Reliability Analysis of Wind Turbine Blades Considering Lightning Strike

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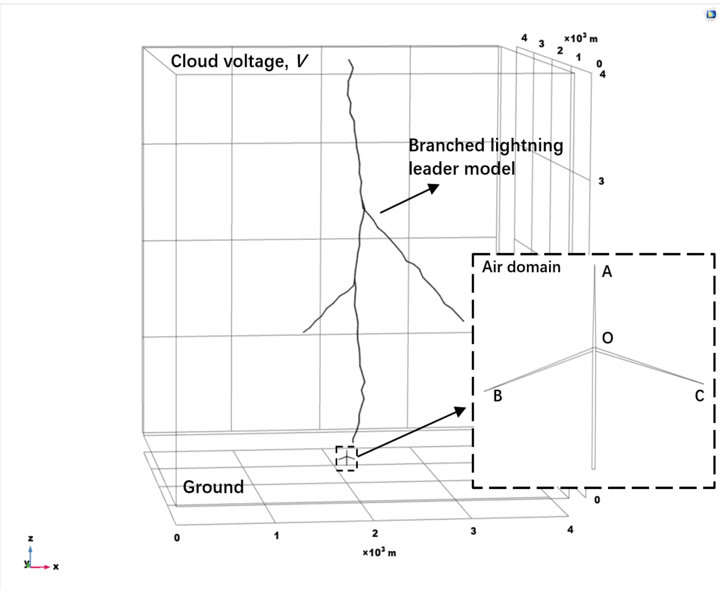
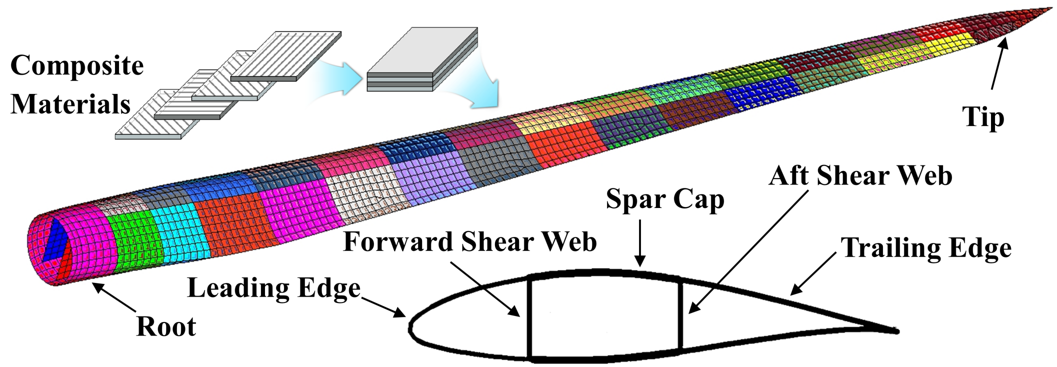
Background & Motivation

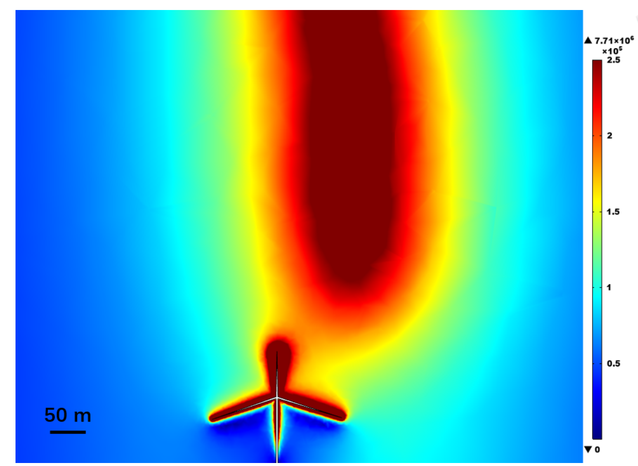
Lightning struck the blade tip.
Information found online.

- Lightning strike damage accounts for ~ 23.4% of wind turbine failure.
- Lightning strike protection cannot 100% prevent lightning damage;
- An accurate evaluation of wind turbines' reliability considering lightning strike is of critical importance.

Overview



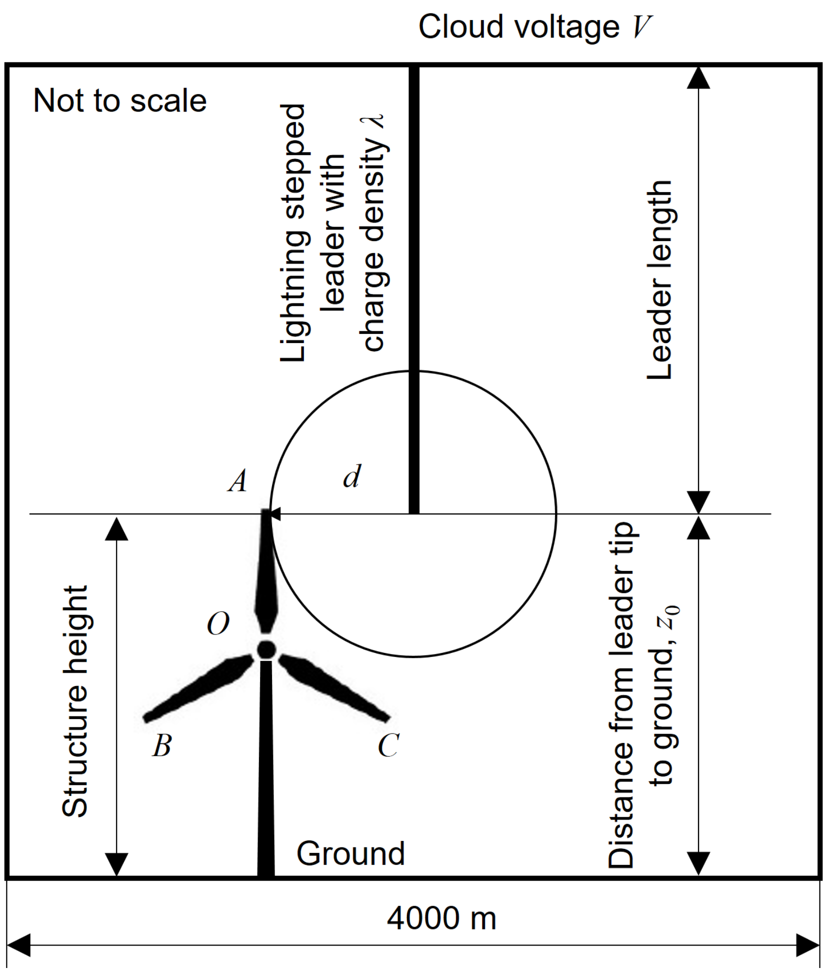




- Parametric lightning stepped leader model
- Problem set up in COMSOL
- Reliability Analysis of Composite Wind Turbine Blades
- Design Optimization Considering Lightning Strike Damage

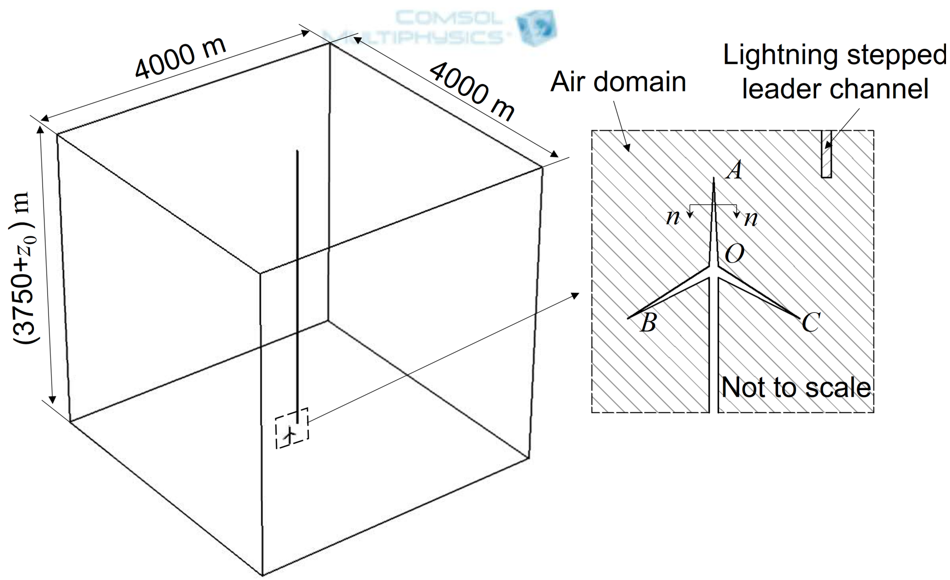
Straight Lightning Stepped Leader Model

- Lightning-strike-induced electric field calculation by finite element models.



Non-uniform charge density

$$\lambda(\eta) = a_0\left(1-\frac{\eta}{H-z_0}\right)G(z_0)I_{peak} + \frac{I_{peak}(a+b\eta)}{1+c\eta+d\eta^2}F(z_0)$$



Lightning-strike-induced electric field calculation setup in COMSOL Multiphysics

The Real Lightning Leader

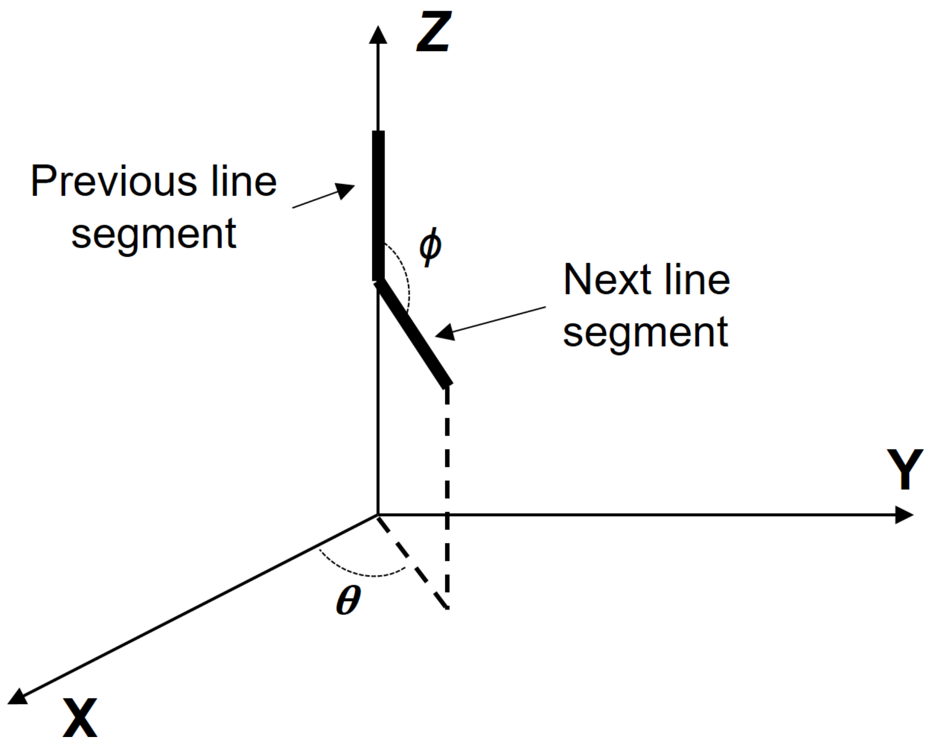
Lightning in the Nature (Picture found online)

Artificial Lightning Arc Channel
(High Voltage Lab at Mississippi State University)

- Both the natural and artificial lightning channels show strong tortuosity.
- Fifty percent of the discharges exist two or three branches, and only twelve percent do not show any branch.

Parametric Lightning Stepped Leader Model

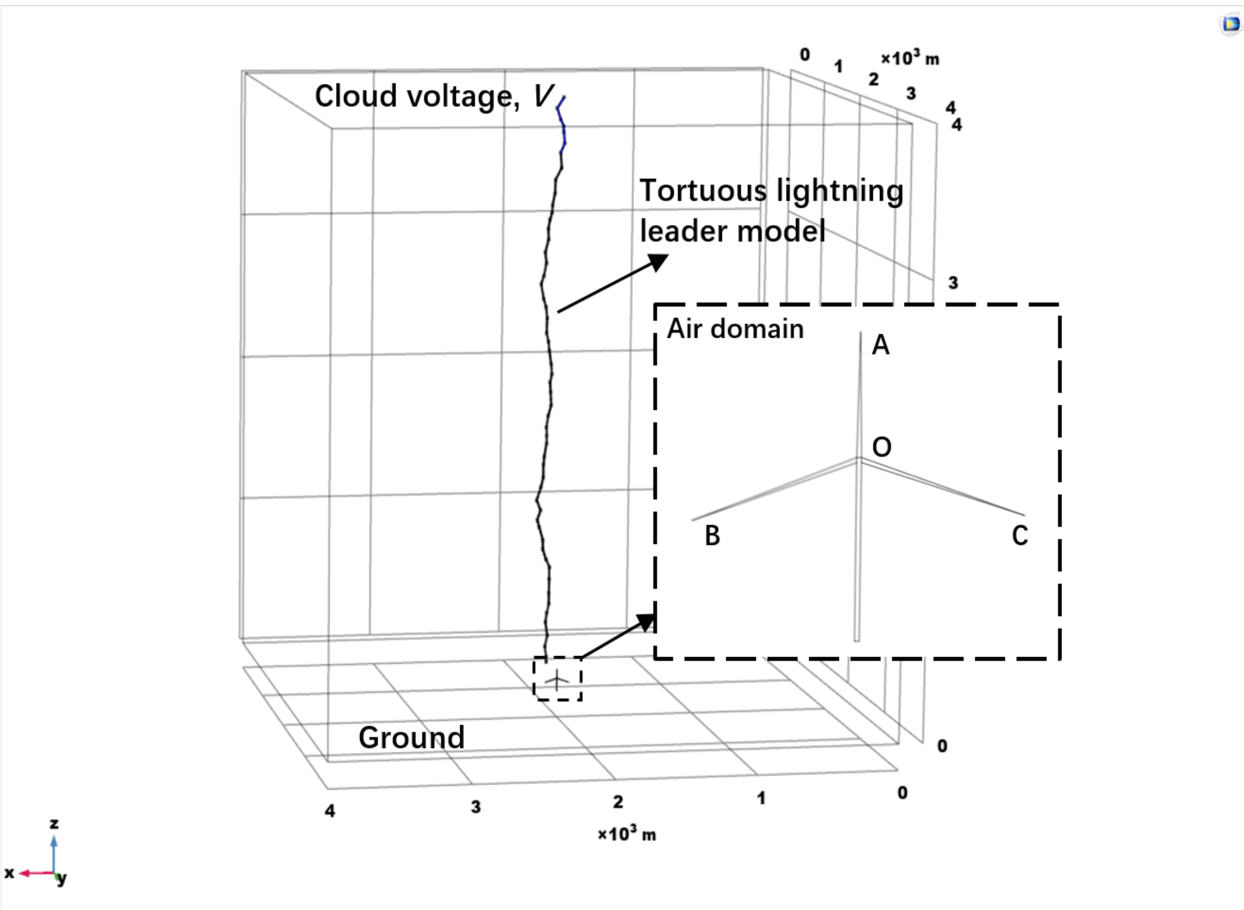
- The azimuthal angle θ in the spherical coordinate follows uniformly distribution;
- The angle between two adjacent line segments ϕ follows a Gaussian distribution;
- The length of each segment follows a uniform distribution from 80m to 100m.



Generation of Leader Steps in Spherical Coordinate

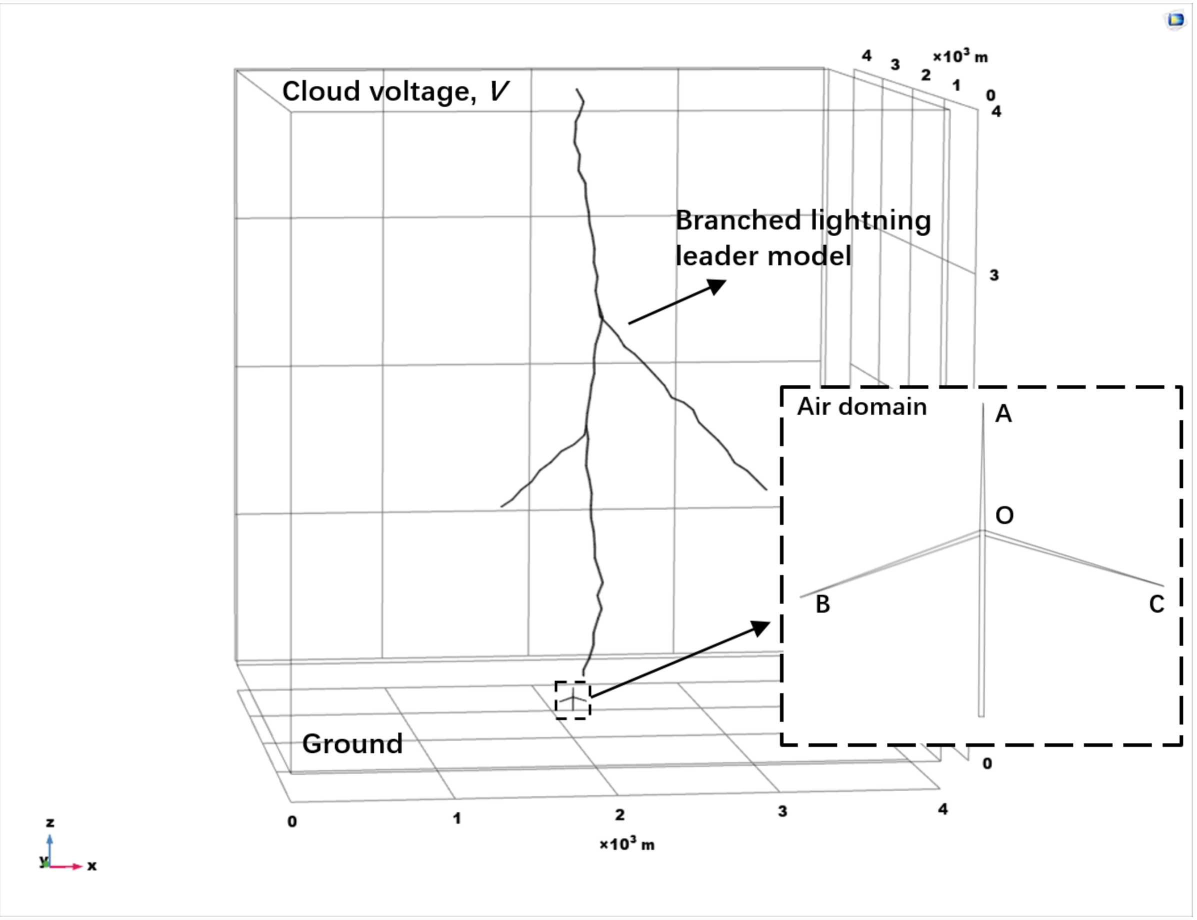
Problem Setup in COMSOL

- The random generation procedure is terminated when the distance between the tip of the tortuous channel and the ground structure becomes smaller than the striking distance



Electric field due to **tortuous lightning leader model** calculation setup in COMSOL Multiphysics

Problem Setup in COMSOL

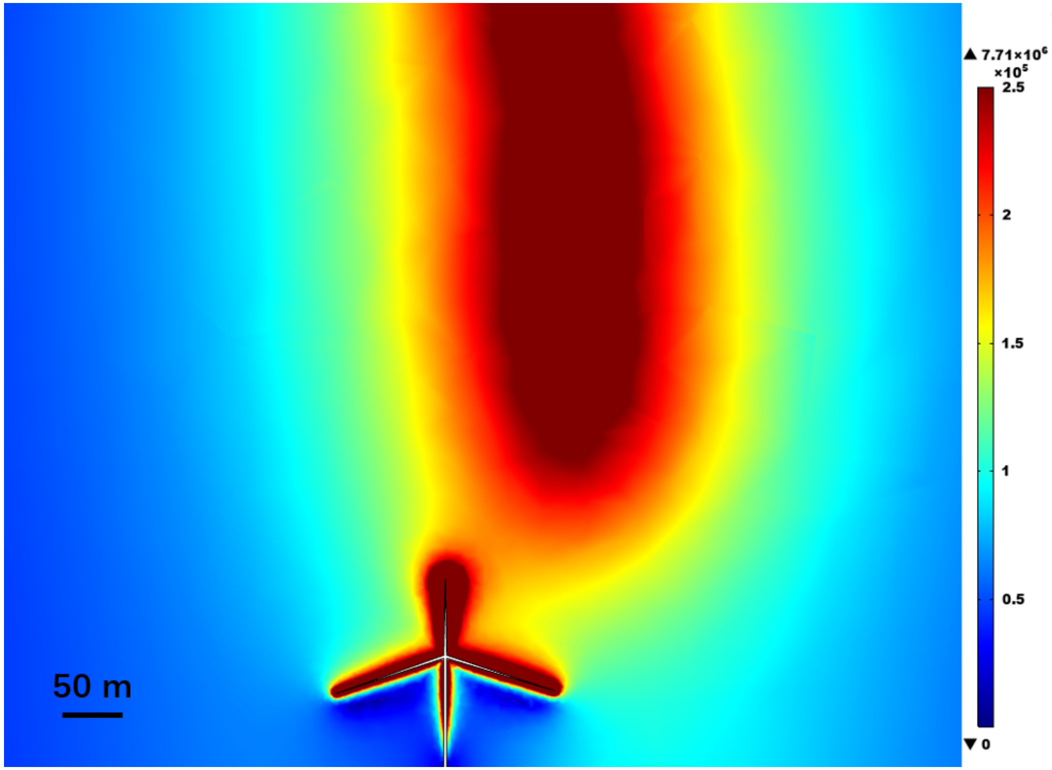


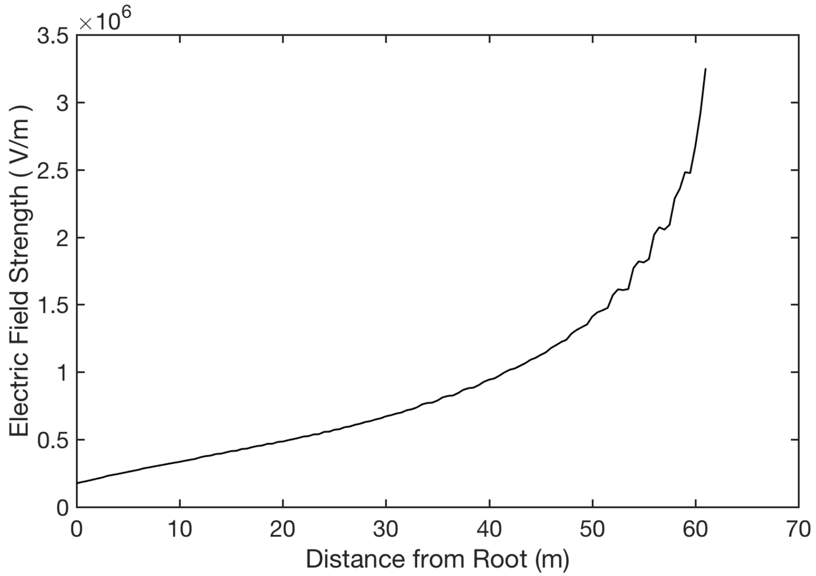
Electric field due to **branched lightning leader model** calculation setup in COMSOL Multiphysics

- The generation of branches keep same;
- The upper bifurcation happens at the height near 2500m;
- The lower bifurcation occurs at the height approaching 1500m.

Estimation of the Electric Field

- Electric field magnitude distribution in the vicinity of wind turbine.

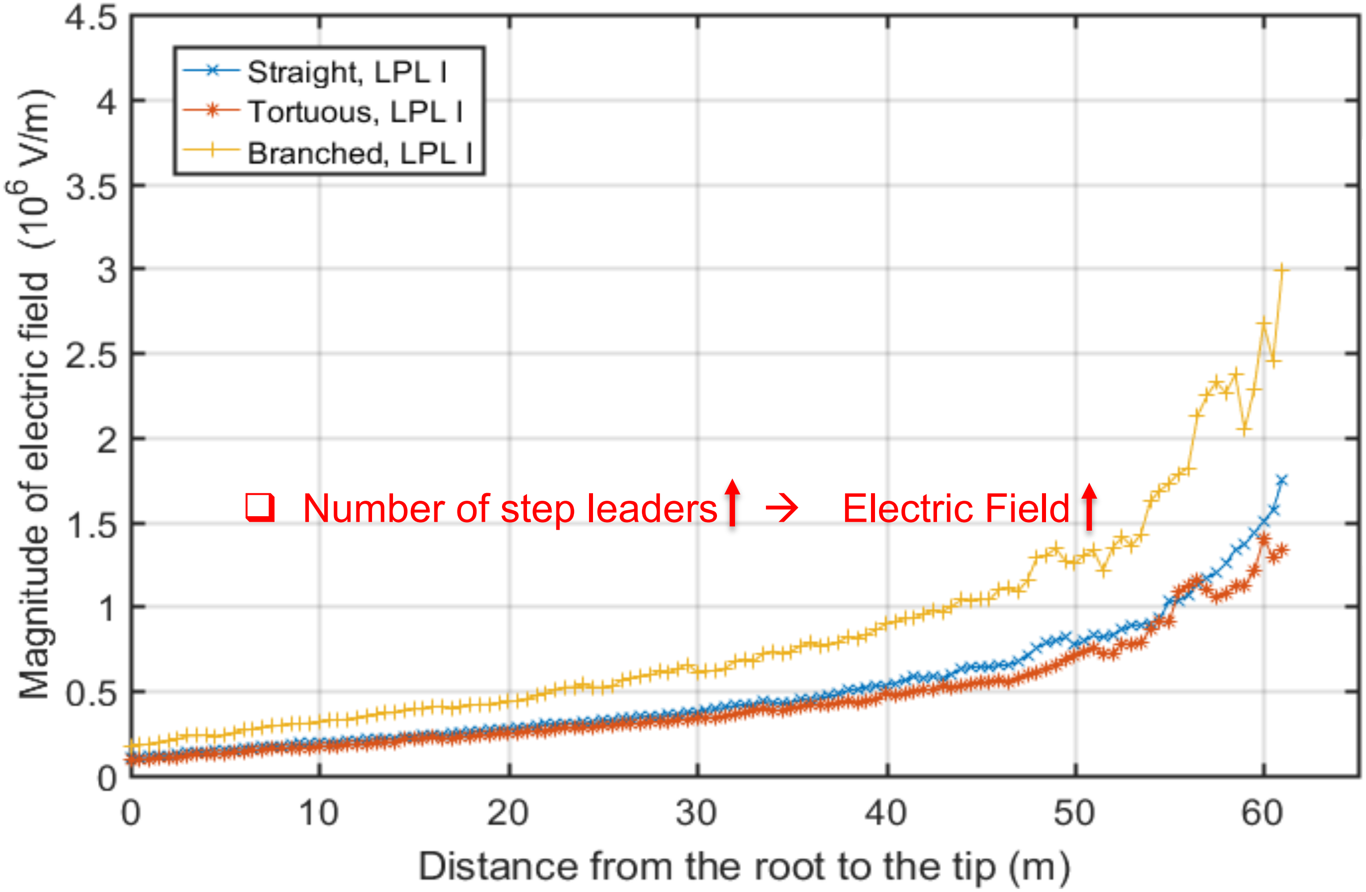


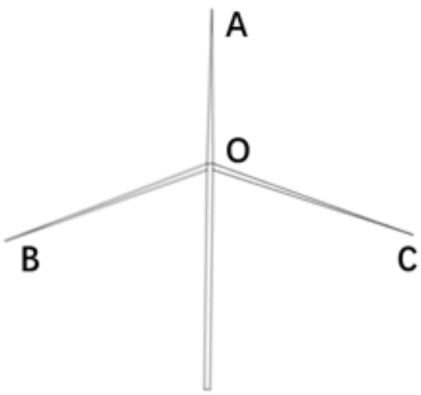


The Electric field along the vertical blade

FEA Result and Discussion

- The magnitude of electric field on the vertical blade OA induced by three different lightning stepped leader models, LPL I.

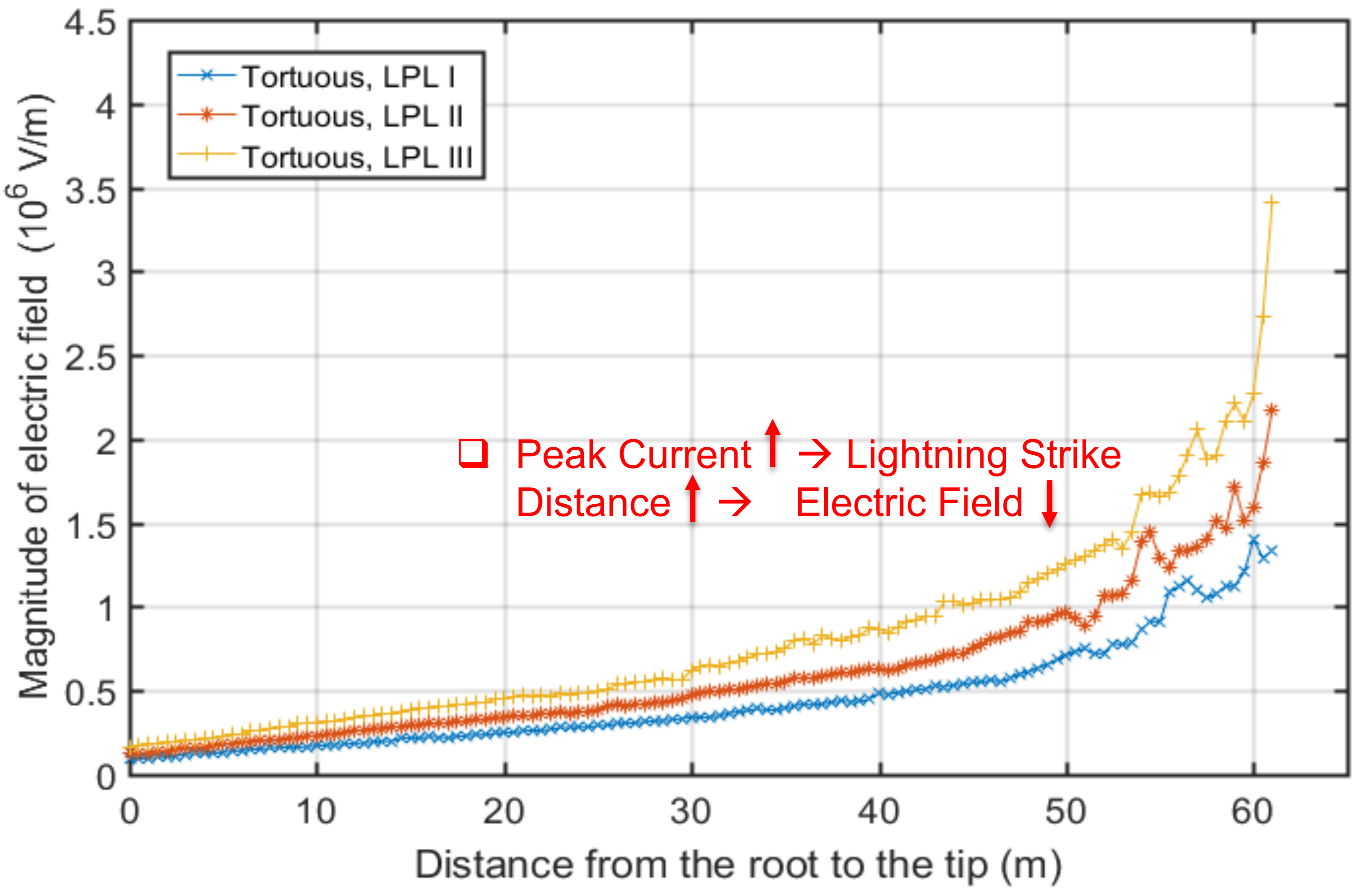


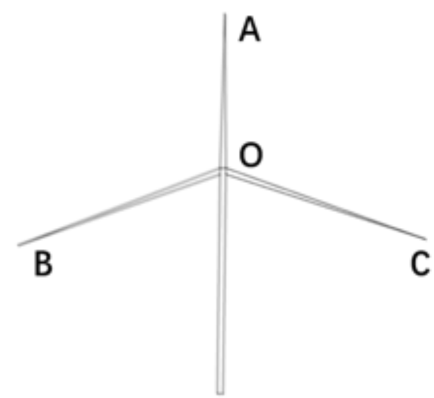


Model of Wind Turbine

FEA Result and Discussion

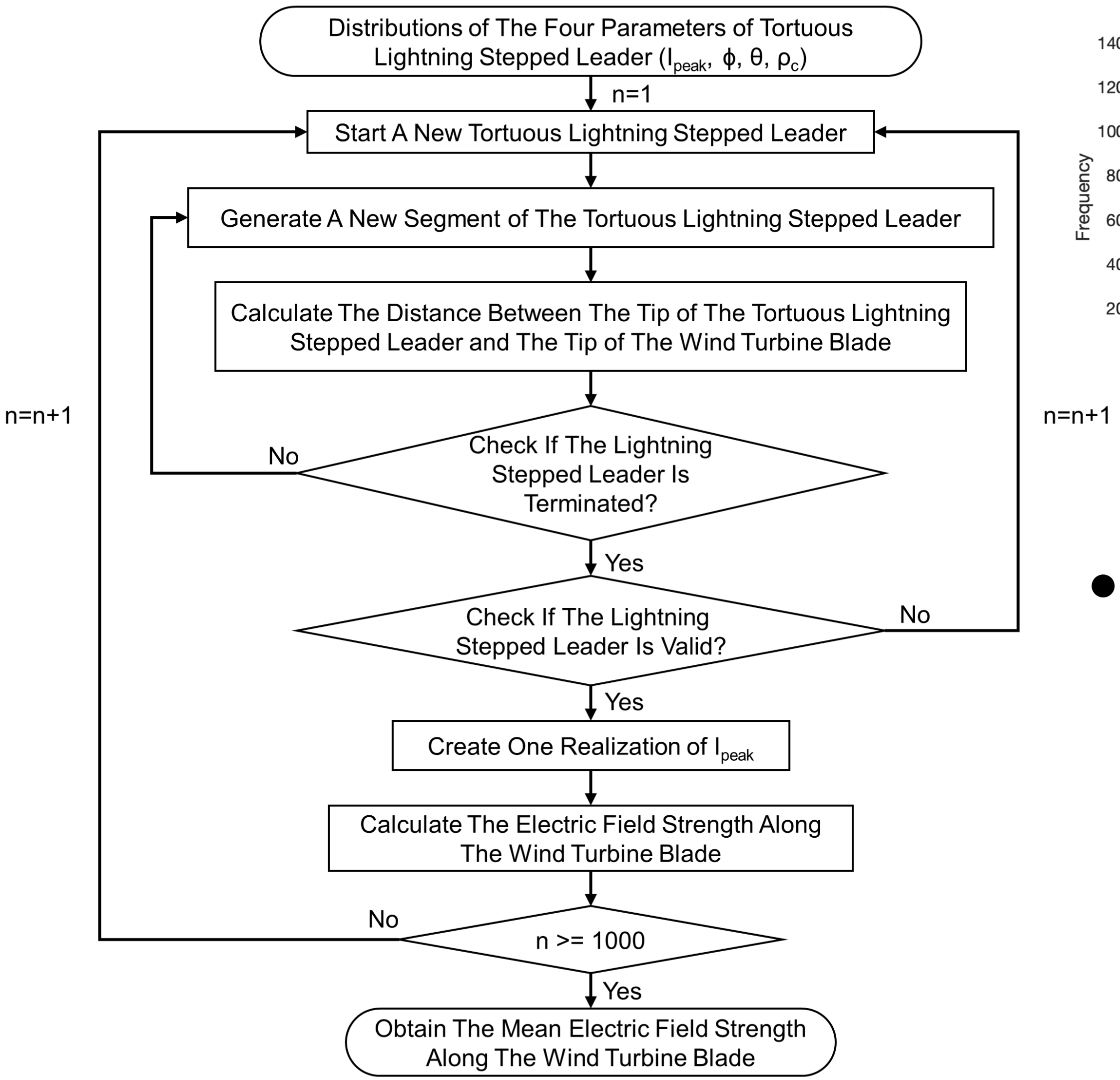
- The magnitude of electric field on the vertical blade OA induced by the tortuous lightning stepped leader models, LPL I, LPL II, LPL III.

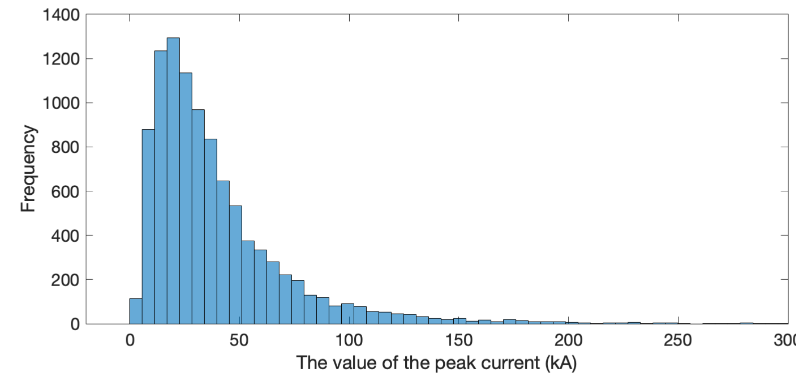




Model of Wind Turbine

Reliability Analysis of Composite Wind Turbine Blades



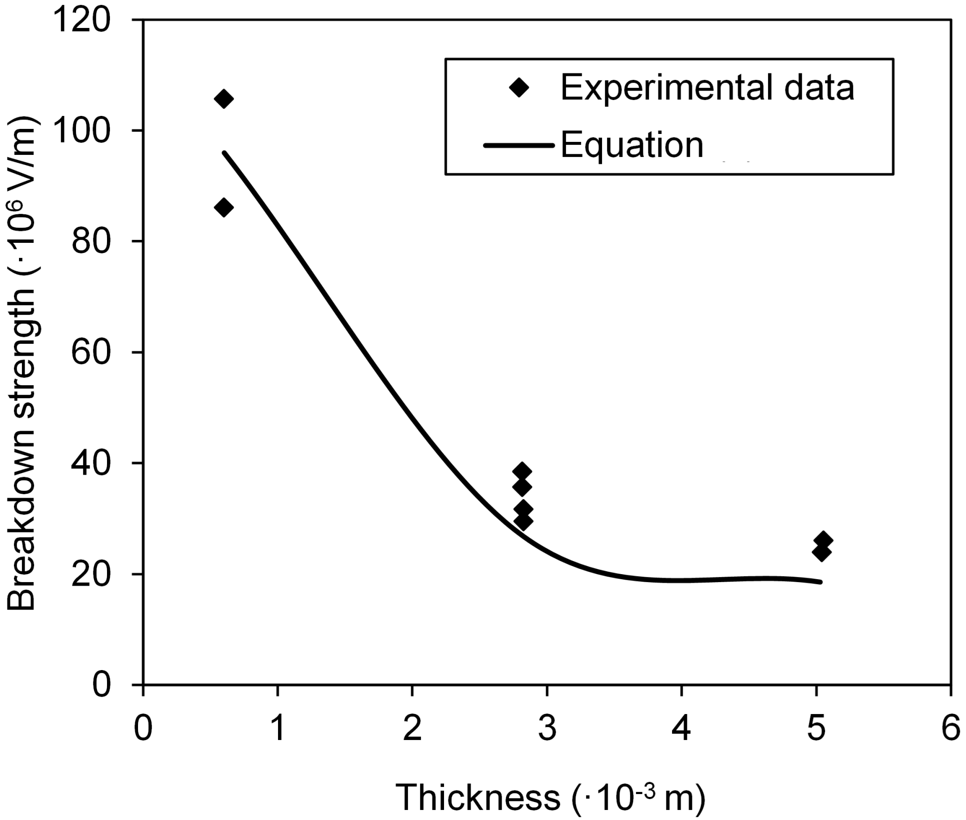


- The values of the peak current follow the log-normal distribution

Estimation of Breakdown Strength and Safety Factor

- Dielectric breakdown strength of composite wind turbine blades

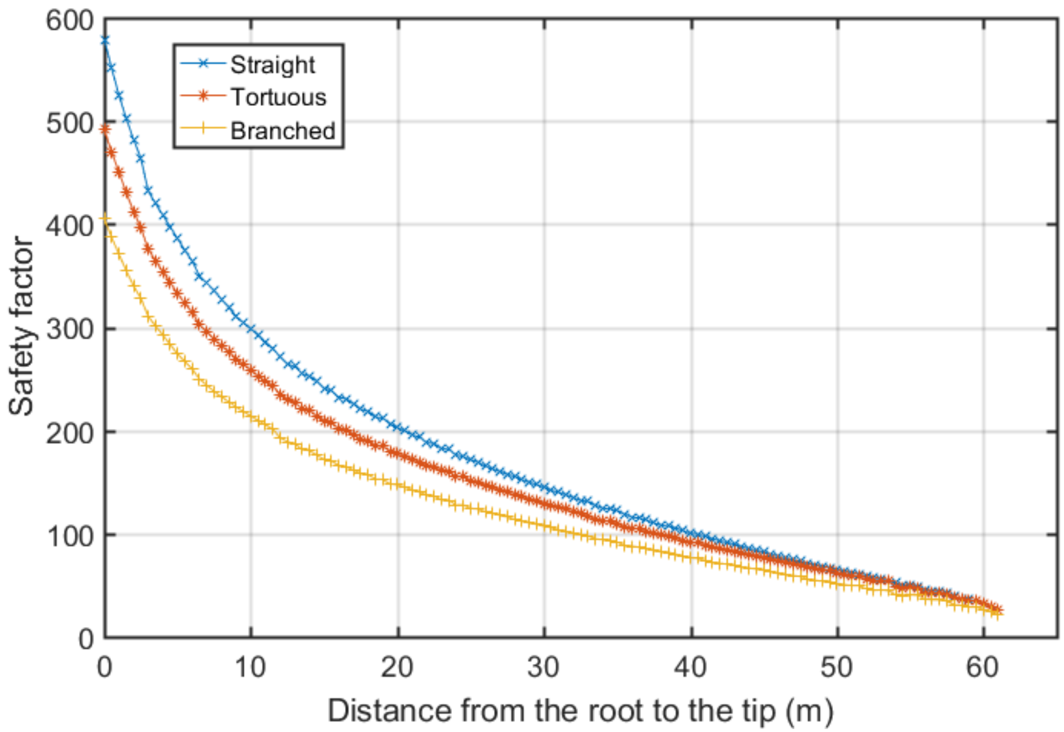
$$E_b = TI \cdot c_1 + c_2 / t,$$



- ❑ TI tracking index is highly dependent on the fiber orientation, fiber and matrix properties, surface defects and wide erosions.
- ❑ TI is not deterministic
- ❑ Dielectric breakdown is also dependent on the temperature
- ❑ E_b is considered only a function of laminate thickness t.

The Result of Reliability Analysis

- The average safety factor on the vertical blade OA induced by three different lightning stepped leader model considering the uncertainty of the peak current.

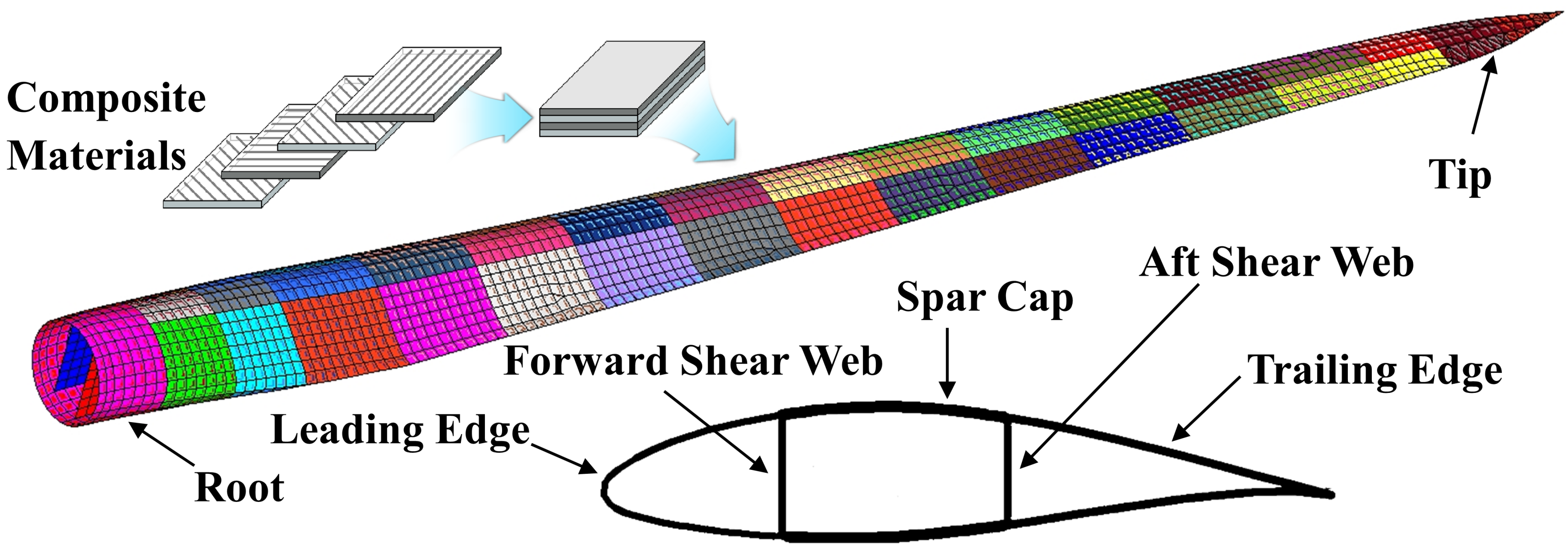


Design Optimization[1]

- Optimization Design Considering Lightning Strike Damage
- Design variables – laminate thicknesses

Parameters
- Material Type
- Layer Thickness
- No. of Layers

Outputs
- Electric field
- Dielectric breakdown strength



[1] W. Hu, W. Zhao, Y. Wang, Z. Liu*, J. Cheng*, and J. Tan, 2019, "Design Optimization of Composite Structures Considering Tortuous Lightning Strike and Non-Proportional Multi-Axial Fatigue Damage", Engineering Optimization, accepted.

Design Optimization[1]

- Optimization problem formulation

$$\text{Minimize}\quad C(\mathbf{d}) = \left(c_{QQ1} \sum_{i}^{12} m_i^o \frac{d_i}{d_i^o} \right) \Big/ C^o$$

$$\text{Subject to}\quad G_i(\mathbf{d}) = 1 - L_i(\mathbf{d}) = 1 - \frac{E_{bi}(\mathbf{d})}{E_i} \le 0,\ \ i = 1, 2, \ldots, NL$$

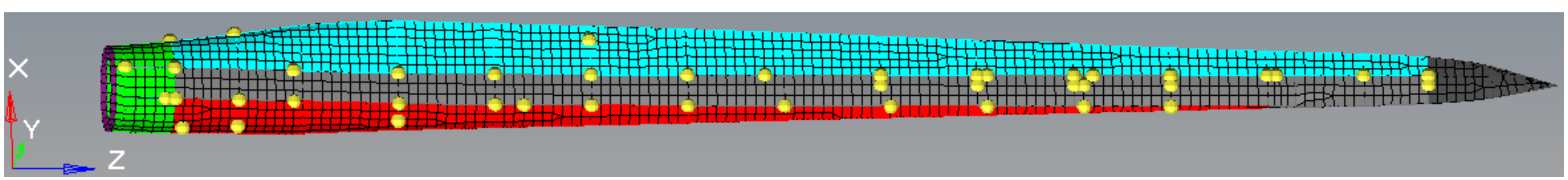
Lightning Constraints

$$G_j(\mathbf{d}) = D^j_{20\,year}(\mathbf{d}) - 1$$

Fatigue Constraints

$$= 52560 \times 20 \times \sum_{i}^{12} \sum_{j}^{50} \overline{P}_{VI}^{i,j}\left(v_{10}^i, i_{10}^i\right) D_{10}^{i,j}\left(\mathbf{d}, v_{10}^i, i_{10}^i\right) - 1 \le 0,\ \ \mathrm{j} = 1, 2, \ldots, NF$$

$$\mathbf{d}^L \le \mathbf{d} \le \mathbf{d}^U, \qquad \mathbf{d} \in \sim^{NDV}$$



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THANK YOU
Q & A