

Programa de Engenharia Oceânica
COPPE/UFRJ
GERO

The image shows four offshore wind turbines in a row, receding into the distance on a calm blue sea under a clear sky. Each turbine has a white tower and three blades with red and white stripes. The text is overlaid on the middle of the image.

Determinação das propriedades geométricas e do material de uma pá da turbina eólica por análise inversa

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2. Análises BEM e FSI

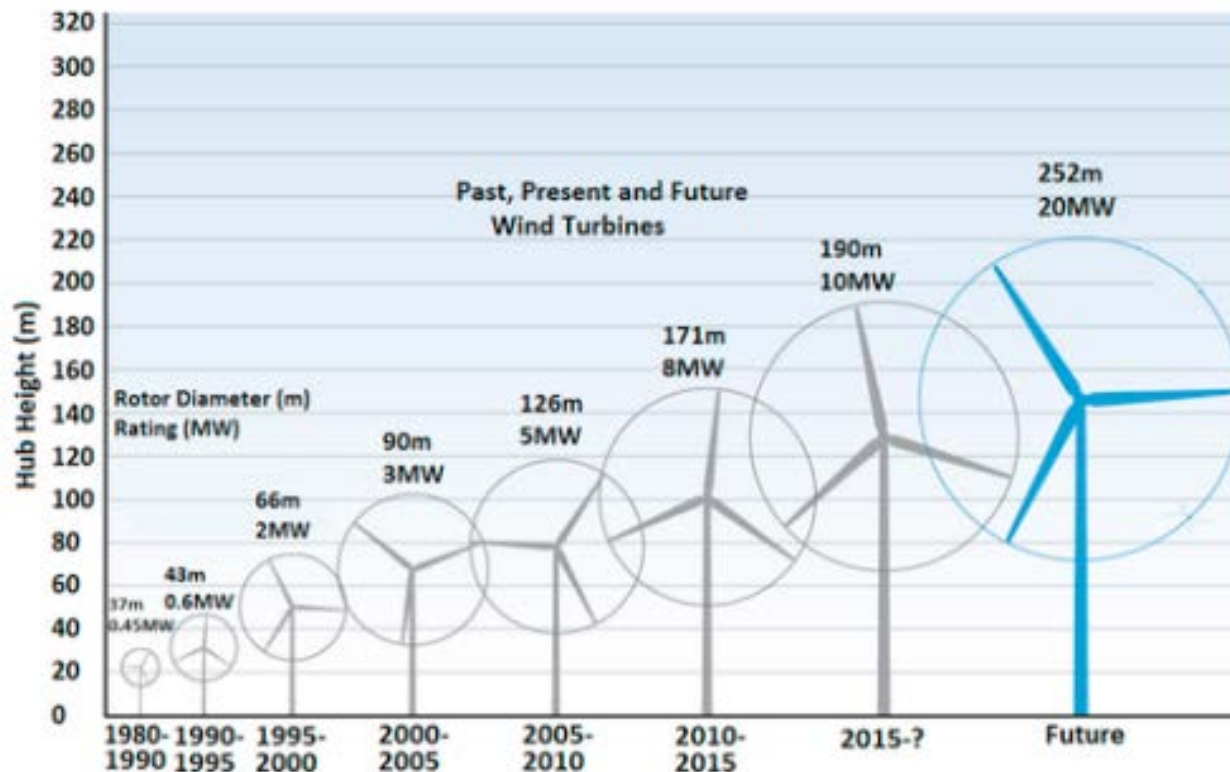
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4. Análise inversa sobre a pá

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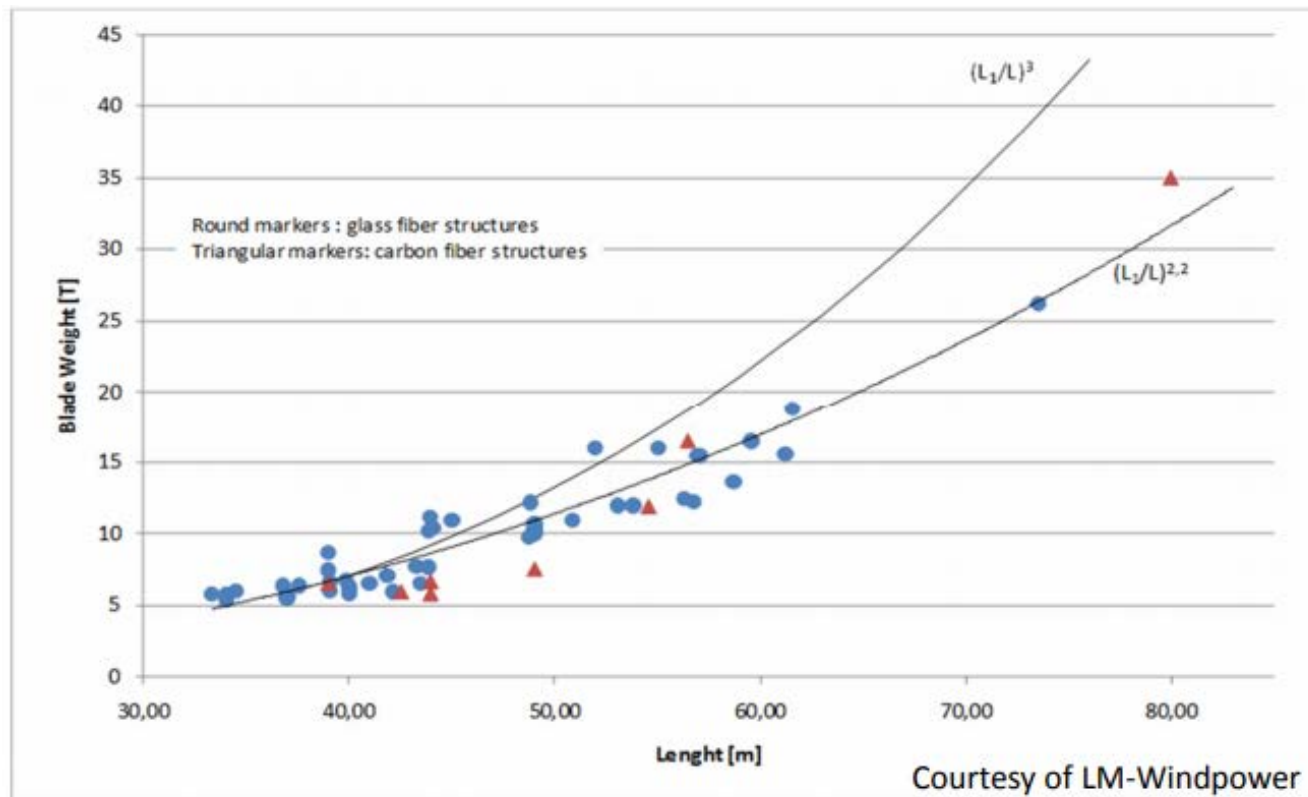
1. Introdução

- Aumento da potência da turbina eólica, conseqüentemente um aumento de tamanho, em especial as torres e as pás.
- Tendência da instalação das turbinas eólicas offshore à distâncias mais afastadas da costa.
- Tendência do uso de plataformas flutuantes.



1. Introdução

- Tamanhos crescentes do rotor levam ao aumento de massa e ao aumento de expoentes (2,2 +) quando as cargas gravitacionais começam a dominar.
- Uso de materiais compósitos mais eficientes, alta relação resistência/peso.



1. Introdução

- A importância da redução de peso do rotor no custo.

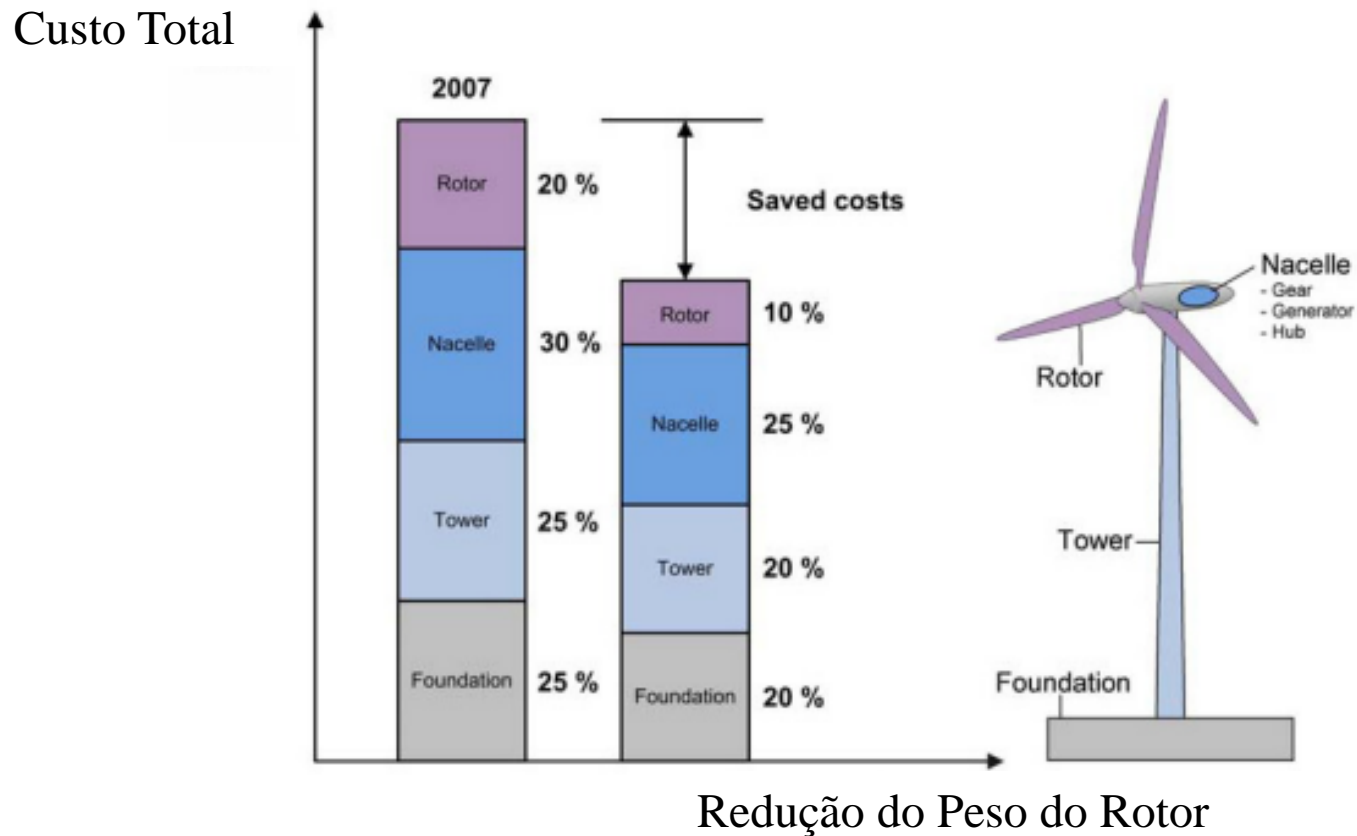
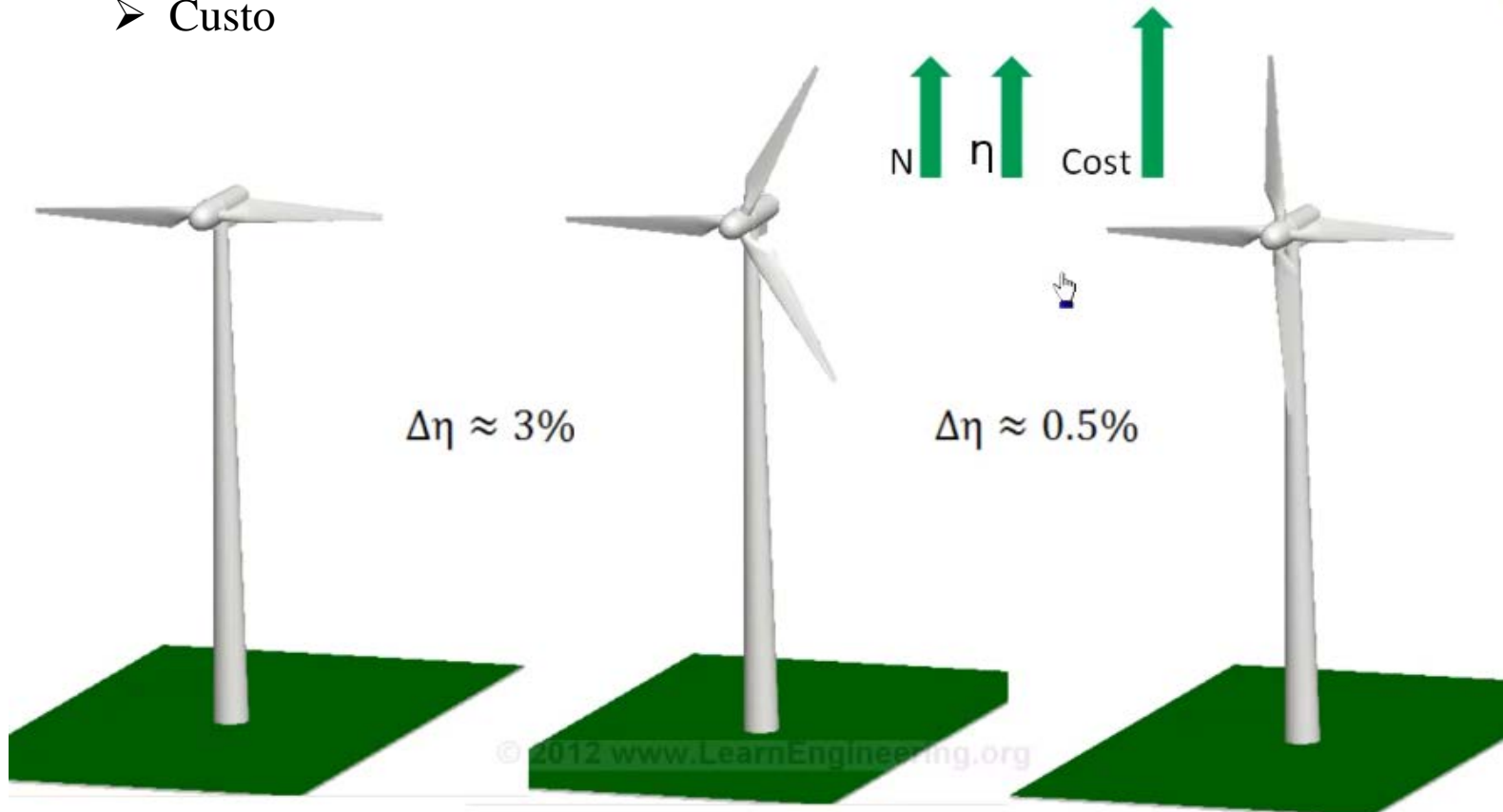


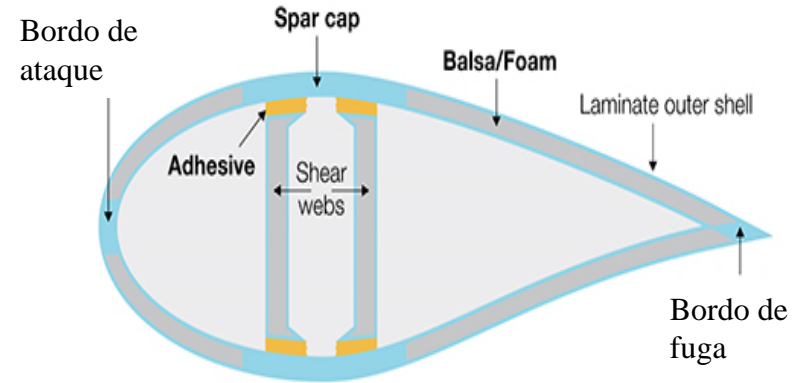
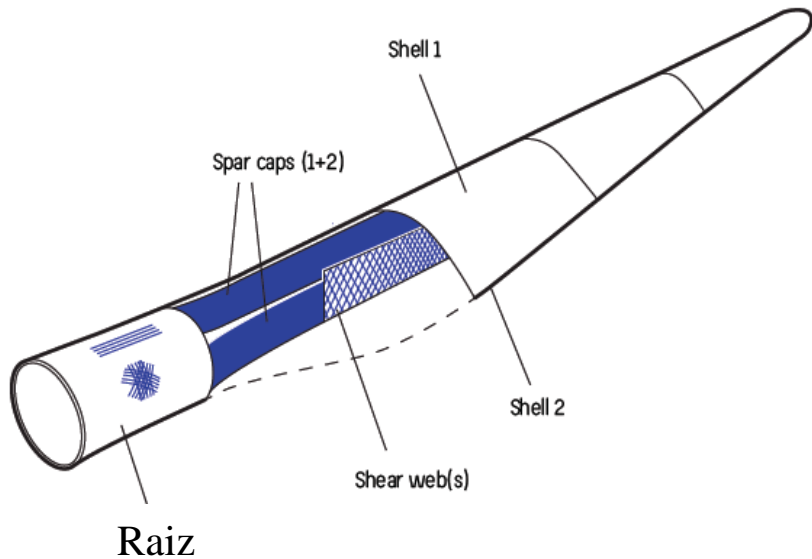
Figure from F.M. Jensen, PhD-thesis, Risø DTU-2008

1. Introdução

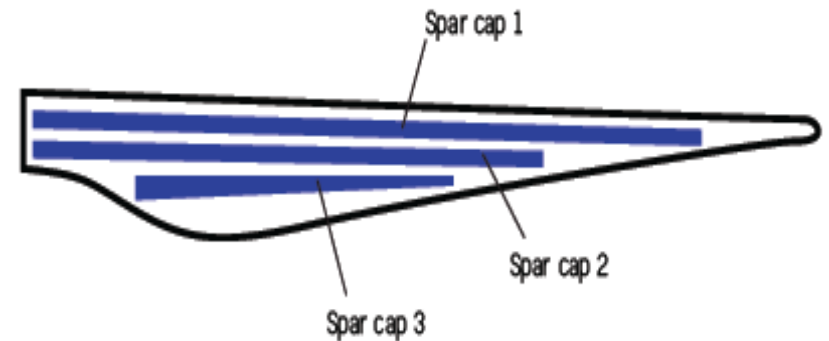
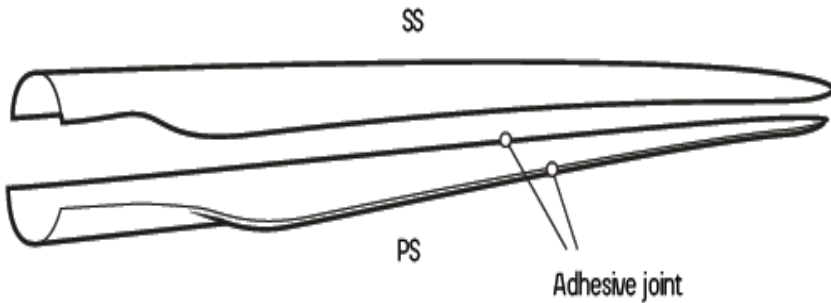
- Número de pás
- Eficiência
- Custo



1.1. Características da pá



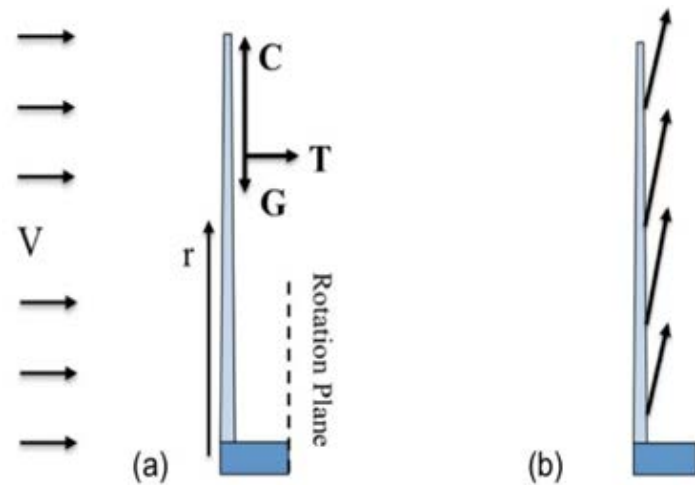
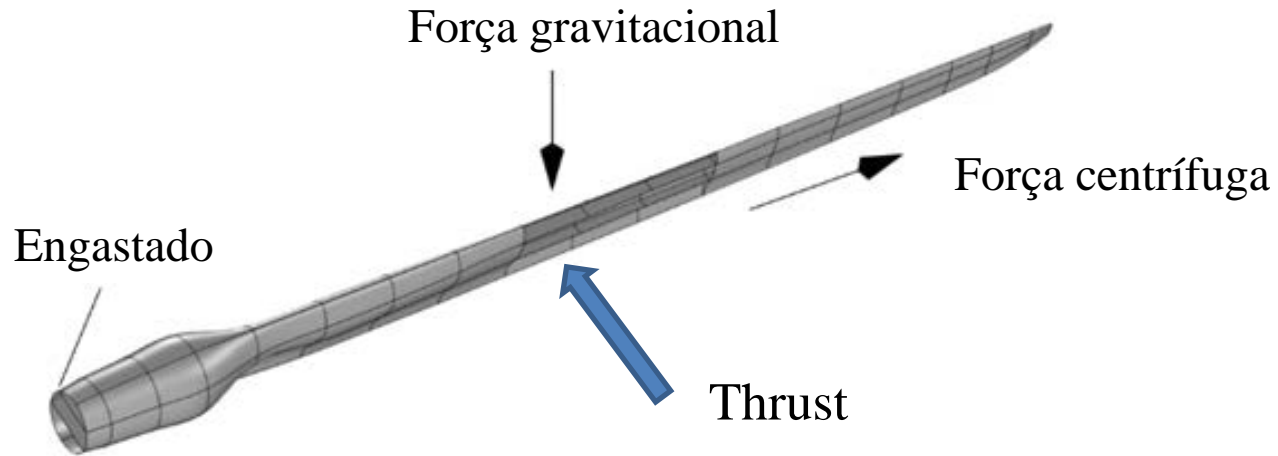
➤ Seção transversal.



➤ Transfere as pressões para os *shear webs*

➤ Capta todas as cargas do perfil aerodinâmico da ponta para a raiz

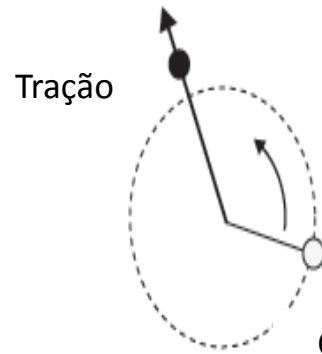
1.2. Carregamentos sobre a pá



1.2. Carregamentos sobre a pá



Ação da gravidade



Centrifuga

1



Compressão

2



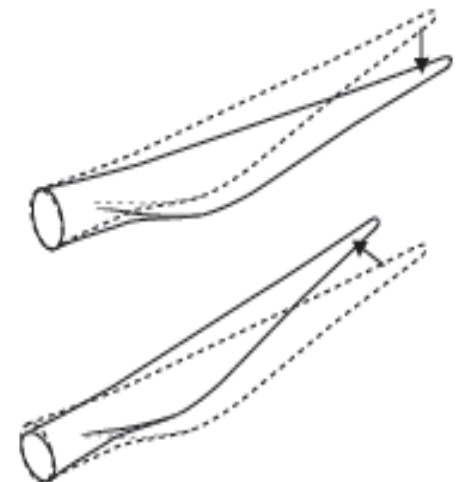
Tração



Forças aerodinâmicas



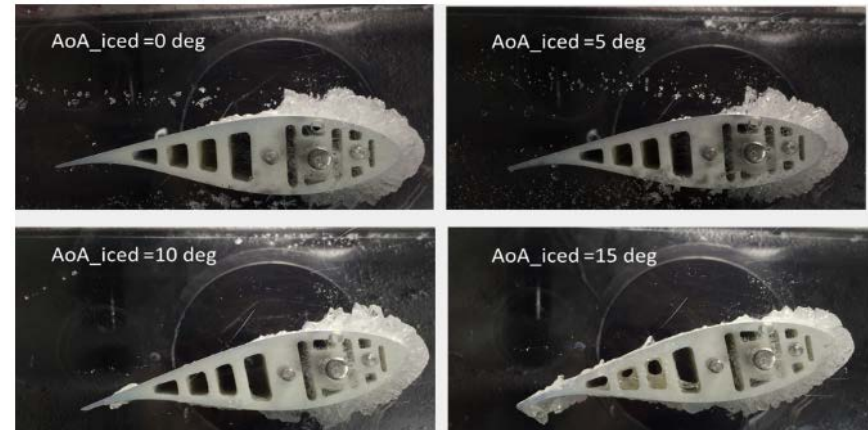
Gravidade



1.3. Problemas mais comuns

Problemas e desafios

- Automação da fabricação
- Transporte e instalação
- Teste experimental
- Erosão na borda de ataque
- Fadiga e Mecanismos de falha: delaminação
- Flambagem e colapso



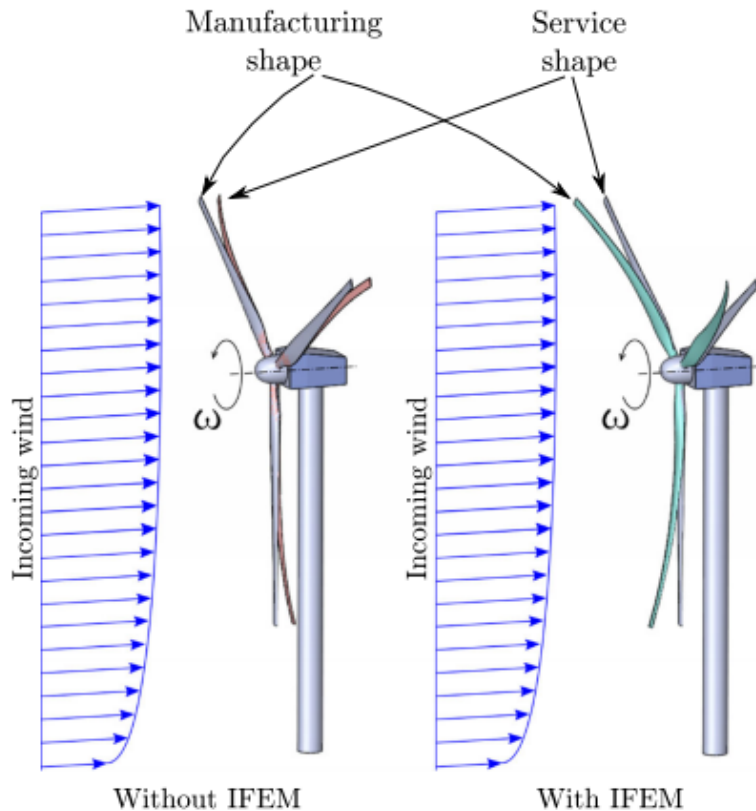
Formação de gelo



1.3. Problemas mais comuns

- Deflexão excessiva na ponta da pá.

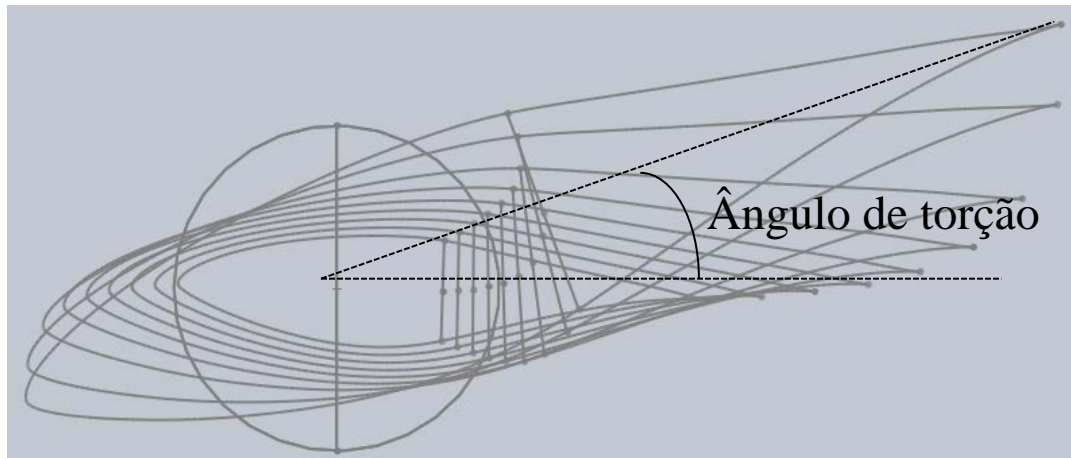
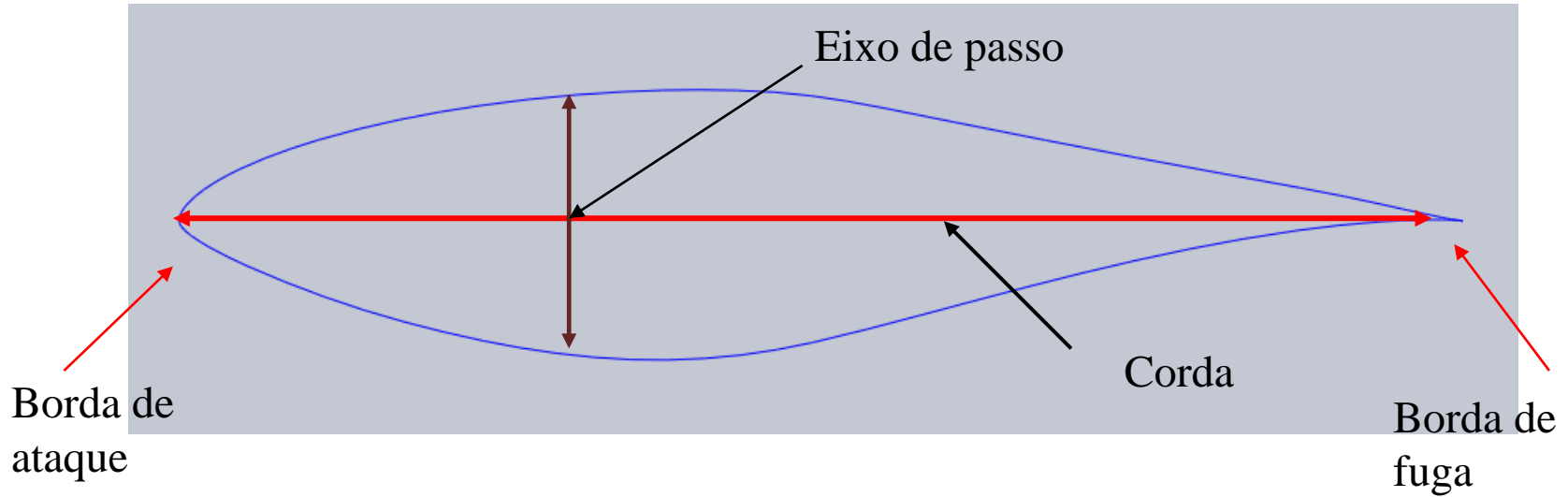
Outras soluções:



- Torre inclinada – inclinação de 5°

1.4. Geometria da pá

Perfil aerodinâmico



Vista da seção transversal

Para melhorar o desempenho aerodinâmico da pá

1.4. Geometria da pá

Pás aerodinamicamente mais finas e com boa resistência estrutural

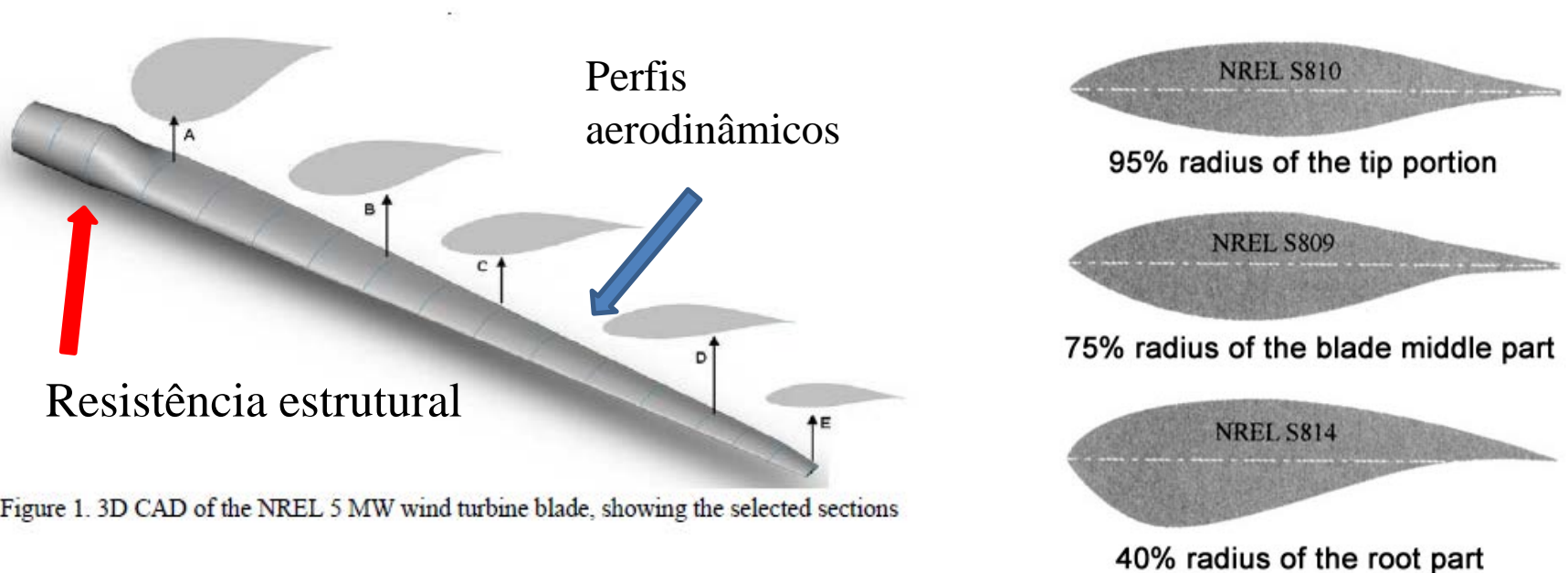
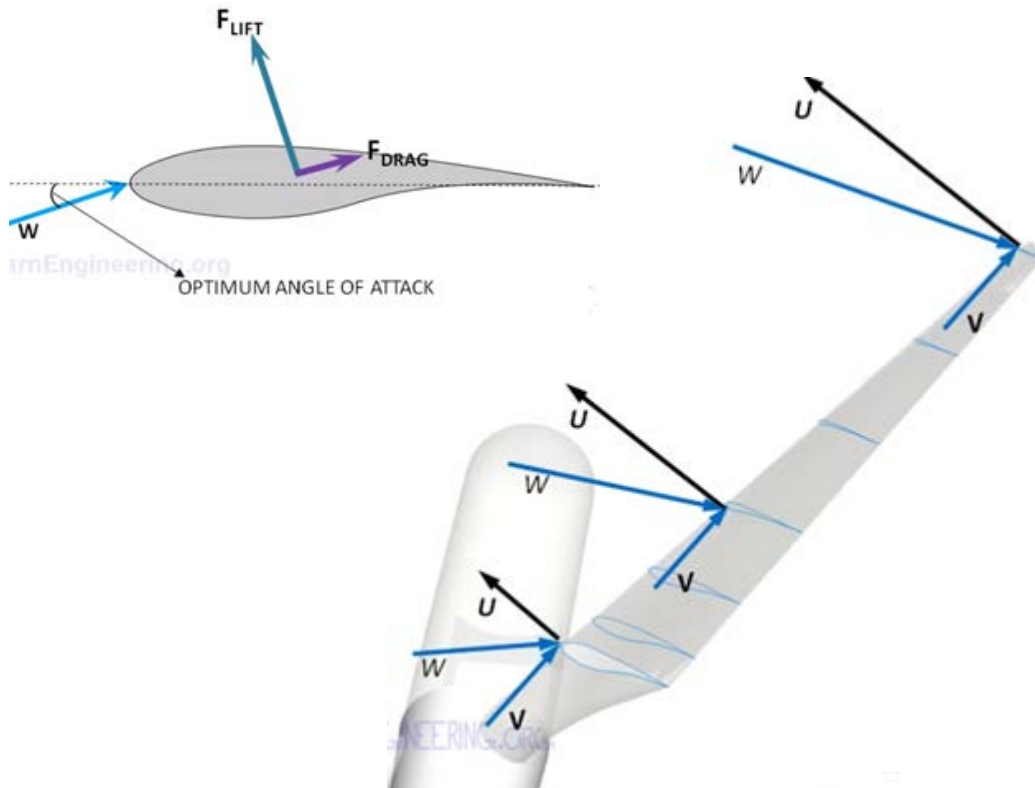


Figure 1. 3D CAD of the NREL 5 MW wind turbine blade, showing the selected sections

O desempenho aerodinâmico deve ser estável e menos sensível à mudança brusca da superfície da borda de ataque da pá.

- *DU -Delft University*
- *NACA - National Advisory Committee for Aeronautics.*

1.4. Geometria da pá

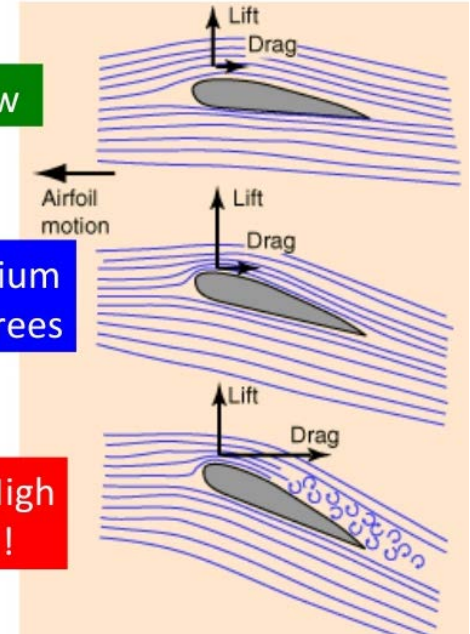


- Força de elevação
- Força de arrasto

$\alpha = \text{low}$

$\alpha = \text{medium}$
<10 degrees

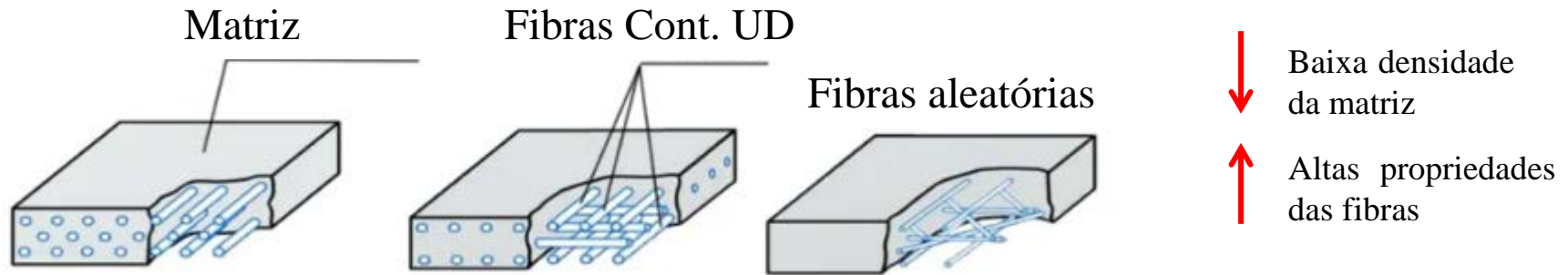
$\alpha = \text{High}$
Stall!!



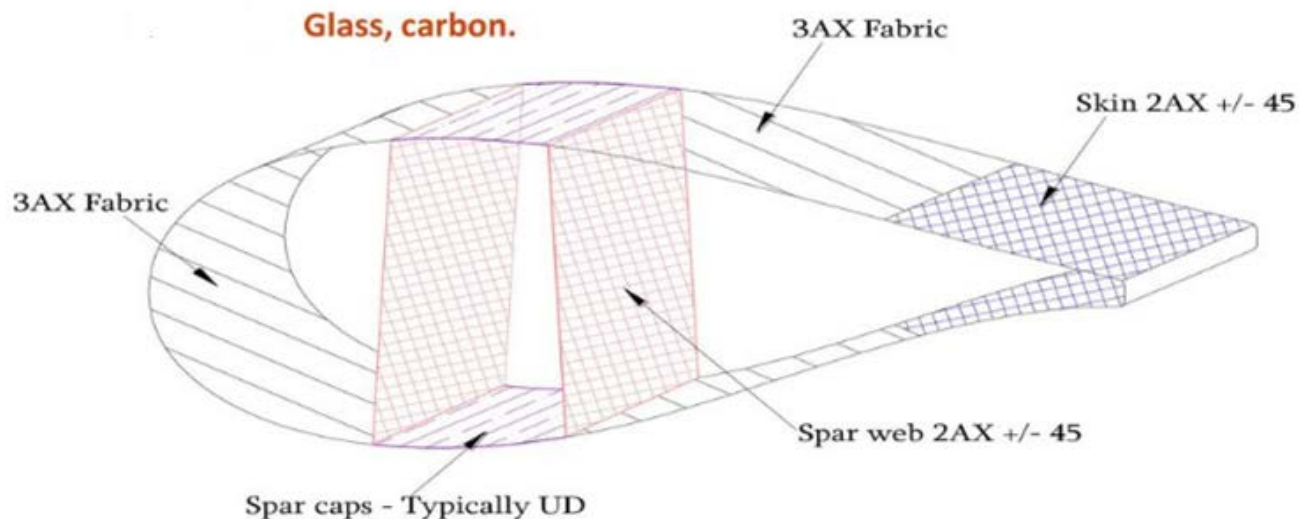
A pá é rotada ao redor de um eixo, a velocidade linear nas diferentes seções ao longo do comprimento da pá é diferente, na ponta é mais rápido e na raiz mais lento.

O ângulo entre a velocidade do vento relativo e o plano do rotor é menor na ponta da pá.

1.5. Materiais compósitos



- **Fase matriz:** Envolve a fase dispersa e a mantém na sua posição relativa. As resinas epóxi e poliéster são as mais usadas, comumente usadas com as fibras reforçadas.
- **Fibra reforçada:** ajuda a melhorar a resistência e a rigidez e atua como barreira à propagação de trincas. As mais comuns são a fibra de vidro e fibra de carbono.



1.5. Materiais compósitos

As propriedades mecânicas do material são geralmente caracterizadas pela fração volumétrica de fibras, isto é, o volume ocupado pelas fibras em relação ao volume do material.

E-Glass

Properties	values
Density(g/cm ³)	2.6
Young's modulus(Gpa)	85
Poisson's ratio	0.23
Shear moduls	36
Tensile stress(MPa)	2050



S-Glass

Properties	values
Density(g/cm ³)	2.495
Young's modulus(Gpa)	93
Poisson's ratio	0.23
Shear moduls	39
Tensile stress(MPa)	4800
Shear stress(MPa)	80



Epóxi - Carbono

Properties	Values
Density(g/cm ³)	1.518
Young's modulus(Gpa)	123.34
Poisson's ratio	0.27
Shear moduls	3080
Tensile stress(MPa)	1632
Shear stress(MPa)	80

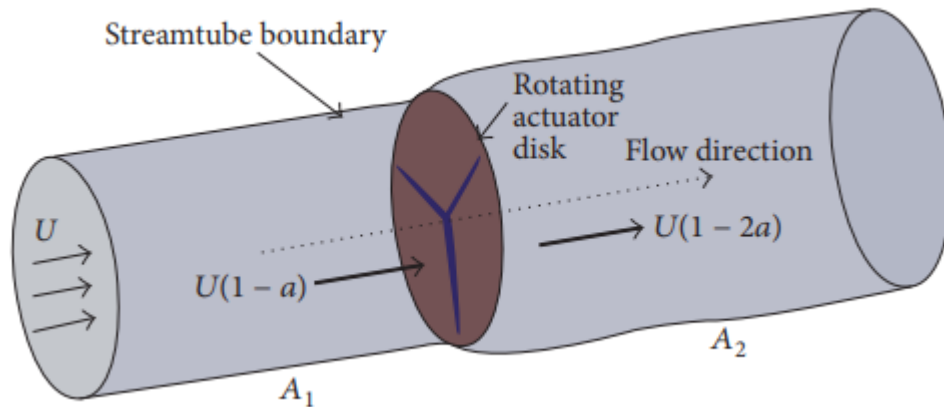


- Espuma
- Adesivos

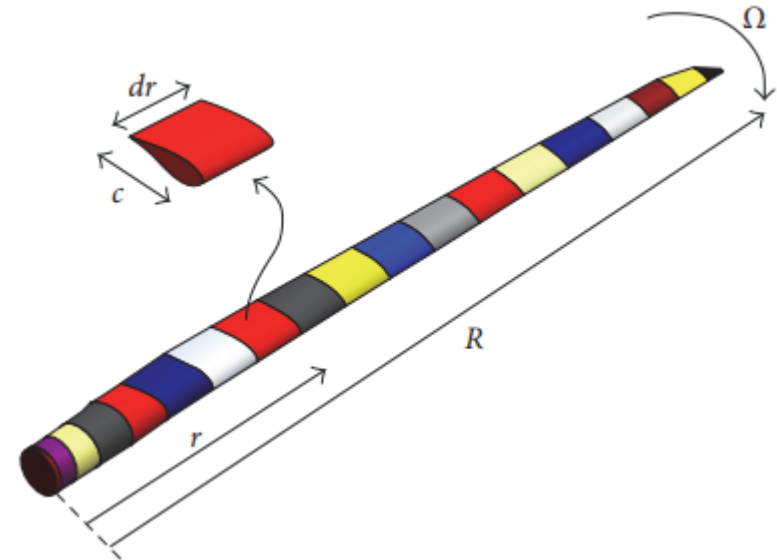
2. Análises BEM e FSI

Método *Blade Element Momentum (BEM)*.

Combina a teoria de quantidade de movimento com os fenômenos locais de pás reais. Um tubo de corrente é dividido em N elementos anulares de altura dr , por conseguinte, as pás também são. Onde r é a posição radial do volume de controle anular, R é raio do rotor, dr o comprimento do volume de controle diferencial e c a corda do aerofólio da pá. O método clássico assume que o escoamento em cada elemento de pá é independente dos elementos vizinhos e que o carregamento aerodinâmico é uniforme em cada elemento anular.



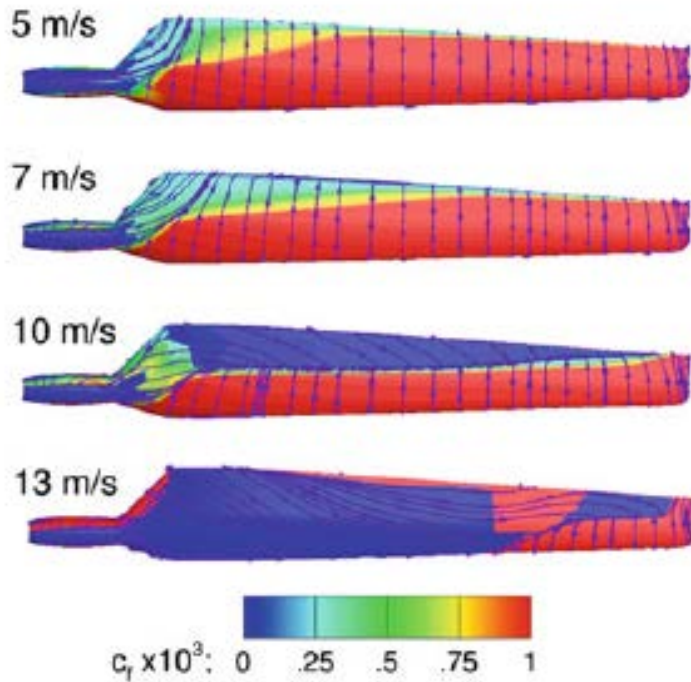
Teoria de momento



Teoria de elementos da pá

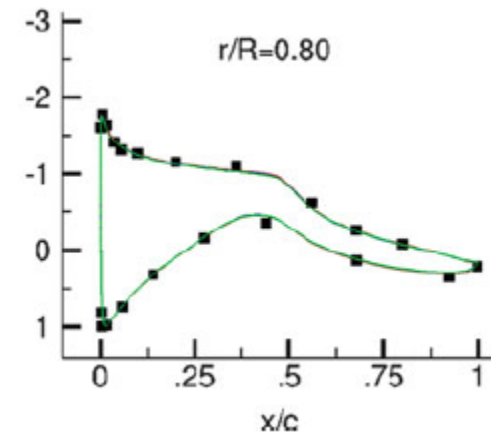
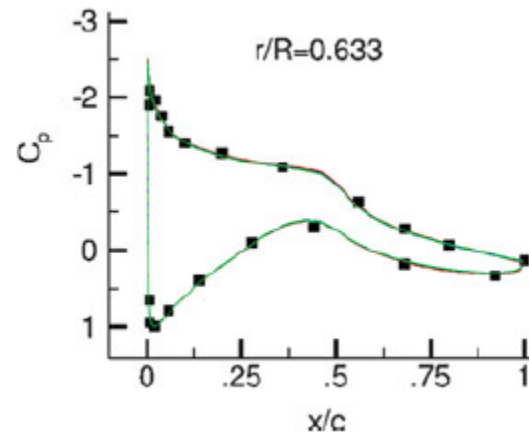
2. Análises BEM e FSI

Método *Blade Element Momentum (BEM)*.

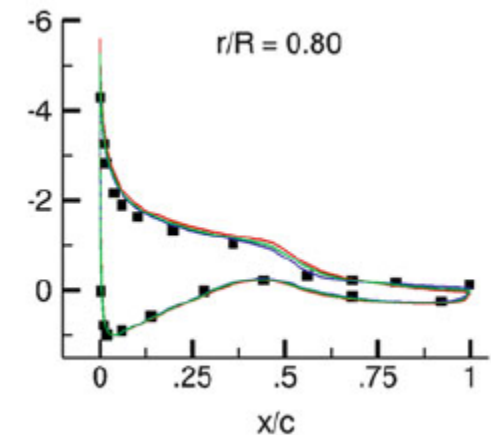
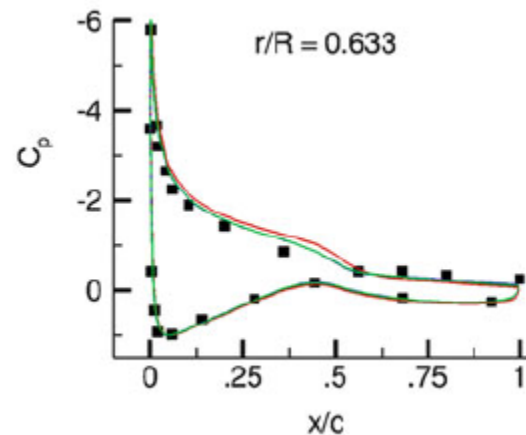


Padrão de fluxo desenvolvido

7 m/s



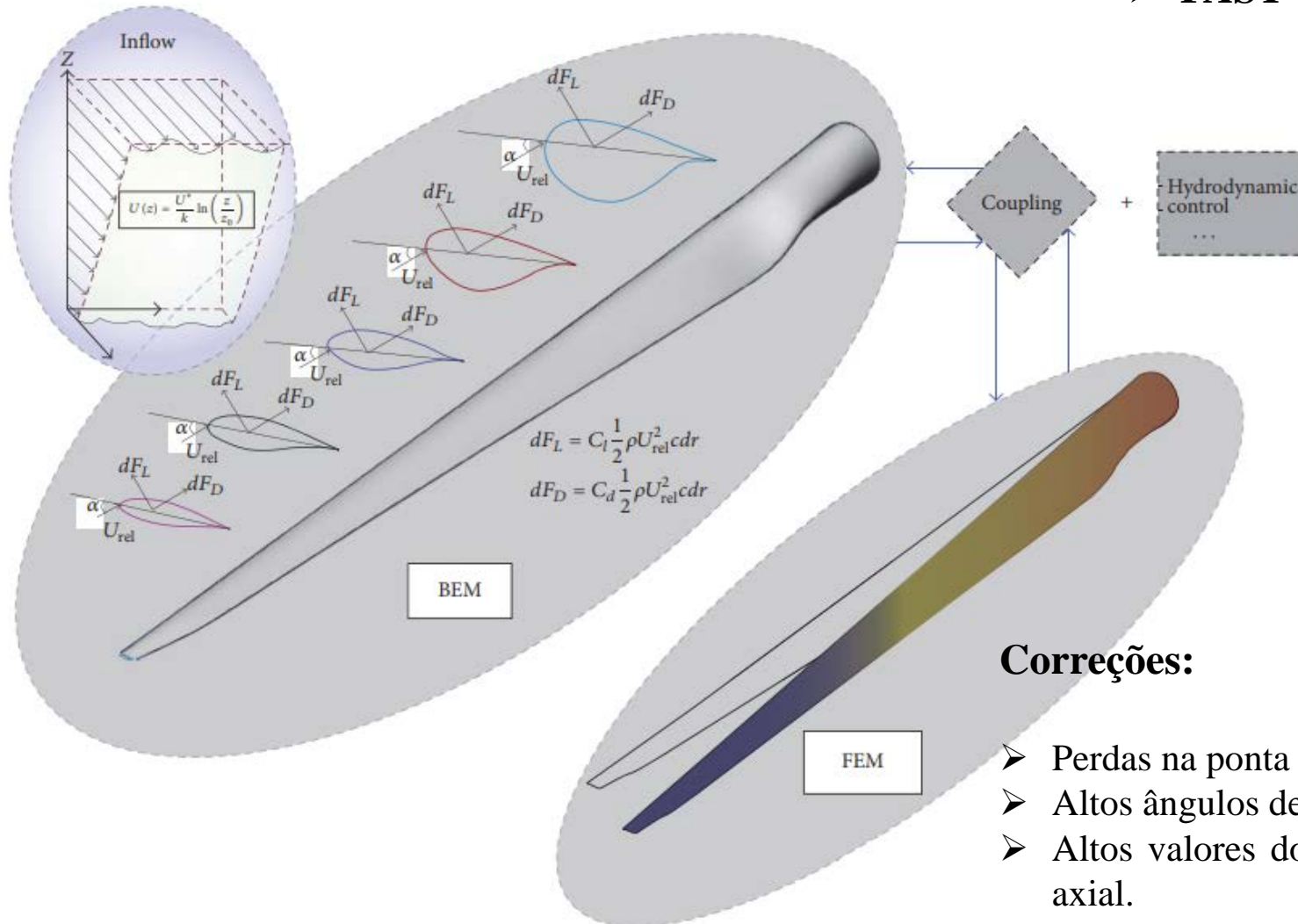
10 m/s



2. Análises BEM e FSI

Método *Blade Element Momentum (BEM)*.

➤ **FAST**



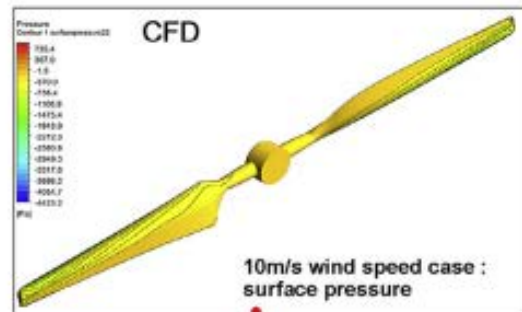
Correções:

- Perdas na ponta e raiz da lâmina;
- Altos ângulos de ataque;
- Altos valores do fator de indução axial.

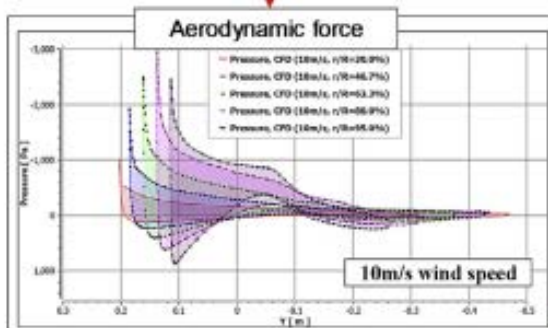
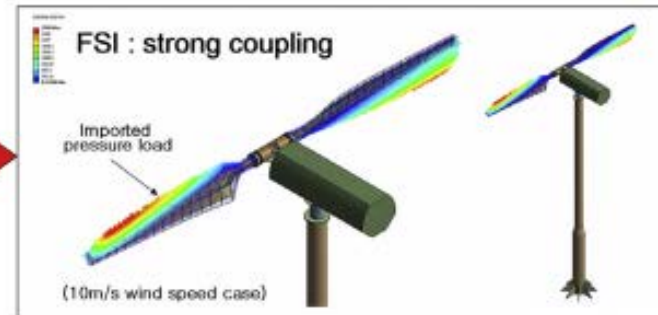
2. Análises BEM e FSI

Interação Fluido-Estrutura (FSI)

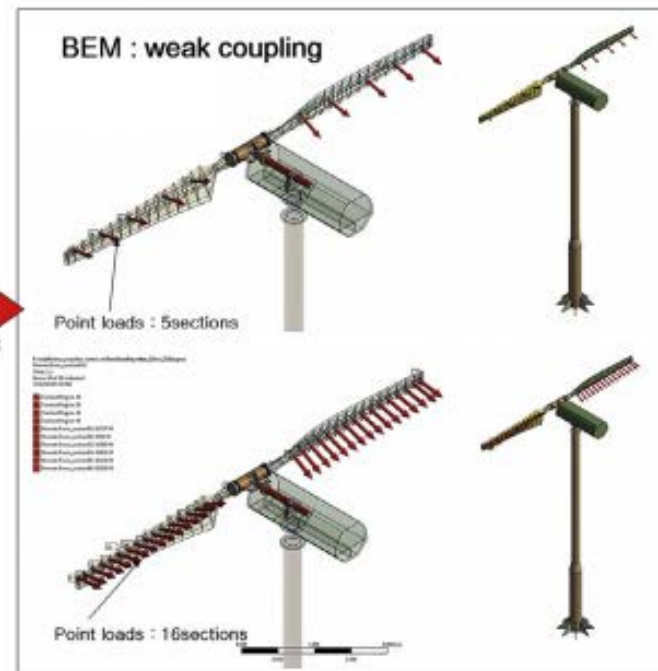
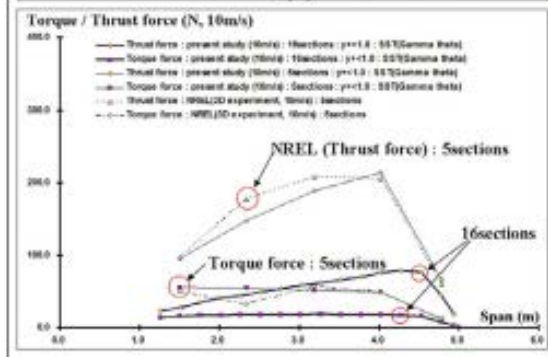
Modelagem 3D



1-way
Surface pressure

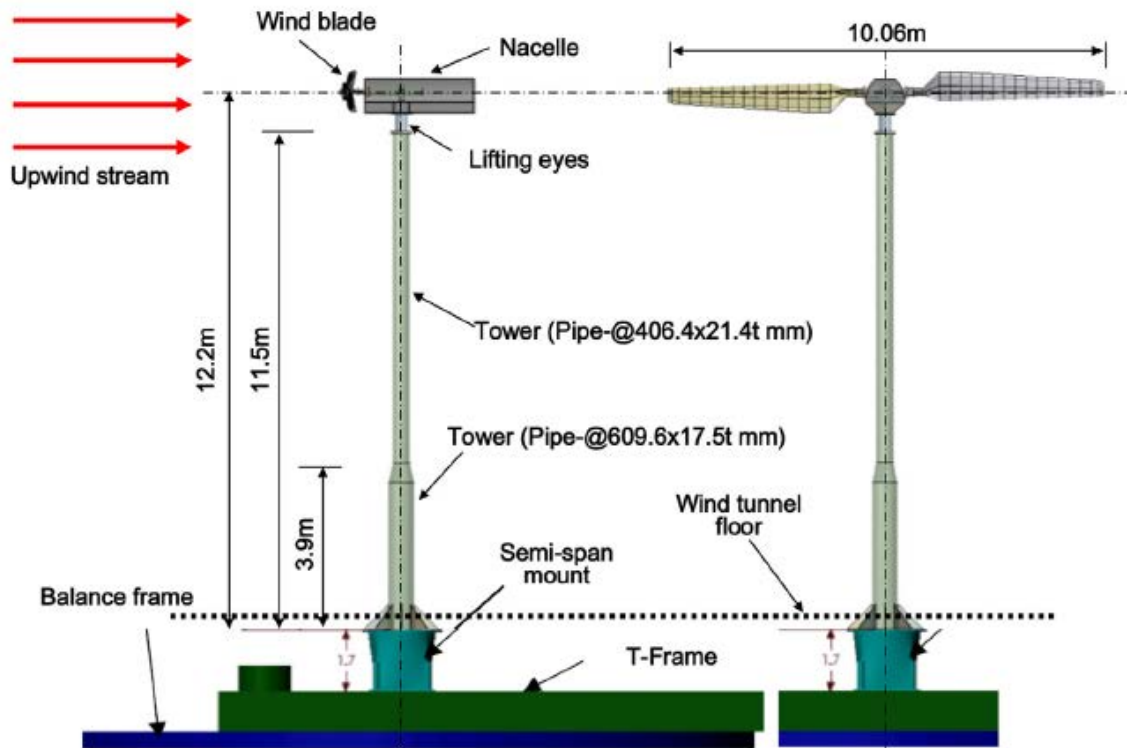


1-way
Aerodynamic force



3. Teste experimental de referência - NREL

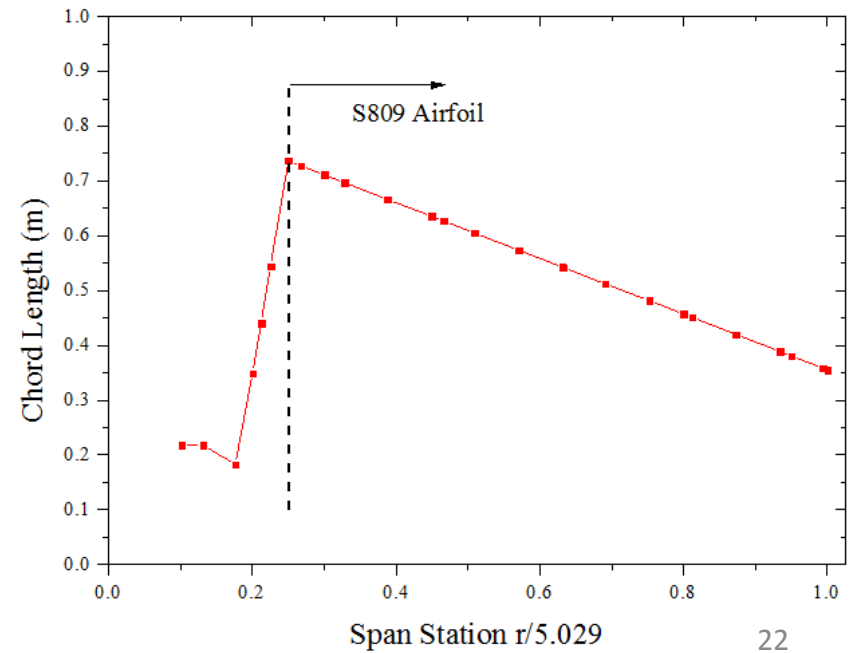
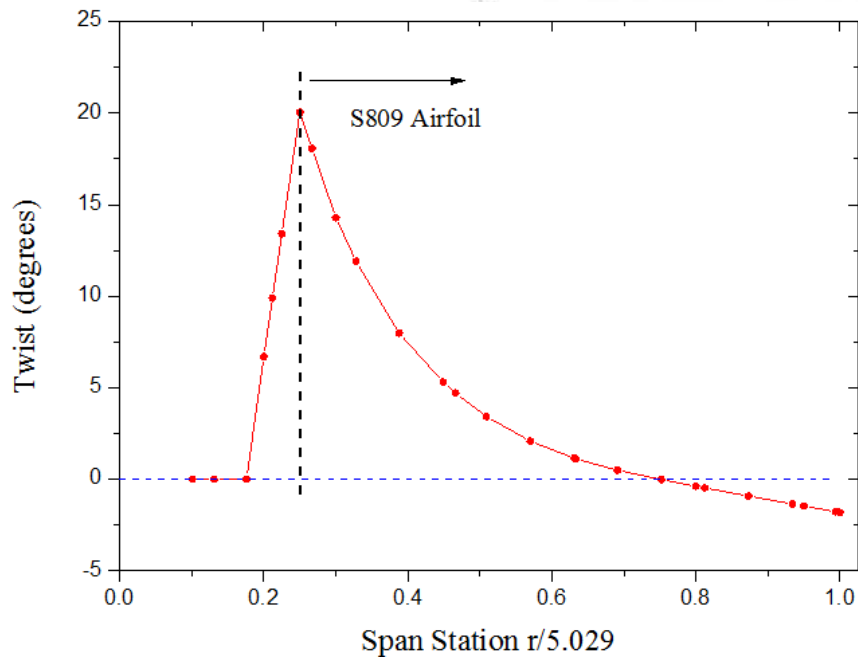
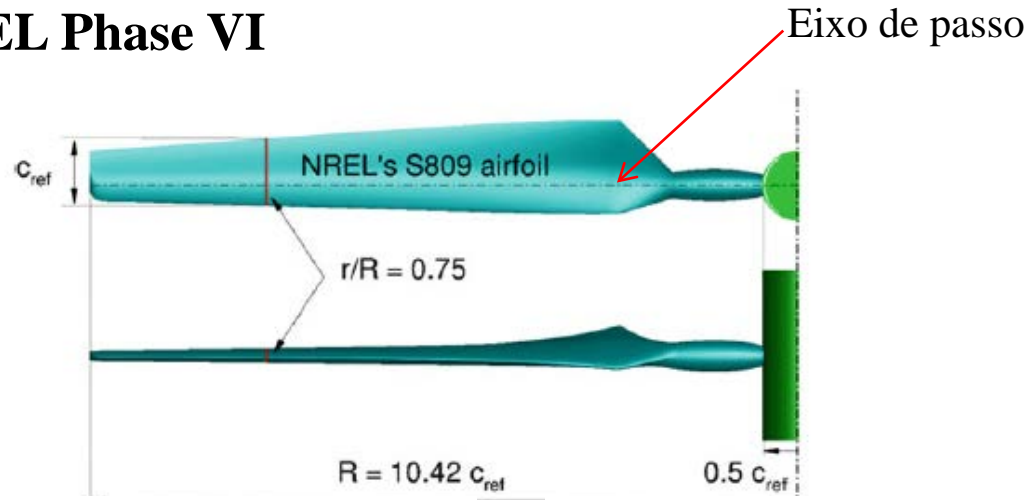
Pá da NREL Phase VI no túnel de vento da NASA Ames - UAE (*Unsteady Aerodynamics Experiment*)



Potência nominal de 20 kW operando a uma velocidade nominal de 72 rpm
Altura do cubo de 12,2 m
Diâmetro do rotor de 10 m.

3. Teste experimental de referência - NREL

Pá da NREL Phase VI



3. Teste experimental de referência - NREL

Pá da NREL Phase VI

Dados: Corda

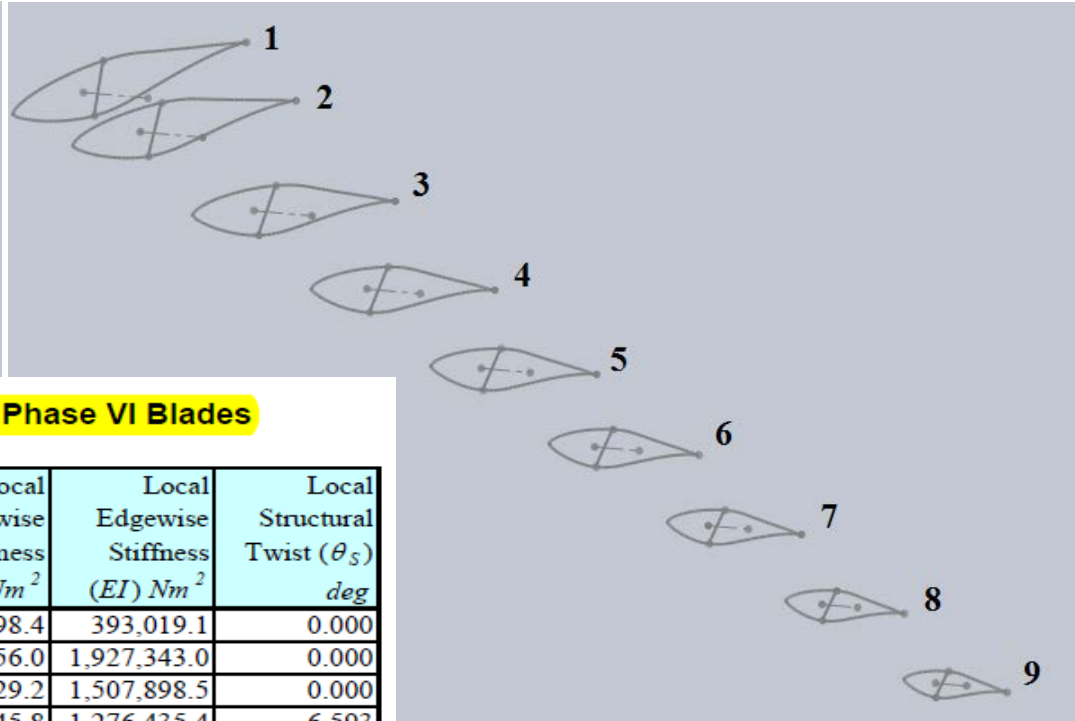
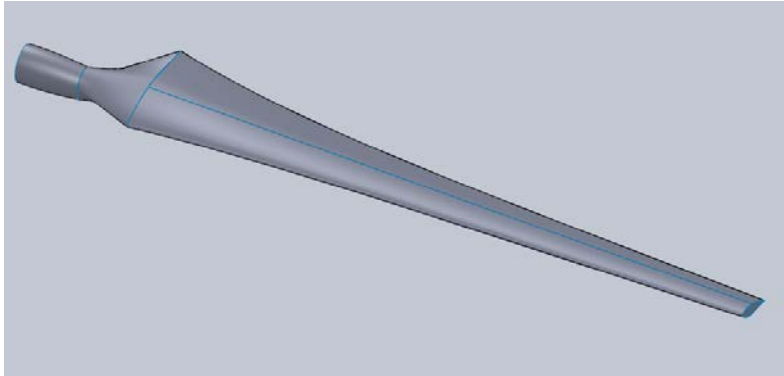


Table 6.6: Calibrated Properties of the UAE Phase VI Blades

Distance from Rotor Center <i>m</i>	Distance Along Blade From Root (<i>r</i>) <i>m</i>	Radial Fraction (<i>r</i> / 4.597 m)	Blade Lineal Density (μ_B) <i>kg/m</i>	Local Flapwise Stiffness (<i>EI</i>) <i>Nm²</i>	Local Edgewise Stiffness (<i>EI</i>) <i>Nm²</i>	Local Structural Twist (θ_S) <i>deg</i>
0.432	0.000	0.00000	0.000	511,398.4	393,019.1	0.000
0.508	0.076	0.01653	8.298	2,506,356.0	1,927,343.0	0.000
0.749	0.317	0.06896	22.109	3,483,529.2	1,507,898.5	0.000
1.006	0.574	0.12486	32.416	1,810,745.8	1,276,435.4	6.593
1.257	0.825	0.17946	28.750	1,144,892.0	1,103,877.7	20.040
1.509	1.077	0.23428	15.349	535,063.2	934,207.7	14.315
2.012	1.580	0.34370	12.115	307,733.2	674,456.7	7.454
2.515	2.083	0.45312	11.512	224,056.5	581,796.3	3.702
3.018	2.586	0.56254	10.611	165,678.0	509,058.2	1.621
3.520	3.088	0.67174	9.744	111,920.2	436,219.0	0.421
4.023	3.591	0.78116	8.806	71,251.9	362,245.2	-0.381
4.526	4.094	0.89058	7.886	39,205.7	313,455.2	-1.111
5.029	4.597	1.00000	7.861	27,702.2	287,462.0	-1.815

EI: rigidez à flexão

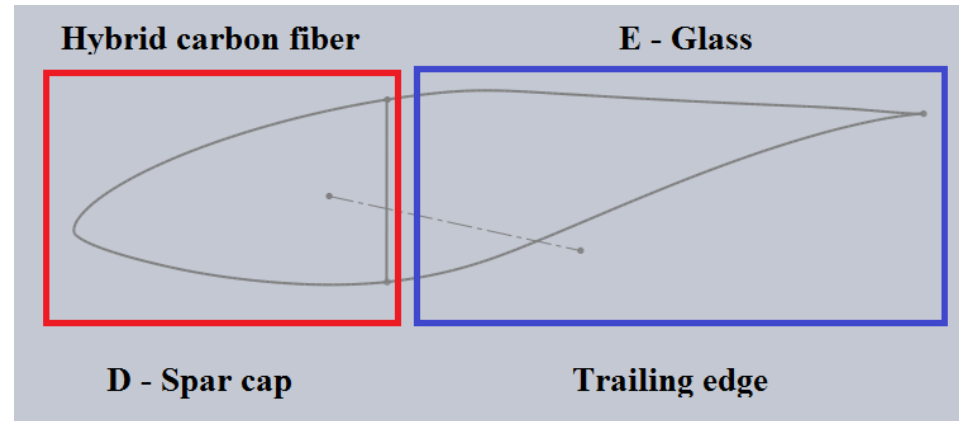
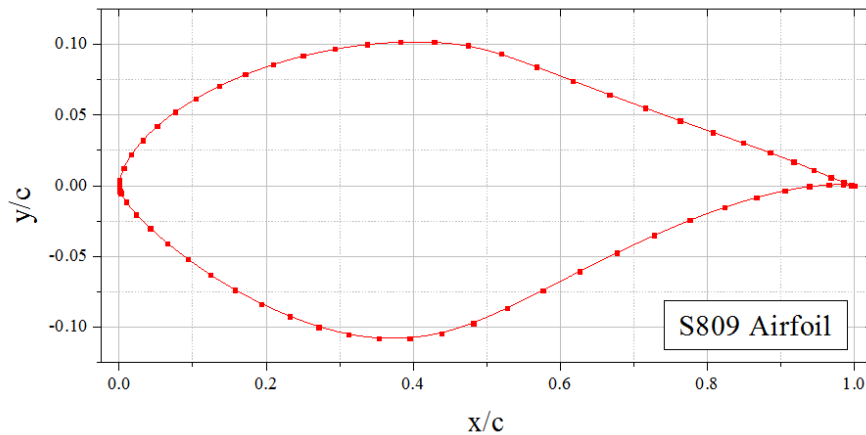
E: Módulo de elasticidade

I: inércia da seção

μ : Densidade de massa linear

3. Teste experimental de referência - NREL

Pá da NREL Phase VI



Propriedades físicas e mecânicas da Prepreg Hybrid unidirecional Carbono/Fibra de vidro composto triax. 70% 0° Tipo

Propriedade	Unidade	Valor
Densidade	kg/m ³	1621
Módulo de Elast., Ex	GPa	74,305
Módulo de Elast., Ey	GPa	9,376
Módulo de Elast., Ez	GPa	9,376
Módulo Cisalhante, Gxy	GPa	4,863
Coef. De Poison, ν		0,35
Espessura da Camada	mm	0,14224

D-Spar

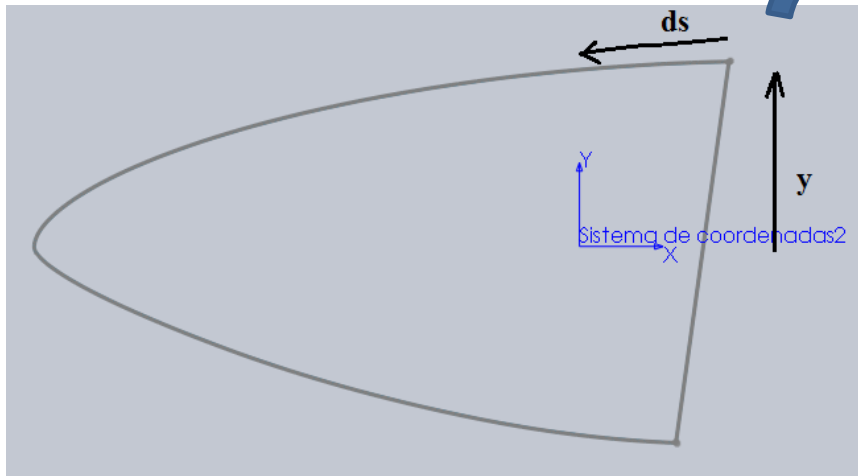
Propriedades físicas e mecânicas da fibra de vidro Harness satin weave fabric 7781/EA93

Propriedade	Unidade	Valor
Densidade	kg/m ³	1859
Módulo de Elast., Ex	GPa	23,786
Módulo de Elast., Ey	GPa	23,235
Módulo de Elast., Ez	GPa	23,235
Módulo Cisalhante, Gxy	GPa	5,225
Coef. De Poison, ν		0,21
Espessura da Camada	mm	0,2159

Trailing edge

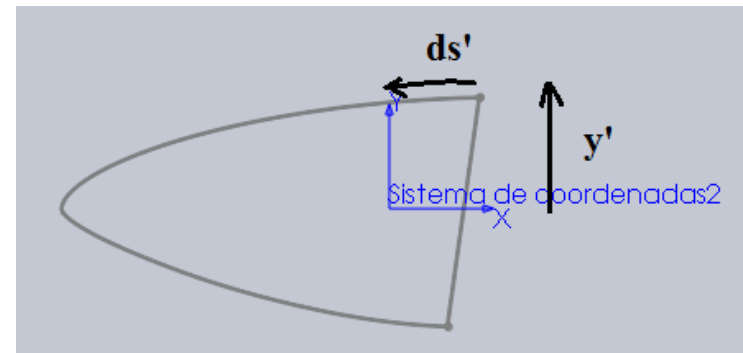
4. Análise inversa sobre a pá

Seção 1 para o D-Spar



K

Escala: Relação entre cordas



Seção N

$$I_x = \int y^2 dA$$

$$dA = ds \cdot t$$

t : constant

$$I_x = t \int y^2 ds$$

$$y = K y'$$

$$ds = K ds'$$

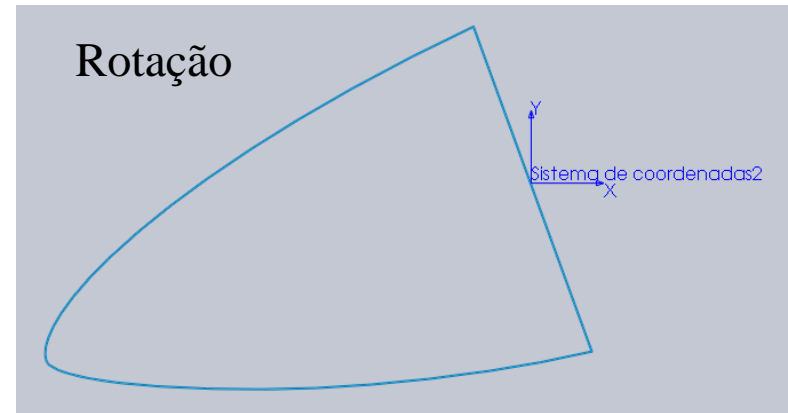
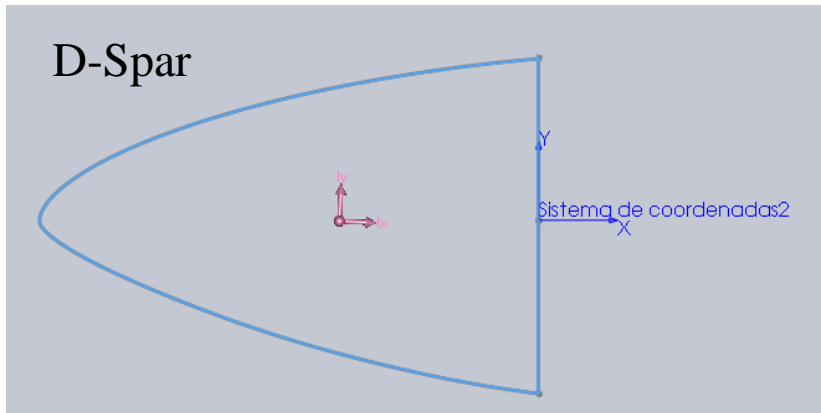
$$dA' = ds' \cdot t'$$

t' : constant

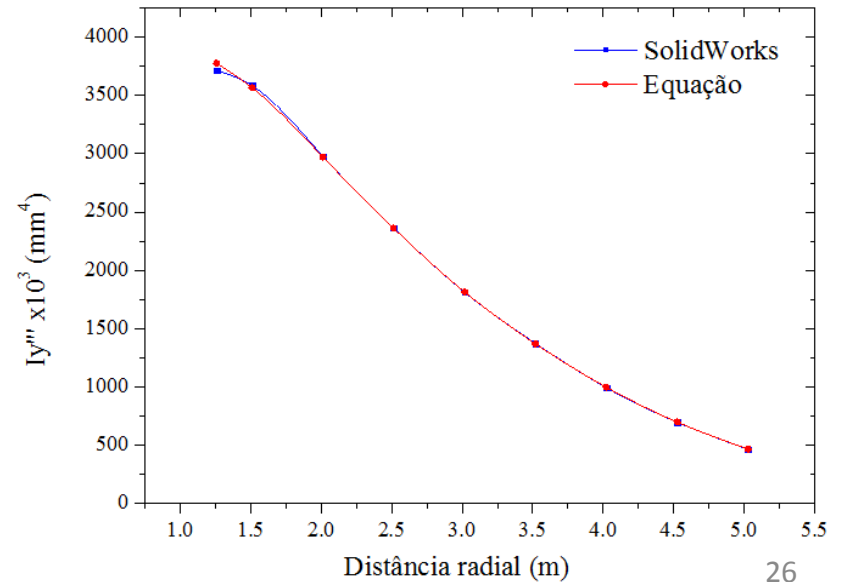
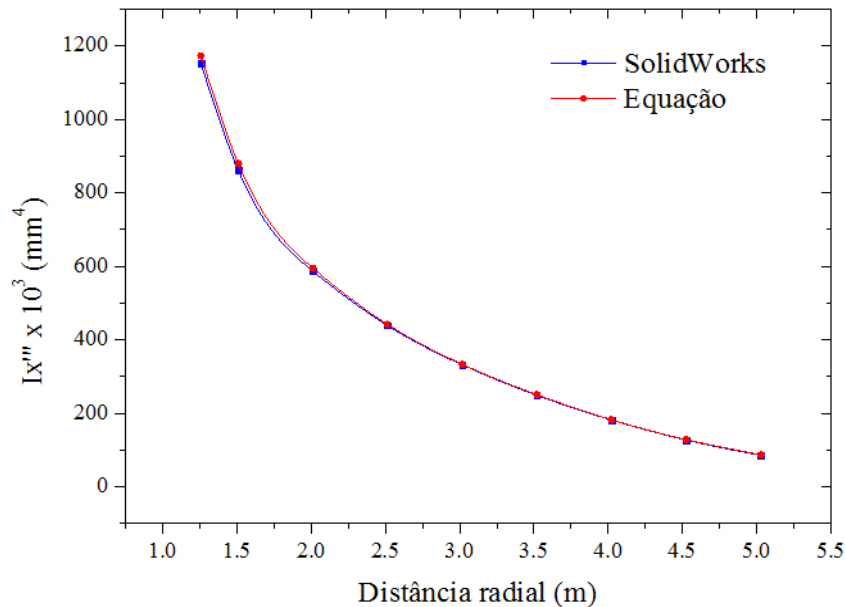
$$I_{x'} = \left(\frac{t'}{K^3} \right) \left(\frac{I_x}{t} \right)$$

4. Análise inversa sobre a pá

Teorema de Steiner



Verificação



4. Análise inversa sobre a pá

D-Spar Trailing edge

Rigidez à flexão: $E_{eq} I x'''_1 = C_1 t_1^1 E_1 + D_1 t_1^2 E_2$

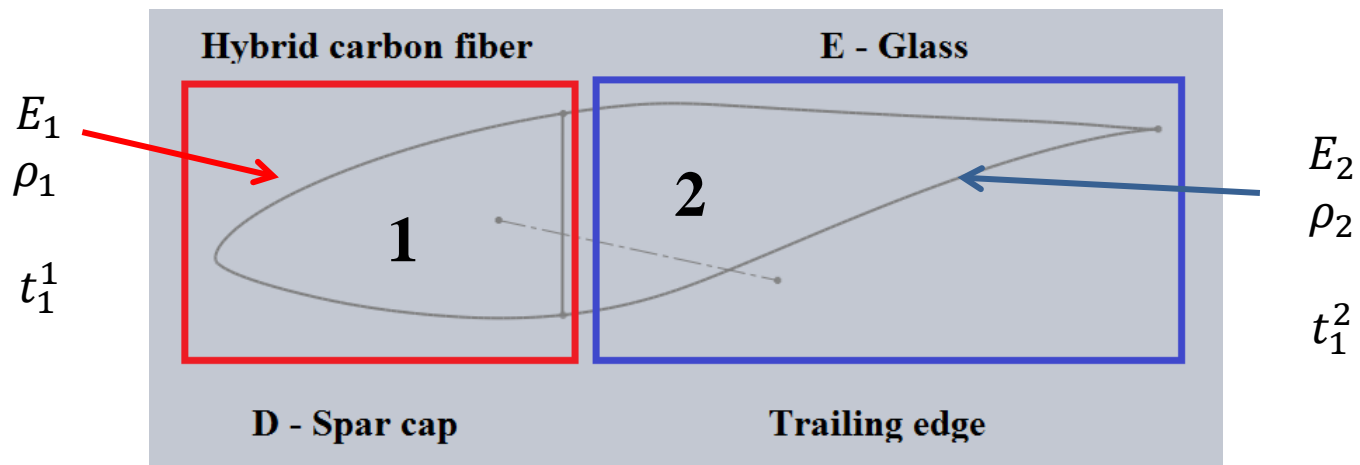
$$E_{eq} I y'''_1 = F_1 t_1^1 E_1 + G_1 t_1^2 E_2$$

Massa:

$$m_1 = V_1 \rho_1 + V_2 \rho_2$$

Massa por unidade de comprimento:

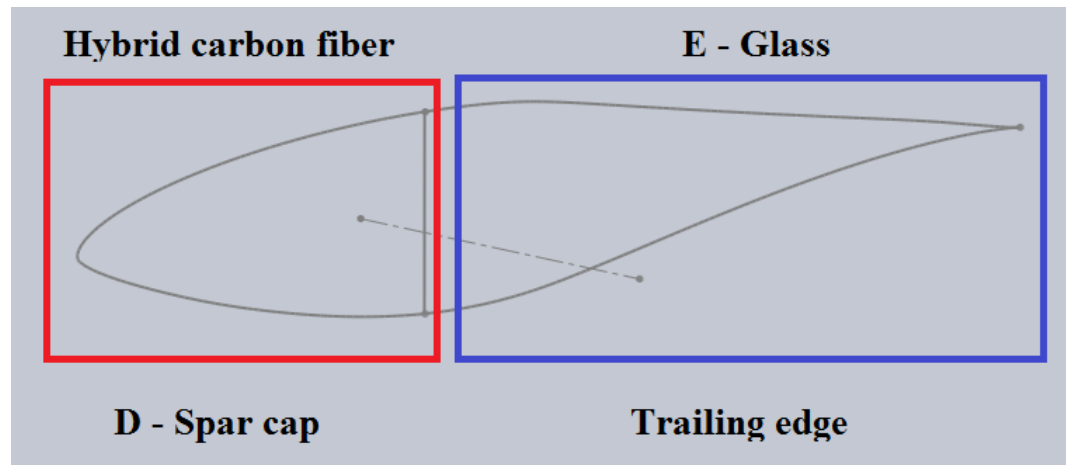
$$\mu_1 = \left(\frac{A_1}{2}\right) \left(\frac{t_1^1}{t}\right) \left(\frac{1}{K_1} + \frac{1}{K_2}\right) \rho_1 + \left(\frac{A_2}{2}\right) \left(\frac{t_1^2}{t}\right) \left(\frac{1}{K_1} + \frac{1}{K_2}\right) \rho_2$$



4. Análise inversa sobre a pá

Consideração da orientação da fibra no módulo de elasticidade

$$E_x^{\text{ply}} = \frac{1}{\frac{1}{E_1} \cos^4(\alpha) + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1} \right) \sin^2(\alpha) \cos^2(\alpha) + \frac{1}{E_2} \sin^4(\alpha)}$$



UD

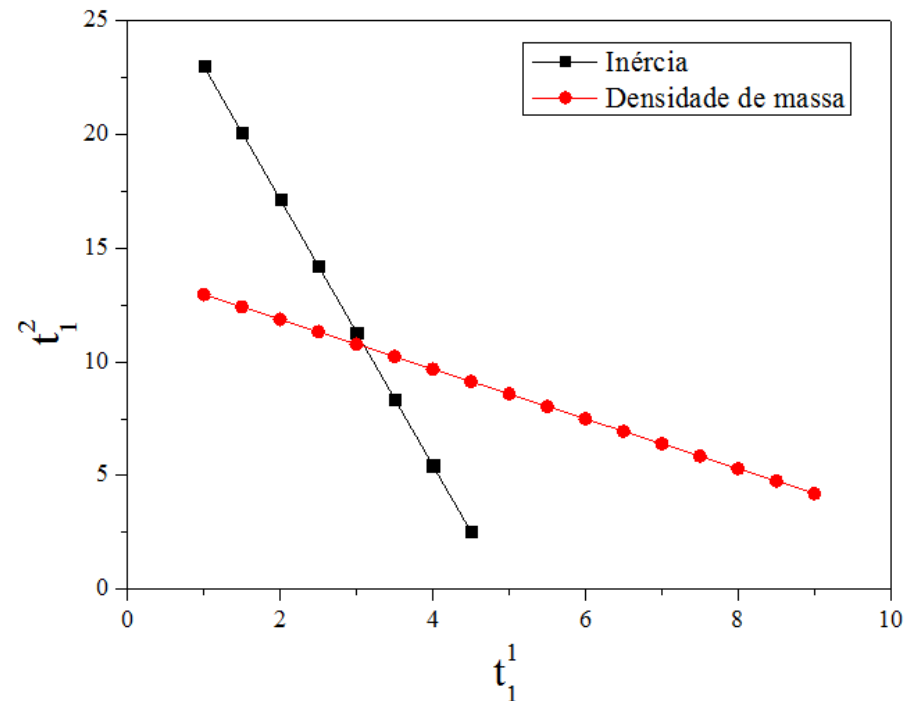
+45/-45

4. Análise inversa sobre a pá

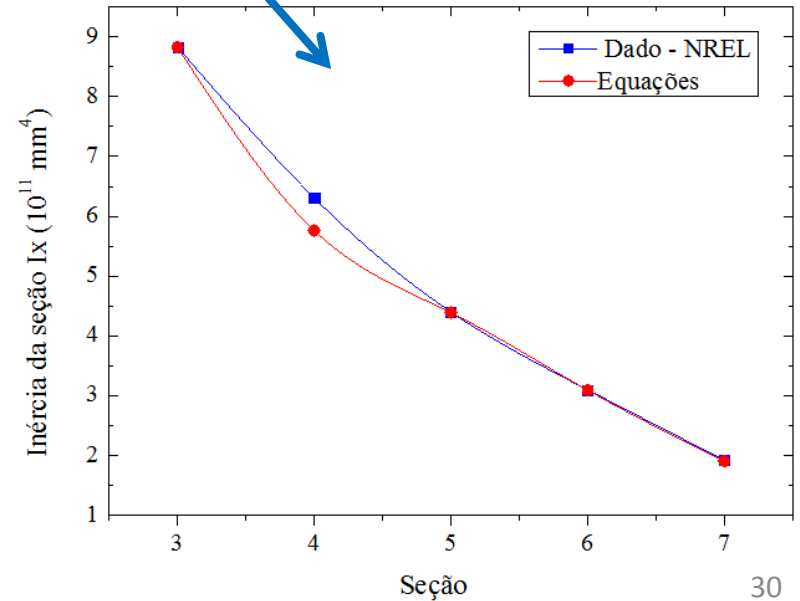
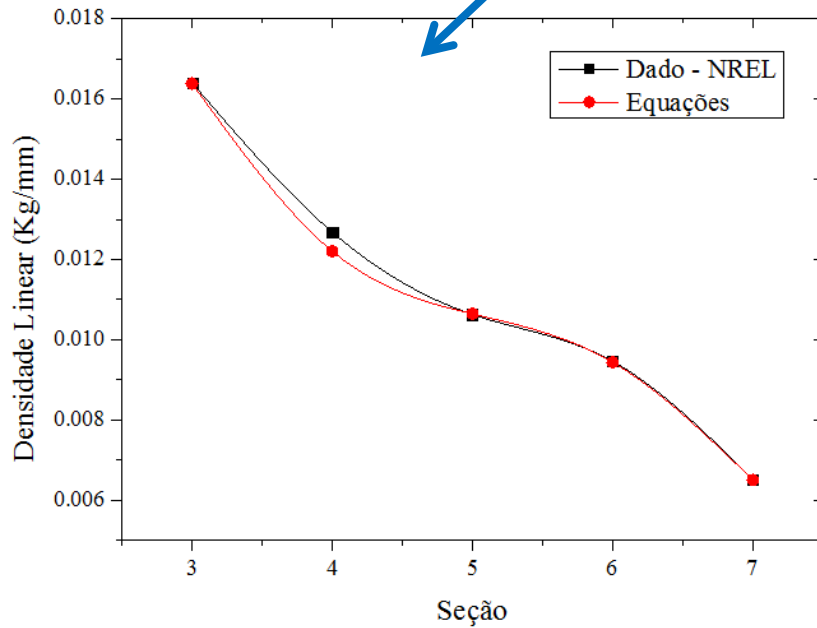
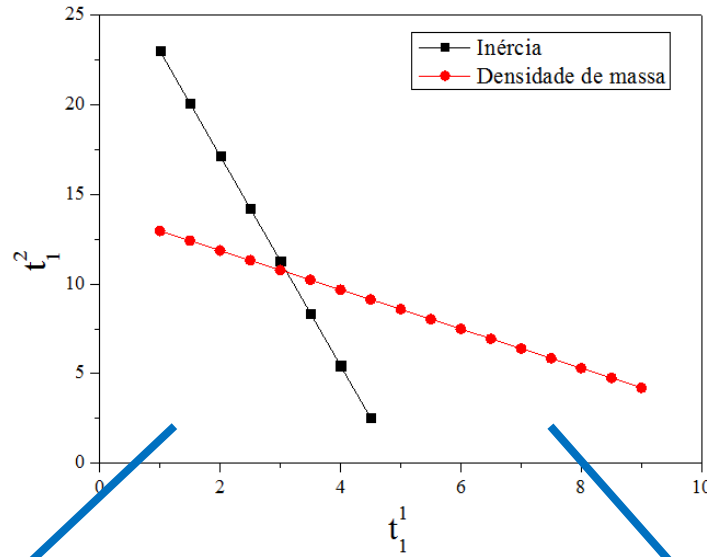
Para uma seção:

$$E_{eq} I x'''_1 = C_1 t_1^1 E_1 + D_1 t_1^2 E_2$$

$$\mu_1 = \left(\frac{A_1}{2}\right) \left(\frac{t_1^1}{t}\right) \left(\frac{1}{K_1} + \frac{1}{K_2}\right) \rho_1 + \left(\frac{A_2}{2}\right) \left(\frac{t_1^2}{t}\right) \left(\frac{1}{K_1} + \frac{1}{K_2}\right) \rho_2$$

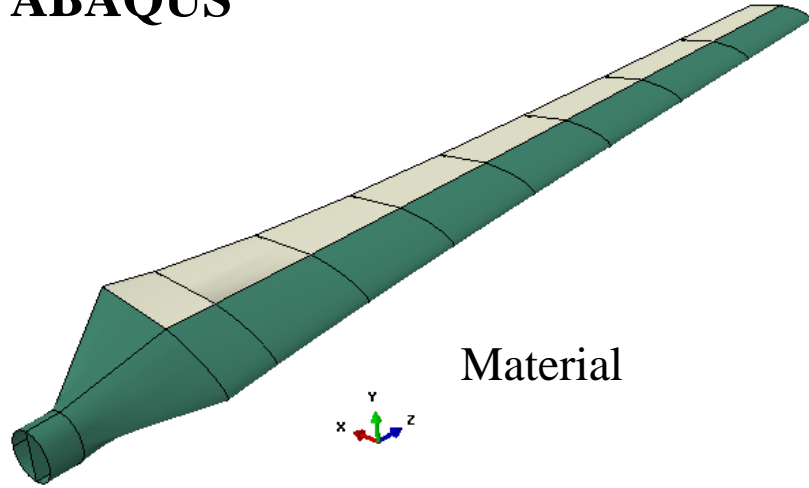


4. Análise inversa sobre a pá



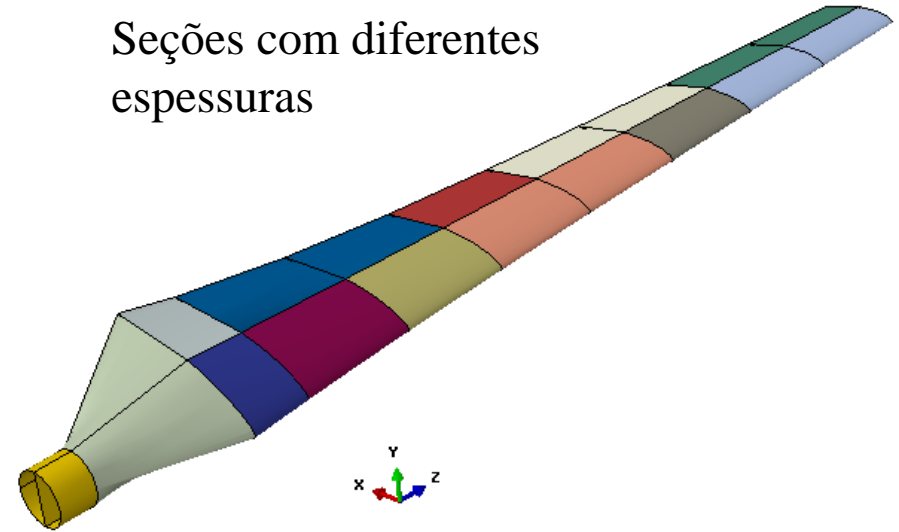
4. Análise inversa sobre a pá

ABAQUS

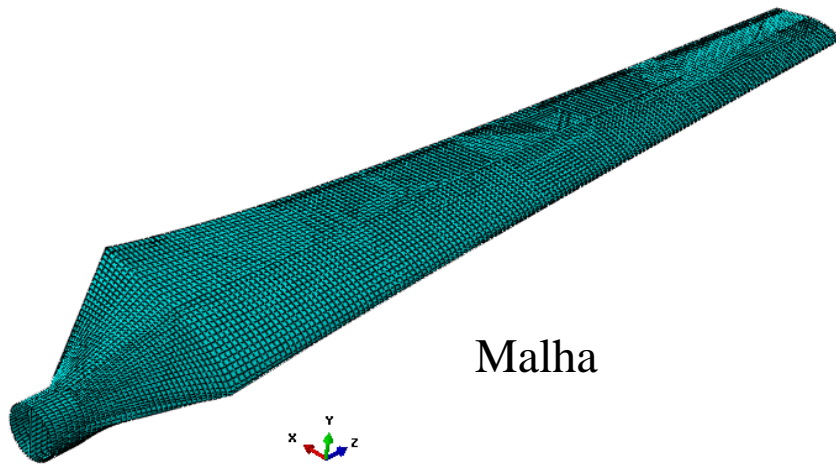


Material

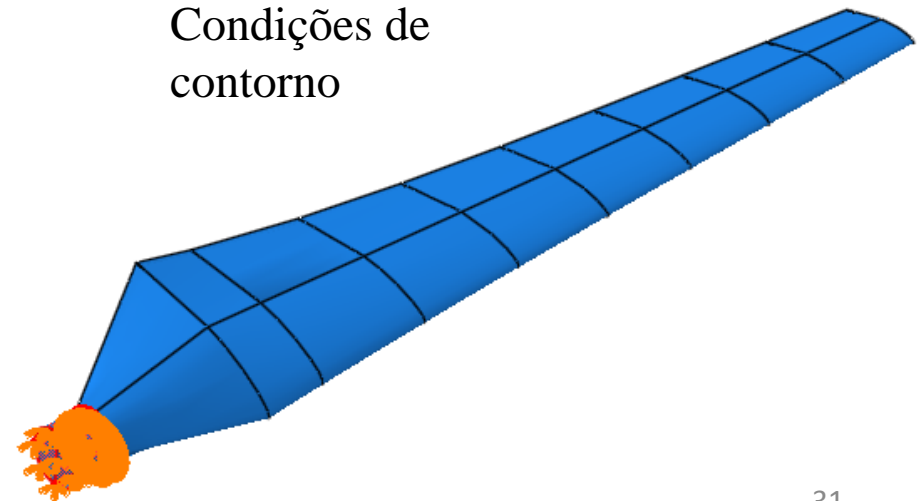
Seções com diferentes espessuras



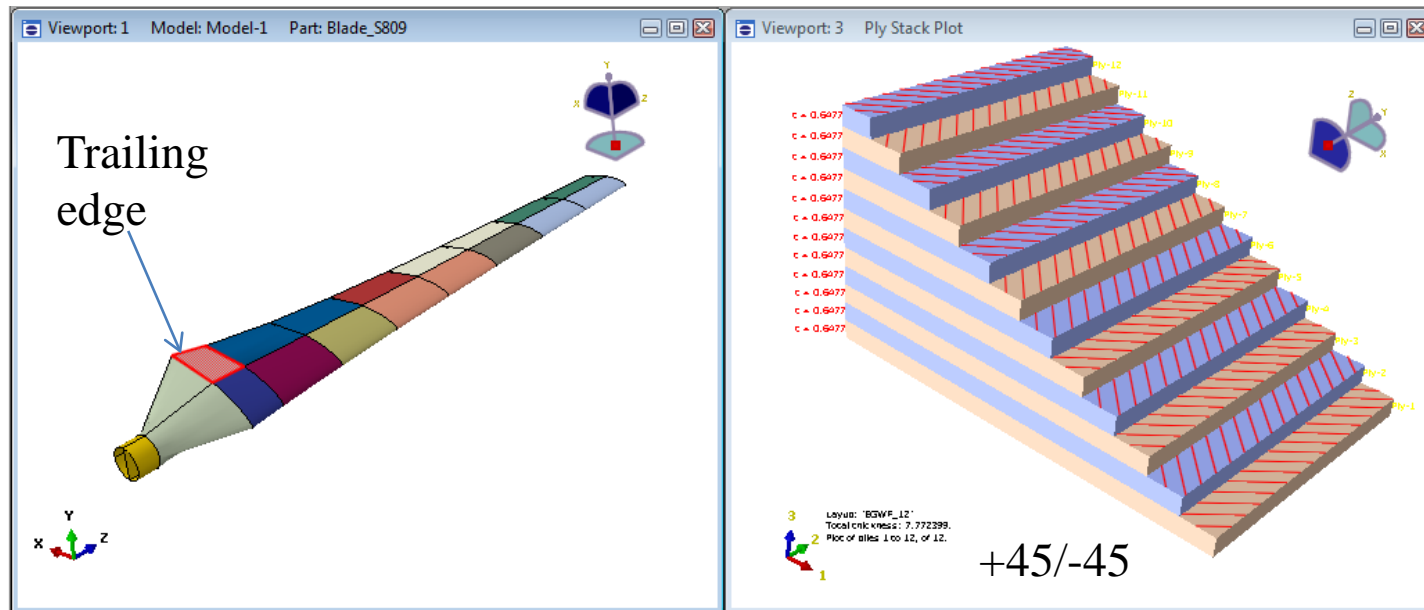
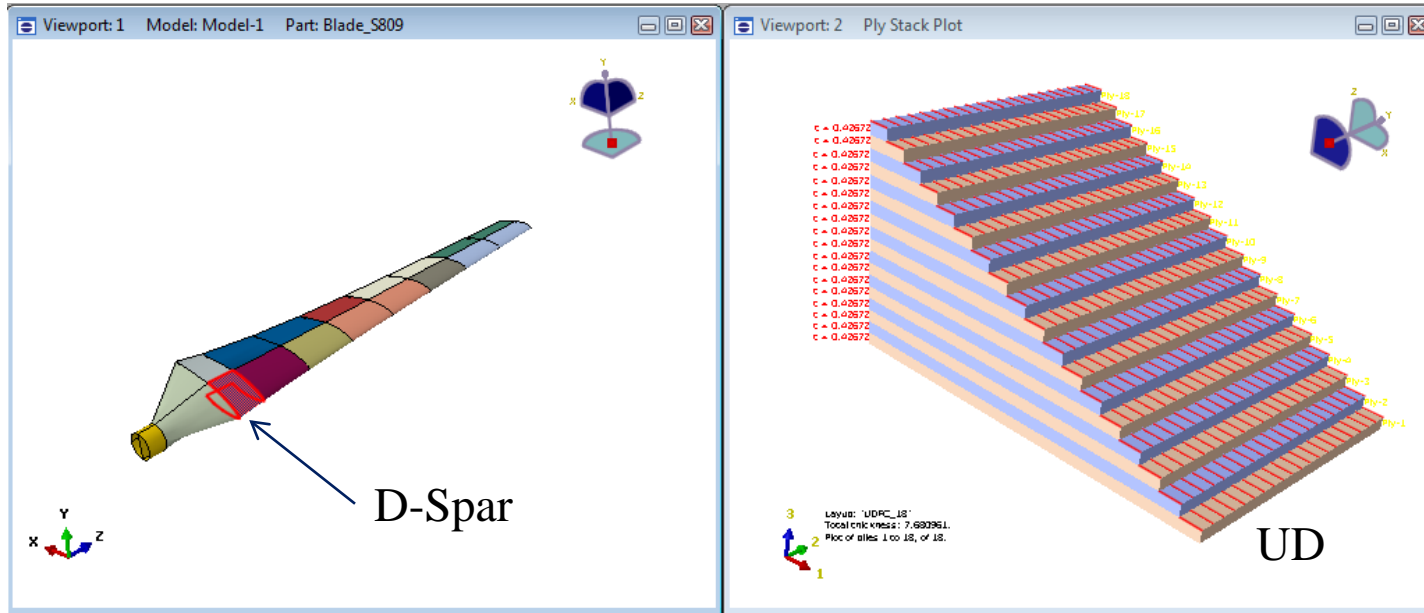
Condições de contorno



Malha

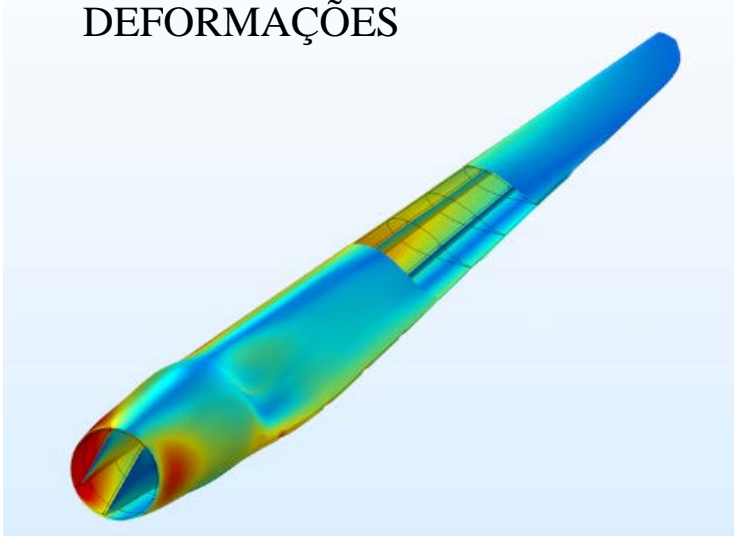


4. Análise inversa sobre a pá

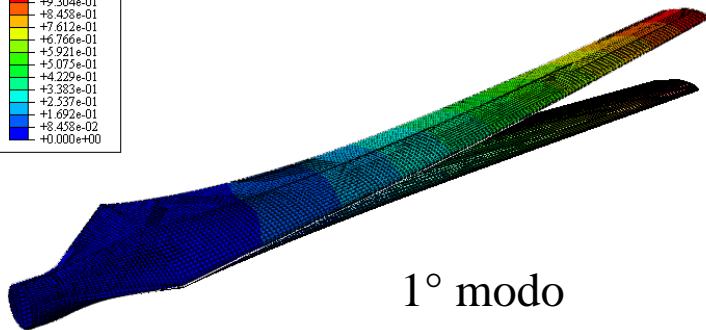
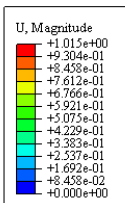


4. Análise inversa sobre a pá

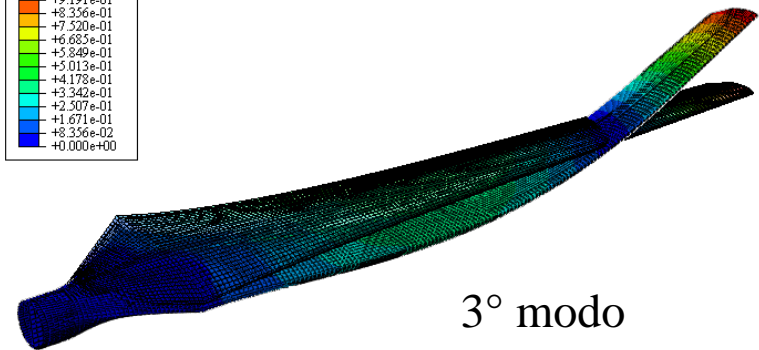
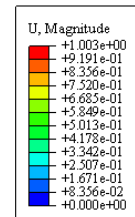
ANÁLISE DE TENSÕES-DEFORMAÇÕES



ANÁLISE MODAL DO SISTEMA



1° modo



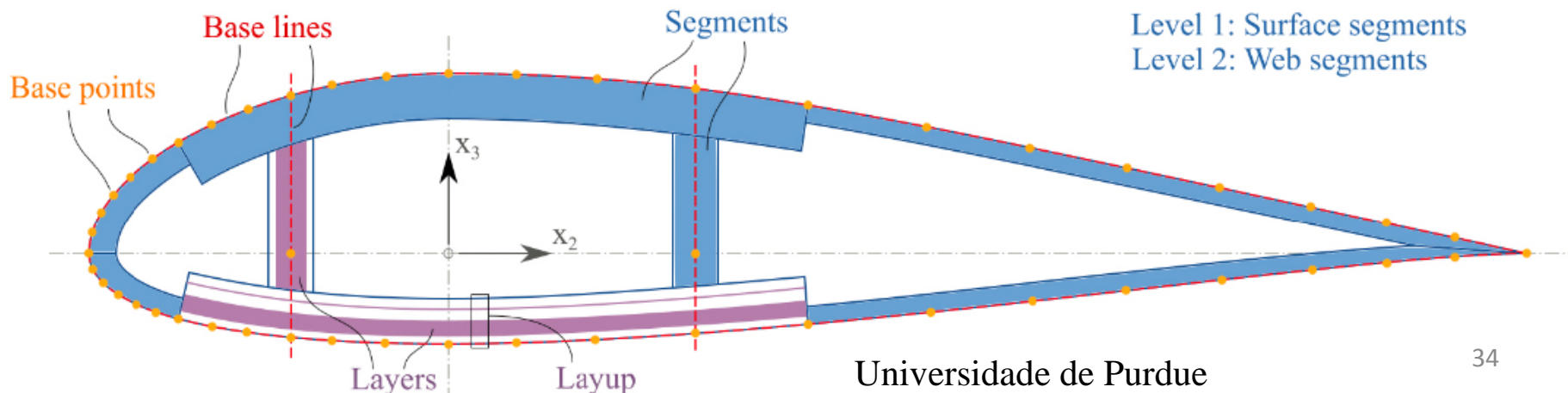
3° modo

5. PreVABS e VABS

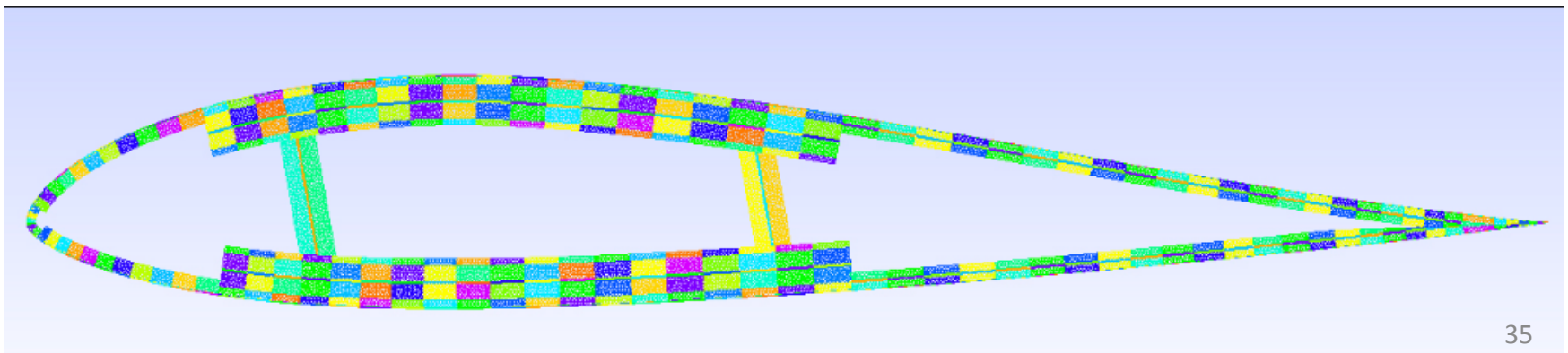
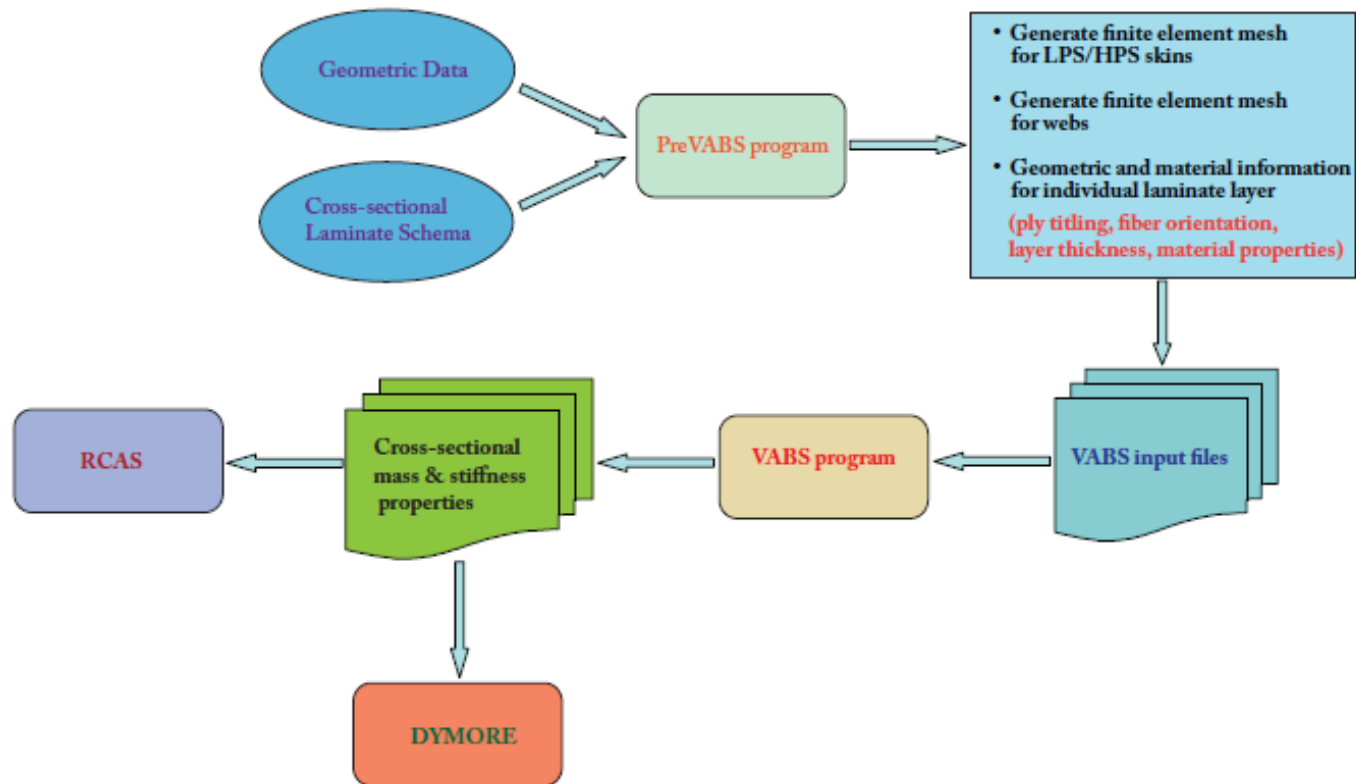
PreVABS

O programa PreVABS tem a capacidade de gerar configurações das seções transversais estruturais complexas para pás de helicópteros e turbinas eólicas com malha de elementos finitos de alta resolução manipulando geometria da seção da pá, parâmetros de malha, coordenadas nodais, propriedades do material e configurações de *lay-up* do material. Basicamente o PreVABS usa 3 input.

1. **Arquivo de dados geométrico do aerofólio.**
2. **Arquivo de dados do *lay-up* das lâminas da seção transversal.**
3. **Arquivos de dados das propriedades do material.**

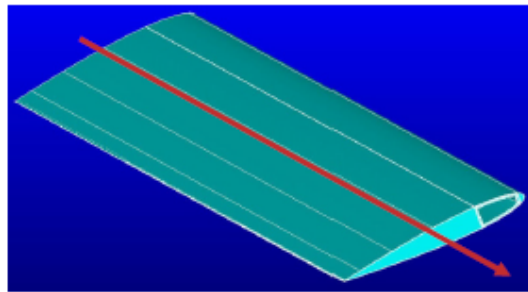


5. PreVABS e VABS



5. PreVABS e VABS

VABS desacopla o problema original 3D em uma análise da seção transversal 2D e análise de viga 1D. VABS calcula as propriedades estruturais tais como a rigidez torsional e rigidez à flexão. Usado na predição do comportamento estático ou dinâmico. Modelos: Euler- Bernoulli, Timoshenko, Vlasov.



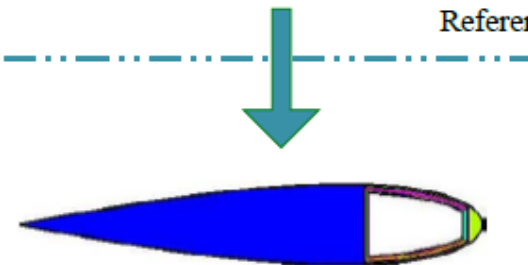
3D Elasticity

$$\sigma_{ij,j} + f_i = 0$$

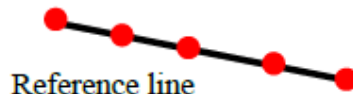
$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$$

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{12} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{13} & c_{23} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{14} & c_{24} & c_{34} & c_{44} & c_{45} & c_{46} \\ c_{15} & c_{25} & c_{35} & c_{45} & c_{55} & c_{56} \\ c_{16} & c_{26} & c_{36} & c_{46} & c_{56} & c_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{Bmatrix}$$

Reference line



$$\begin{Bmatrix} F_1 \\ M_1 \\ M_2 \\ M_3 \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{23} & S_{24} \\ S_{13} & S_{23} & S_{33} & S_{34} \\ S_{14} & S_{24} & S_{34} & S_{44} \end{bmatrix} \begin{Bmatrix} \gamma_{11} \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{Bmatrix}$$



1D beam analysis

$$\begin{aligned} \gamma_{11} &= \bar{u}'_1 \\ \kappa_1 &= \Phi'_1 \\ \kappa_2 &= -\bar{u}''_3 \\ \kappa_3 &= \bar{u}''_2 \end{aligned}$$

$$\begin{aligned} \frac{dF_1}{dx_1} + p_1 &= 0 \\ \frac{dM_1}{dx_1} + q_1 &= 0 \\ \frac{d^2 M_2}{dx_1^2} + p_3 + \frac{dq_2}{dx_1} &= 0 \\ \frac{d^2 M_3}{dx_1^2} - p_2 + \frac{dq_3}{dx_1} &= 0 \end{aligned}$$

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Obrigado !!!

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