AIRCRAFT DESIGN USING VARIABLE DENSITY MODELS

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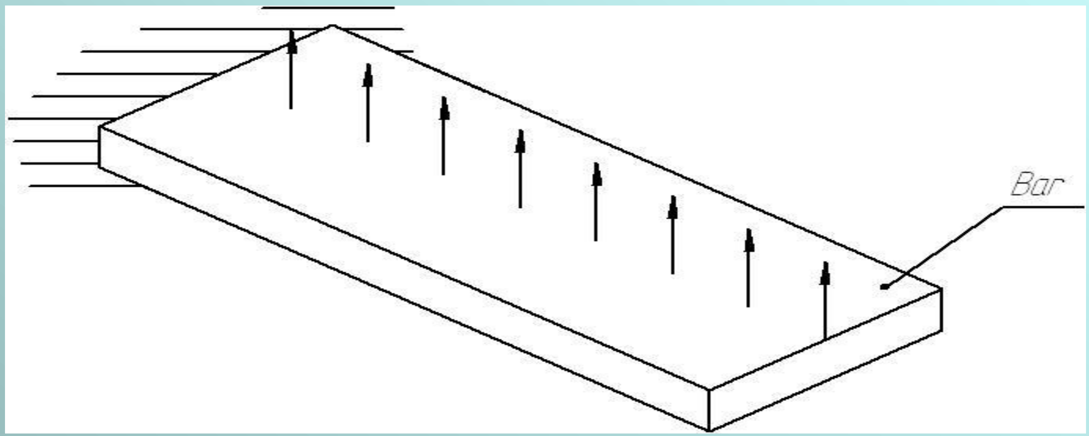
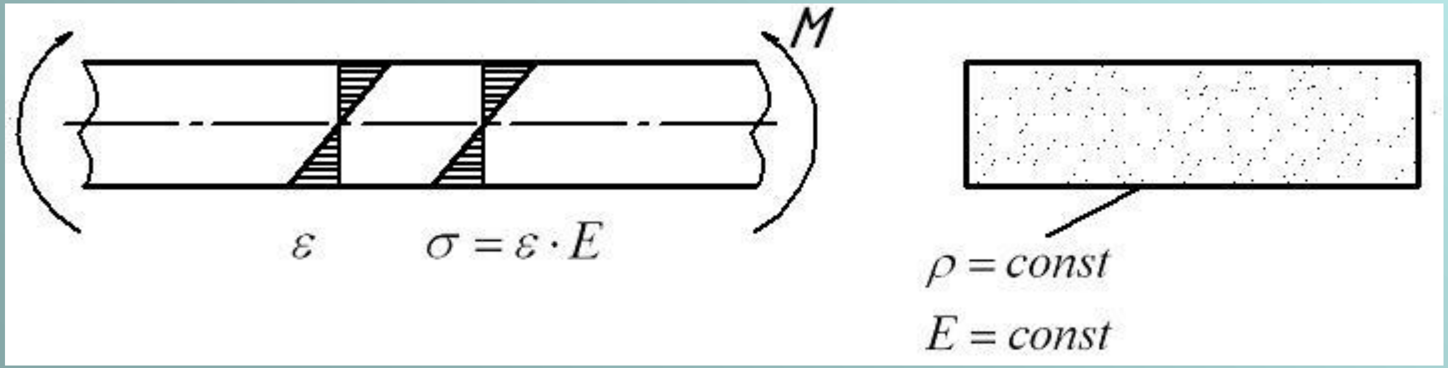
Using 3D-model with variable density

Model



Conventional material



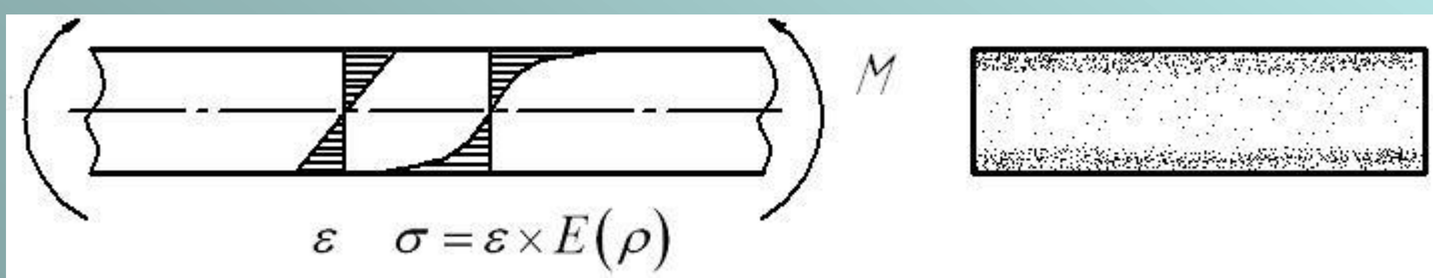
Hypothetic material with variable density

$\sigma_u = \rho \cdot \bar{\sigma}_u$ $\sigma_u, \bar{\sigma}_u$ - ultimate tensile stress, unit ultimate tensile stress

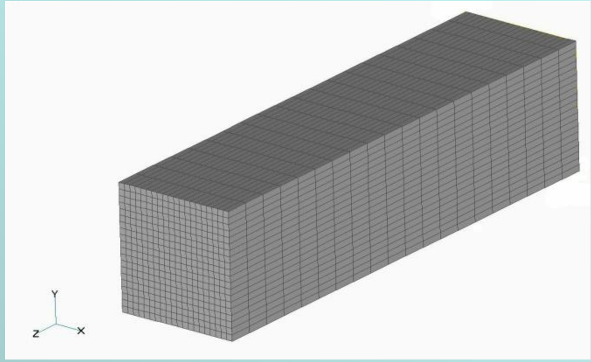
$E = \rho \cdot \bar{E}$ $E, \bar{E}$ - Young‘s modulus, unit Young‘s modulus

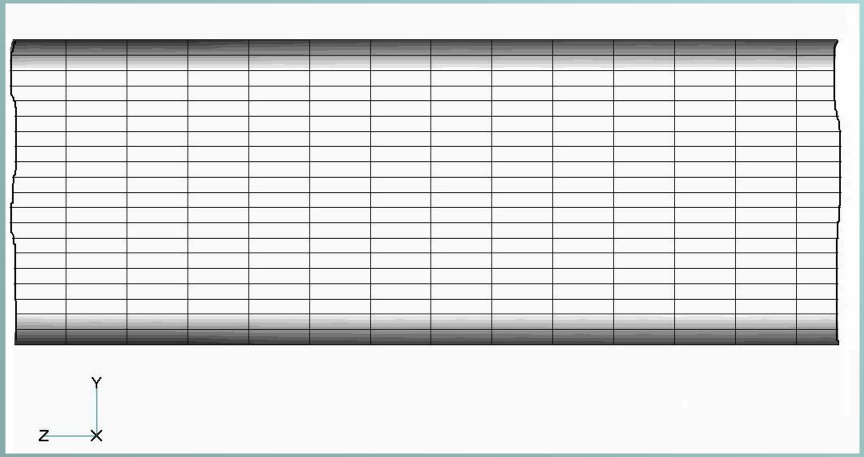
Algorithm of density distribution optimization

1. $\rho_{0i} = const$
2. σ_i
3. $\rho_{1i} = \sigma_{0i}^{eqv} / \bar{\sigma}_u$

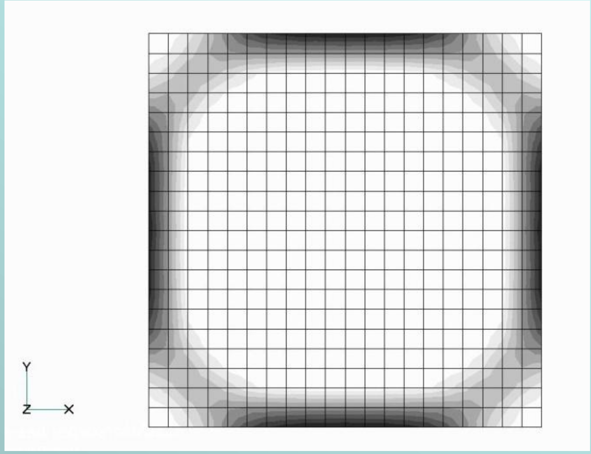


Example of optimization: bar



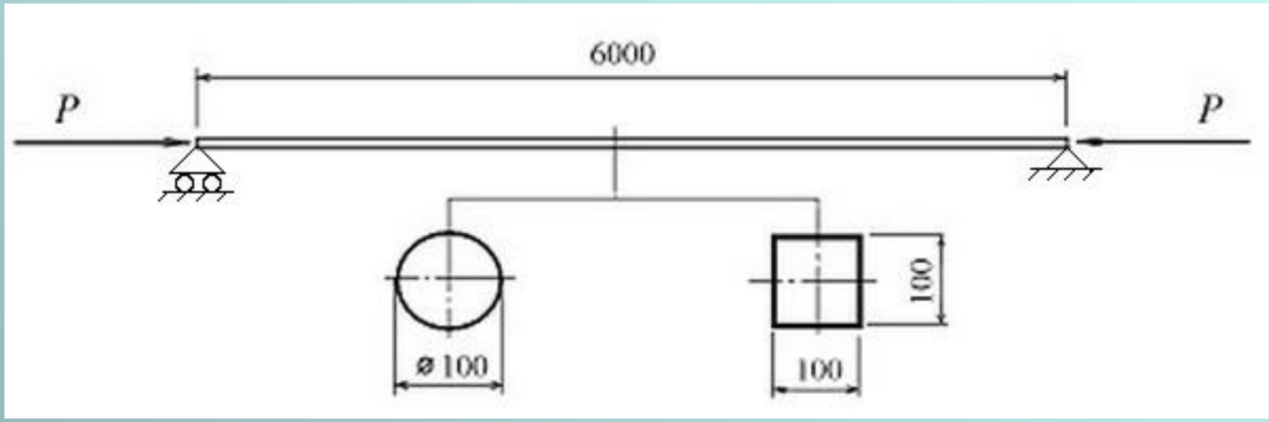


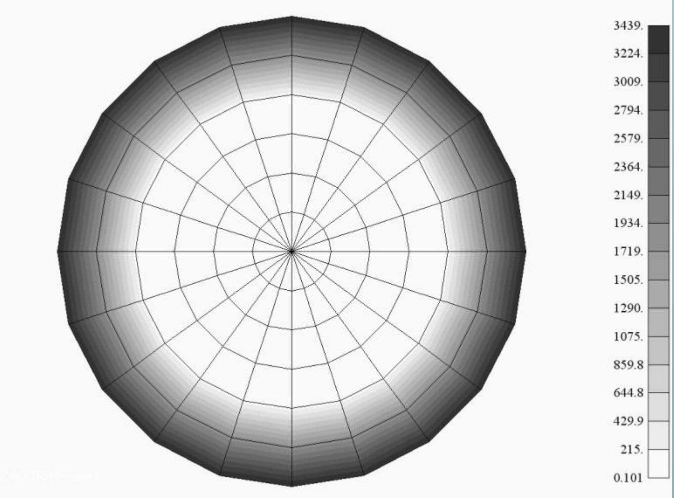
Bending

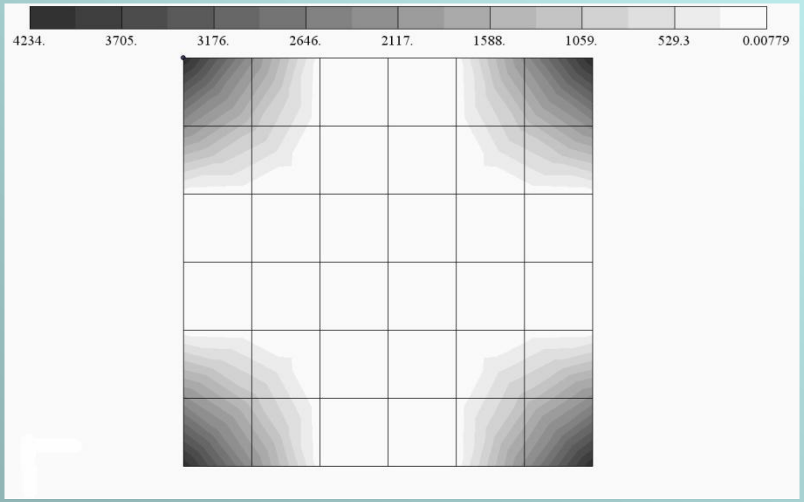


Torsion

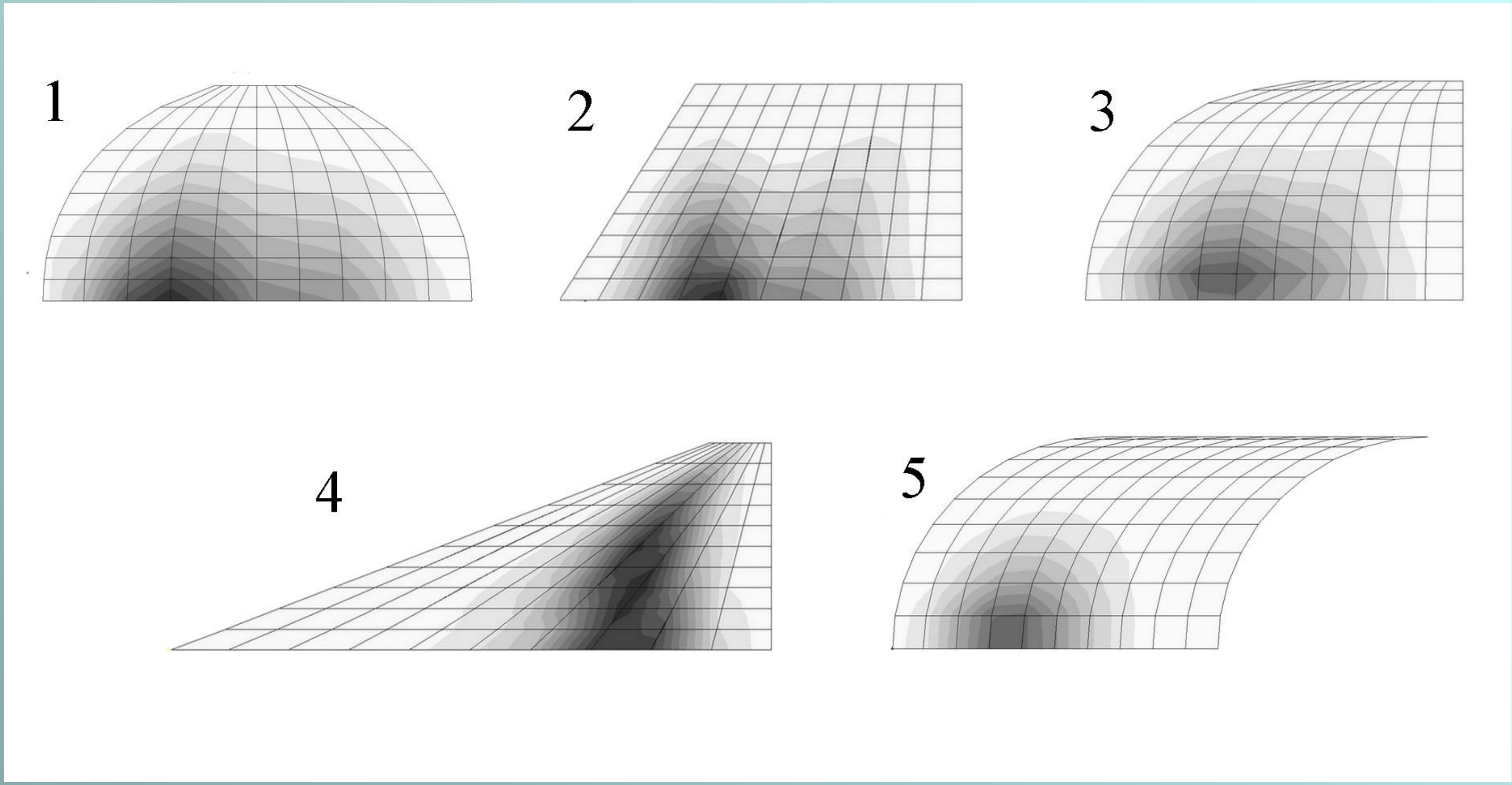
Structural optimization with buckling constraints







Material Distribution for wings



Weight analysis

Load-carrying factor

Truss $$G = \sum_{i=1}^{n} \left| N_i \right| \cdot l_i$$

Thin-walled structure $$G = \sum_{i=1}^{n} R_i \cdot S_i$$

3D-structure $$G = \int_V \sigma^{eqv} dV$$

Structural mass estimation via "load-carrying factor"

load-bearing structural volume

$$V_T = \sum_{i=1}^{n} \frac{|N_i|}{\sigma_u} \cdot l_i = \sum_{i=1}^{n} F_i \cdot l_i$$

Actual mass of structure

$$m_{st} = \varphi \cdot \rho \cdot V_T = \varphi \cdot \rho \cdot \frac{G}{\sigma_u}$$ or $$m_{st} = \varphi \frac{G}{\sigma_u}$$

G –topology, geometry and external loads

σ_u – unit strength of material

φ – nonoptimum factor (design and manufacturing technology perfection)

G - criteria allows to estimate actual (absolute) mass of unconventional structure with high accuracy

Nondimensional criteria of load carrying perfection of structure

Load-carrying factor is proportional to the linear sizes (coordinates of nodes) of structure and value of nodal forces (for constant distribution of external loads) – ***dimensional quantity***

Nondimensional criteria –

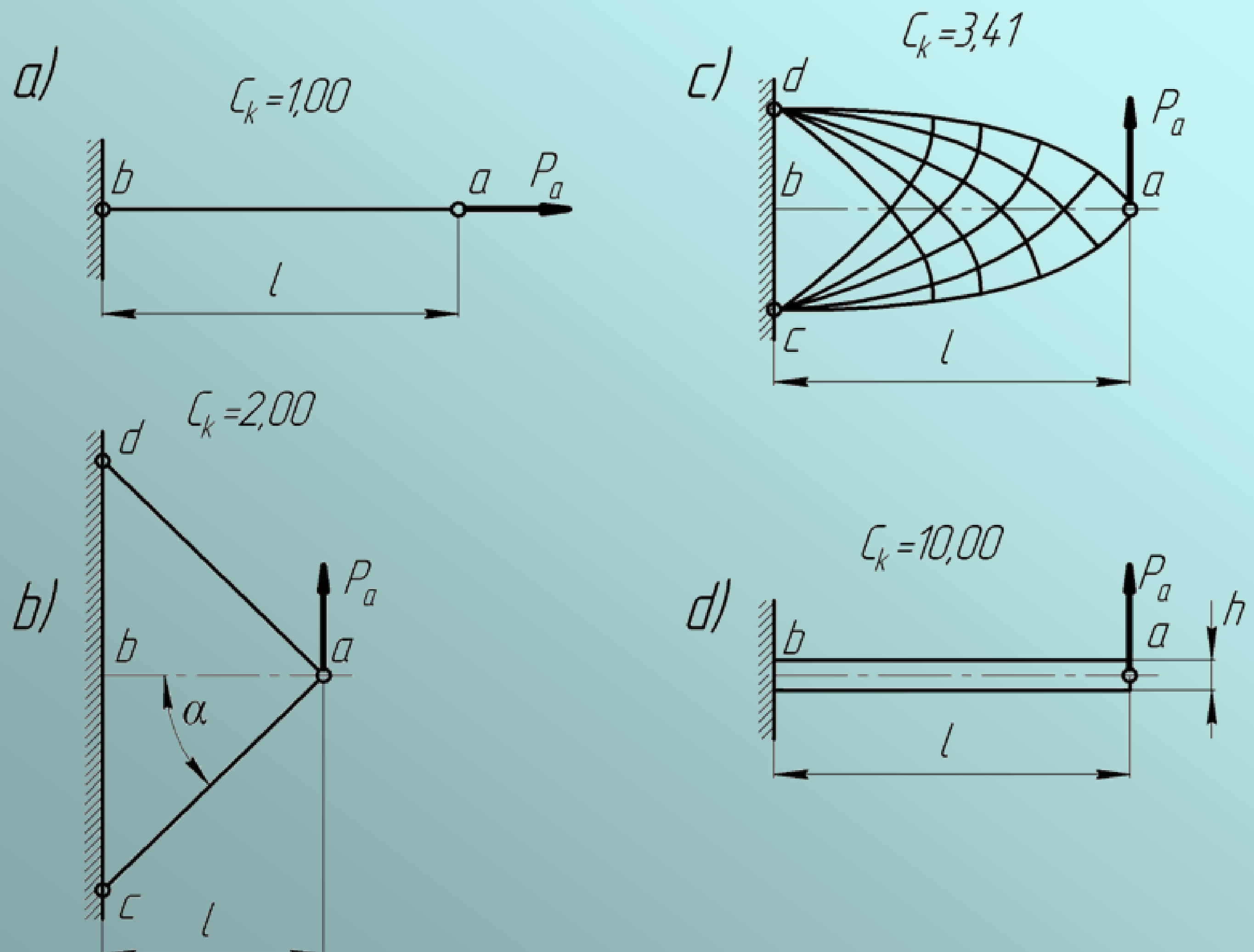
Load-carrying factor coefficient

$$C_K = \frac{G}{P \cdot L}$$

where P- reference load
L- reference size

Hence $G = C_K PL$ aerodynamic analogy : $L = C_L qS$

Examples of simple structures



New weight equation for full wing mass estimation and wing mass fraction estimation

Reference size – square root of wing area - $\sqrt{S}$

Reference load – lift $L = n \cdot m_{to} \cdot g$

$$G = C_K \cdot n \cdot m_{to} \cdot g \cdot \sqrt{S}$$

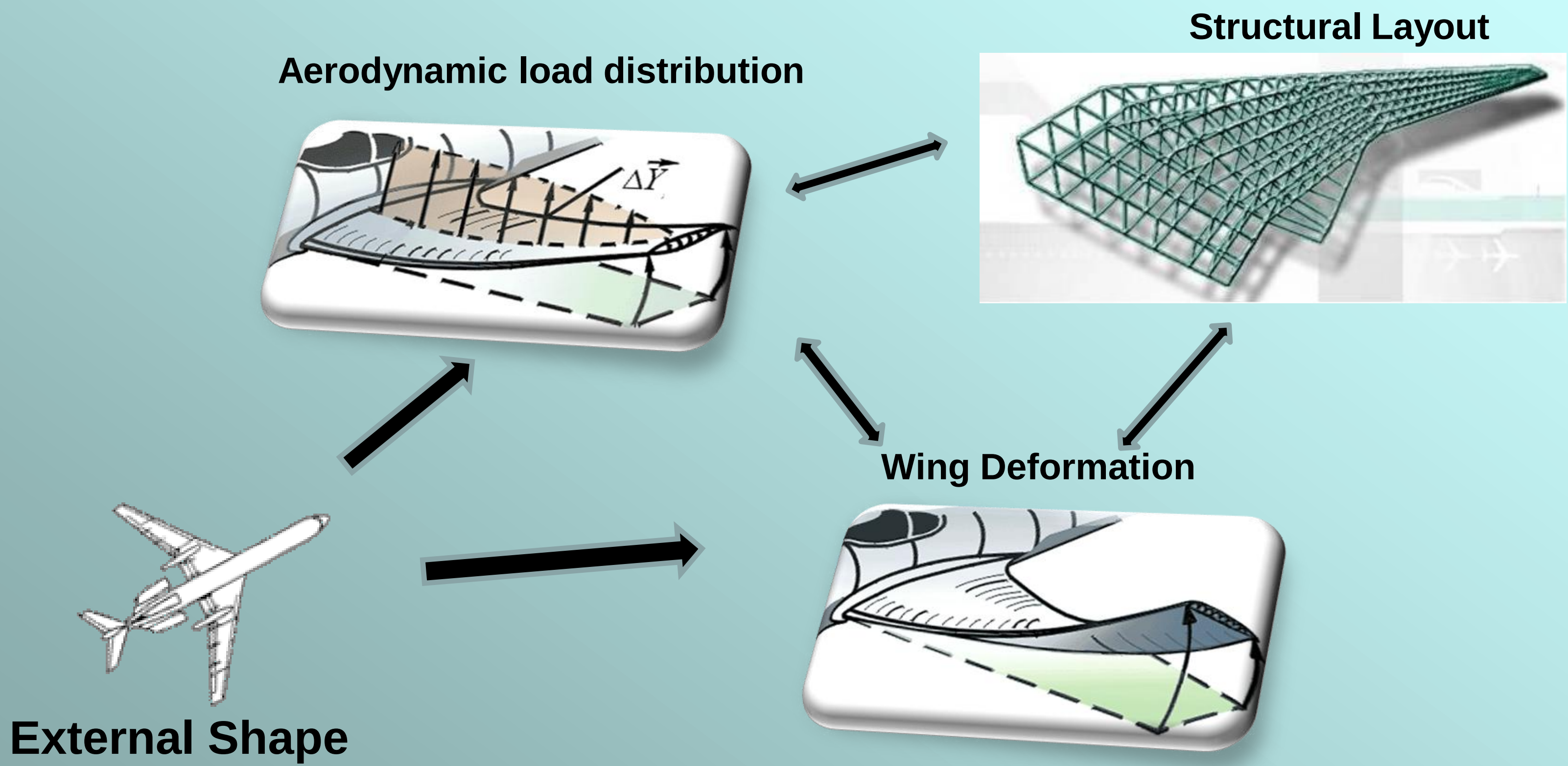
Hence

$$C_K = \frac{G^*}{n^* \cdot m_{to}^* \cdot g \cdot \sqrt{S^*}}$$

Weight equation :

$$\overline{m}_{wing} = \frac{\varphi}{\overline{\sigma}_u} C_K \cdot n \cdot g \cdot \sqrt{S} \qquad m_{wing} = \frac{\varphi}{\overline{\sigma}_u} C_K \cdot n \cdot m_{to} \cdot g \cdot \sqrt{S}$$

Wing Deformations



Reducing the uncertainties between loads, structure and deformations is of great importance at early stages of design

Algorithm

- Wing loads are calculated using a CFD for a rigid wing shape.
- The structural design domain – the space between external surface of the aircraft and internal compartments (passenger cabin, landing gear well, etc.) - is filled with hypothetic body with variable density .This body potentially contains all possible layouts including the optimal one.

$$\sigma_u = \rho \cdot \bar{\sigma}_u$$

$$E = \rho \cdot \bar{E}$$

- The optimization of material distribution (density of each element) is carried out by the special algorithm.

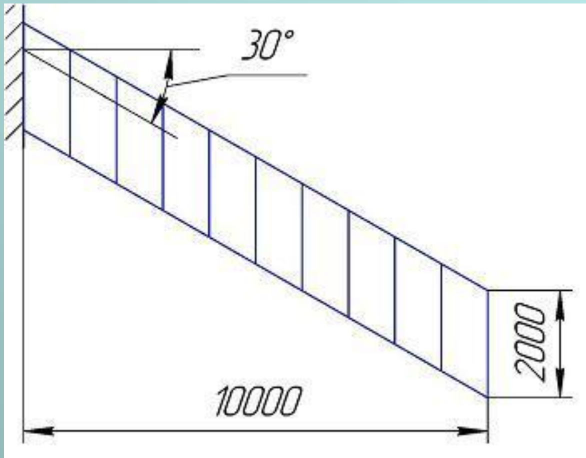
$$1.\ \rho_{0i} = const$$

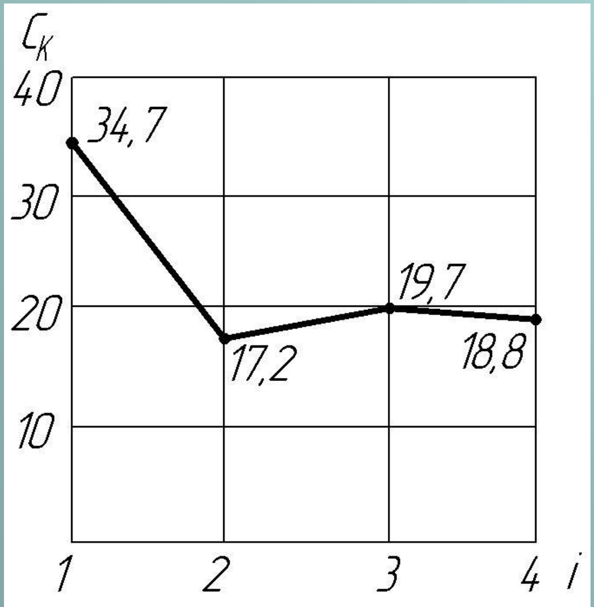
$$2.\ \sigma_i$$

$$3.\ \rho_{1i} = \sigma_{0i}^{eqv} / \bar{\sigma}_u \quad or \quad \rho_{1i} = \rho_{\min}$$

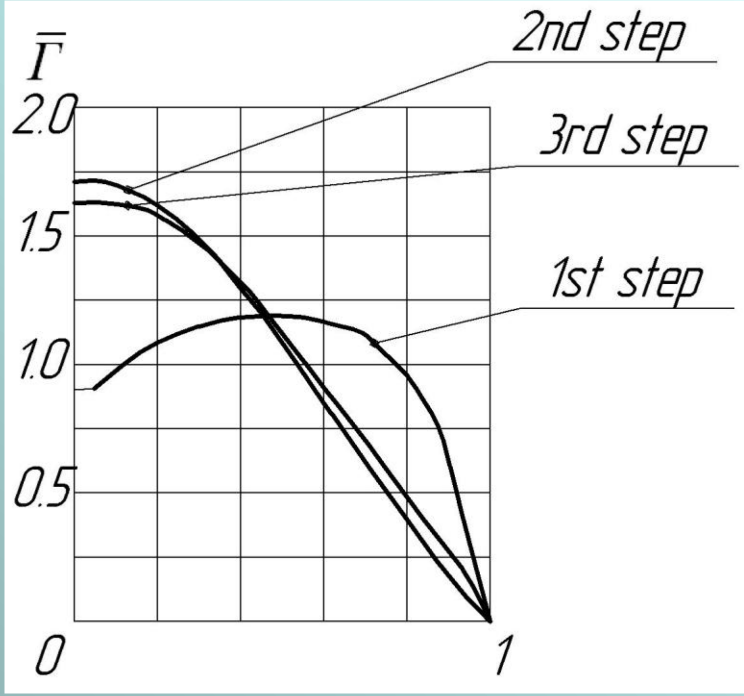
- The wing deformations are calculated, and obtained displacements are used for building a new CFD-model of deformed wing for estimating a new load distribution. The estimation is repeated until the process convergence.

Aerodynamic load distribution

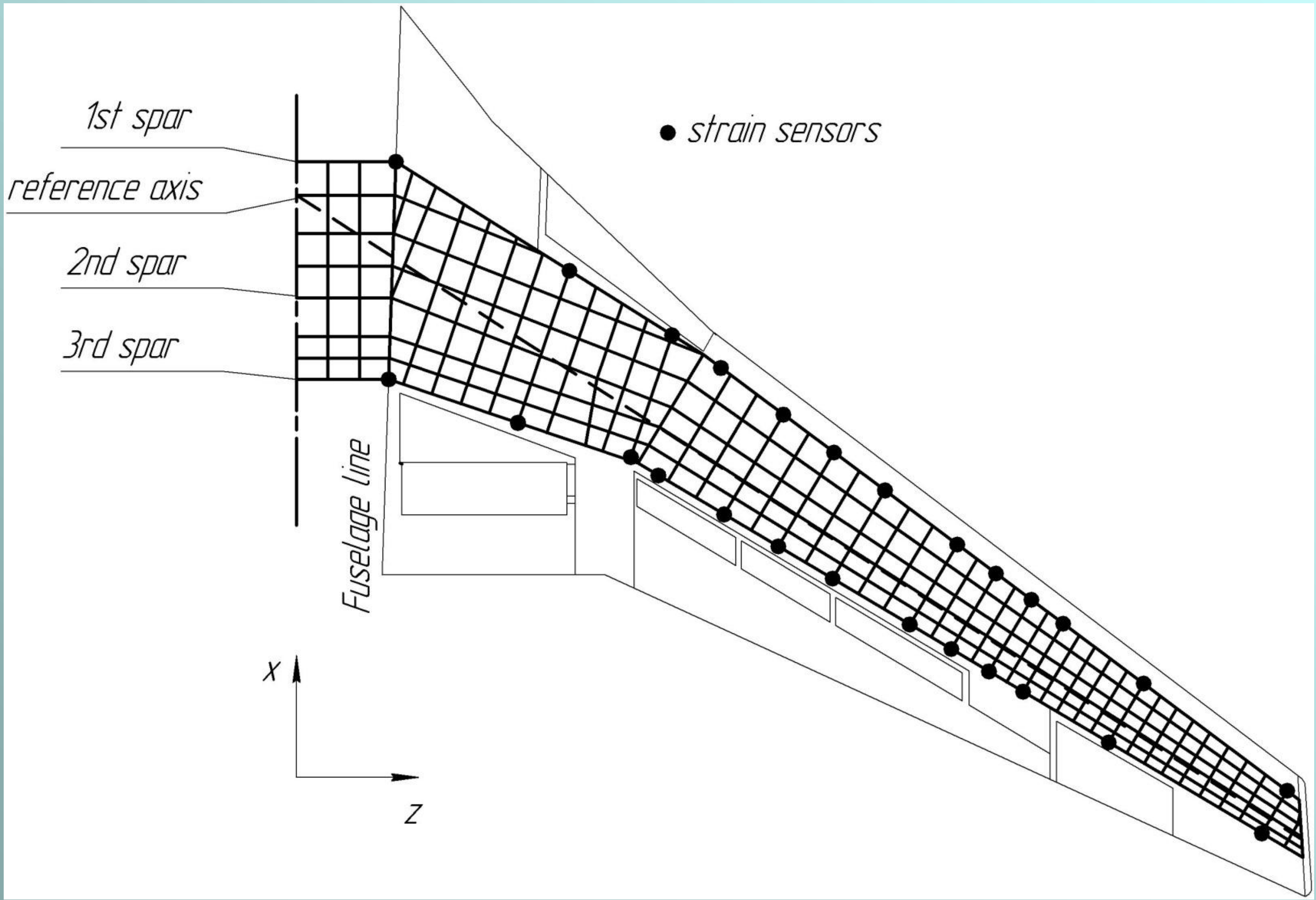




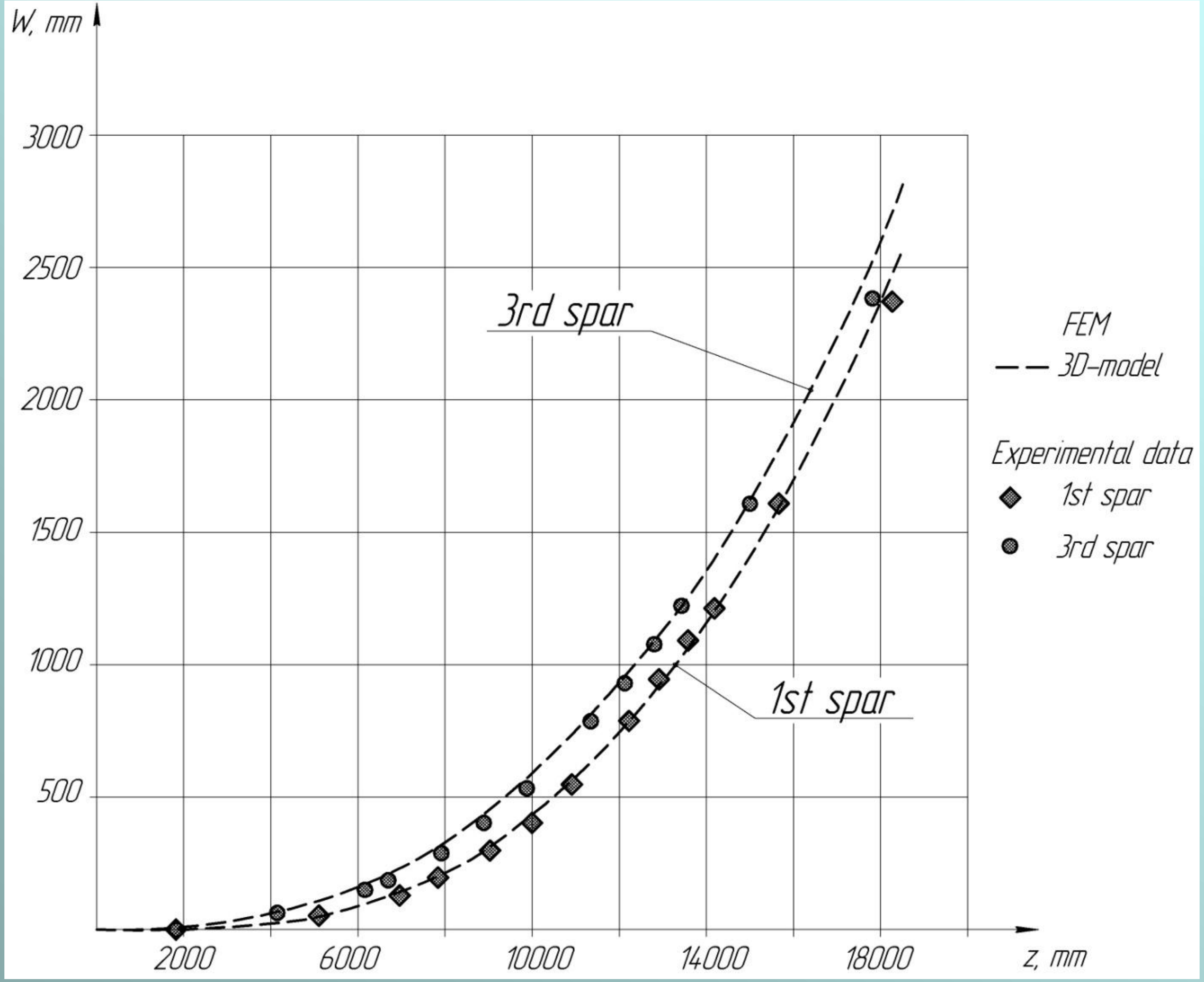
Aerodynamic load spanwise distribution and load-caring factor coefficient change by iterations



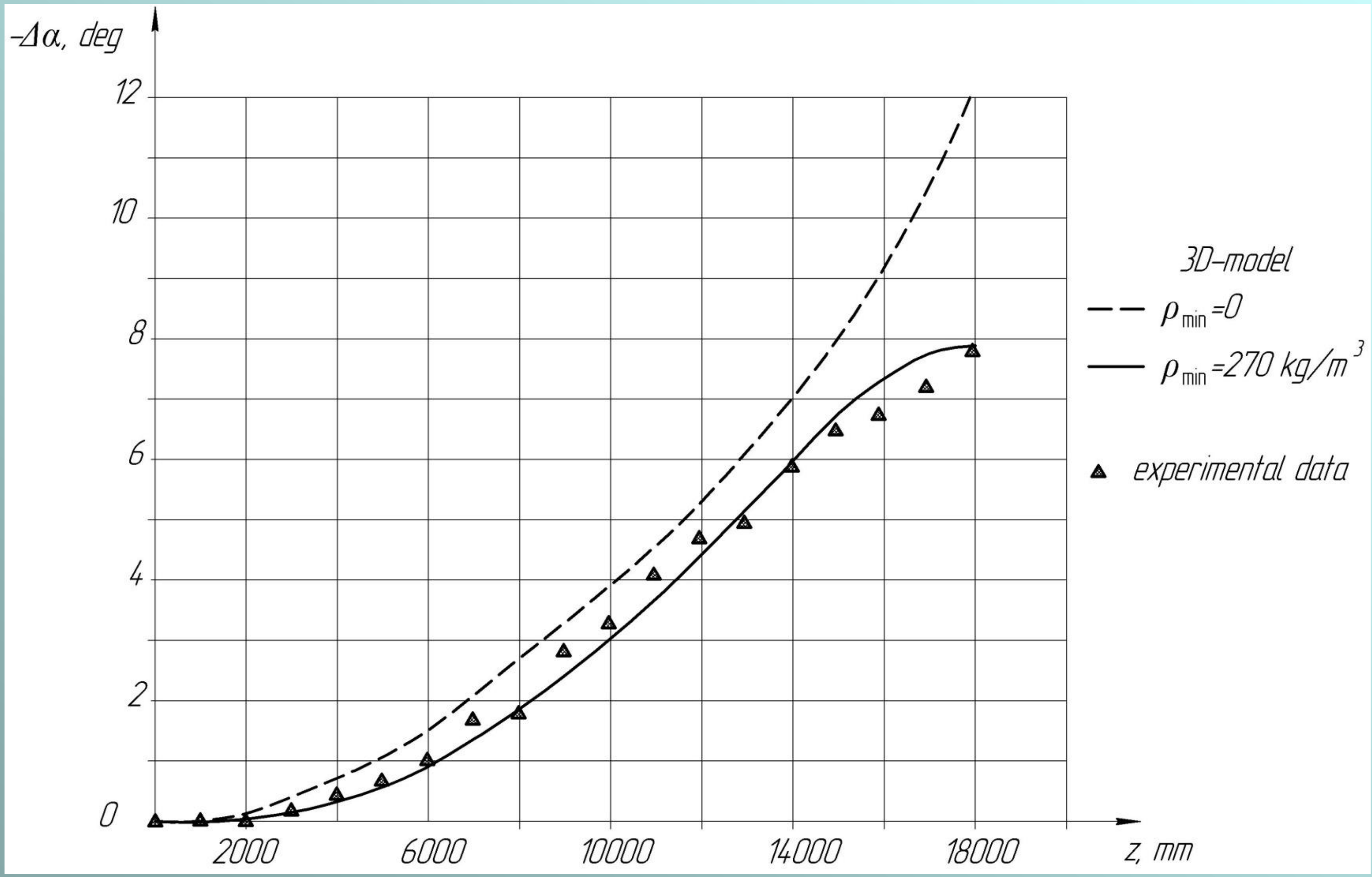
Method validation



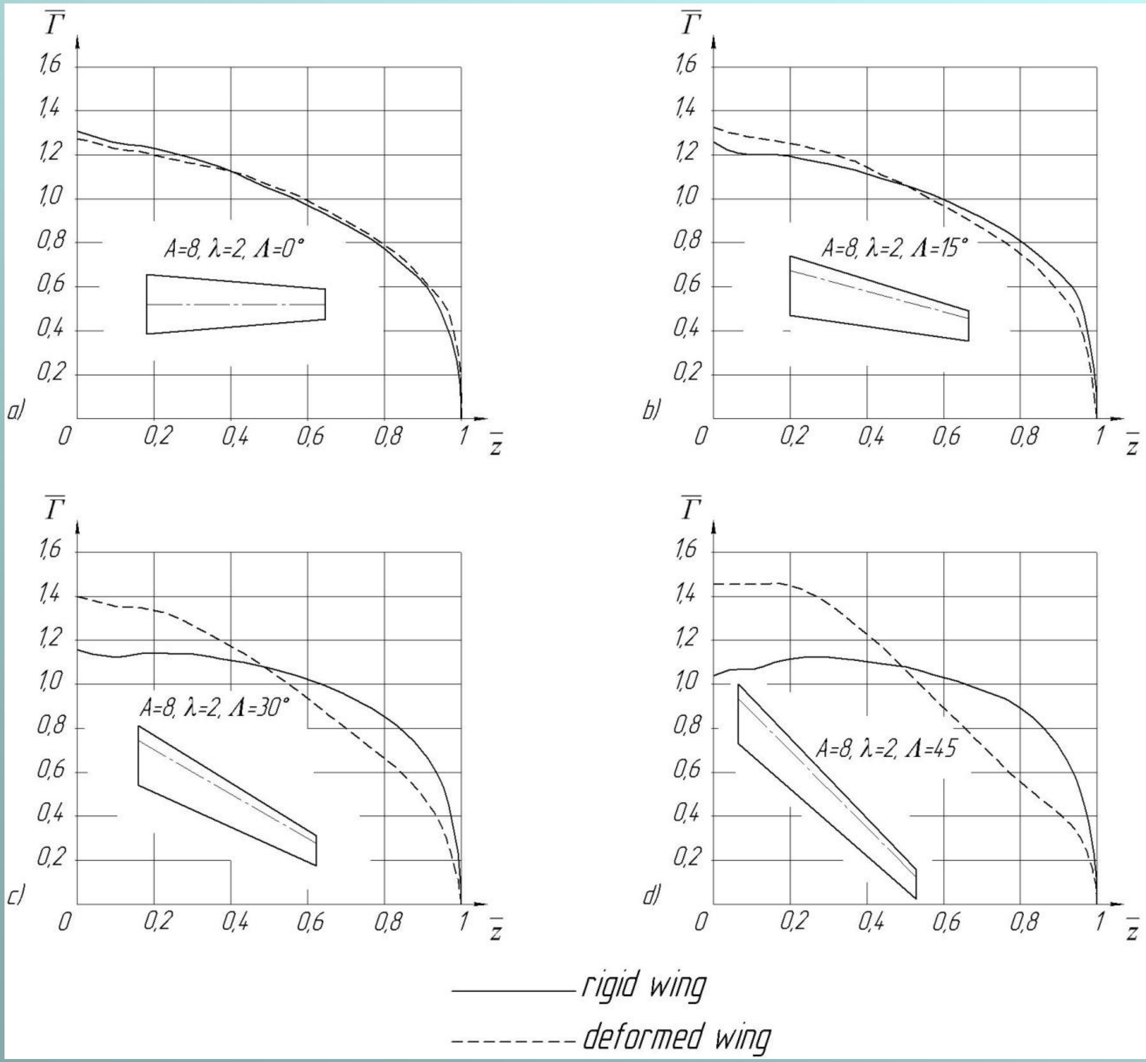
Displacements obtained from 3D model and from the experiment



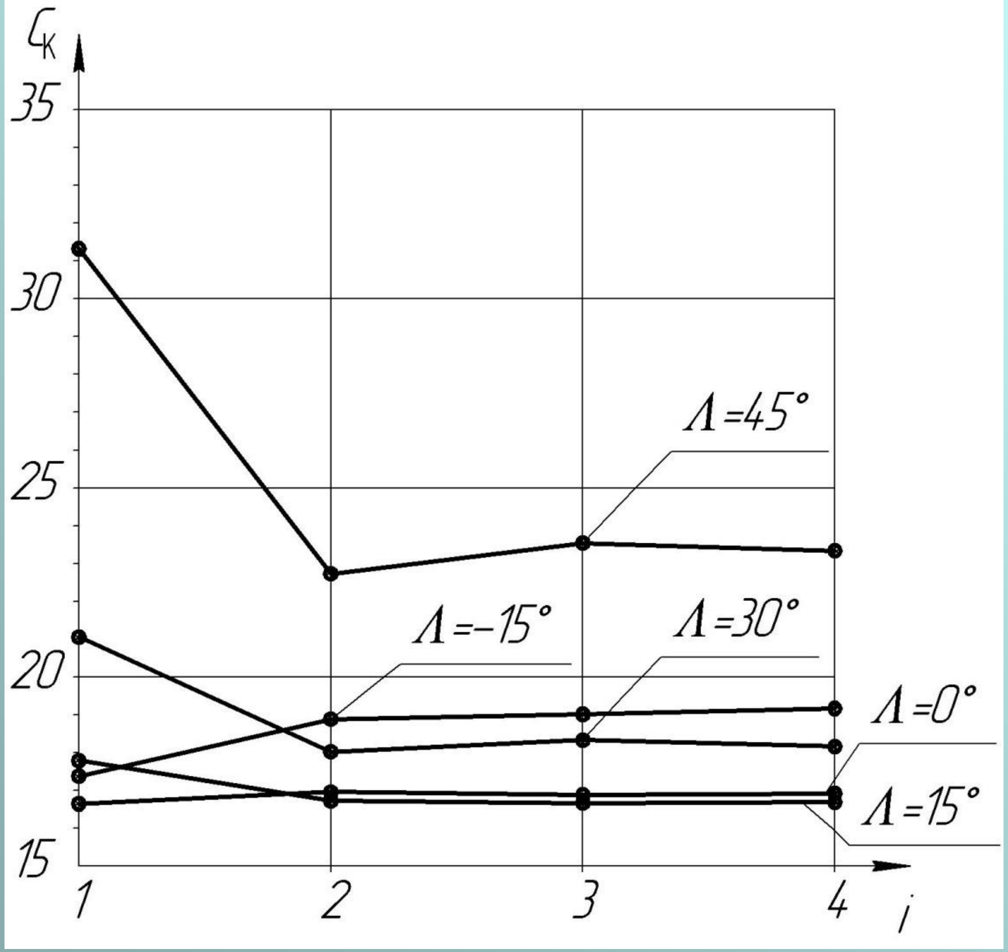
Twist angle increments in spanwise direction obtained from 3D model and from the experiment



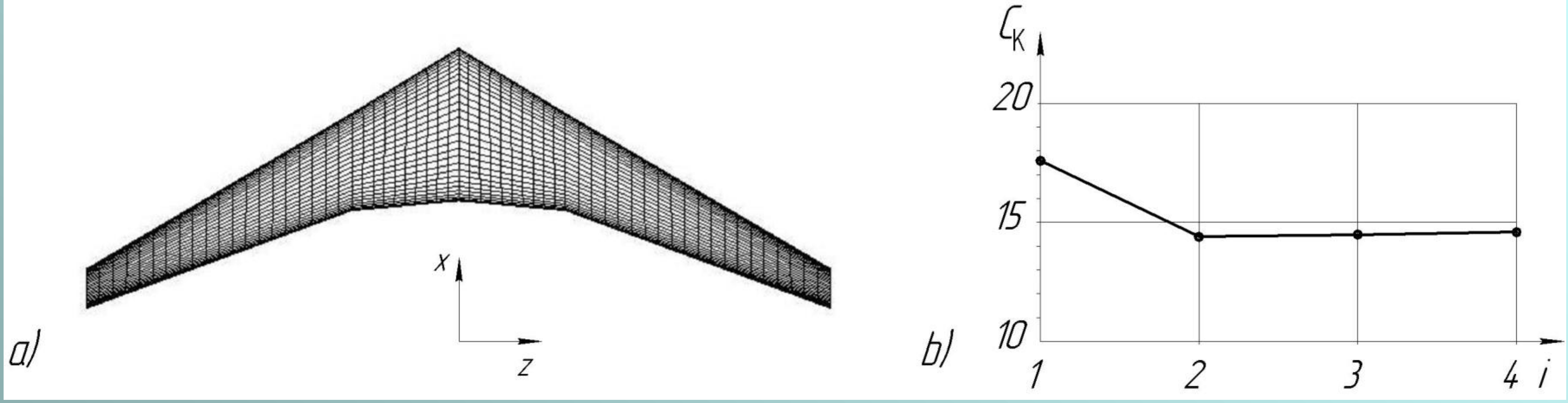
Aerodynamic load spanwise distribution for different sweep angles



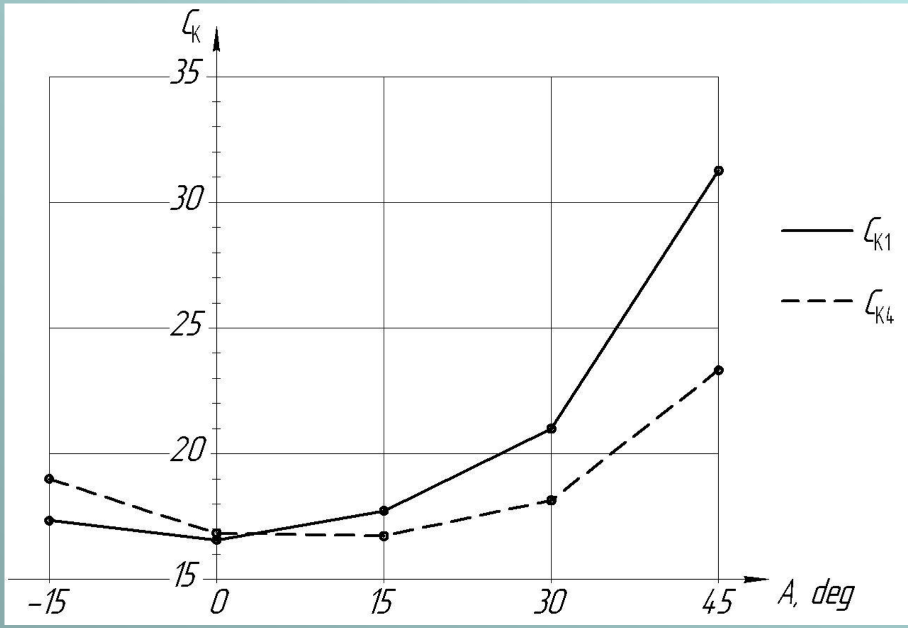
Load-caring factor coefficient change by iterations

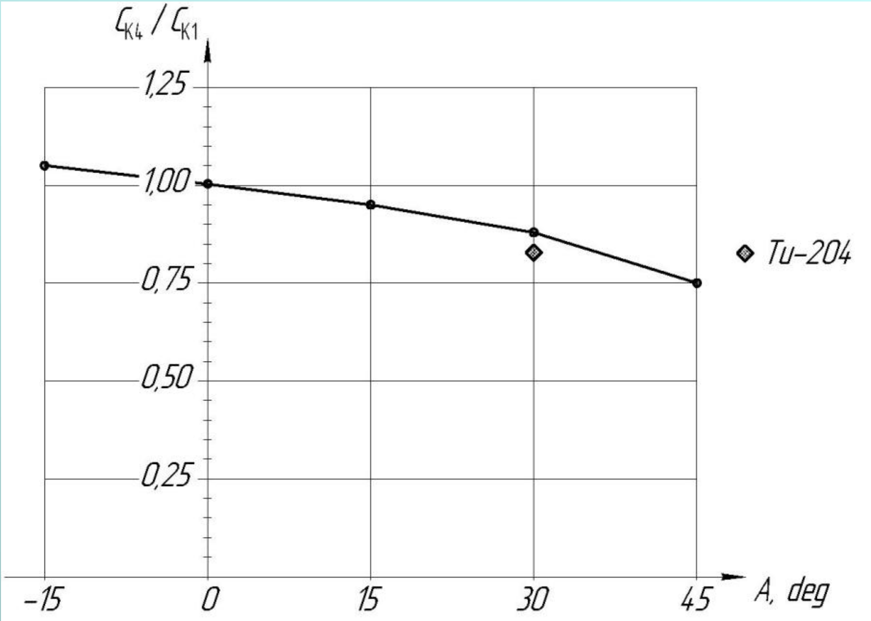


Results for modern commercial airliner



Load-caring factor coefficient change by sweep angle





Providing a reliable estimation of deformations

The following three factors should be considered:

- average stress values in real structures;
- outer layer thicknesses;
- the minimal acceptable density of 3D-model elements.

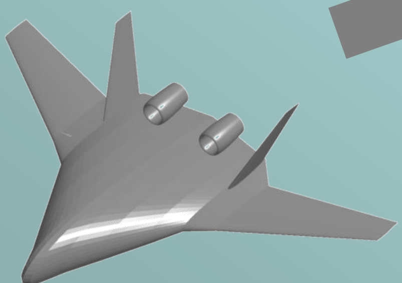
This enables to obtain the reliable forecast of wing deformations in the early stages of design.

It is not necessary to make decisions about the structural layout for the 3D–model and , moreover, this model can be useful for layout design. The set-up time for creating the 3D-models is by an order of magnitude less than creating a thin-walled FEM .

Multidisciplinary Aircraft Design

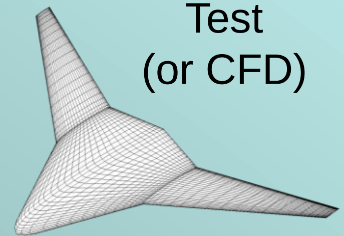
Aerodynamic and structural efficiency

Aircraft layout
(nondimensional)



Aerodynamic efficiency estimation

Wind Tunnel
Test
(or CFD)

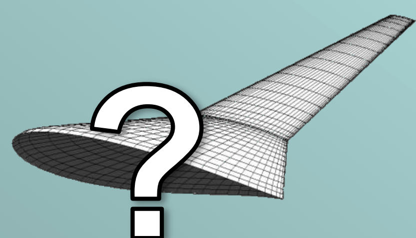


Nondimensional Criteria of Aerodynamic Efficiency

Lift-to-Drag Ratio

$$L / D = \frac{C_L}{C_D}$$

Weight efficiency estimation



Structural Design

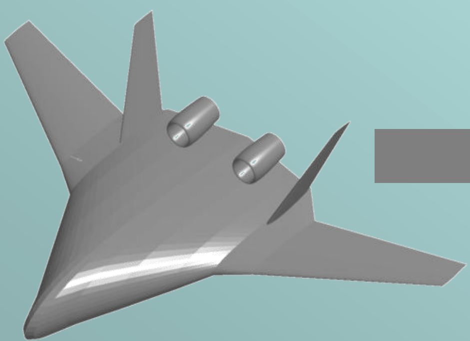
Criteria of Structural Efficiency

Structural Mass Fraction

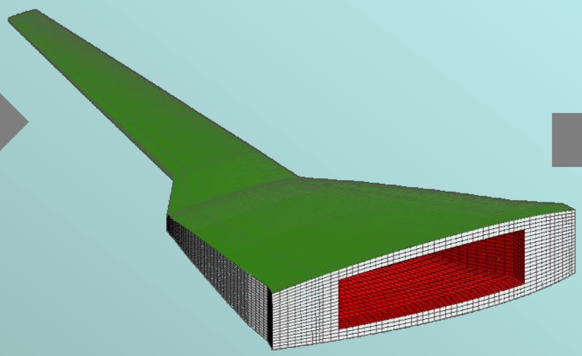
$$\bar{m}_{str} = f(S, m_{to})$$

Structural efficiency estimation

Aircraft layout



FEM with variable density



$$\sigma_u = \rho \cdot \bar{\sigma}_u$$
$$E = \rho \cdot \bar{E}$$

$$\rho_{1i} = \sigma_{0i}^{eqv} / \bar{\sigma}_u$$

Continuous Elastic Media → Fully Stressed Design

Non dimensional criteria of structural efficiency

$$C_K$$

Load-caring factor coefficient

$$C_K = \frac{G}{P \cdot L}$$

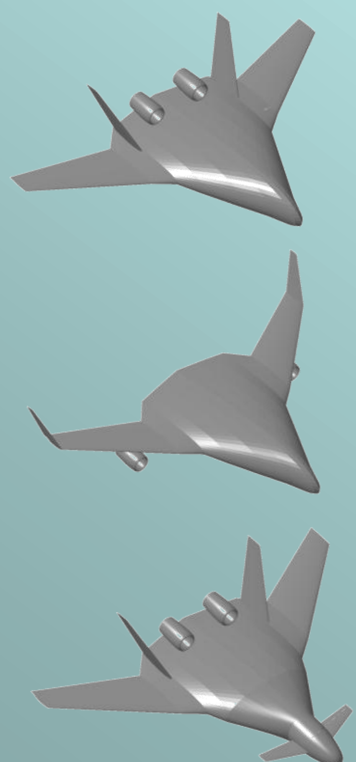
P - Reference load
L - Reference Size
G - Load-caring Factor

$$G = \int_V \sigma^{eqv} \cdot dV$$

$$\bar{\boldsymbol{m}}_{wing} = \varphi \cdot \boldsymbol{n} \cdot \boldsymbol{g} \cdot \sqrt{\boldsymbol{S}} \cdot \boldsymbol{C}_K \cdot \frac{1}{\bar{\sigma}_u}$$

Aircraft Conceptual Design

Nondimensional Aircraft → Layout Optimization → Sizing Optimization (wing loading, thrust-to-weight ratio)



$(L/D)_1$, $C_{K\,1}$

$(L/D)_2$, $C_{K\,2}$

$(L/D)_3$, $C_{K\,3}$

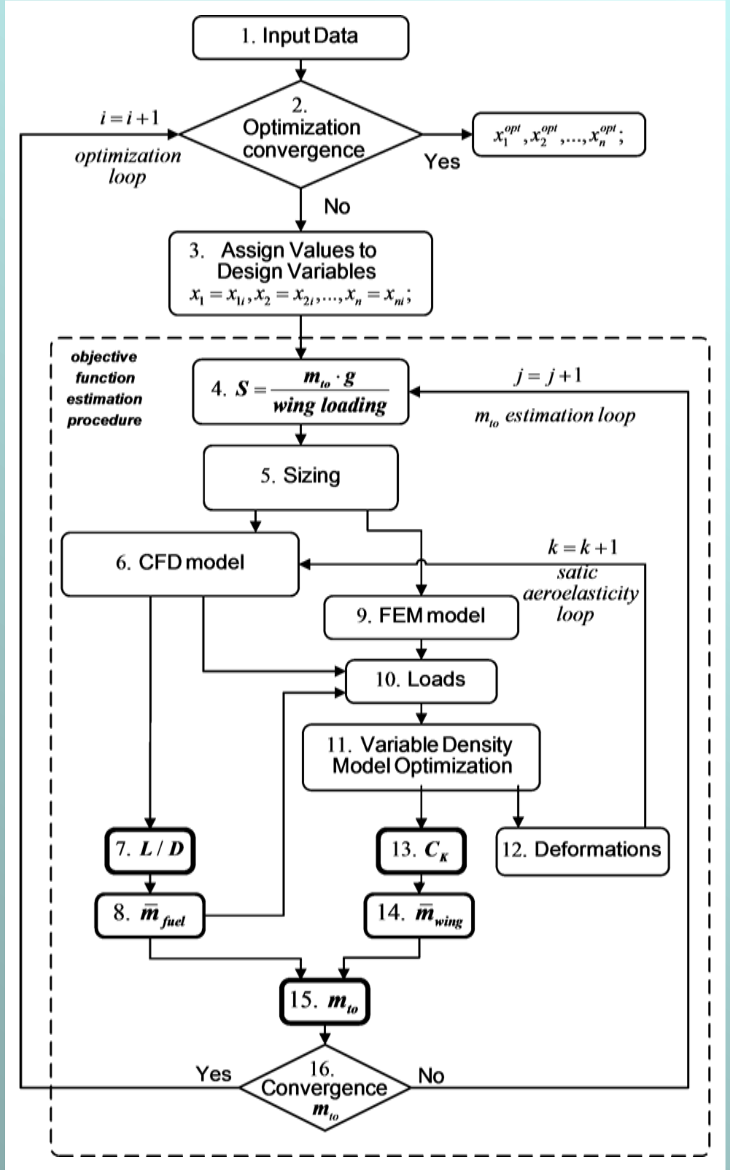
$$\left.\begin{matrix}(L/D)_1, C_{K\,1}\\(L/D)_2, C_{K\,2}\\(L/D)_3, C_{K\,3}\end{matrix}\right\} \Rightarrow (L/D)_{opt},\ C_{k\,opt}$$

$$S_1 \rightarrow \bar{m}_{fuel\,1},\ \bar{m}_{str\,1}$$

$$S_2 \rightarrow \bar{m}_{fuel\,2},\ \bar{m}_{str\,2}$$

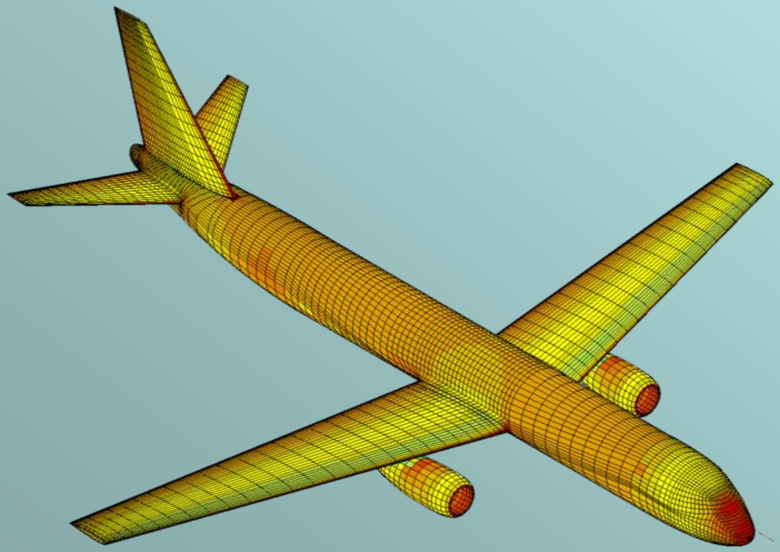
$$S_3 \rightarrow \bar{m}_{fuel\,3},\ \bar{m}_{str\,3}$$

Algorithm

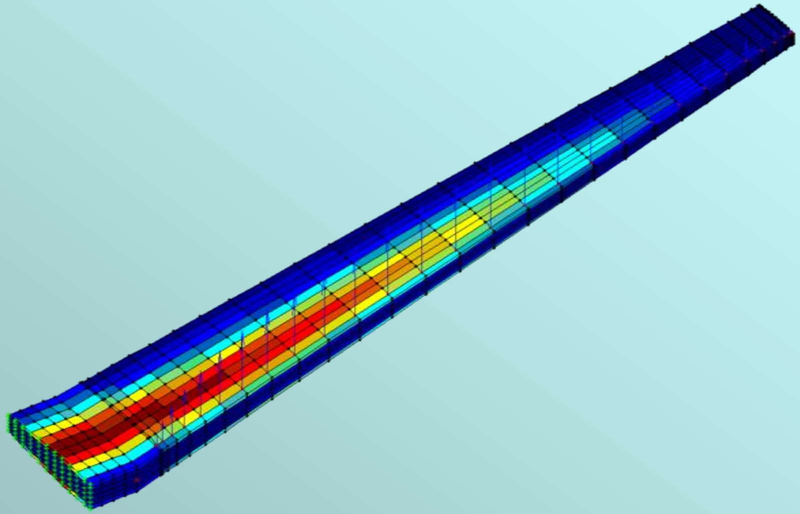

1. Input Data
2. Optimization convergence
i = i + 1
optimization loop
Yes
No
3. Assign Values to Design Variables
objective function estimation procedure
4. S = m_to · g / wing loading
j = j + 1
m_to estimation loop
5. Sizing
6. CFD model
k = k + 1
satic aeroelasticity loop
9. FEM model
10. Loads
11. Variable Density Model Optimization
7. L / D
13. C_K
12. Deformations
8. m_fuel
14. m_wing
15. m_to
Yes
16. Convergence m_to
No

Models

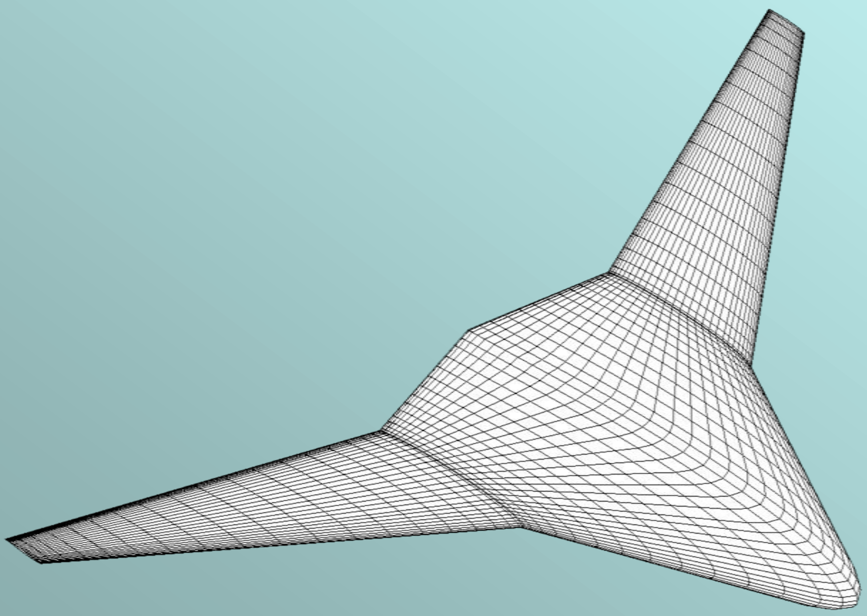
CFD Panel Method

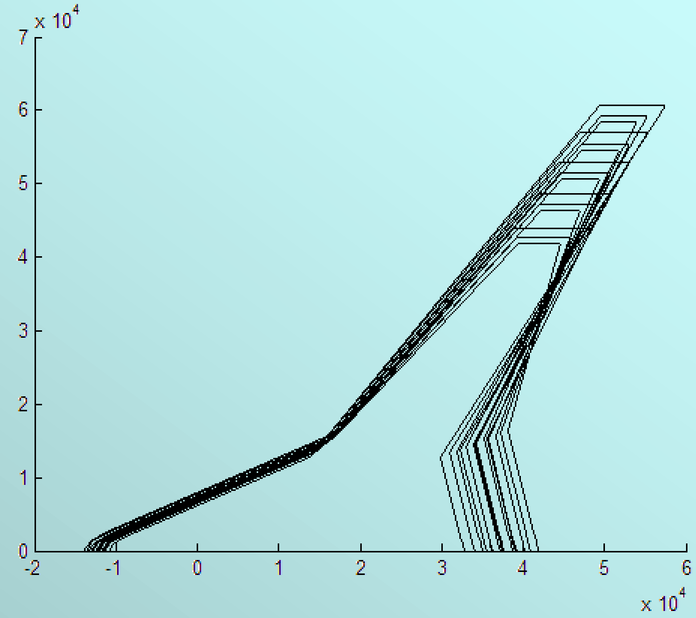


FEM with Variable Density



Results





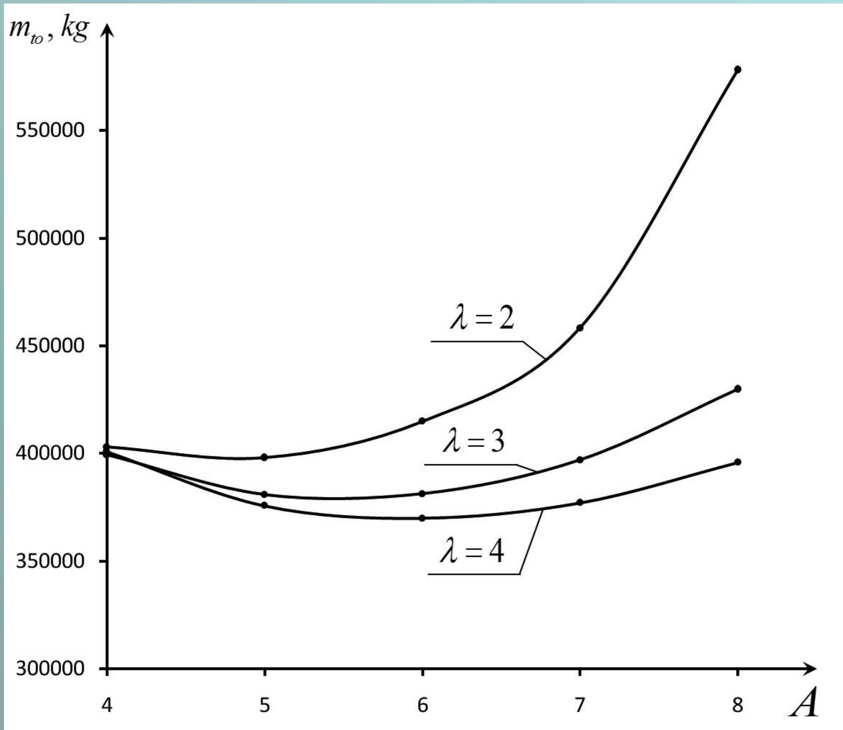
Wing loading	$p_0 = 3500\ N/m^2$
Payload Mass	$m_{payload} = 83000\ kg$
Range	$R = 10\,000\ km$

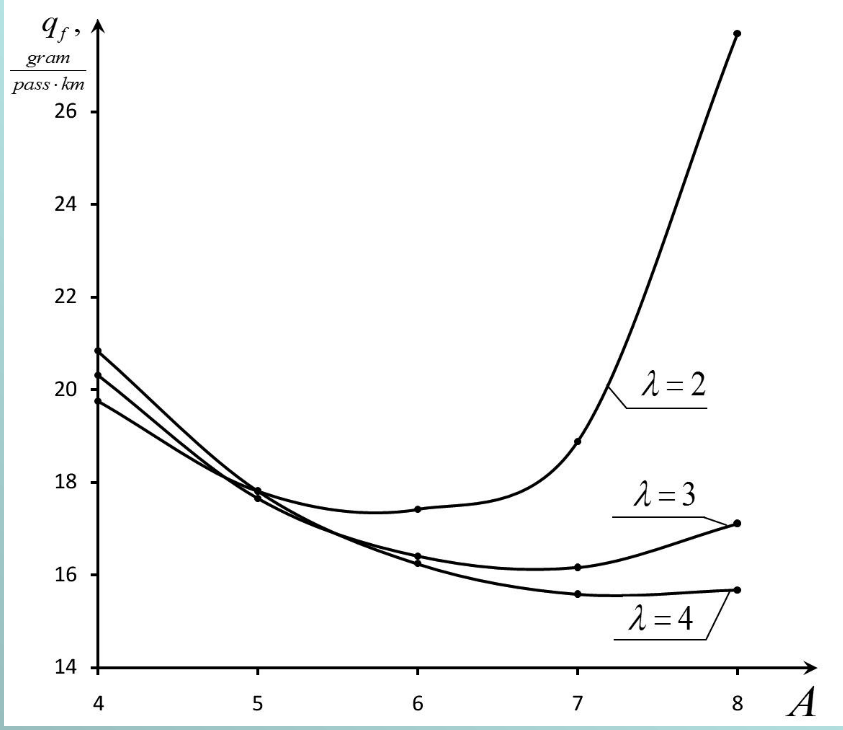
Outer wing Aspect Ratio	$A = [4\ 5\ 6\ 7\ 8]$
Outer wing Taper Ratio	$\lambda = [2\ 3\ 4]$

Results

Take-off mass $m_{to} = f(A, \lambda)$

Fuel Efficiency $q_f = \dfrac{m_{fuel}}{n_{pass} \cdot R} = f(A, \lambda)$





Method Implementation

Matlab

(overall process control, CFD and FEM model generation, calculation of loads, postprocessing of the results)

CFD - Apame

(open source panel code www.3dpanelmethod.com)

Custom Variable-Density-Model Optimization Script "Opt-Vdb"

FEM – MD Nastran

We are open for collaboration in the field of code testing, application, development and integration to other software

References

1. Komarov A.A. The basics of aircraft structural design. Kuybyshev: Kuybyshev book publisher, 1965. 82 p. (in Russian).
2. Komarov V.A. The aircraft structural layout design. Actual problems of aviation science and technology. www.mashin.ru, 1984. P.114-129. (in Russian).
3. Bendsoe M.P., Kikuchi N. Generating Optimal Topologies in Structural Design Using a Homogenization Method // Computer Methods in Applied Mechanics and Engineering. 1988. V. 71. P. 197–224
4. Komarov V.A. The weight analysis of the aircraft structure: theoretical basis. Scientific and technical journal «Polyot» («Flight») (ISSN 1684-1301). 2000, №1. P. 31-39. (in Russian)
5. Eschenauer H.A., Olhoff N. Topology optimization of continuum structures: A review. Appl. Mech. Rev. 2001. V. 54. № 4. P.331-389.
6. Boldyrev A.V., Komarov V.A. Structural optimization of lifting surfaces with regard to static aeroelasticity. Russian Aeronautics (ISSN 1068-7998). http://allertonpress.com/journals/aer.htm (ISSN 1934-7901). 2008. T. 51. № 2. P. 109-113
7. Boldyrev A.V., Komarov V.A., Lapteva M.Yu., Popovich K.F. Account of static aeroelasticity on early stages of design. Scientific and technical journal «Polyot» («Flight») (ISSN 1684-1301). 2008, №1. C.34-39. (in Russian).
8. Boldyrev A.V. A development of aircraft structure design technique based on a model of solid deformable body with variable density. Scientific and technical journal «Polyot» («Flight») (ISSN 1684-1301). 2009, № 11. P. 23-28.(in Russian).
9. Boldyrev A.V. Weight analysis of wings with unconventional shape. Scientific and technical journal «Polyot» («Flight») (ISSN 1684-1301). 2009, №10. P. 57-60. (in Russian).
10. Boldyrev A.V., Komarov V.A., Lapteva M.Yu. On assessment of prediction accuracy at the wing deformations by using the model of variable density. www.kai.ru/vestnik. 2009, № 3. P. 13-15. (in Russian).
11. Vyrypaev A.A., Kozlov D.M. Komarov V.A., Kuznetsov A.S. Integrated estimation of wing weight and aerodynamic efficiency in aircraft design. Scientific and technical journal «Polyot» («Flight») (ISSN 1684-1301). 2010, №10. P. 35-44 (in Russian).
12. Komarov V.A. Lapteva M.Yu. Wing deformations estimation. Scientific and technical journal «Polyot» («Flight») (ISSN 1684-1301). 2011, №3. P. 8-12. (in Russian). .

Thank you for your attention!