  - Control loads


Collar's triangle

The importance of aeroelasticity

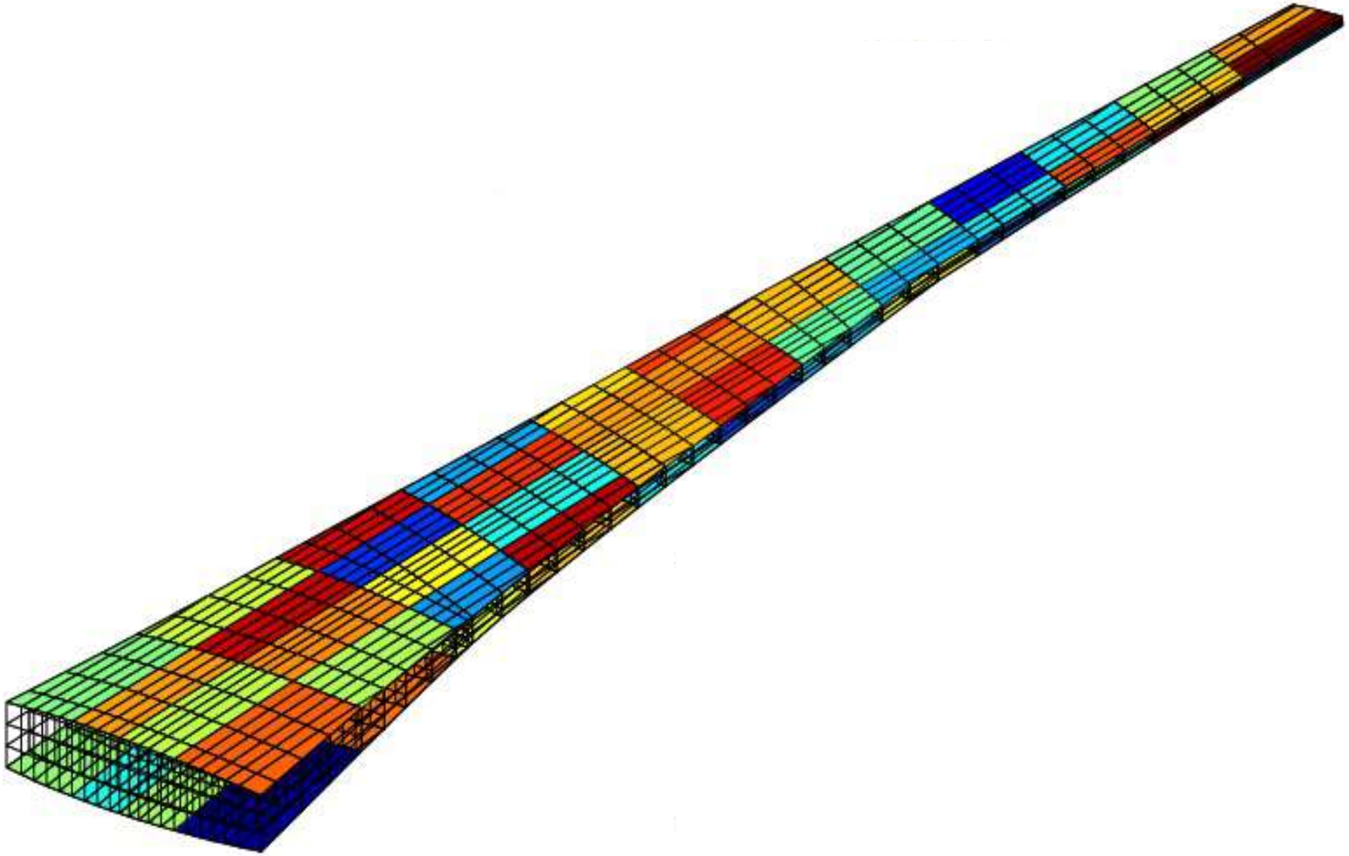
- Calculation of jig shape of the aircraft wing
- Aircraft performance optimisation
- Aircraft weight minimisation
- Flight envelope constraining
- Ride comfort

Aeroelastic tailoring? What is it?

The embodiment of directional stiffness into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way.

Weisshaar, 1986

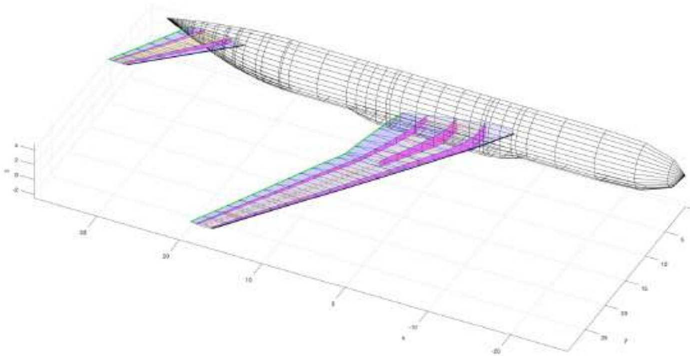
Aeroelastic tailoring: the challenges

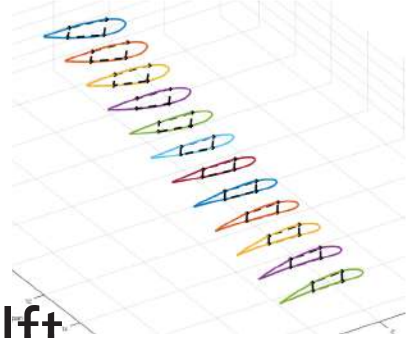


PROTEUS

Flight conditions
Manoeuvre/gust

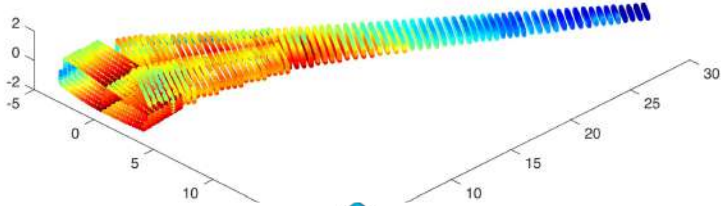
Fuel and mass cases





Static/dynamic aeroelastic stability and response

Skin and spar strains



Cross-sectional modeller

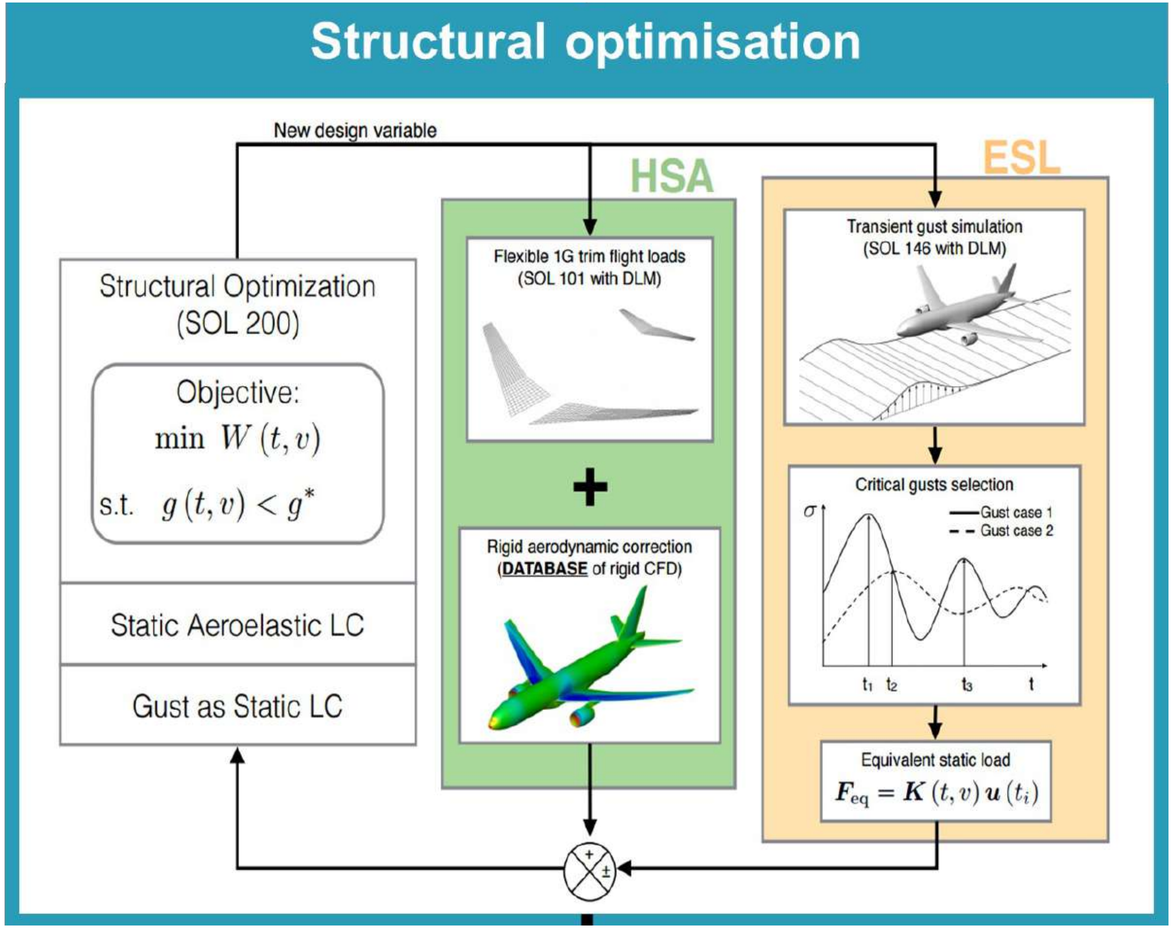
Aeroelastic analysis
- NL Timoshenko beam
- High-subsonic aero (continuous time)

HiFi NASTRAN model

- NASTRAN has limitations:
    1. High subsonic aerodynamics only (DLM)
    2. Limited capability to model airfoil curvature
    3. No sensitivity analysis of dynamic loads for optimization

- 2 proposed methods to solve issues with limitations 1/2 and 3
    1. Hybrid static approach (HSA)
    2. Equivalent static loads (ESL)

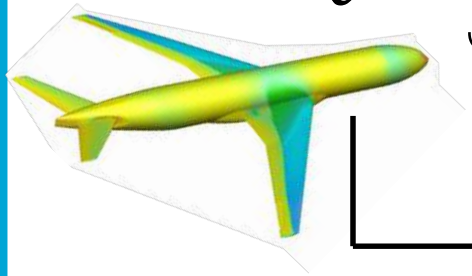
NASTRAN design loop



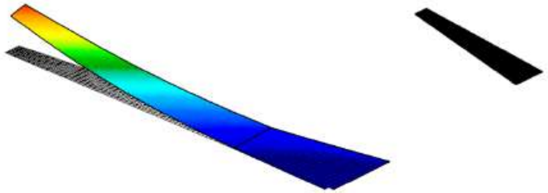
Correction for manoeuvres using the HSA

Developed by MSC Software, implemented in MSC NASTRAN:

$$Q = \underbrace{Q^{CFD}_{rigid}(\alpha)}_{\text{From rigid CFD database}} + \underbrace{\Delta Q^{DLM}_{elastic}(u)}_{\text{Elastic increment (DLM)}}$$



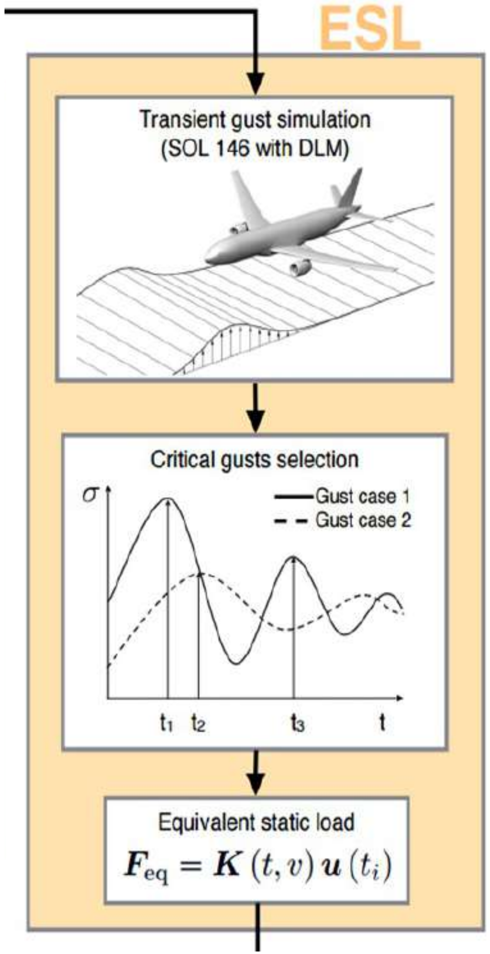
+



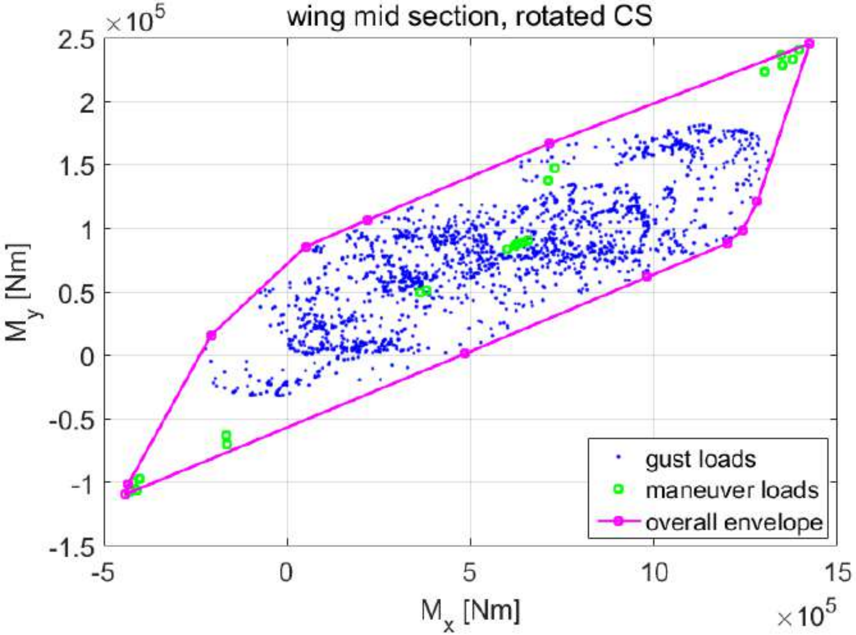
Aircraft flying at Mach 0.85, wing tip deflection approx. 5%

	Lift	Root bending	Root torsion
Coupled CFD/CSM	1.	1.	1.
Trimmed HSA	1.	1.0196	1.0093
Trimmed DLM	1.	1.1568	1.0018

Equivalent static load



$$\boldsymbol{F}_{\mathrm{eq}} = \boldsymbol{K}\,(t, v)\,\boldsymbol{u}\,(t_i)$$

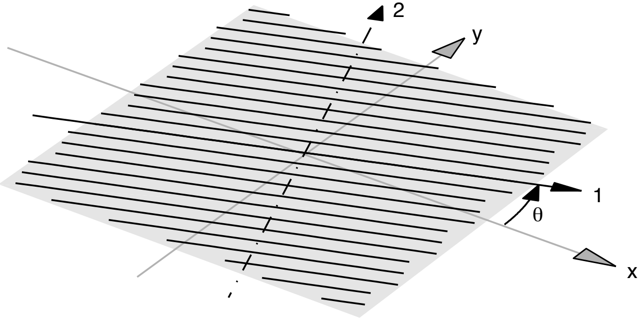


What will we discuss for the optimisation?

1. Design variables
2. Aeroelastic constraints
3. Structural constraints
4. Manufacturing constraints
5. Flight shape constraint
6. Objectives

Design variables

Homogenisation



$$\begin{aligned} Q_{11} &= \frac{E_1}{1-\nu_{12}\nu_{21}} , \\ Q_{22} &= \frac{E_2}{1-\nu_{12}\nu_{21}} , \\ Q_{12} &= \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} = \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} , \\ Q_{66} &= G_{12} . \end{aligned}$$

$$\begin{aligned} \mathbf{A} &= \sum_{k=1}^{n} \bar{\mathbf{Q}}_{(k)}(h_k - h_{k-1}) , \\ \mathbf{B} &= \frac{1}{2}\sum_{k=1}^{n} \bar{\mathbf{Q}}_{(k)}(h_k^2 - h_{k-1}^2) , \\ \mathbf{D} &= \frac{1}{3}\sum_{k=1}^{n} \bar{\mathbf{Q}}_{(k)}(h_k^3 - h_{k-1}^3) , \end{aligned}$$

$$\begin{aligned} \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} &= \mathbf{A}\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + \mathbf{B}\begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \\ \begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} &= \mathbf{B}\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + \mathbf{D}\begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \end{aligned}$$

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ \hline M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \left[\begin{array}{ccc:ccc} A_{11} & A_{12} & A_{13} & B_{11} & B_{12} & B_{13} \\ & A_{22} & A_{23} & & B_{22} & B_{23} \\ sym. & & A_{33} & sym. & & B_{33} \\ \hdashline B_{11} & B_{12} & B_{13} & D_{11} & D_{12} & D_{13} \\ & B_{22} & B_{23} & & D_{22} & D_{23} \\ sym. & & B_{33} & sym. & & D_{33} \end{array}\right] \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \hline \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}$$

Lamination parameters

$$
\begin{aligned}
(V_{1\mathbf{A}}, V_{2\mathbf{A}}, V_{3\mathbf{A}}, V_{4\mathbf{A}}) &= \frac{1}{h}\int_{-h/2}^{h/2} (cos2\theta, sin2\theta, cos4\theta, sin4\theta)\, dz \ , \\
(V_{1\mathbf{B}}, V_{2\mathbf{B}}, V_{3\mathbf{B}}, V_{4\mathbf{B}}) &= \frac{4}{h^2}\int_{-h/2}^{h/2} z\,(cos2\theta, sin2\theta, cos4\theta, sin4\theta)\, dz \ , \\
(V_{1\mathbf{D}}, V_{2\mathbf{D}}, V_{3\mathbf{D}}, V_{4\mathbf{D}}) &= \frac{12}{h^3}\int_{-h/2}^{h/2} z^2\,(cos2\theta, sin2\theta, cos4\theta, sin4\theta)\, dz \ .
\end{aligned}
$$

$$
\begin{aligned}
\mathbf{A} &= h(\mathbf{\Gamma}_0 + \mathbf{\Gamma}_1 V_{1\mathbf{A}} + \mathbf{\Gamma}_2 V_{2\mathbf{A}} + \mathbf{\Gamma}_3 V_{3\mathbf{A}} + \mathbf{\Gamma}_4 V_{4\mathbf{A}}) \ , \\
\mathbf{B} &= \frac{h^2}{4}(\mathbf{\Gamma}_1 V_{1\mathbf{B}} + \mathbf{\Gamma}_2 V_{2\mathbf{B}} + \mathbf{\Gamma}_3 V_{3\mathbf{B}} + \mathbf{\Gamma}_4 V_{4\mathbf{B}}) \ , \\
\mathbf{D} &= \frac{h^3}{12}(\mathbf{\Gamma}_0 + \mathbf{\Gamma}_1 V_{1\mathbf{D}} + \mathbf{\Gamma}_2 V_{2\mathbf{D}} + \mathbf{\Gamma}_3 V_{3\mathbf{D}} + \mathbf{\Gamma}_4 V_{4\mathbf{D}}) \ .
\end{aligned}
$$

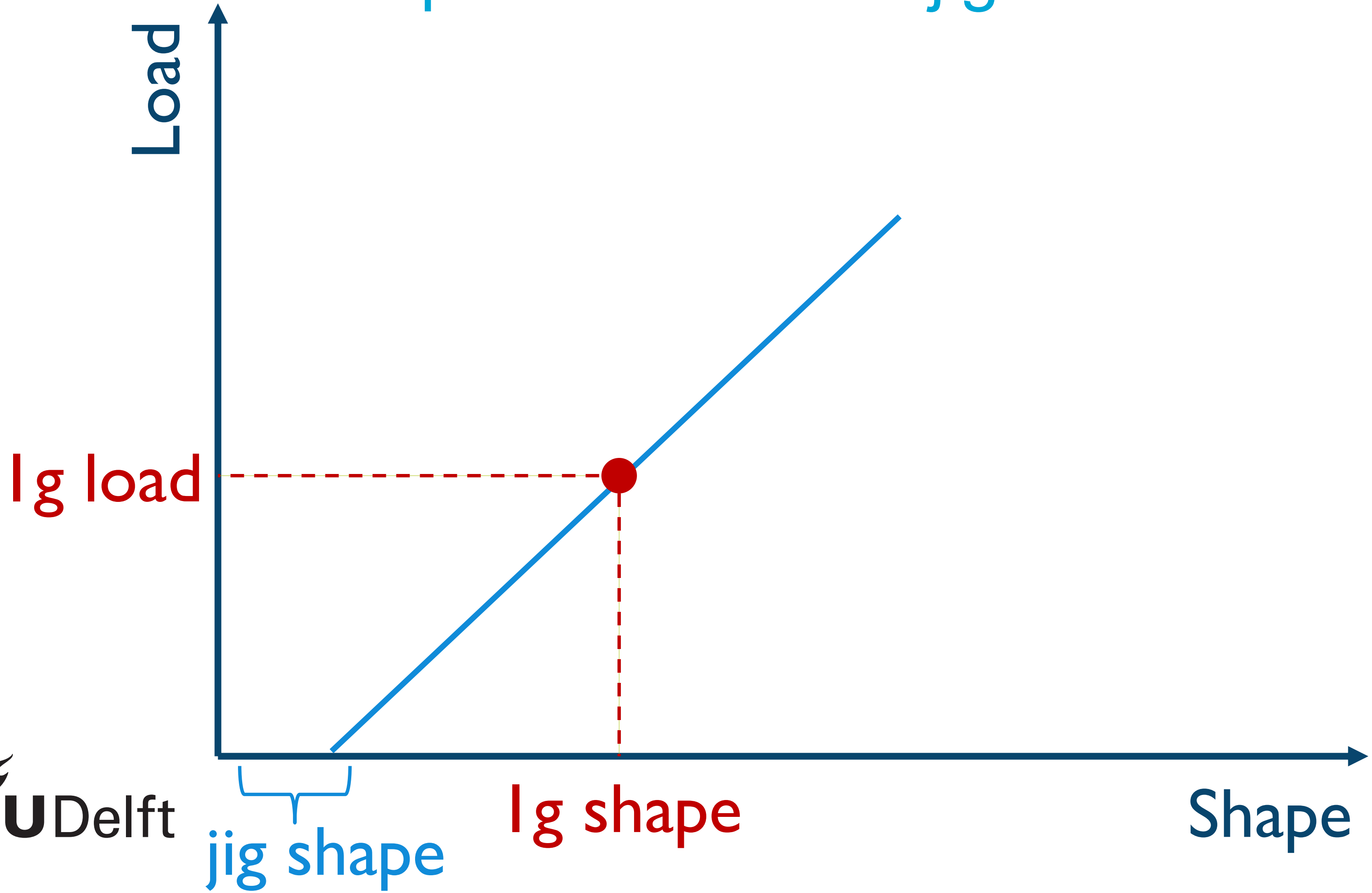
$$
\mathbf{\Gamma}_0 = \begin{bmatrix} U_1 & U_4 & 0 \\ U_4 & U_1 & 0 \\ 0 & 0 & U_5 \end{bmatrix}, \quad
\mathbf{\Gamma}_1 = \begin{bmatrix} U_2 & 0 & 0 \\ 0 & -U_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad
\mathbf{\Gamma}_2 = \begin{bmatrix} 0 & 0 & U_2/2 \\ 0 & 0 & U_2/2 \\ U_2/2 & U_2/2 & 0 \end{bmatrix},
$$

$$
\mathbf{\Gamma}_3 = \begin{bmatrix} U_3 & -U_3 & 0 \\ -U_3 & U_3 & 0 \\ 0 & 0 & -U_3 \end{bmatrix}, \quad
\mathbf{\Gamma}_4 = \begin{bmatrix} 0 & 0 & U_3 \\ 0 & 0 & -U_3 \\ U_3 & -U_3 & 0 \end{bmatrix} . \qquad (1.30)
$$

Jig shape parameters

- 1g flight shape is usually determined by aerodynamics.
- Most common procedure is to reverse that 1g loads and apply them to the 1g shape to retrieve the jig shape.
- This approach does not work in case of large deflections.
- 1g shape twist is driving the aerodynamic performance, to a lesser extent also 1g shape deflection.
- Jig shape twist distribution part of the optimization, constraint on 1g twist distribution.

Importance of free jig twist



Aeroelastic constraints

Aeroelastic stability

- There are two types of aeroelastic stability:
  - Divergence
  - Flutter

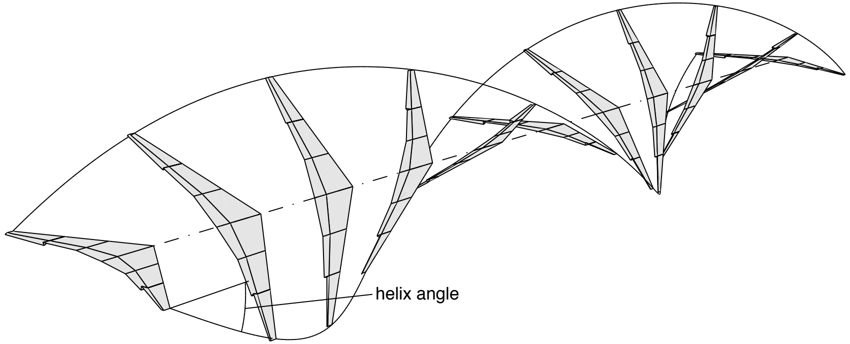
- Both can be approached as an eigenvalue equation.

- Divergence is calculated automatically when carrying out a flutter analysis.

Aileron effectiveness

- Deflecting control surfaces and cause a nose down twist of the wing counteracting the intended roll moment.
- A minimum control effectiveness is required to keep the aircraft controllable.
- Control surface use can differ for high speed and low speed flight.

$$\begin{aligned} M_\delta + M_p &= 0\ , \\ C_{l_\delta}\delta(qS_{ref}s) + C_{l_p}p\frac{s}{V_\infty}(qS_{ref}s) &= 0\ , \\ -\frac{C_{l_\delta}}{C_{l_p}}\delta &= \frac{ps}{V_\infty} \end{aligned}$$



Handling Qualities

MIL-HDBK-1797

Class of Aircraft

Level of Maneuverability

Category of Maneuver

Handling Qualities

MIL-HDBK-1797

Class of Aircraft

- Class I
  Ultralight aircraft.
- Class II
  Assault, bomber etc.
- Class III
  Commercial etc.

Level of Maneuverability

Category of Maneuver

Handling Qualities

MIL-HDBK-1797

Class of Aircraft

Level of Maneuverability

- L1
  Adequate.
- L2
  Acceptable.
- L3
  Controllable.

Category of Maneuver

Handling Qualities

MIL-HDBK-1797

Class of Aircraft

Level of Maneuverability

Category of Maneuver

- A
  Combat.
- B
  Gradual maneuvers.
- C
  Take-off, landing.

Handling Qualities

MIL-HDBK-1797

Class of Aircraft

- Class I
  Ultralight aircraft.
- Class II
  Assault, bomber etc.
- Class III
  Commercial etc.

Level of Maneuverability

- L1
  Adequate.
- L2
  Acceptable.
- L3
  Controllable.

Category of Maneuver

- A
  Combat.
- B
  Gradual maneuvers.

Handling Qualities

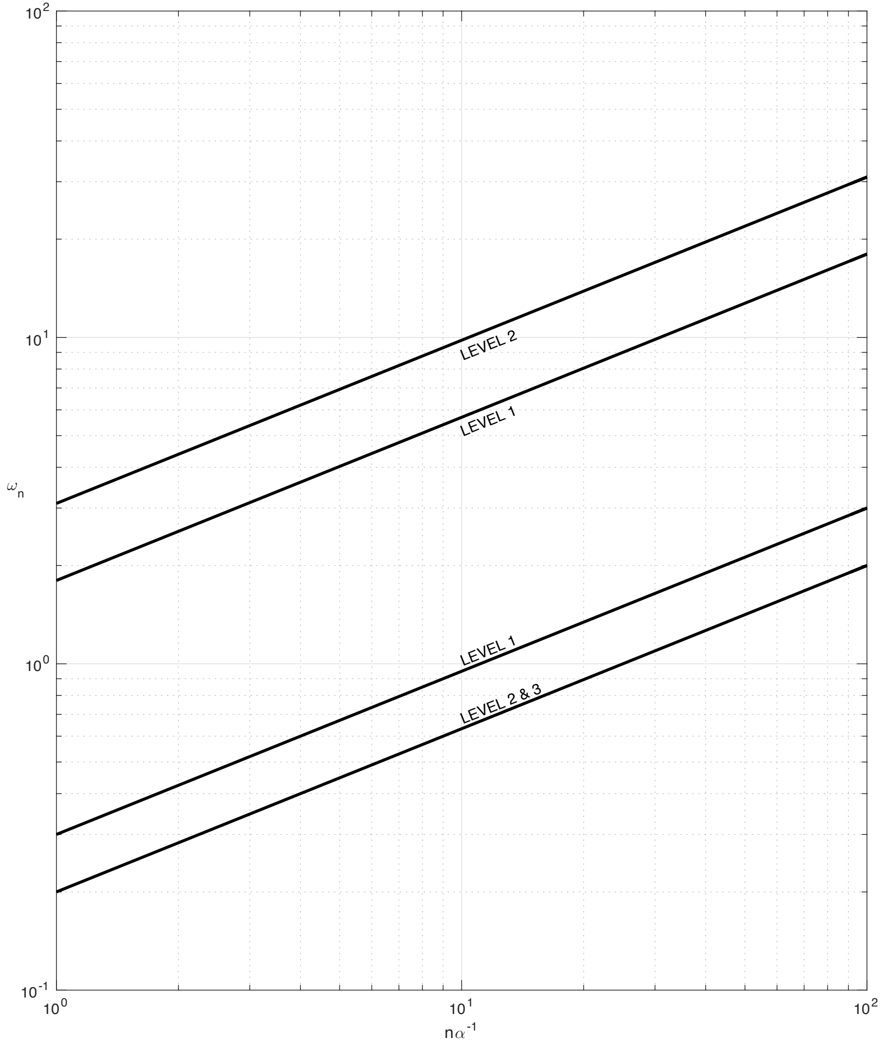
MIL-HDBK-1797

3.2 Longitudinal Flight Qualities

- Short-Period Frequency and Damping
- Phugoid Damping
- Flight Path Angle

Example

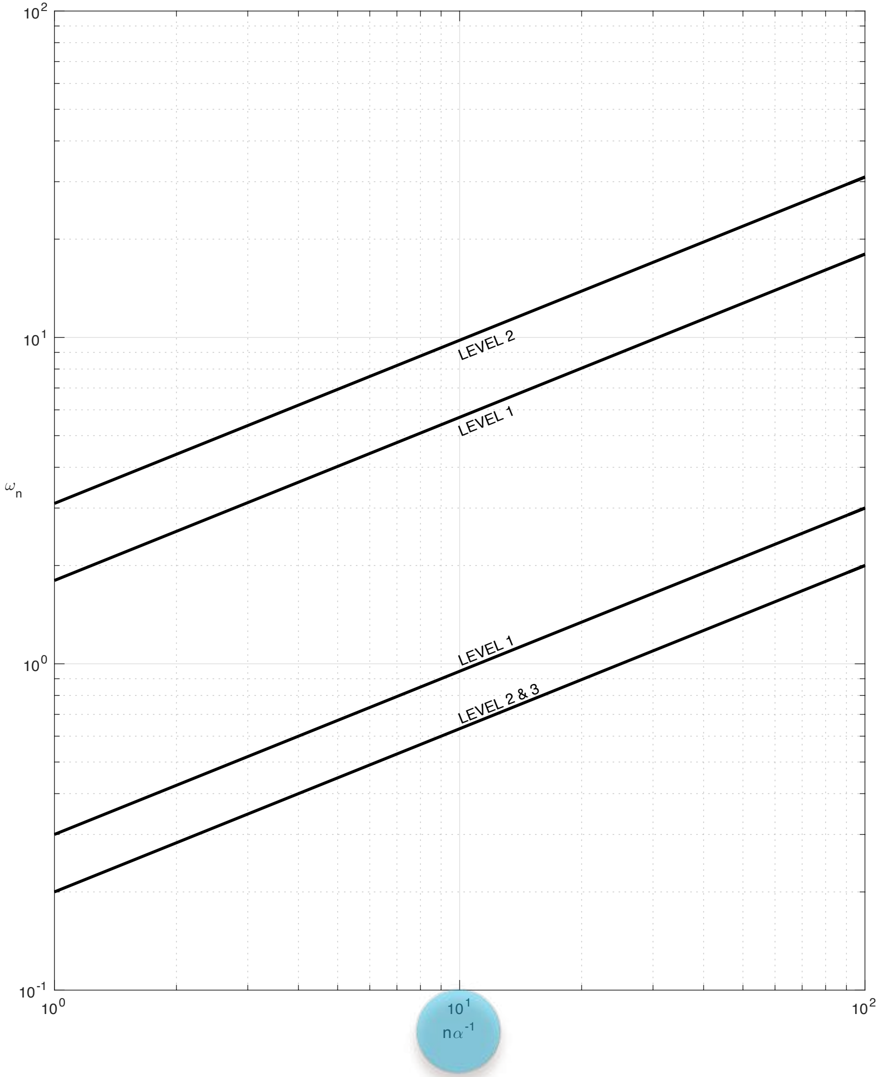
Short-Period Frequency
Class III
Category B



Example

Short-Period Frequency
Class III
Category B

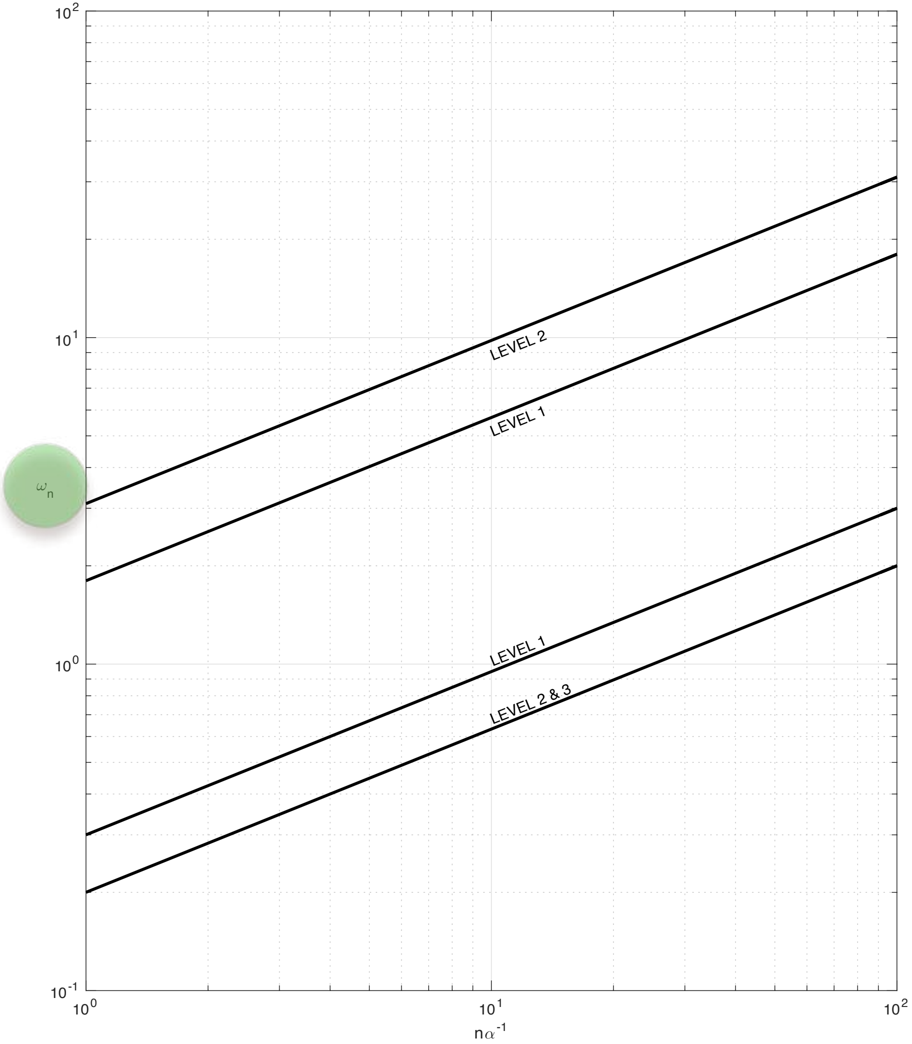
$\frac{\text{Load Factor}}{\text{Trim Angle}}$



Example

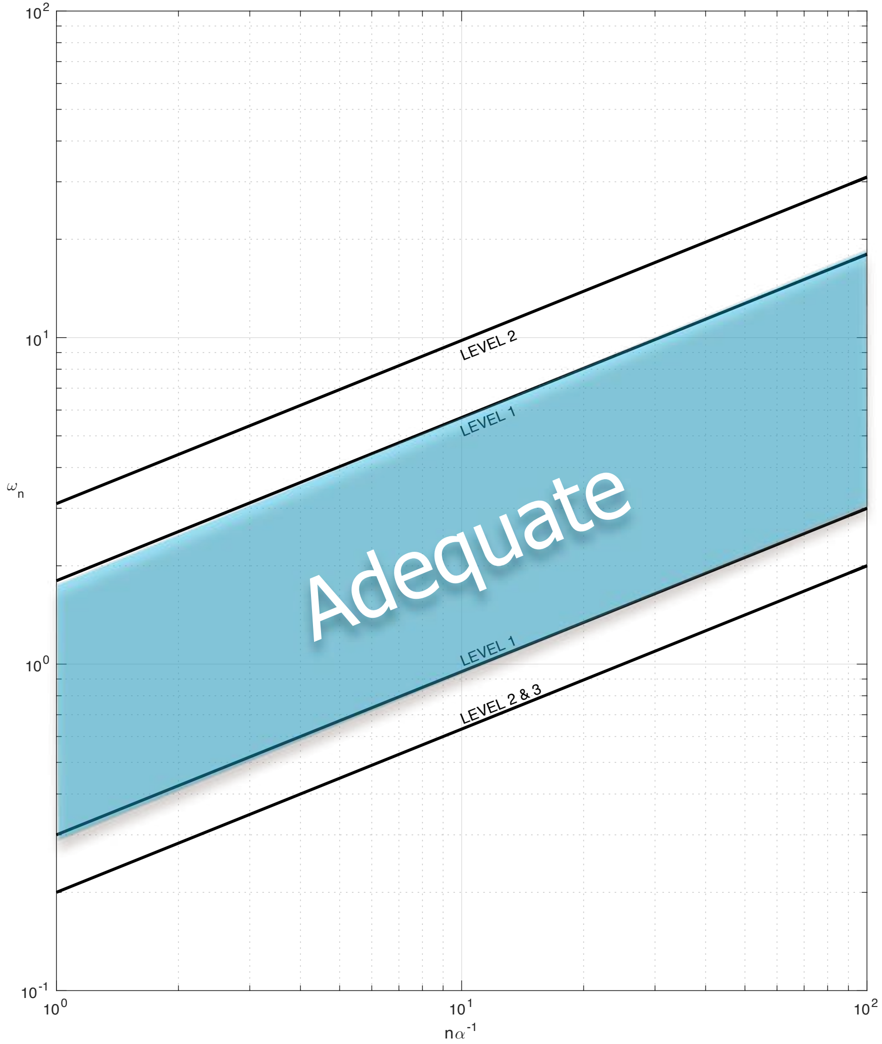
Short-Period Frequency
Class III
Category B

Modal Frequency



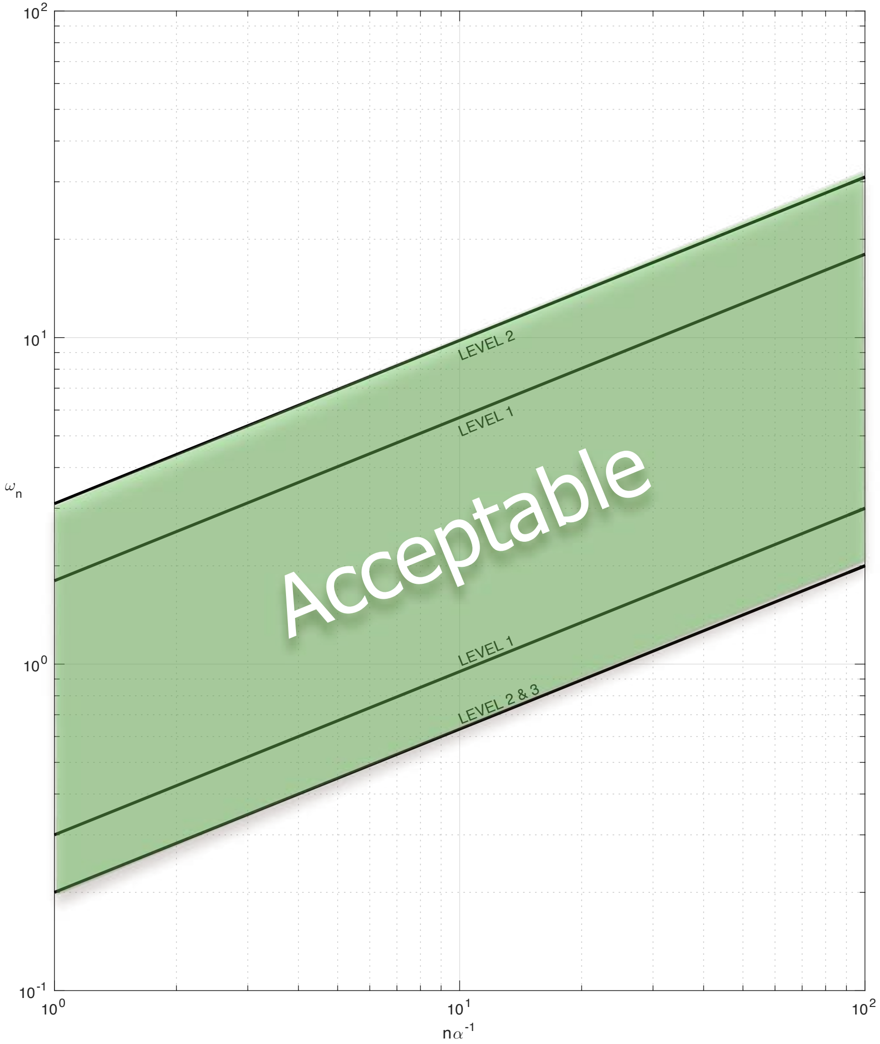
Example

Short-Period Frequency
Class III
Category B



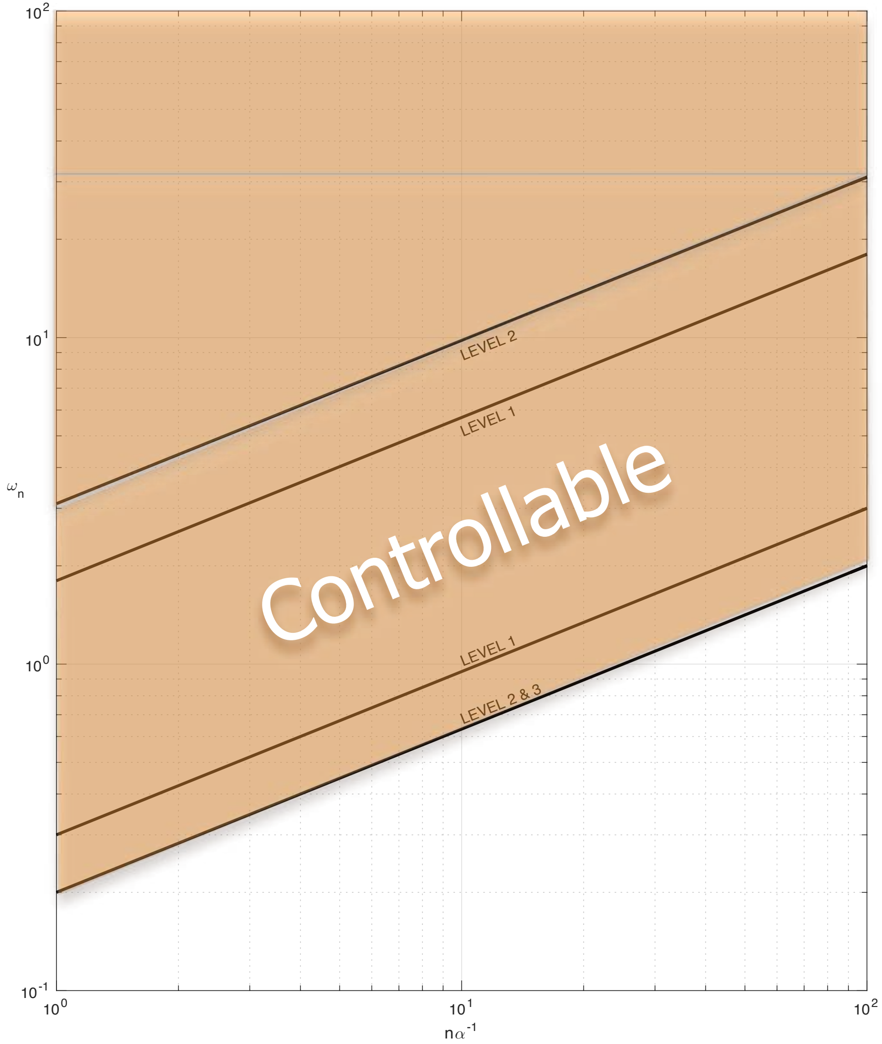
Example

Short-Period Frequency
Class III
Category B



Example

Short-Period Frequency
Class III
Category B



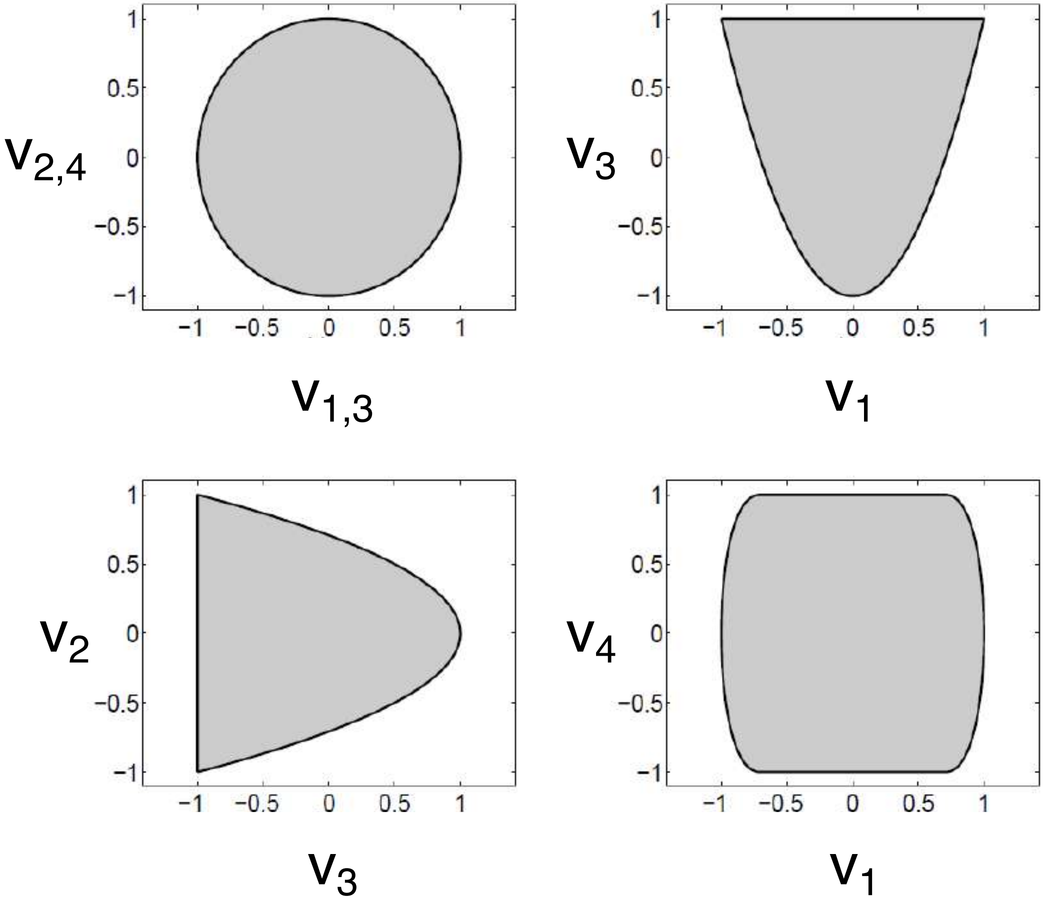
Structural constraints

Laminate feasibility

- There must be a feasible combination between lamination parameters to retrieve feasible stacking sequence.
- In-plane and out-of-plane lamination parameters can not be chosen independently.

$$\begin{aligned} 2V_1^2\left(1-V_3\right)+2V_2^2\left(1+V_3\right)+V_3^2+V_4^2-4V_1V_2V_4 &\leq 1 \\ V_1^2+V_2^2 &\leq 1 \\ -1\leq V_i &\leq 1 \end{aligned}$$

Laminate feasibility



Buckling

- Only inter-rib and inter-stiffener buckling is considered.
- The buckling panels are assumed to be simply supported.
- Panels transformed to a domain ranging from -1 to 1 using a bilinear transformation.
- The load is assumed to be constant over a panel in a certain direction.

Failure

- Tsai-Wu first ply failure criterion.

$$F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\sigma_1\sigma_2 = 1$$

$$F_{11} = \frac{1}{X_t X_c} \qquad F_{22} = \frac{1}{Y_t Y_c} \qquad F_1 = \frac{1}{X_t} - \frac{1}{X_c}$$

$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c} \qquad F_{12} = \frac{-1}{2\sqrt{X_t X_c Y_t Y_c}} \qquad F_{66} = \frac{1}{S^2}$$

- Related to strain measures through the Q matrix:

$$G_{11}\epsilon_1^2 + G_{22}\epsilon_2^2 + G_{66}\epsilon_{12}^2 + G_1\epsilon_1 + G_2\epsilon_2 + 2G_{12}\epsilon_1\epsilon_2 = 1$$

- Transformation from material strains to laminate strains

$$\begin{bmatrix} \frac{1}{2}(1+c) & \frac{1}{2}(1-c) & s \\ \frac{1}{2}(1-c) & \frac{1}{2}(1+c) & -s \\ -\frac{1}{2}s & \frac{1}{2}s & c \end{bmatrix}$$

Khani, A., IJsselmuiden, S. T., Abdalla, M. M., & Gürdal, Z. (2011). Design of variable stiffness panels for maximum strength using lamination parameters. *Composites Part B: Engineering*, *42*(3), 546-552.

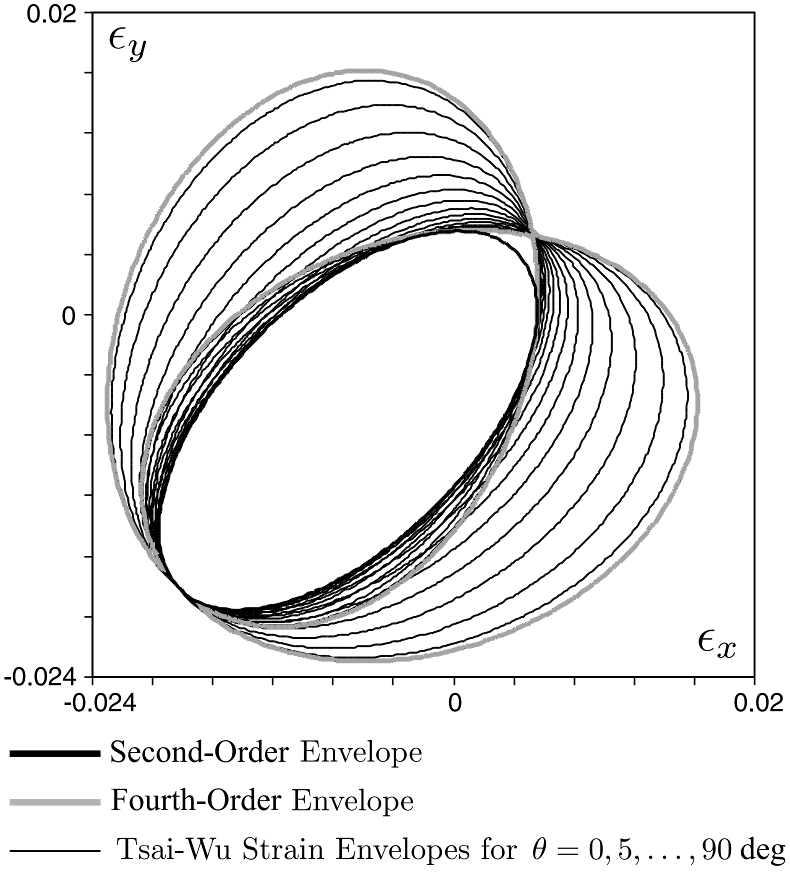
Failure

- Failure is governed by this equation:

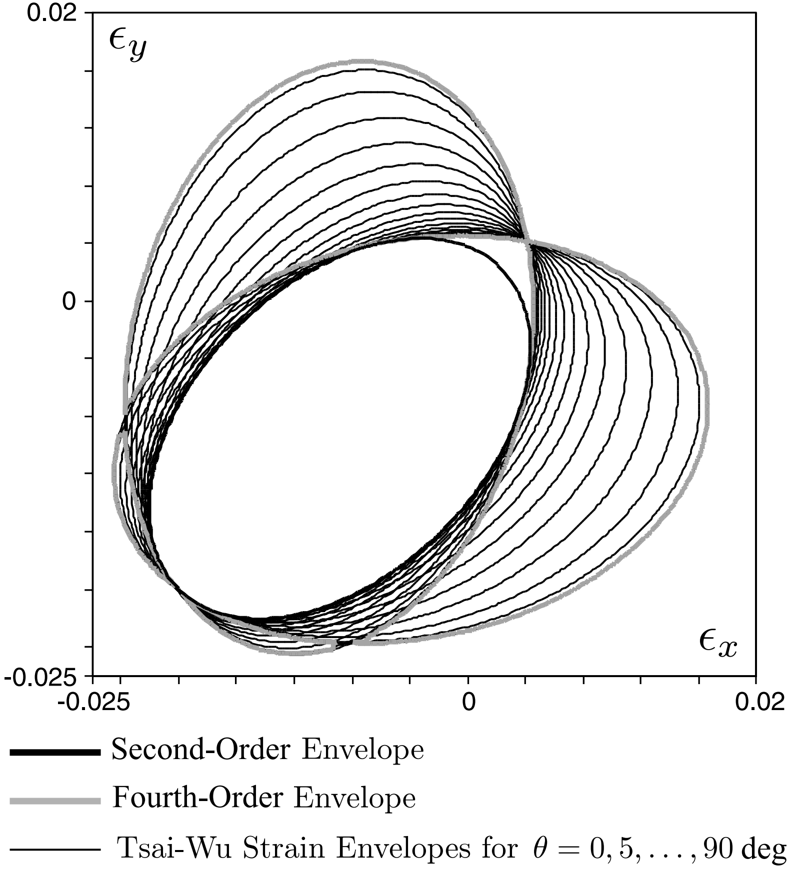
$$F(\epsilon_x, \epsilon_y, \epsilon_{xy}, s, c) = 0$$

- Needs to be written for lamination parameters, i.e. independent of the ply angles: eliminate the ply angle by imposing two additional equations
  - The trigonometric relation $\cos^2\theta + \sin^2\theta = 1$
  - A surface tangential to all failure functions for each θ, $\frac{dF}{d\theta} = 0$

Failure envelope examples

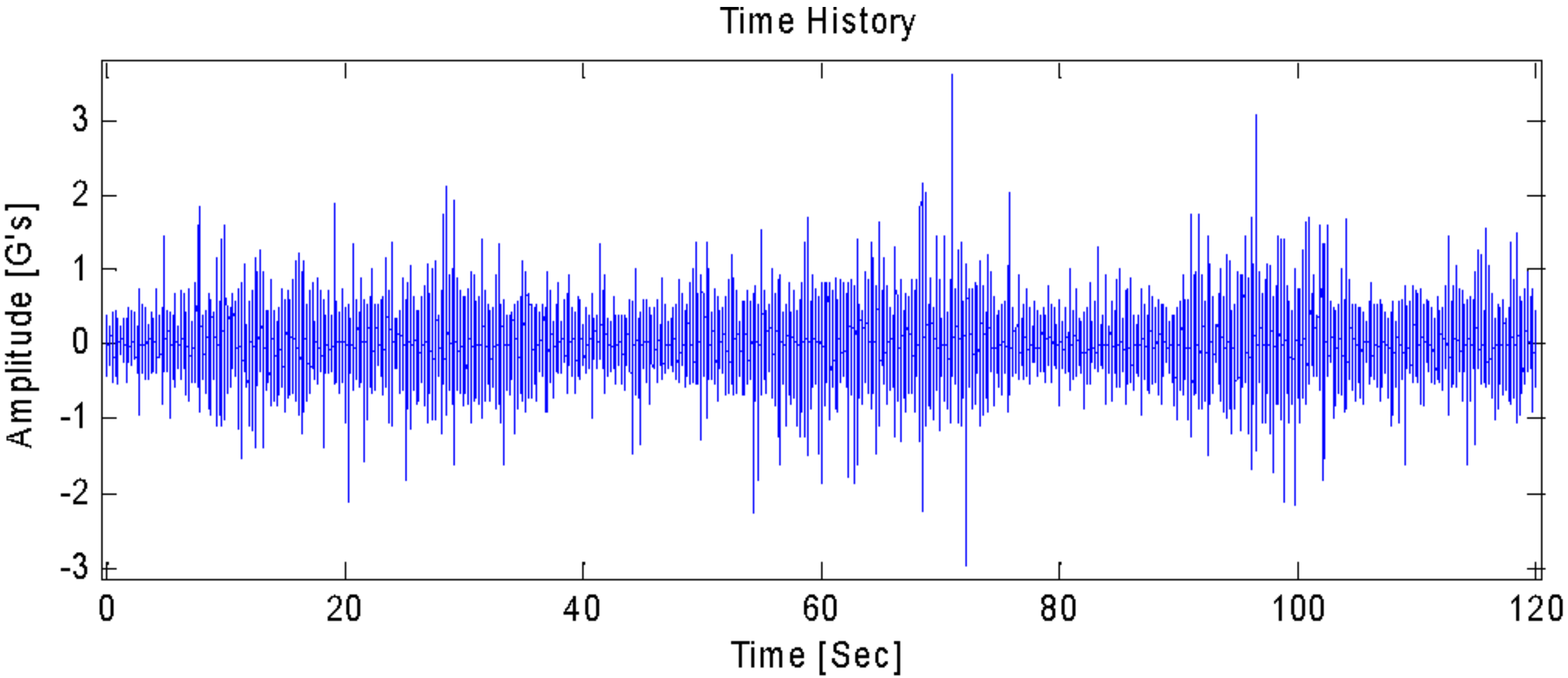


AS4



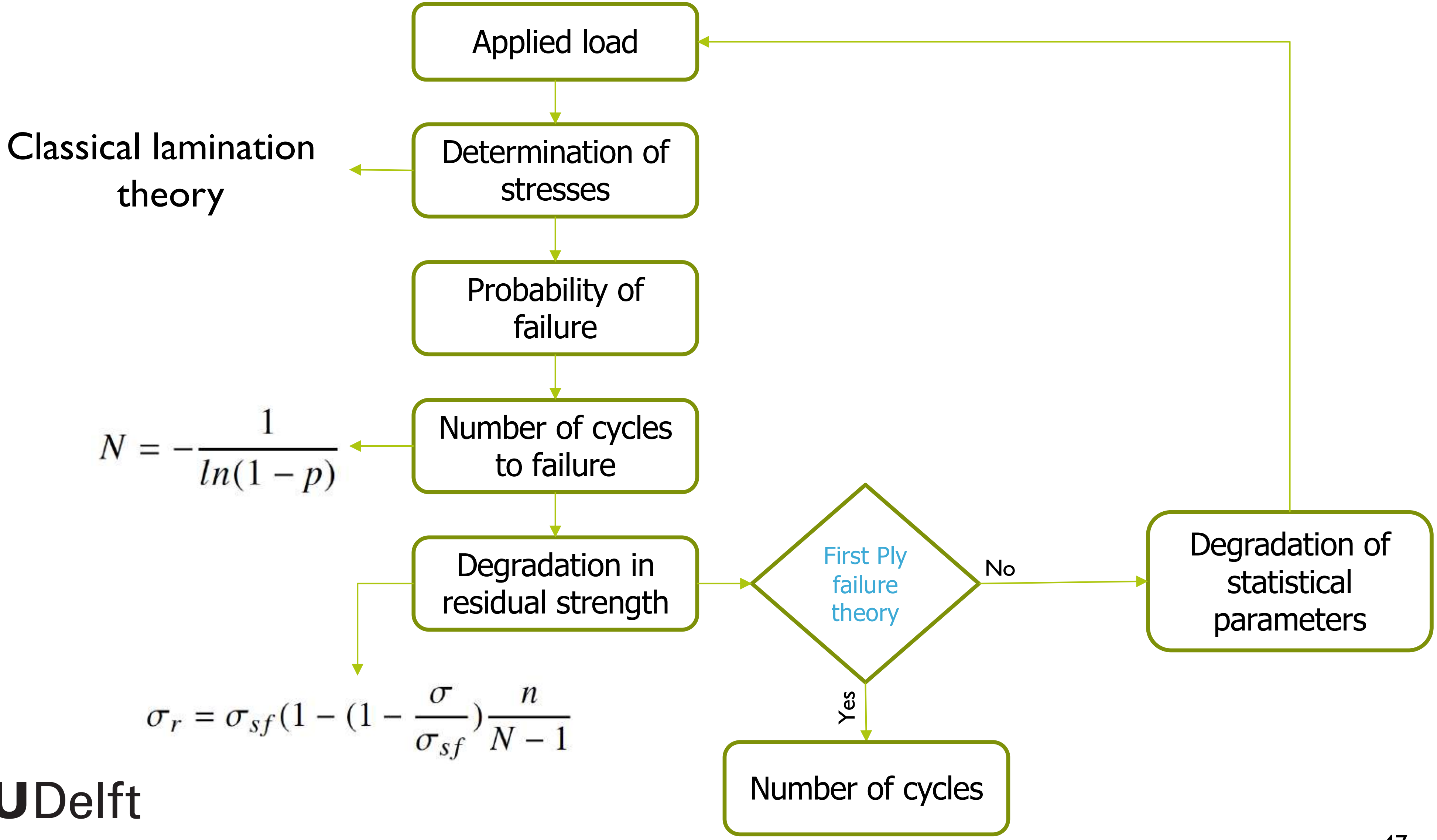
IM7

Effect of fatigue loads



Design for number of flight cycles

- **Standard practice**: apply knock-down factor to material allowables to ensure a no-fatigue design.
- **Proposed solution**: design the lifting surface to fail at a prescribed amount of flights.
- **Methodology**: combine probability of failure at a certain number of cycles with Tsai-Wu failure theorem.



Applied load

Determination of stresses

Classical lamination theory

Probability of failure

Number of cycles to failure

$$N = -\frac{1}{ln(1-p)}$$

Degradation in residual strength

$$\sigma_r = \sigma_{sf}(1-(1-\frac{\sigma}{\sigma_{sf}})\frac{n}{N-1}$$

First Ply failure theory

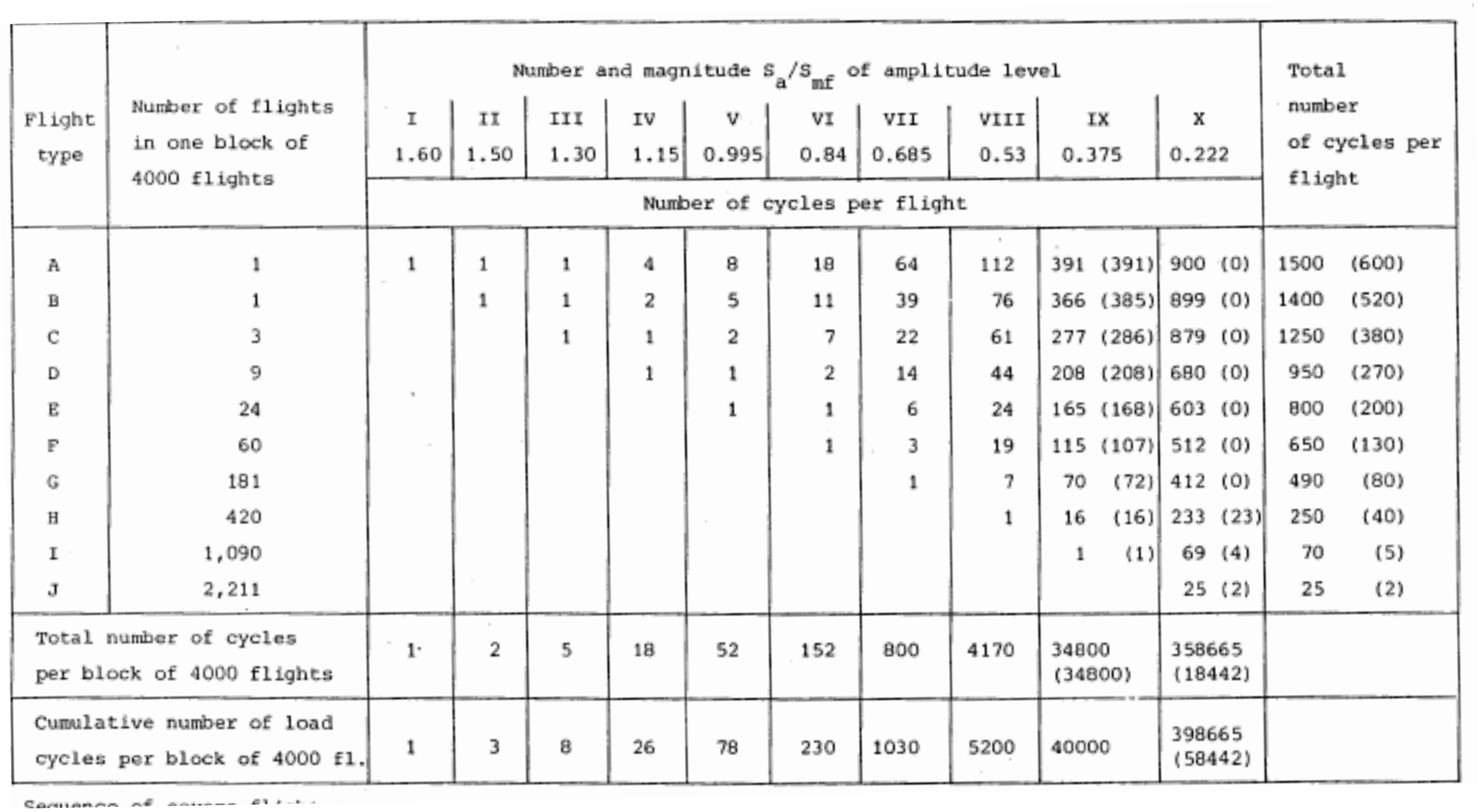
No

Degradation of statistical parameters

Yes

Number of cycles

Applied loads are obtained from TWIST



Flight type	Number of flights in one block of 4000 flights	Number and magnitude S_a/S_{mf} of amplitude level										Total number of cycles per flight
		I 1.60	II 1.50	III 1.30	IV 1.15	V 0.995	VI 0.84	VII 0.685	VIII 0.53	IX 0.375	X 0.222	
		Number of cycles per flight										
A	1	1	1	1	4	8	18	64	112	391 (391)	900 (0)	1500 (600)
B	1		1	1	2	5	11	39	76	366 (385)	899 (0)	1400 (520)
C	3			1	1	2	7	22	61	277 (286)	879 (0)	1250 (380)
D	9				1	1	2	14	44	208 (208)	680 (0)	950 (270)
E	24					1	1	6	24	165 (168)	603 (0)	800 (200)
F	60						1	3	19	115 (107)	512 (0)	650 (130)
G	181							1	7	70 (72)	412 (0)	490 (80)
H	420								1	16 (16)	233 (23)	250 (40)
I	1,090									1 (1)	69 (4)	70 (5)
J	2,211										25 (2)	25 (2)
Total number of cycles per block of 4000 flights		1	2	5	18	52	152	800	4170	34800 (34800)	358665 (18442)	
Cumulative number of load cycles per block of 4000 fl.		1	3	8	26	78	230	1030	5200	40000	398665 (58442)	

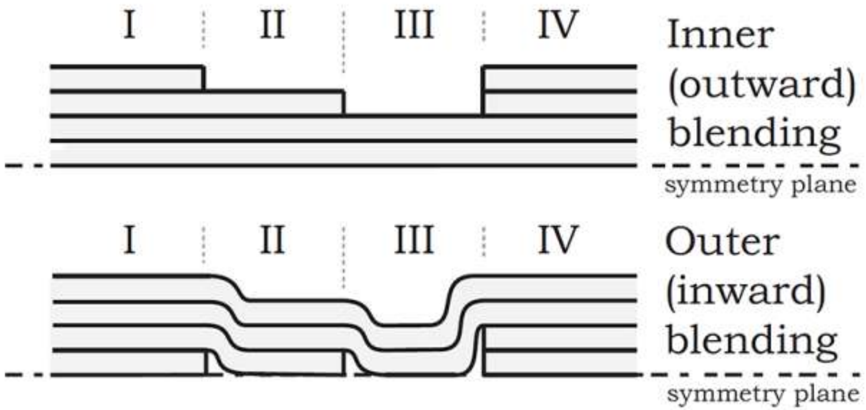
Lowak, H., DeJonge, J., Franz, J., and Schütz, D., "MINITWIST - A shortened version of TWIST," *NLR MP79018U*, 1979.

Manufacturing constraints

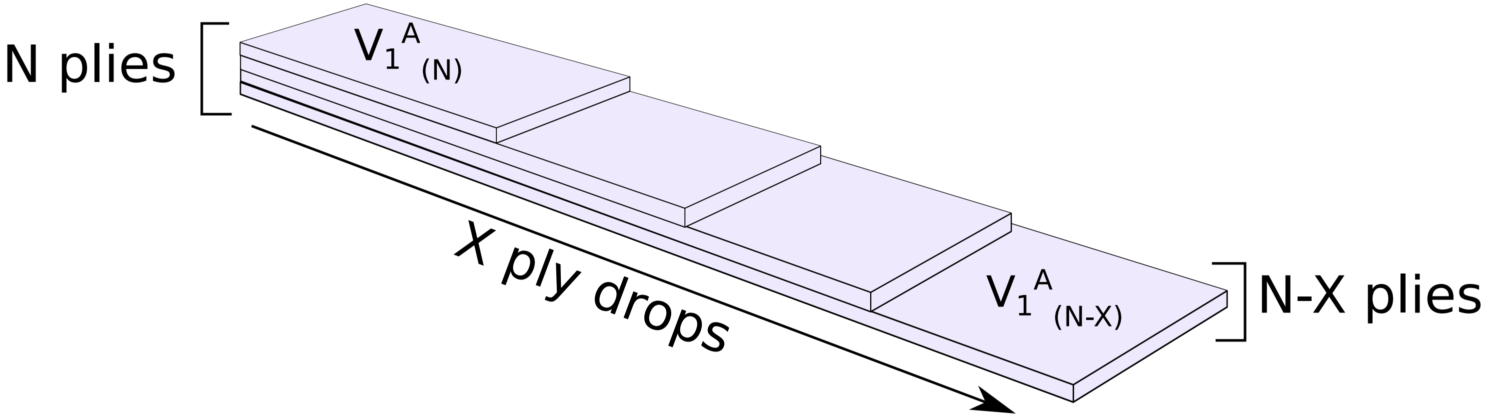
NASA rules for composite manufacturing

- Symmetric laminates: This rule is generally applied to avoid out of plane deformation during the curing process, due to the in-plane extension of the laminate.
- Balanced laminates: same number of plies with orientation equal to θ and $-\theta$ so that $A_{16}=A_{26}=0$.
- Contiguity rule: no more than 4 successive plies with the same orientation.
- Blending rule: ply continuity need to be ensured from one panel to another.
- Restricted angle: a limited set of ply orientation is available to build the laminate. Known as the classical orientation, they are equivalent to [0/90/±45].
- Disorientation rule: no more than ±45 difference between successive layers in order to avoid inter-plies stresses.
- Percentage rule: a minimum of 10% of the plies must be in each of the following direction: 0, 45, 90 and -45. This should ensure that the structure is robust enough to carry secondary loading.

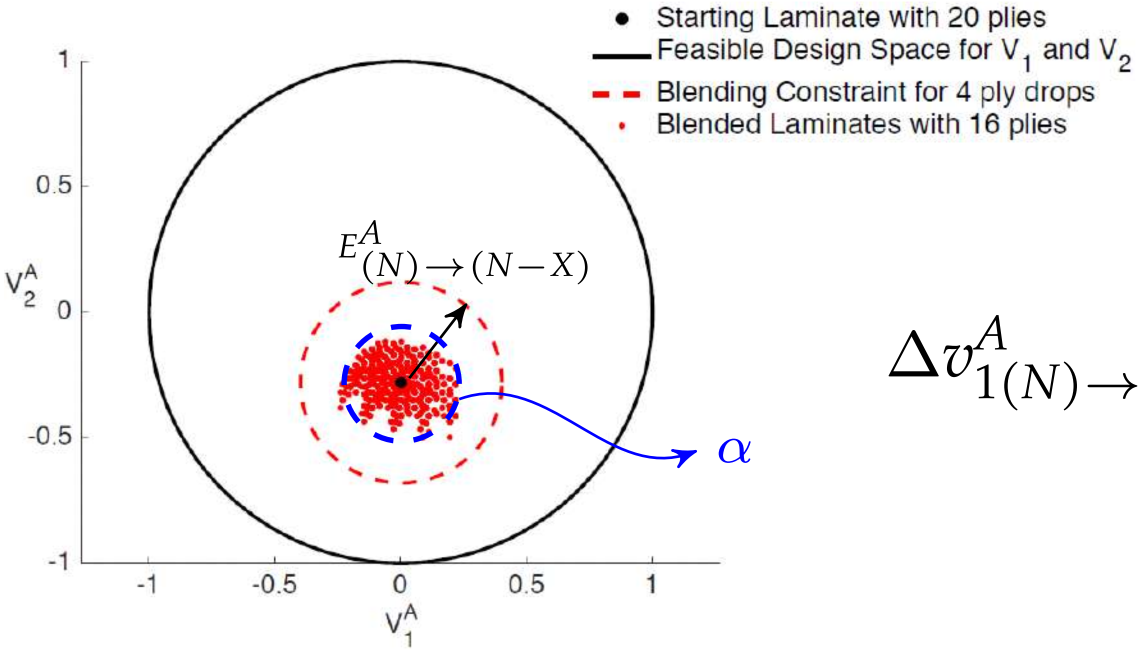
Blending constraints



- Inner vs outer blending.
- Blending can be defined:
  - During stacking sequence retrieval.
  - During continuous optimization.



Blending in lamination parameter space



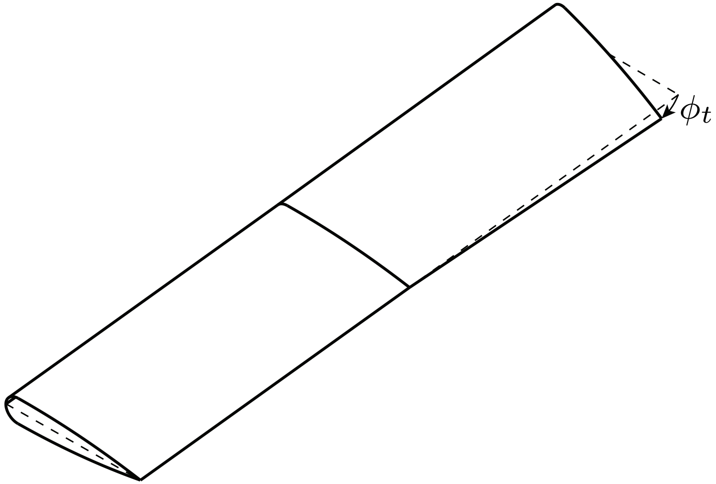
$$\Delta v^A_{1(N)\rightarrow(N-X)} < 2\,(X/N)$$

$$E^A_{(N)\rightarrow(N-X)} < \alpha\, 2\left(\frac{X}{N}\right)$$

Flight shape constraint

1g shape constraint

- 1g shape or flight shape or cruise shape is given by the aerodynamics department.
- Often multiple points are defined during a cruise phase.
- Cruise shape depends on stiffness distribution of the wing and the jig shape.
- Jig shape optimization can be approached in two ways:
  - Classical: take 1g loads and 1g shape and retrieve jig shape by inverting 1g loads.
  - Advanced: include jig twist as design variables.



Objectives

Objectives

- Structural mass minimization → payload increase.
- Range

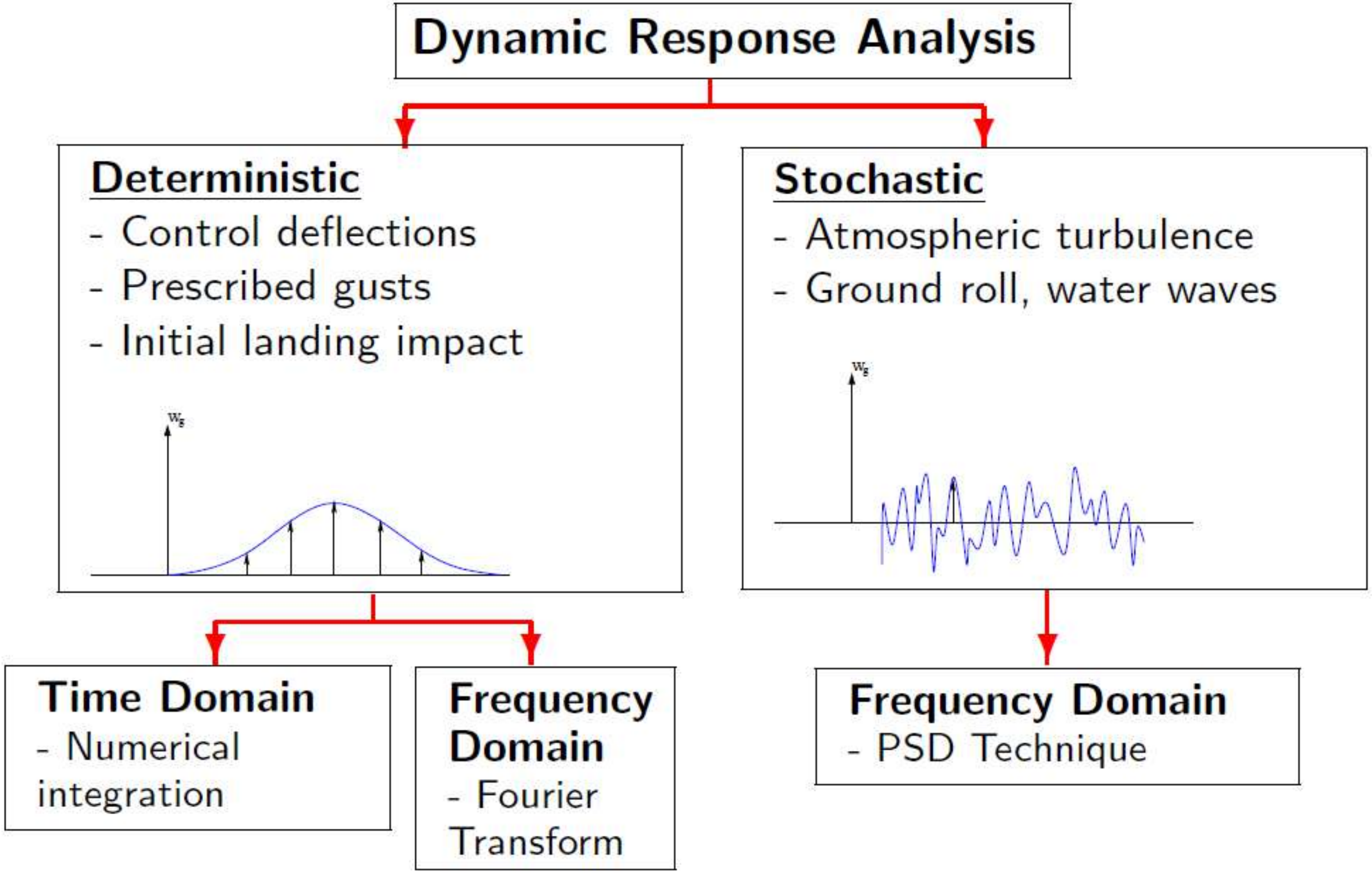
$$R = \frac{V}{g \cdot SFC} \frac{C_L}{C_D} ln\left(\frac{W_i}{W_f}\right)$$

- Material coupling is not a goal in itself.

Types of loads

- Flight loads
  - Manoeuvre/static loads
  - Dynamic loads
- Ground loads

Dynamic loads



Dynamic Response Analysis

Deterministic
- Control deflections
- Prescribed gusts
- Initial landing impact

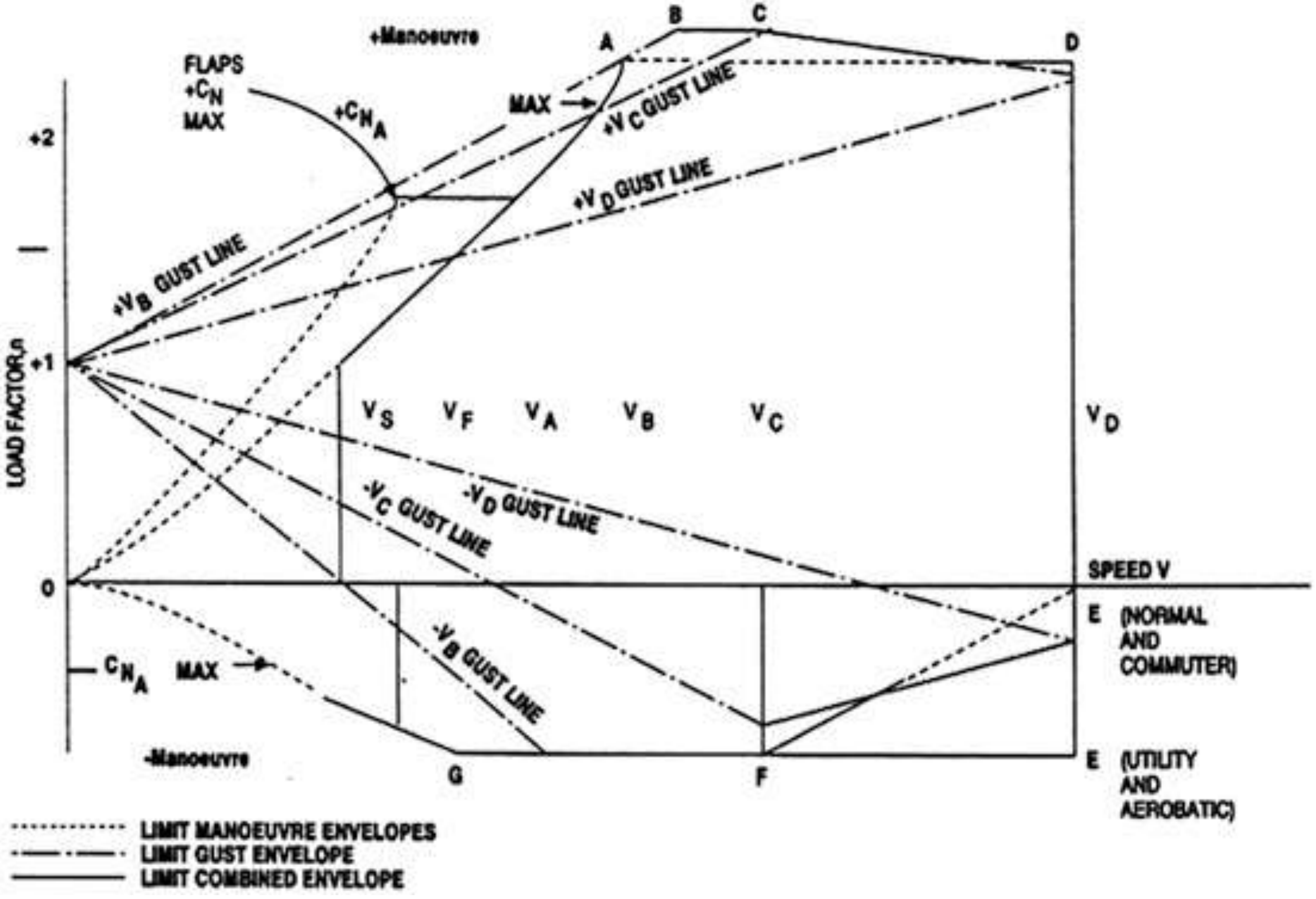
Stochastic
- Atmospheric turbulence
- Ground roll, water waves

Time Domain
- Numerical integration

Frequency Domain
- Fourier Transform

Frequency Domain
- PSD Technique

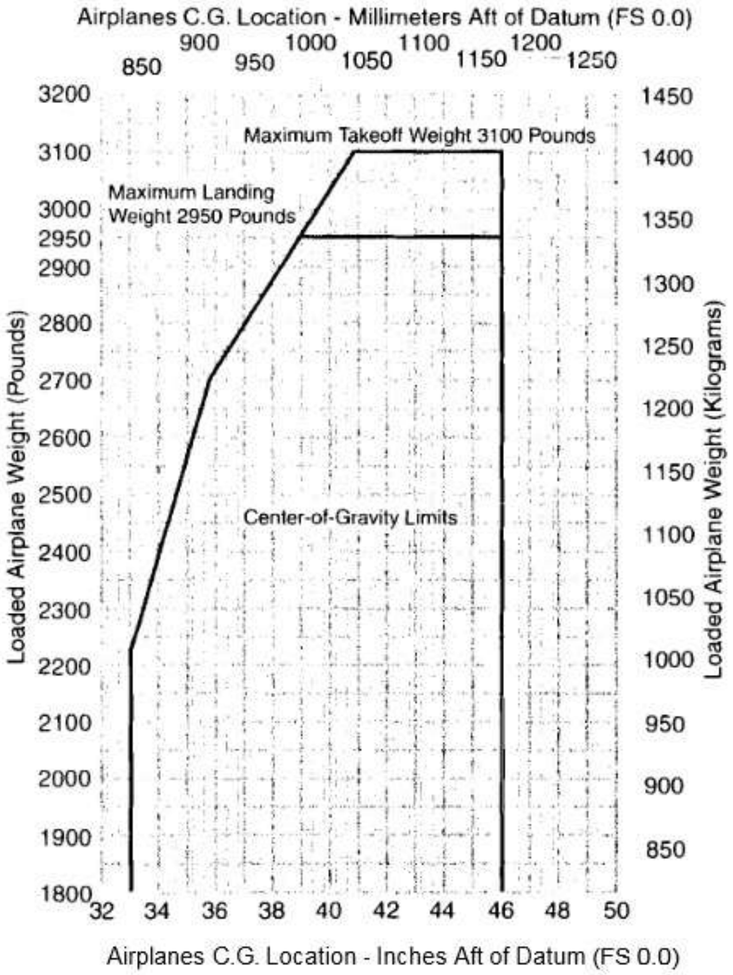
V-n diagram


+Manoeuvre
FLAPS
+C_N
MAX
+C_NA
MAX
A
B
C
D
+V_C GUST LINE
+V_D GUST LINE
+V_B GUST LINE
+2
+1
0
LOAD FACTOR, n
V_S
V_F
V_A
V_B
V_C
V_D
-V_D GUST LINE
-V_C GUST LINE
-V_B GUST LINE
SPEED V
E (NORMAL AND COMMUTER)
E (UTILITY AND AEROBATIC)
C_NA MAX
-Manoeuvre
G
F
LIMIT MANOEUVRE ENVELOPES
LIMIT GUST ENVELOPE
LIMIT COMBINED ENVELOPE

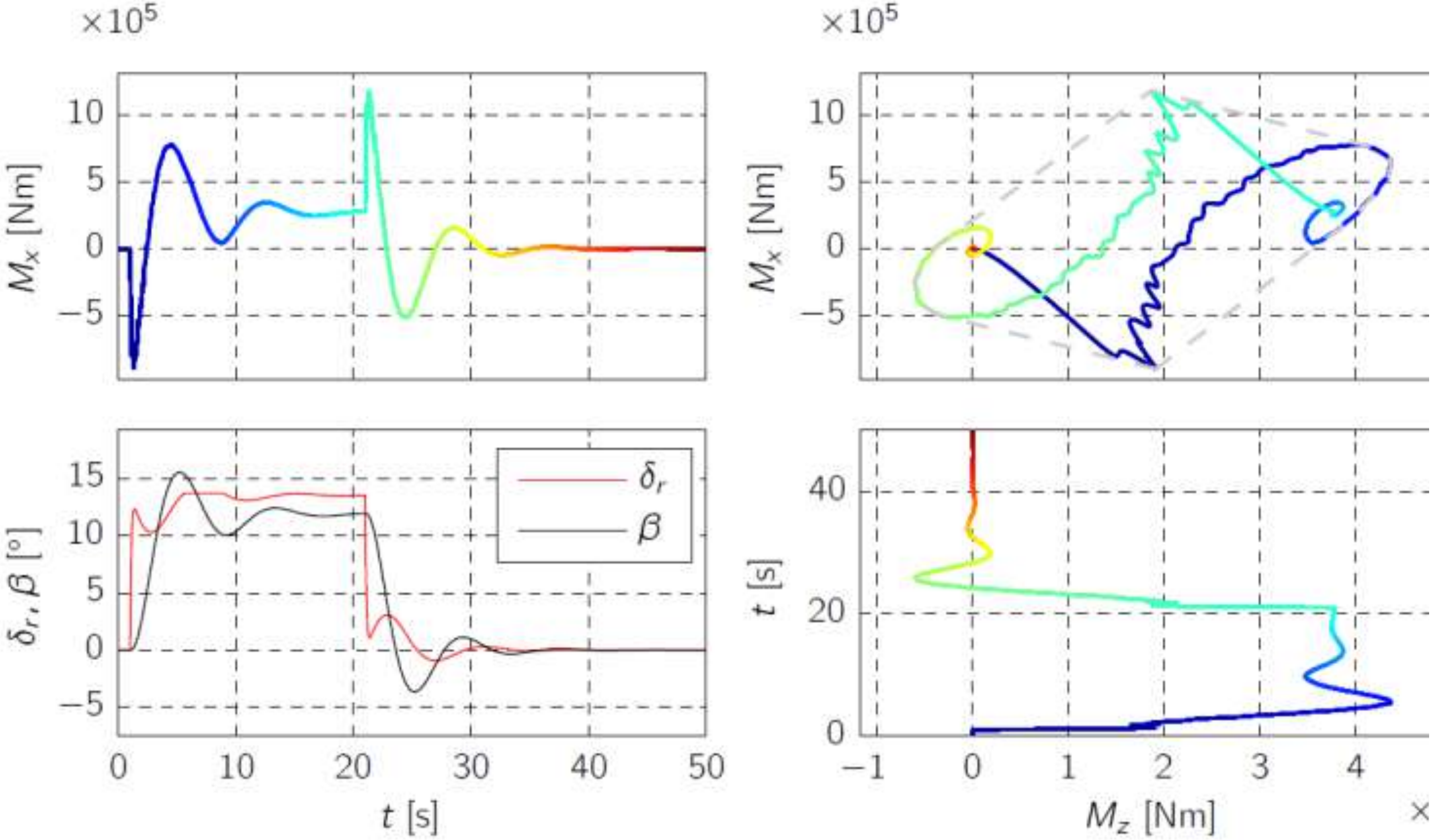
CESSNA
MODEL 182T NAV III

SECTION 6
WEIGHT AND BALANCE/EQUIPMENT LIST

CENTER-OF-GRAVITY LIMITS

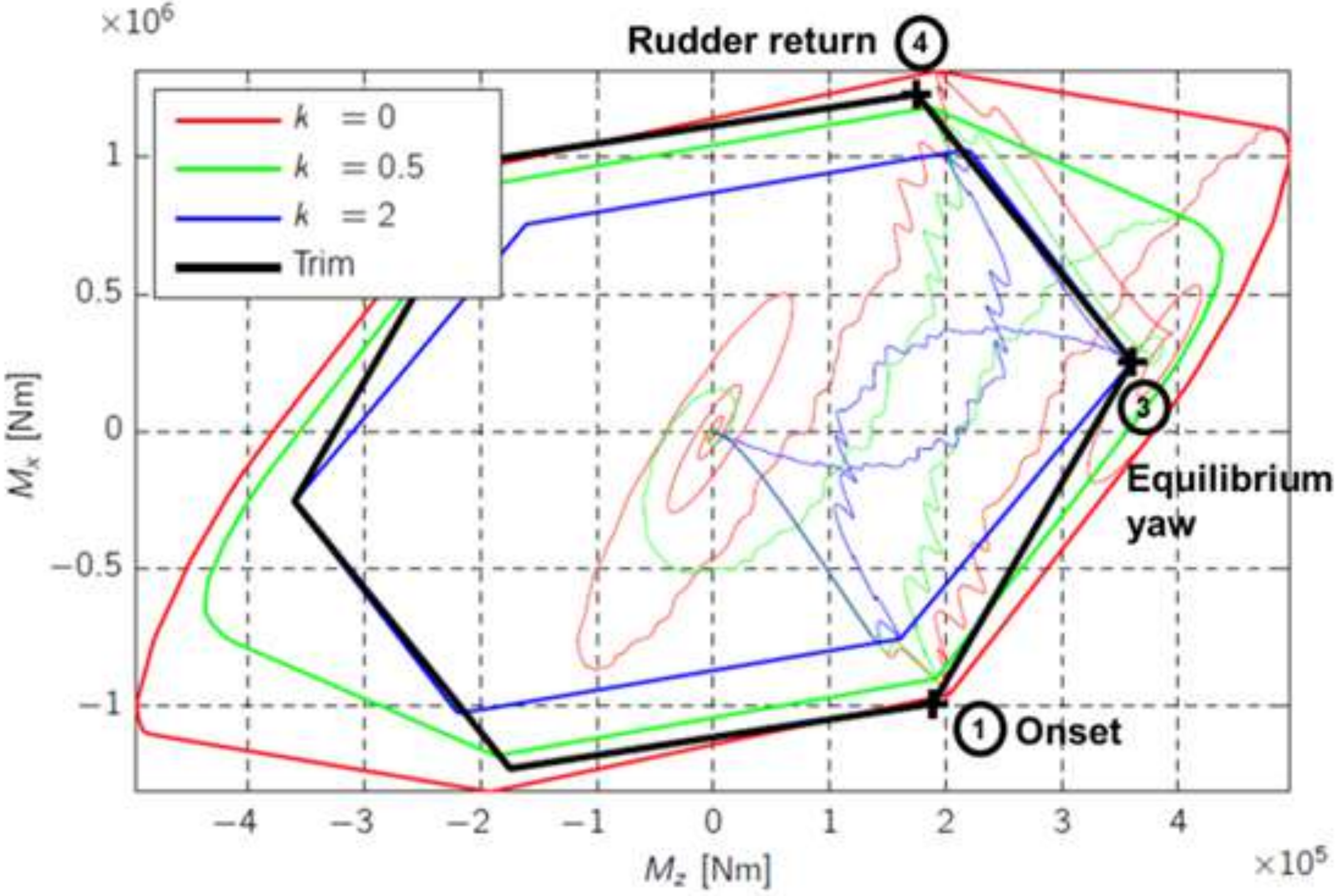


Correlated loads



Cumnuantip, S., Kier, T., Risse, K., & Chiozzotto, G. P. (2016). *Methods for the quantification of aircraft loads in DLR-Project iLOADS*. DLR

Load envelopes



Cumnuantip, S., Kier, T., Risse, K., & Chiozzotto, G. P. (2016). *Methods for the quantification of aircraft loads in DLR-Project iLOADS*. DLR

Typical number of load cases

Flight Points	50
Mass Cases	100
Control Surface Configuration	10
Manoeuvres and Gusts	50
Control Laws	4
Total Number of Cases	10,000,000

Load case selection

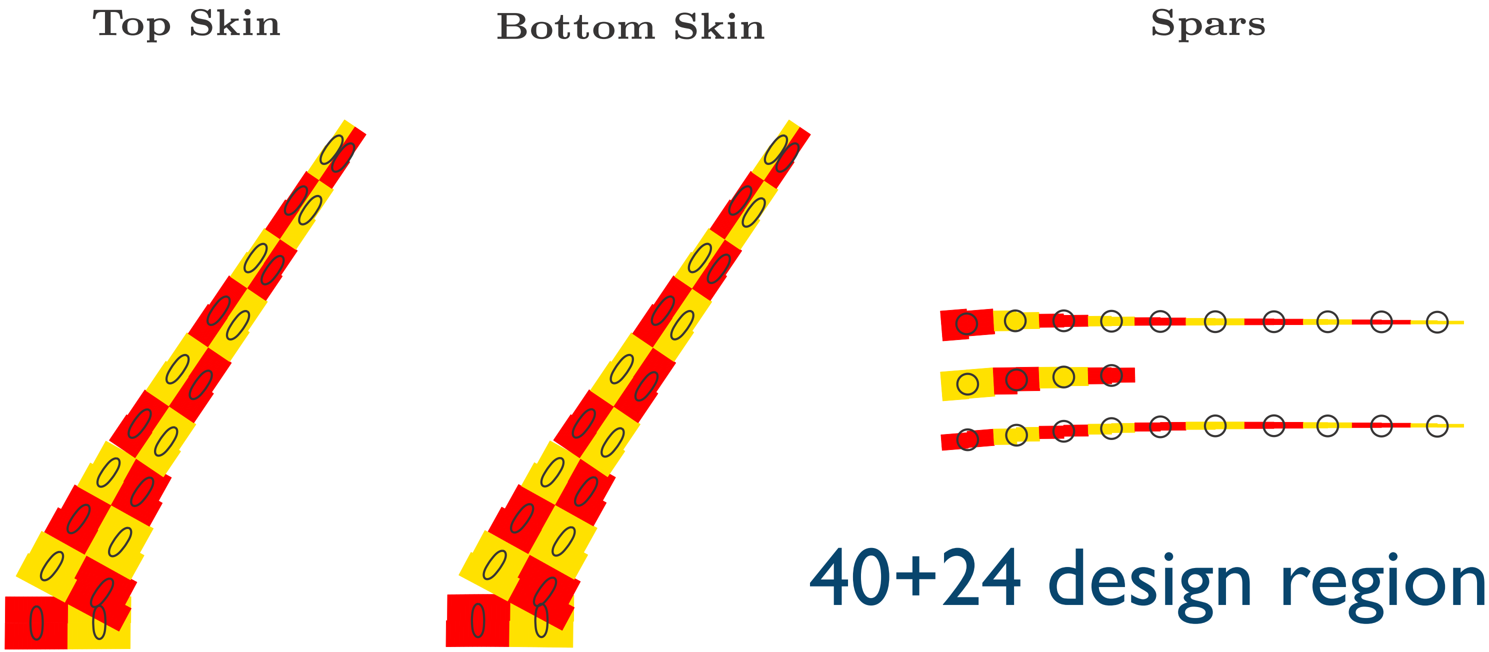
- A significant amount of load cases need to be considered to size the wing structure.
- The entire loads process is too time consuming.
- Only a few load cases are sizing.
- The sizing load cases could change during the design process.

Aeroelastically tailored results

- Typical tailored wing results
- Effect of aileron effectiveness
- Effect of 1g shape constraint and free jig shape
- Effect of MLA
- Effect of fatigue constraints
- Effect of blending
- Criticality of gust loads

Design regions

UD carbon/epoxy (AS4/3501-6)



40+24 design regions

1. Predefined laminates
2. Unbalanced laminates

Visualisation of the laminate stiffness

$$E_{m_{11}}(\theta) = \frac{1}{A_{11}^{-1}(\theta)}$$

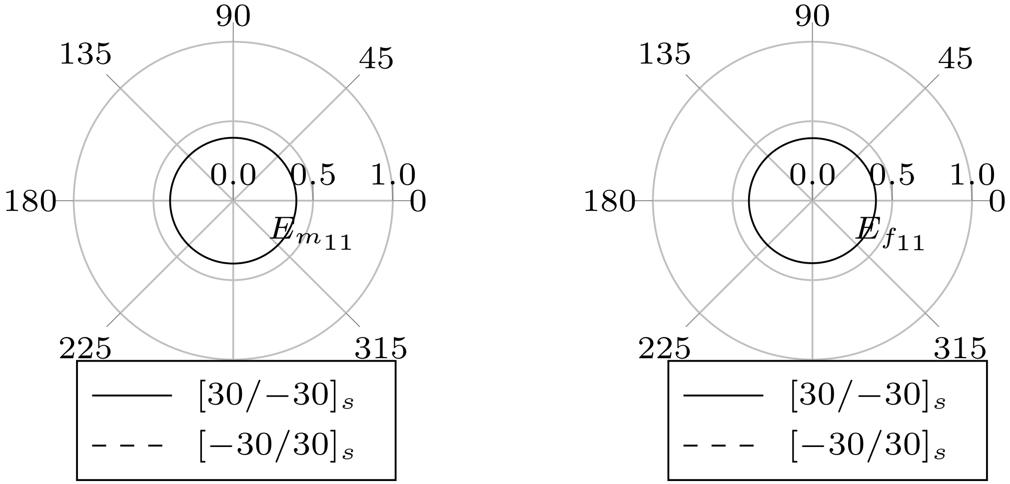
$$E_{f_{11}}(\theta) = \frac{1}{D_{11}^{-1}(\theta)}$$

$$A_{11}^{-1}(\theta) = T^T A_{11}^{-1} T$$

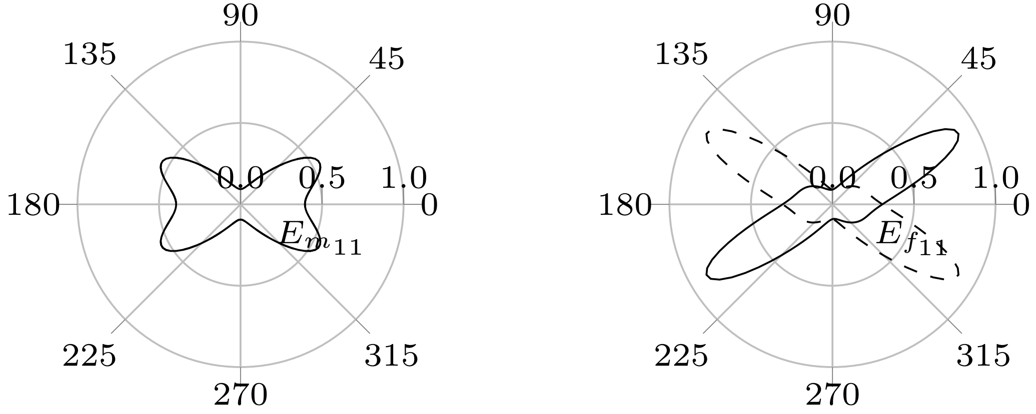
$$D_{11}^{-1}(\theta) = T^T D_{11}^{-1} T$$

$$T = \begin{bmatrix} \cos^2(\theta) & \sin^2(\theta) & 2\cos(\theta)\sin(\theta) \\ \sin^2(\theta) & \cos^2(\theta) & -2\cos(\theta)\sin(\theta) \\ -\cos(\theta)\sin(\theta) & \cos(\theta)\sin(\theta) & \cos^2(\theta) - \sin^2(\theta) \end{bmatrix}$$

Examples of the visualisation



Quasi-isotropic



Symmetric balanced

Optimisation responses

	Type	# responses
Objective	Mass	1
Design variables	Lamination parameters	512
	Laminate thickness	64
	Jig twist	20
Constraints	Lamination parameters feasibility	384
	1g twist	20
	Aeroelastic stability	10 per LC
	Local AoA	34 per LC
	Aileron effectiveness	1 per LC
	Tsai-Wu failure criterion	1024 per LC
	Buckling factor	4096 per LC
	Total	**1001 + 5156 per LC**

Load cases

ID	Description	EAS [m/s]	Altitude [m]	Mach [-]	n_z [-]	Fuel
1	Cruise	136	11,000	0.85	1.0	70%
2	Pull up	240	3,000	0.85	2.5	80%
3	Push down	198	0	0.60	-1.0	80%
4	Dynamic	156	0	0.46	1.0	80%
	Gust length [m]	50, 60, 70, 80, 90, 100, 107				

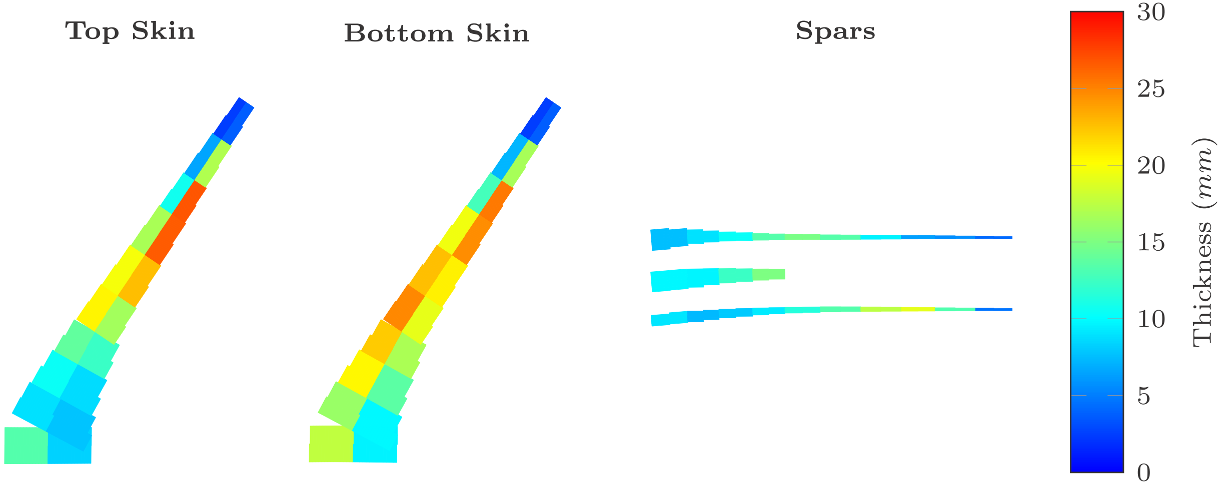
Static design: 3 LC

Dynamic design: 10+ LC (multiple points in time history)

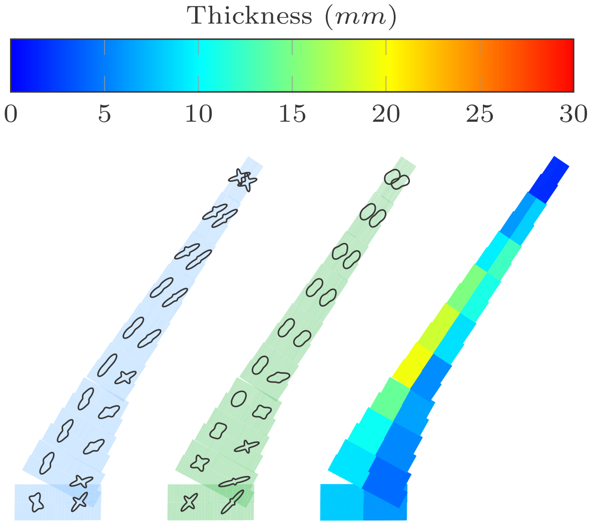
Aeroelastically tailored results

- Typical tailored wing results
- Effect of aileron effectiveness
- Effect of 1g shape constraint and free jig shape
- Effect of MLA
- Effect of fatigue constraints
- Effect of blending
- Criticality of gust loads

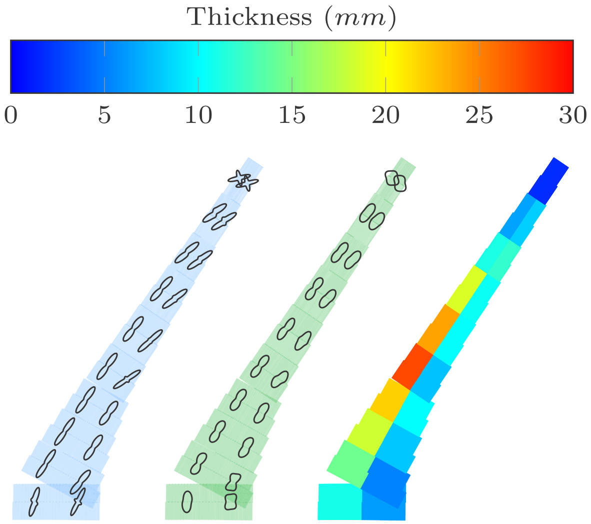
Conventional optimisation



Predefined
6,877 kg



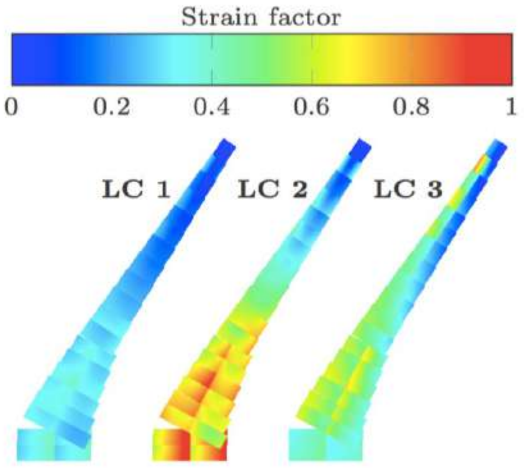
(a) Top skin.



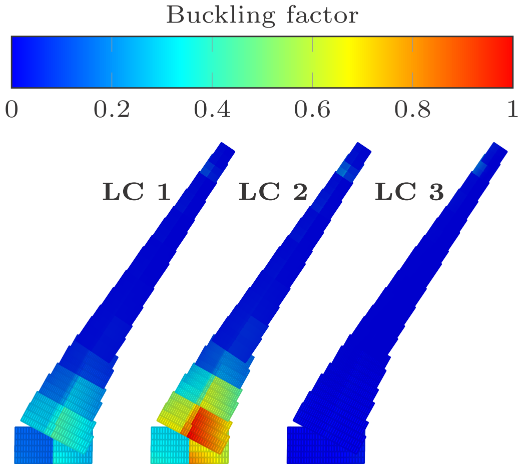
(b) Bottom skin.

Unbalanced
4,784 kg (-30%)

Conventional optimisation

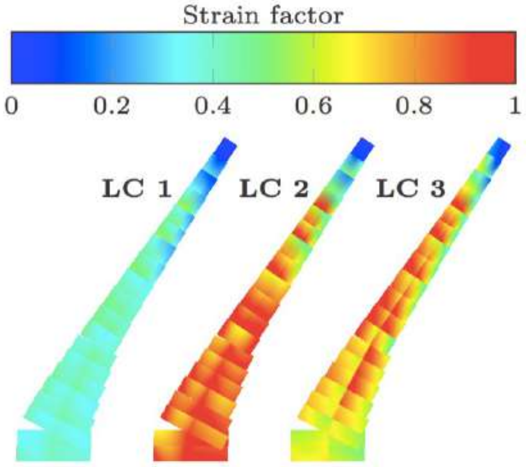


(a) Top skin.

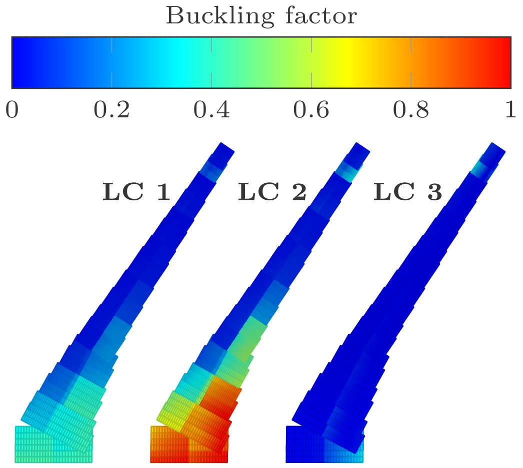


(b) Top skin.

Predefined



(a) Top skin.



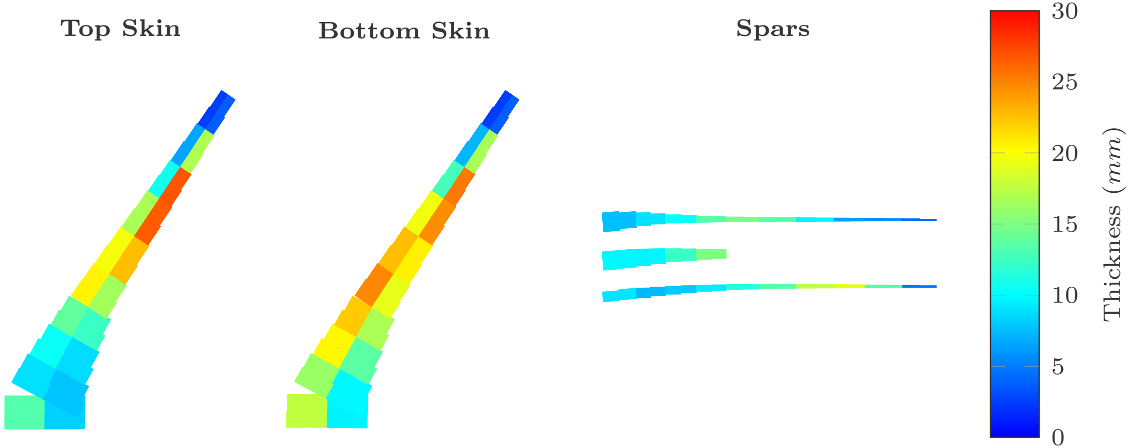
(b) Top skin.

Unbalanced

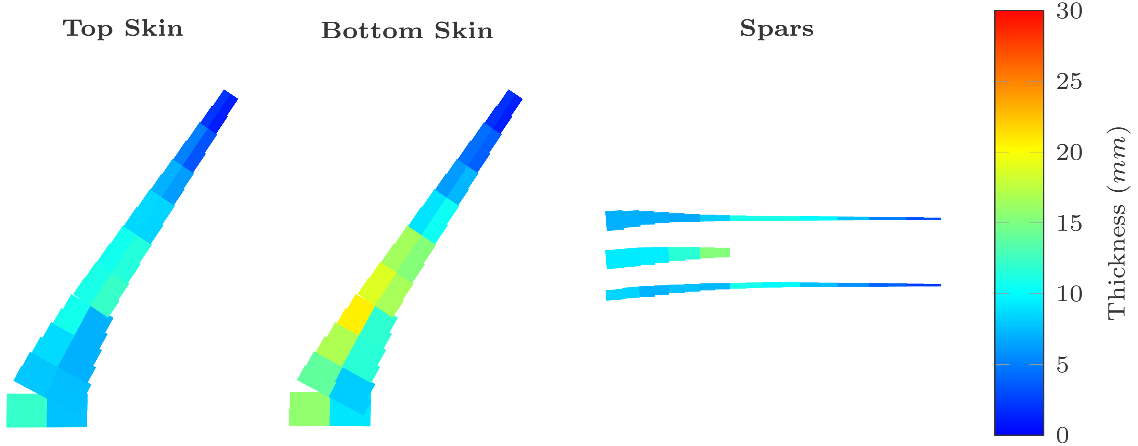
Predefined laminates

Conventional optimisation

Effect of control effectiveness



With constraint
6,877 kg

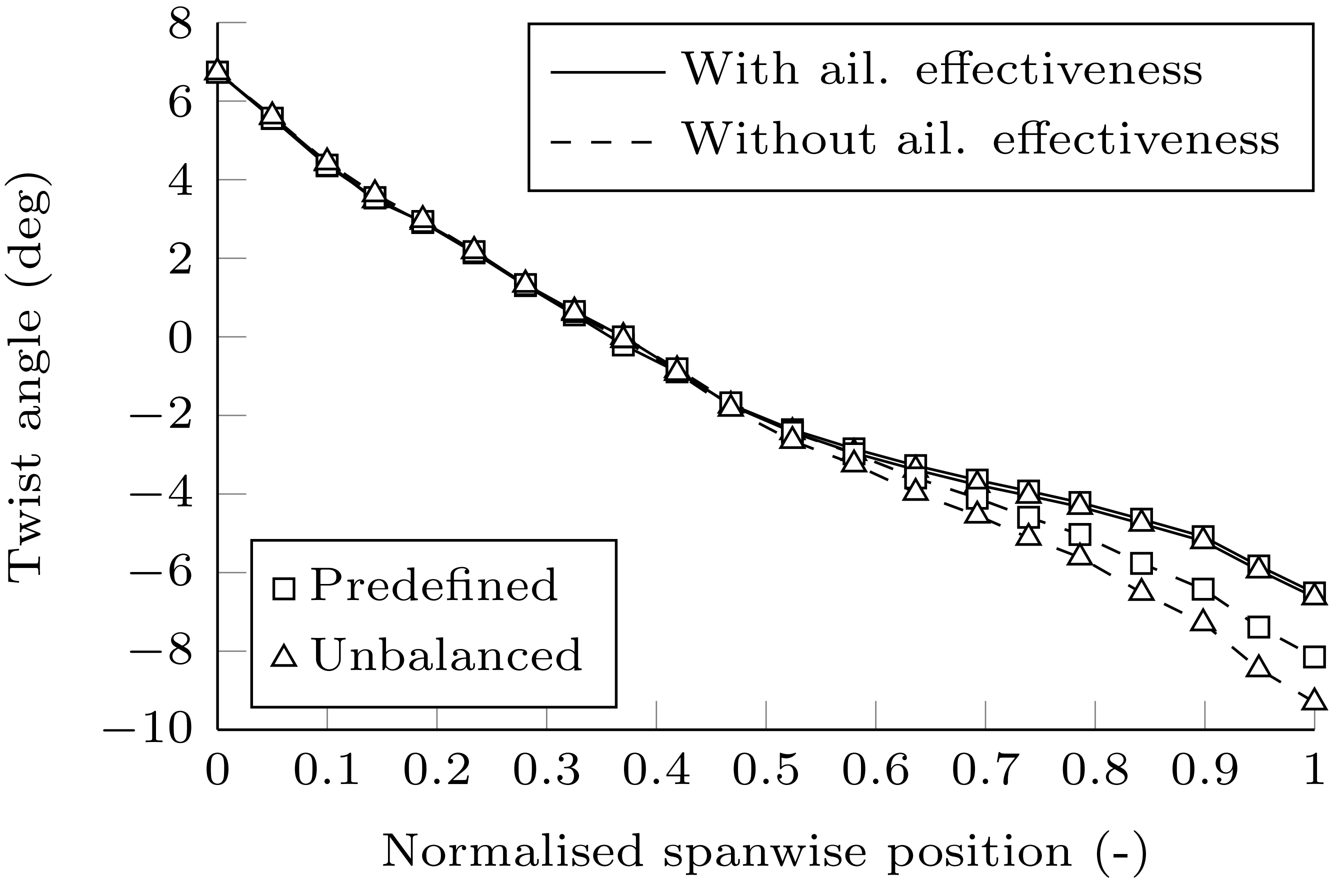


Without constraint
4,803 kg (-30%)

Aeroelastically tailored results

- Typical tailored wing results
- Effect of aileron effectiveness
- Effect of 1g shape constraint and free jig shape
- Effect of MLA
- Effect of fatigue constraints
- Effect of blending
- Criticality of gust loads

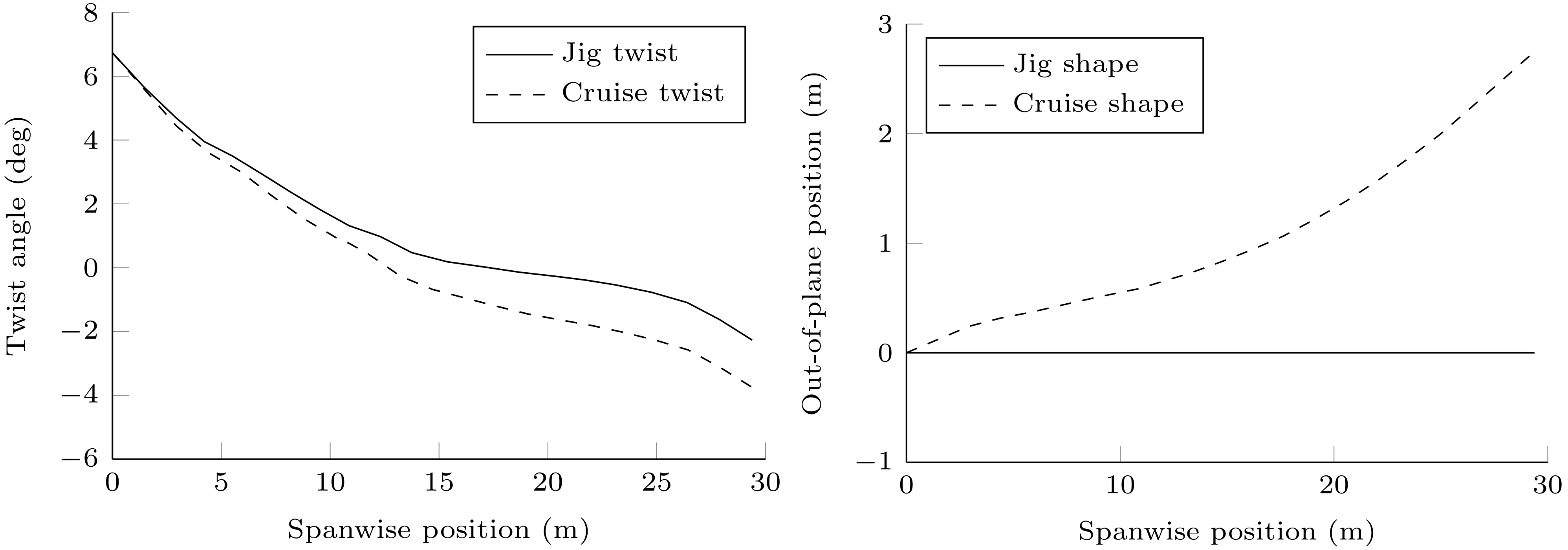
2.5g twist


With ail. effectiveness
Without ail. effectiveness
□ Predefined
△ Unbalanced
Twist angle (deg)
8
6
4
2
0
−2
−4
−6
−8
−10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalised spanwise position (-)

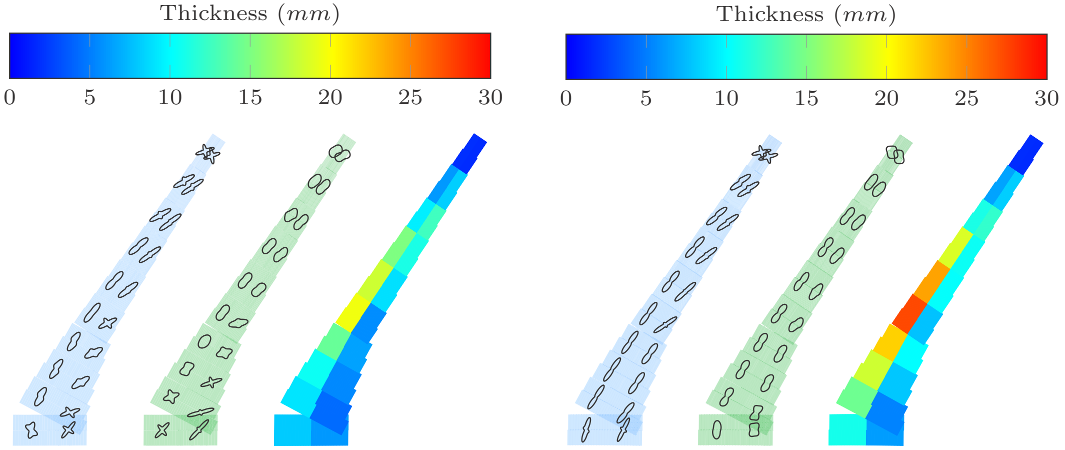
Aeroelastically tailored results

- Typical tailored wing results
- Effect of aileron effectiveness
- Effect of 1g shape constraint and free jig shape
- Effect of MLA
- Effect of fatigue constraints
- Effect of blending
- Criticality of gust loads

Predefined jig shape



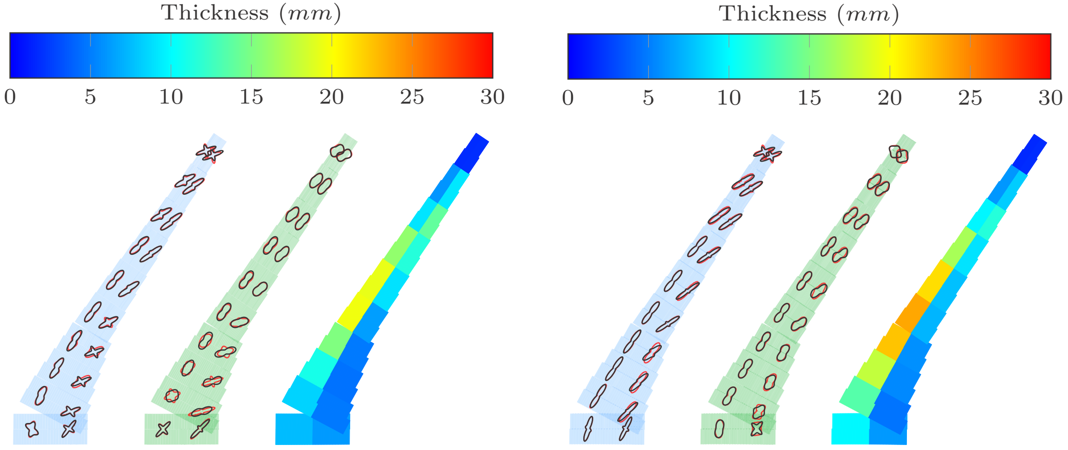
Including free jig twist



(a) Top skin. **(b)** Bottom skin.

Fixed jig twist

4,784 kg

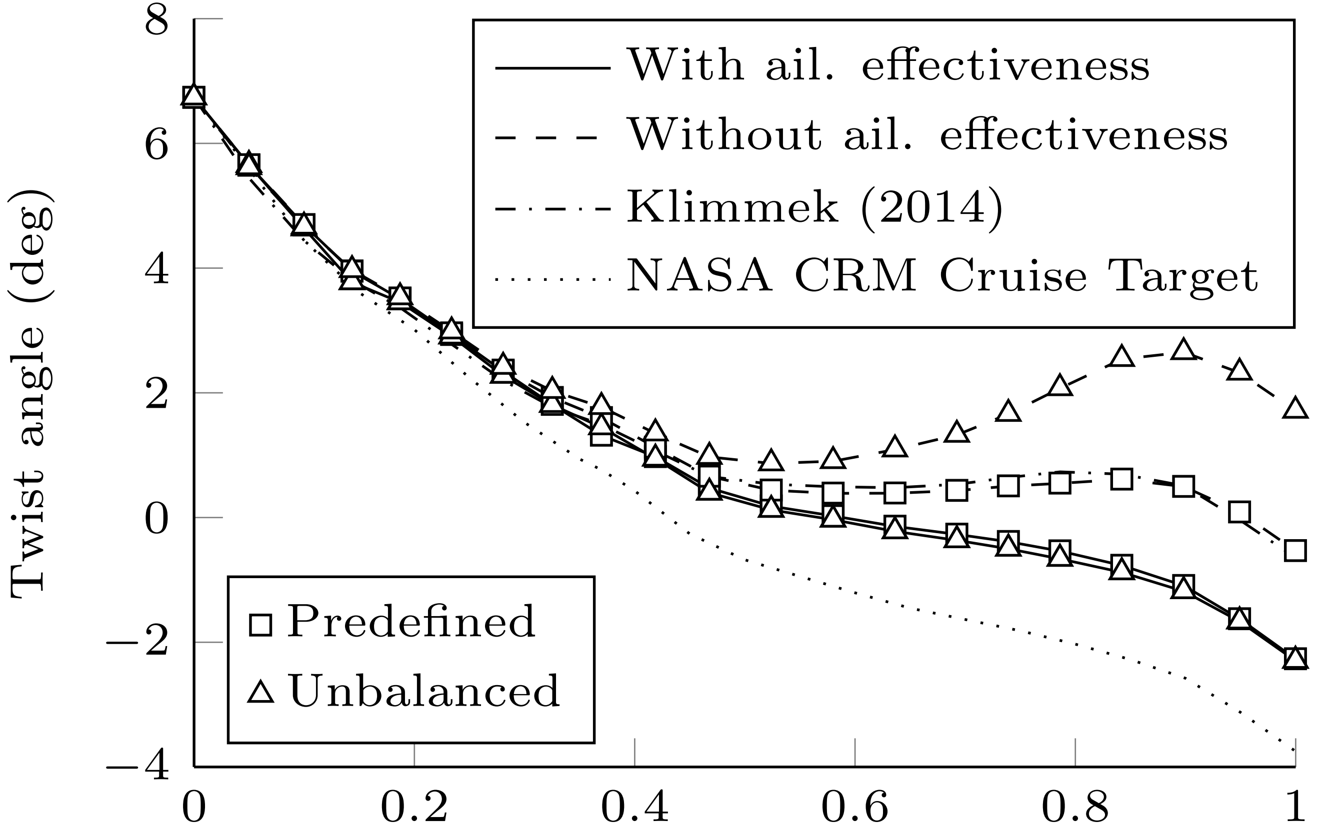


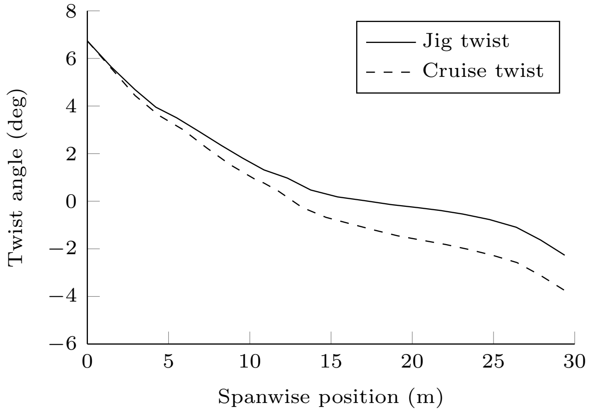
(a) Top skin. **(b)** Bottom skin.

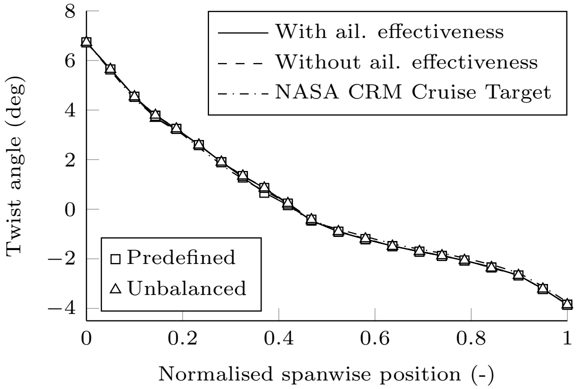
Free jig twist

4,517 kg (-6%)

Optimised jig shape



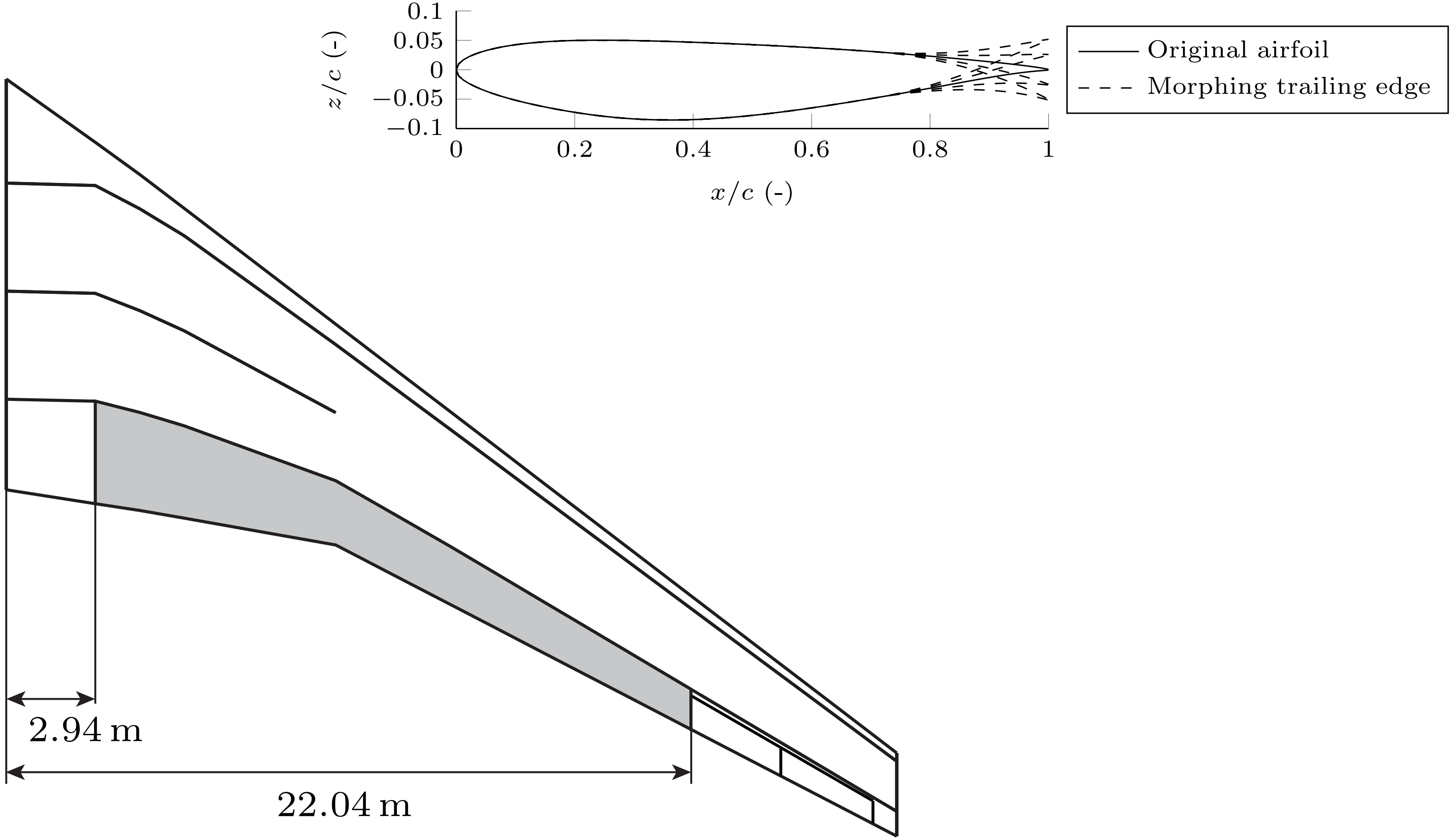




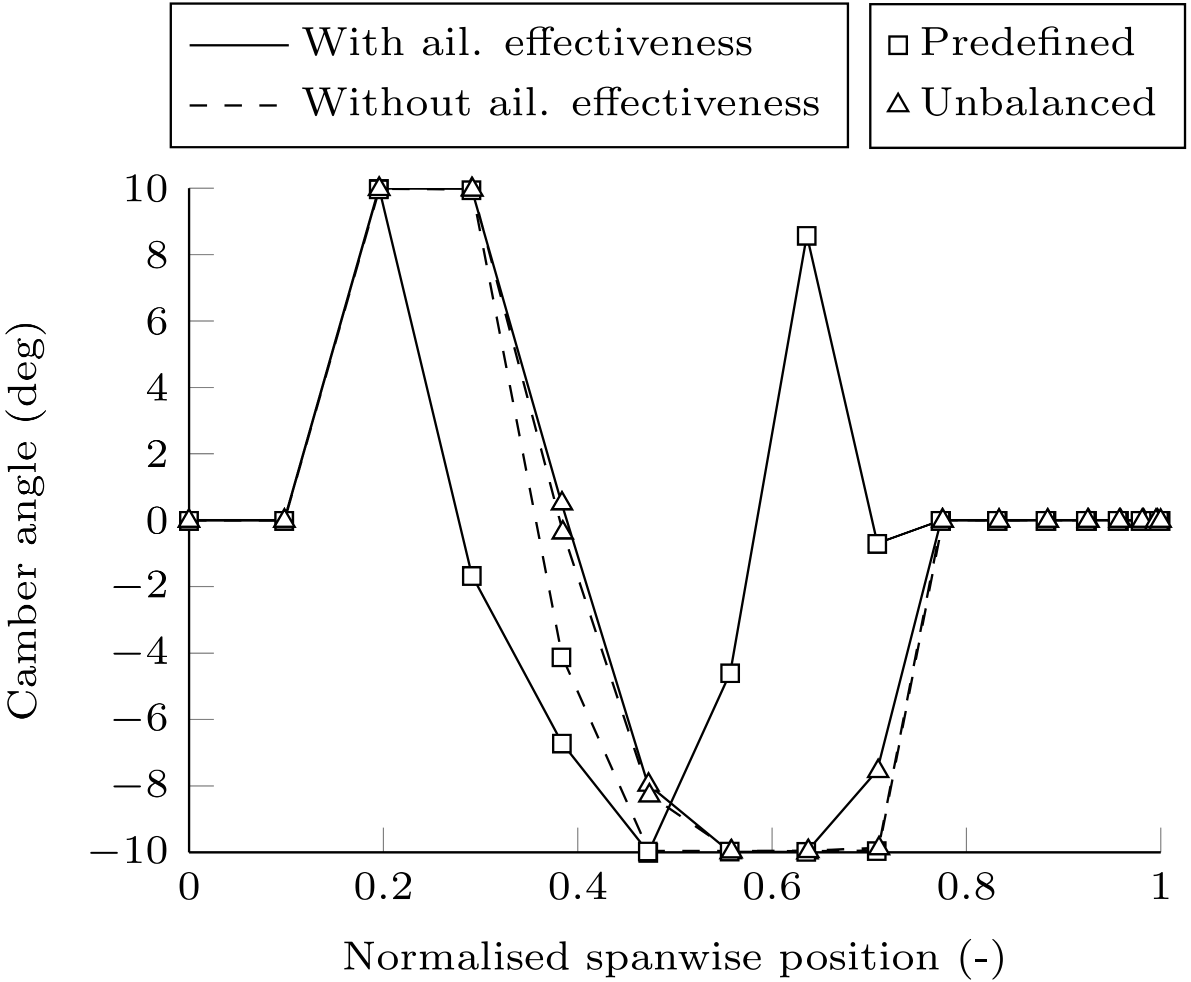
Aeroelastically tailored results

- Typical tailored wing results
- Effect of aileron effectiveness
- Effect of 1g shape constraint and free jig shape
- Effect of MLA
- Effect of fatigue constraints
- Effect of blending
- Criticality of gust loads

Active control surfaces

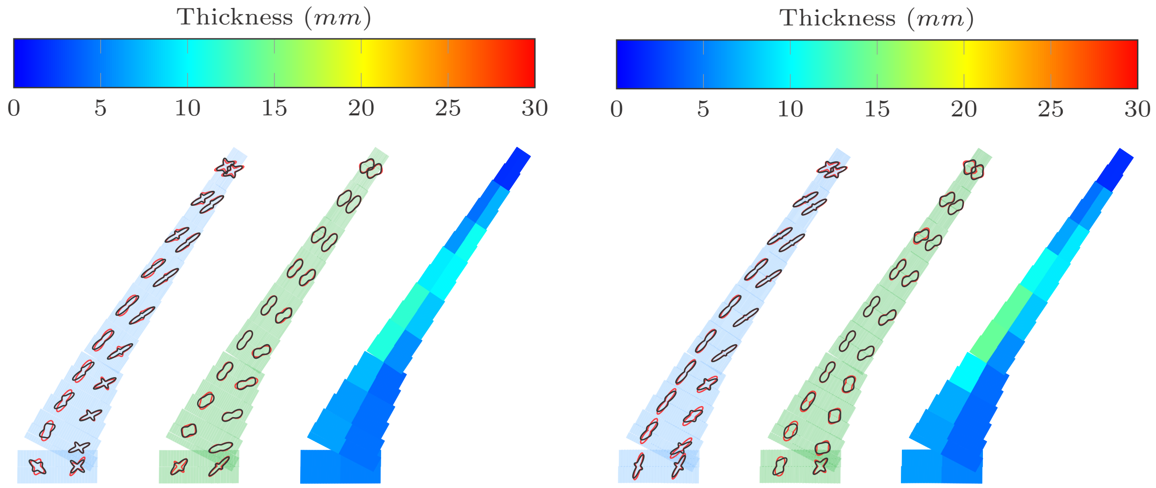


Control deflections under 2.5g load



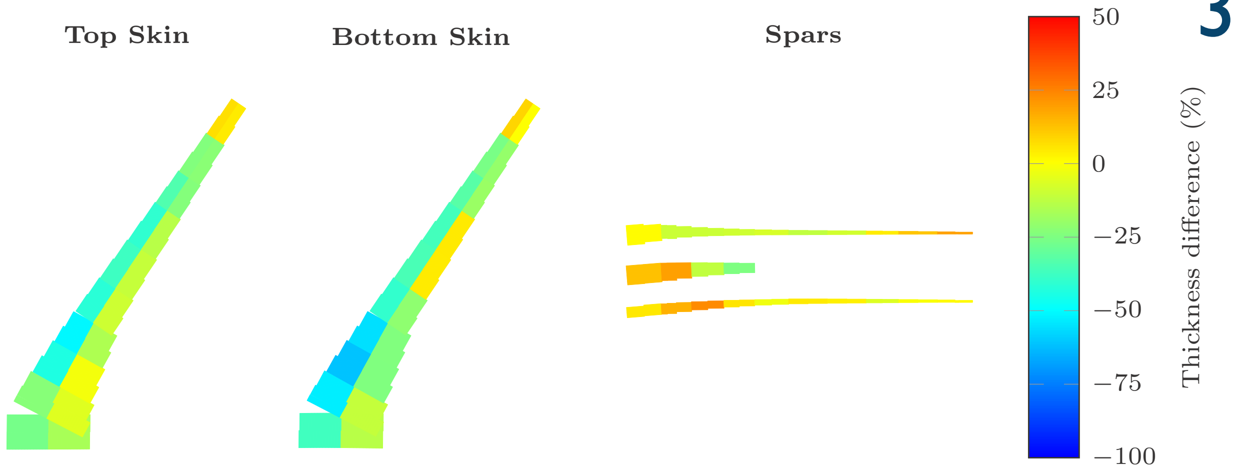
Unbalanced laminates

Thickness distribution



(a) Top skin.

(b) Bottom skin.



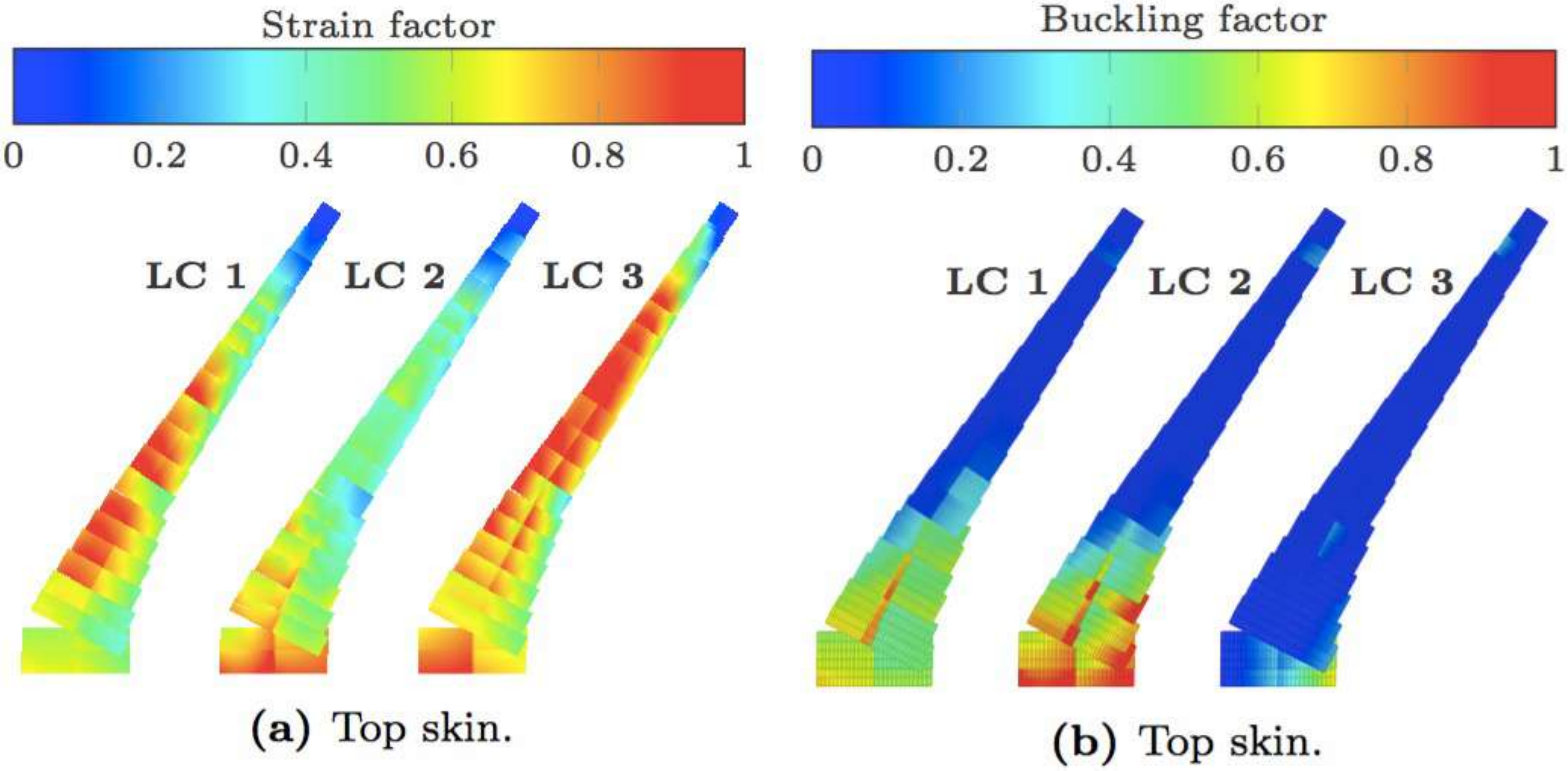
Without MLA

4,784 kg

With MLA

3,215 kg (-33%)

Strain and buckling



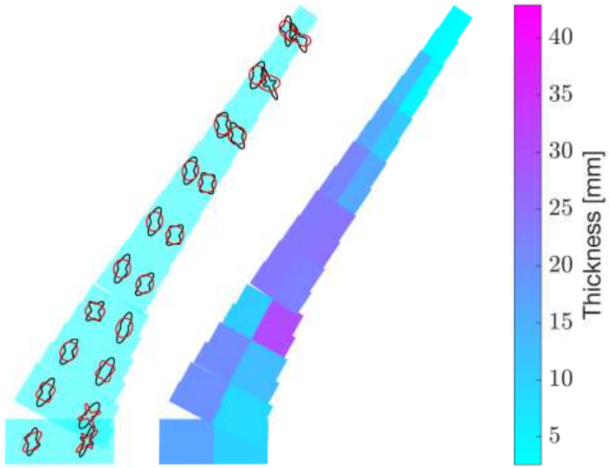
(a) Top skin.

(b) Top skin.

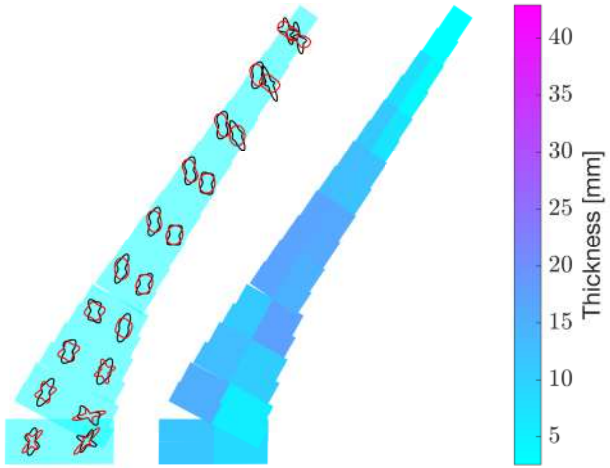
Aeroelastically tailored results

- Typical tailored wing results
- Effect of aileron effectiveness
- Effect of 1g shape constraint and free jig shape
- Effect of MLA
- Effect of fatigue constraints
- Effect of blending
- Criticality of gust loads

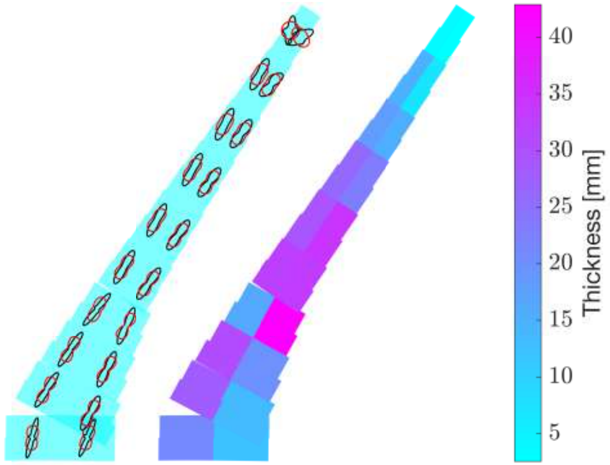
Skin thickness results



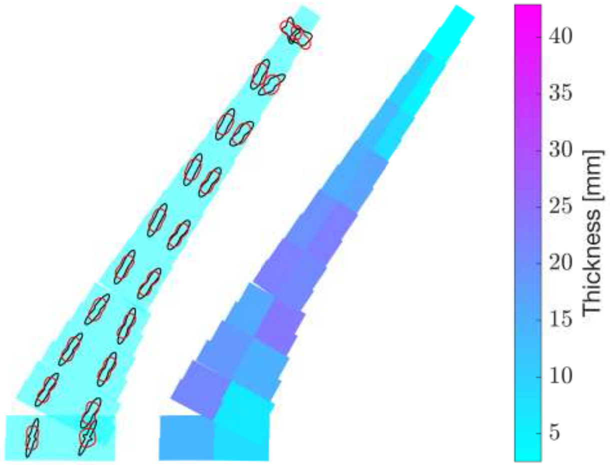
(a) Top Skin without fatigue model



(b) Top Skin with fatigue model

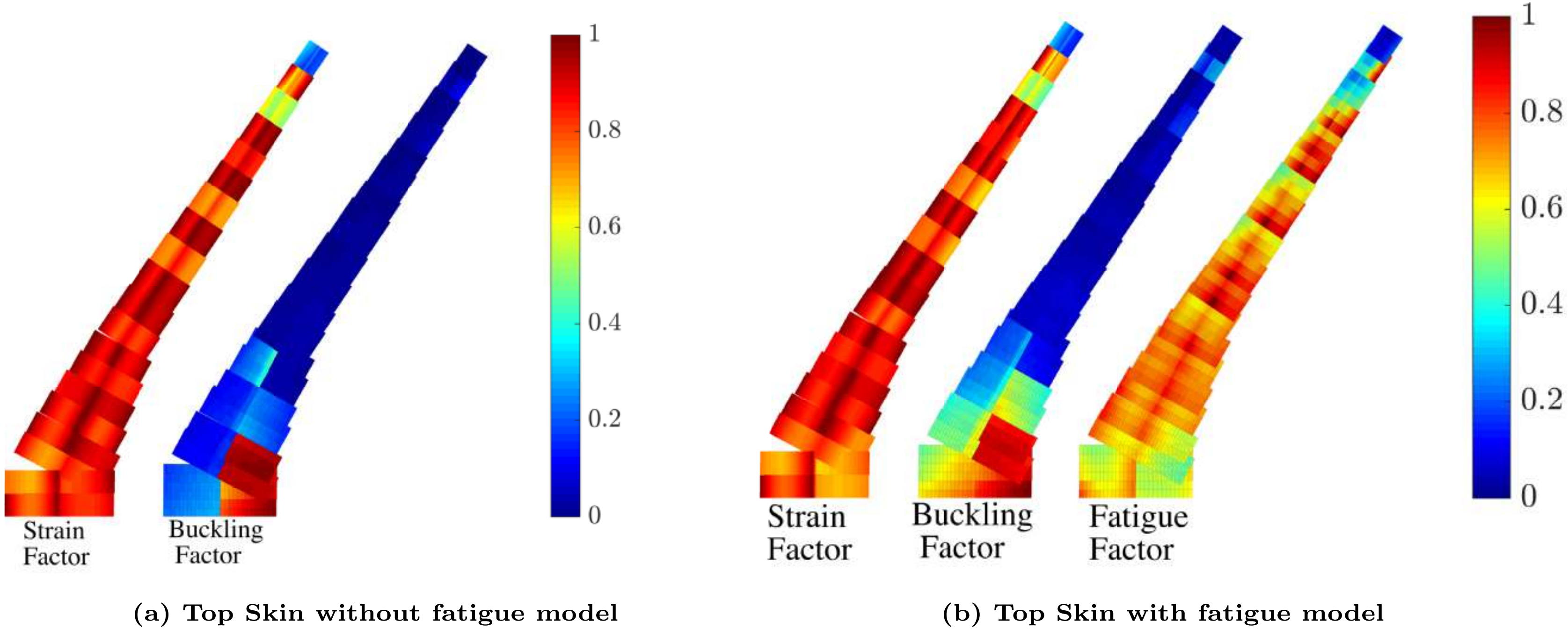


(c) Bottom Skin without fatigue model



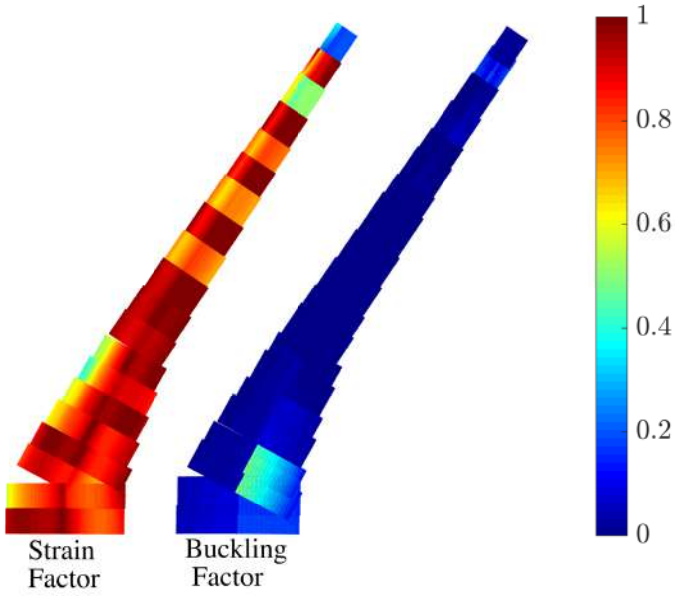
(d) Bottom Skin with fatigue model

Constraint values top skin

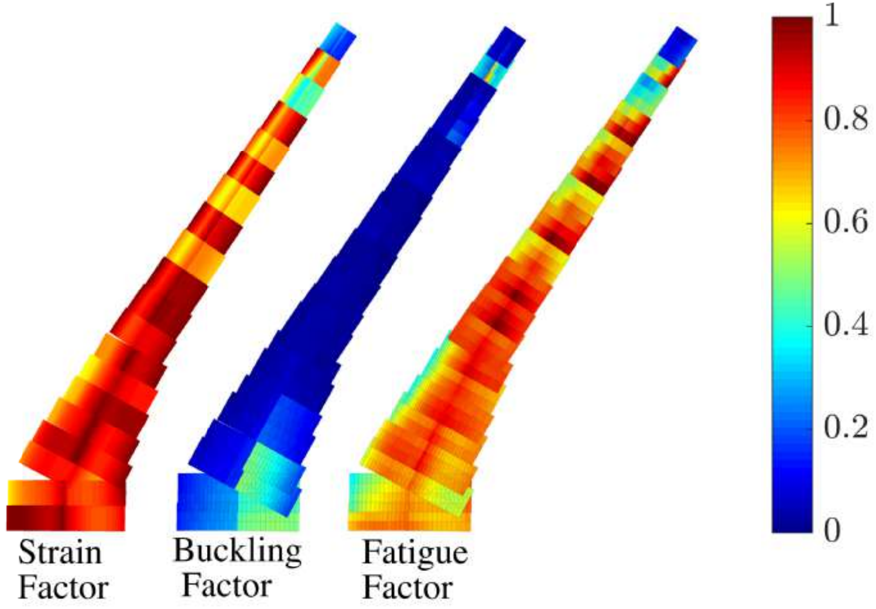


(a) Top Skin without fatigue model **(b) Top Skin with fatigue model**

Constraint values bottom skin



(c) Bottom Skin without fatigue model



(d) Bottom Skin with fatigue model

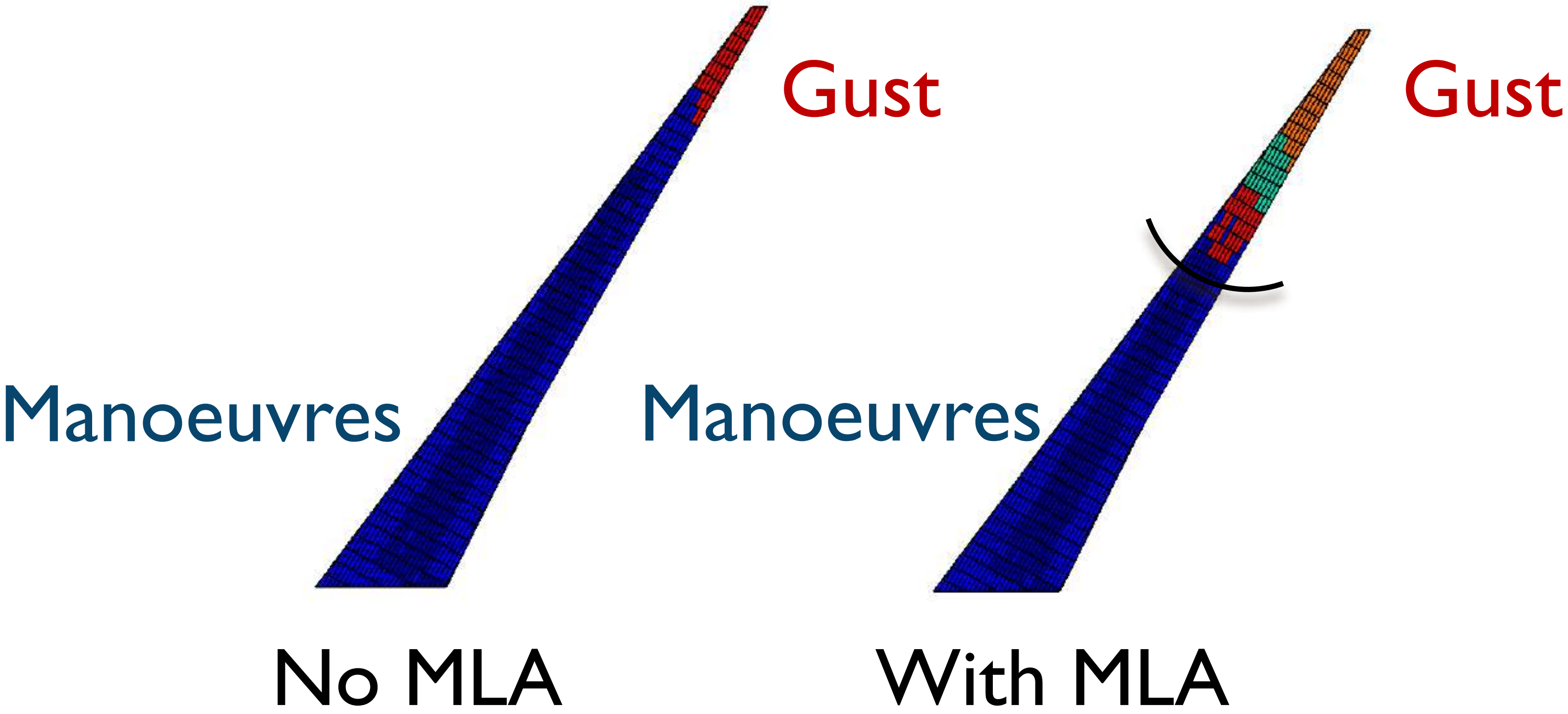
Mass comparison

Type	Tailored	Units
With fatigue model	9,416	kg
Without fatigue model	12,129	kg
Difference (%)	22	%

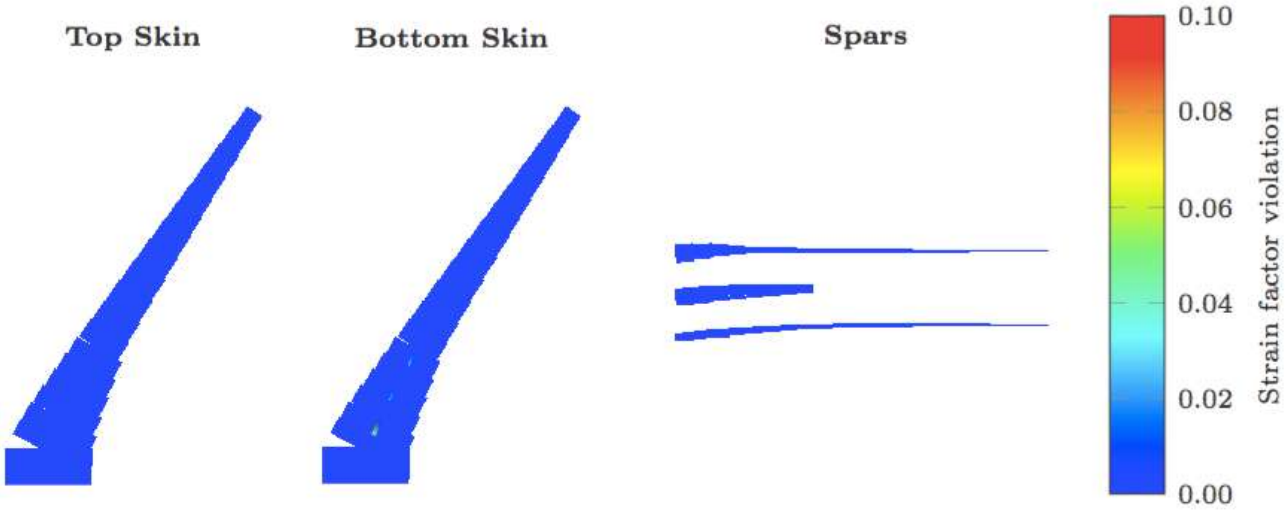
Aeroelastically tailored results

- Typical tailored wing results
- Effect of aileron effectiveness
- Effect of 1g shape constraint and free jig shape
- Effect of MLA
- Effect of fatigue constraints
- Effect of blending
- Criticality of gust loads

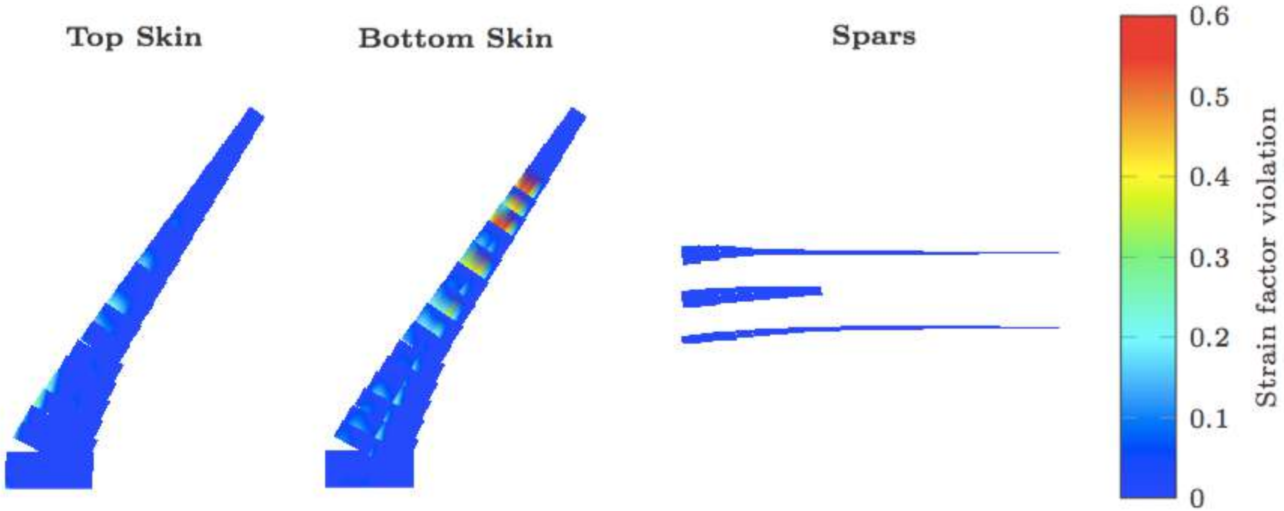
Are gust loads sizing?



Gust loads critical?



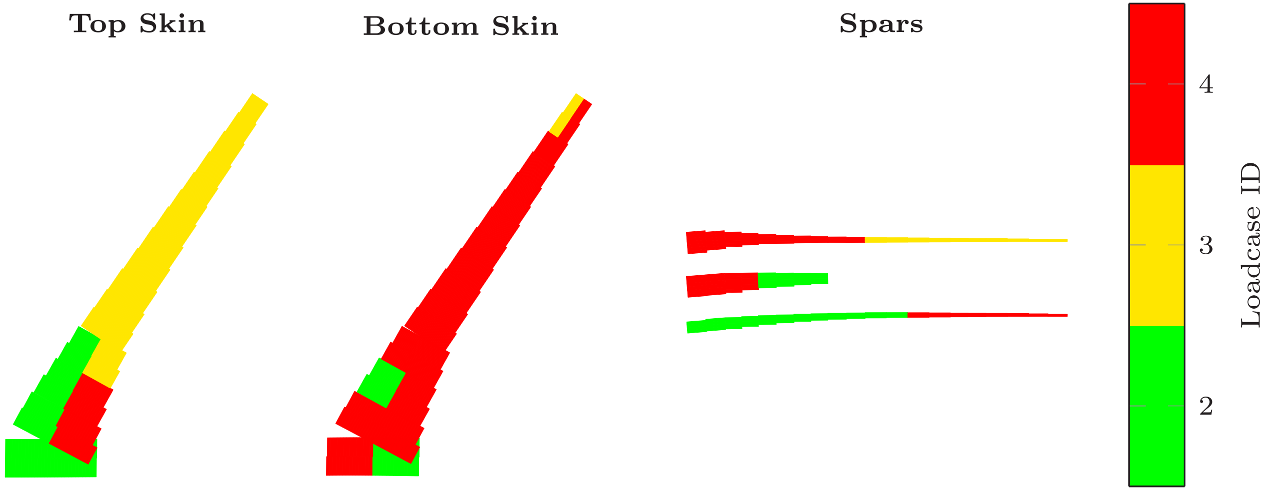
Predefined

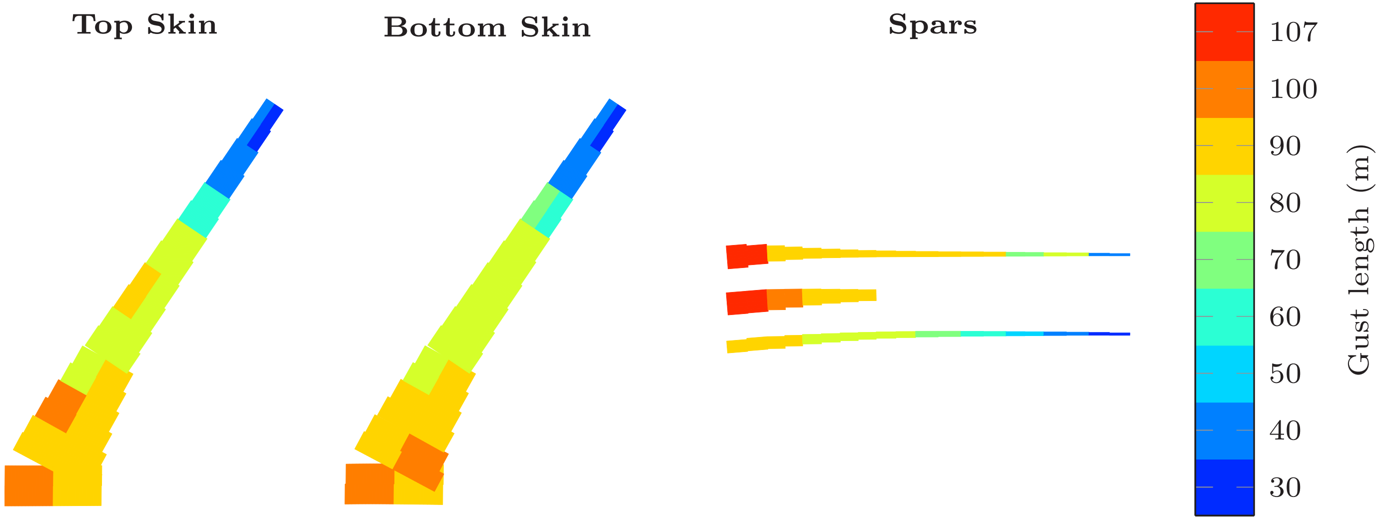


Unbalanced

Unbalanced laminates

Critical load cases and gust lengths





Without DL
4,517 kg

With DL
4,850 kg (+7%)

What’s next in aeroelastic tailoring

- More focus on high fidelity methods.
- Include control into the design.
- Coupling to other disciplines (MDAO).
- More advanced measuring techniques, also in flight.
- Scaled flight testing.
- Industrialisation of the technology – link to advanced manufacturing.
- Novel (composite) materials.