Possible Approaches to Turbine Structural Design

Rick Damiani, Ph.D., P.E.
Jeroen van Dam

National Wind Technology Center –NREL - 11/13/14

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Turbine Design – Possible Approaches

It is some sort of tragedy that many get caught up in the idea of generating power from the wind and attempt to build machines before they have mastered the disciplines required….

-Eggleston & Stoddard (1987)

Turbine Design – Aspects to consider

Key Disciplines

- Aerodynamics
- Structural Dynamics
- Material Mechanics
- Control Systems
- Aeroacoustics
- Electrical Engineering
- Geotechnical Engineering
- System Engineering

Key Components

- Blades
- Hub
- Shaft
- Gearbox
- Generator
- Bedplate
- Yaw system
- Tower
- Foundation

Turbine Design – IEC Perspective

- "Type Certification shall confirm that the wind turbine type is designed in conformity with the design assumptions, specific standards and other technical requirements." [IEC WT01]
- "The wind turbine type shall be evaluated for compliance with the technical requirements of this part of IEC WT 01, IEC 61400-1 or IEC 61400-2 and additional codes or standards chosen by the designer, with the agreement of the Certification Body" [IEC WT01]

Turbine Design – IEC Perspective

- "It shall be verified that Limit States are not exceeded" (implies FEA or equivalent analysis to assess utilization)

- 3 ways to determine design loads
  - 1. Simplified Loads Methodology
  - 2. Simulation Model
  - 3. Full Scale Load Measurement

IEC 61400-2

- Loads to Consider:
  - Inertial, vibrational, seismic, and gravitational loads
  - Aerodynamic Loads
  - Operational (e.g., due to yawing/furling/grid faults etc.)
  - Other (e.g., transportation, ice, wake, maintenance)

Turbine Design – IEC Perspective – Load Cases

- Major Load Cases:
  - Operational with normal external conditions
  - Operational with extreme external conditions
  - Fault with ‘appropriate’ external conditions
  - Transportation, maintenance, installation

+ checks on

- Flutter
- Vibration
- Rotor speed
- Cable twist

61400-2 Ed3

Turbine Design – Simplified Loads

- Provides *key loads for key components*
- Does Not Cover All of the loads explicitly but the designer should make use of good judgment
- Crude Approximation of the loads, especially for fatigue
- Must be *fairly conservative*
- Does Not guide toward the understanding of the key dynamic aspects of the turbine
- Valid only for: HAWTs, Rigid Hub, Cantilevered Blades, collective not individual blade control
- Assumes turbine data verified by tests (to follow-12,-13)

Turbine Design – Simplified Loads - Inputs

- Design rotational speed, n_{design} -From Test
- Design wind speed, V_{design} -From IEC $1.4V_{ave}$
- Design Power, P_{design} -From Test
- Design shaft torque, Q_{design} -From Test
  - Drivetrain efficiency, η (use IEC or test)
- Maximum yaw rate, $\omega_{yaw,max}$ FROM IEC (except for active yaw)
- Maximum rotational speed, n_{max} -From Test (2h with 30 mins @15+m/s and loss of load + extrapolation to Vref)

Turbine Design – Simplified Loads - DLCs

- **E.g. DLC B: Yawing**

$$M_{yB.B} = m_B \omega^2_{yaw,\max} L_{rt} R_{COG} + 2\omega_{yaw,\max} I_B \omega_{n,design} + \frac{R}{9} \Delta F_{xshaft}$$

Strictly IEC-specified

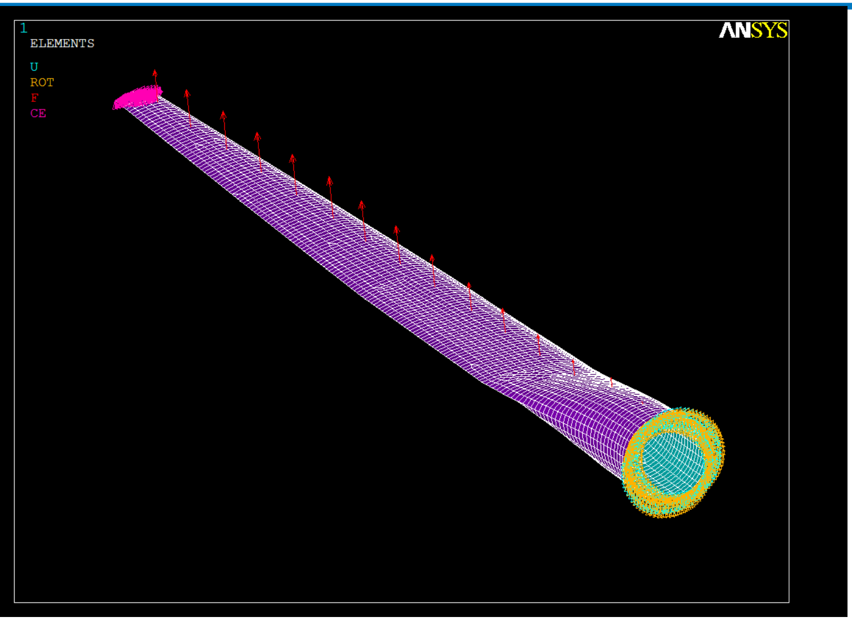
But also, assuming design conditions:

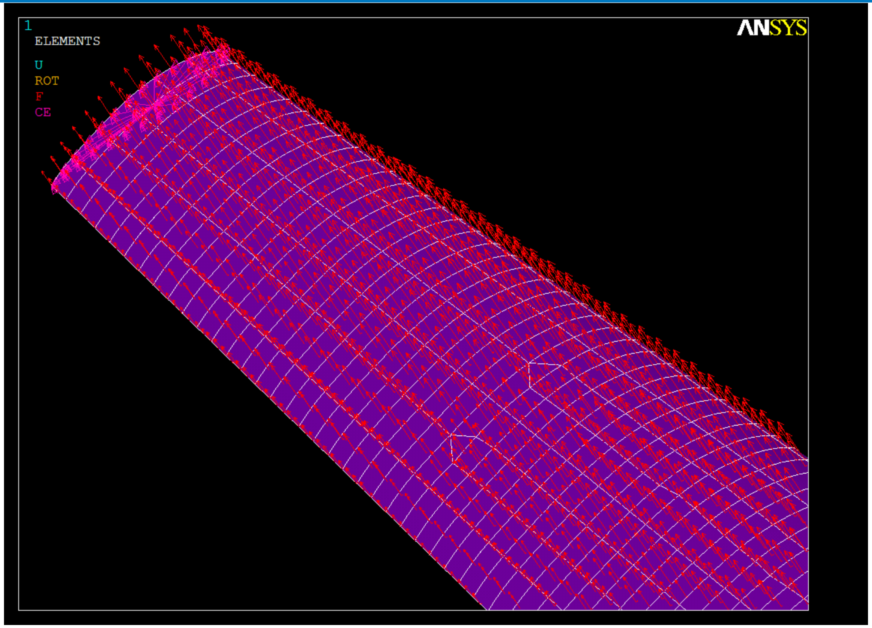
$$F_{zB.B} = m_B \omega^2_{n,design} R_{COG}$$

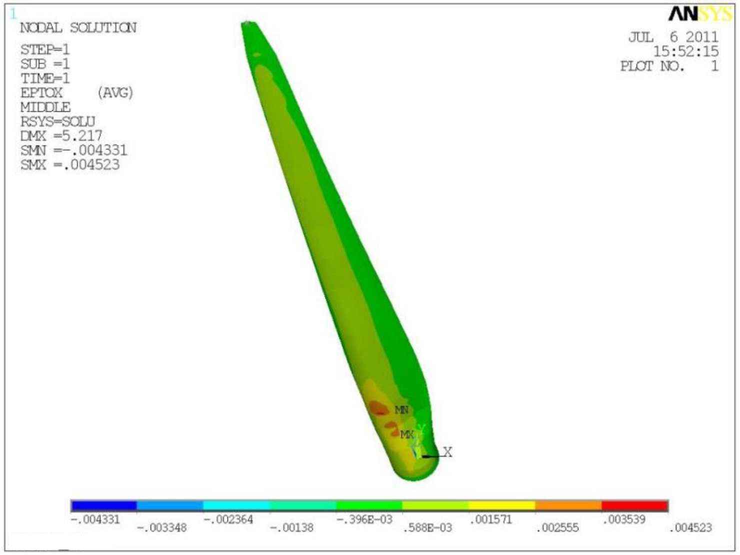
$$M_{xB.B} = m_B g R_{COG} + \frac{Q_{design}}{B}$$

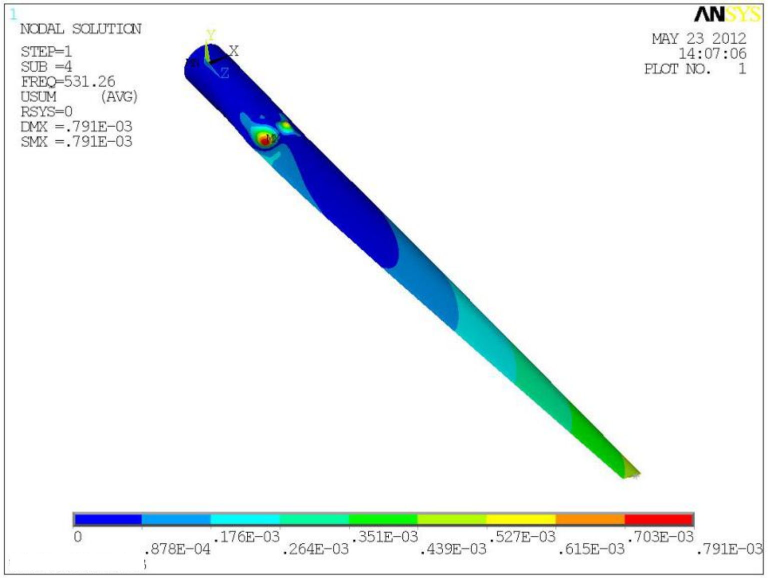
- Consider all applicable loads for FEA analysis,
- Investigate beyond the SL equations,
- Determine best strategy to apply loads to model and its sensitivities

Turbine Design – Limit State Analysis - FEA







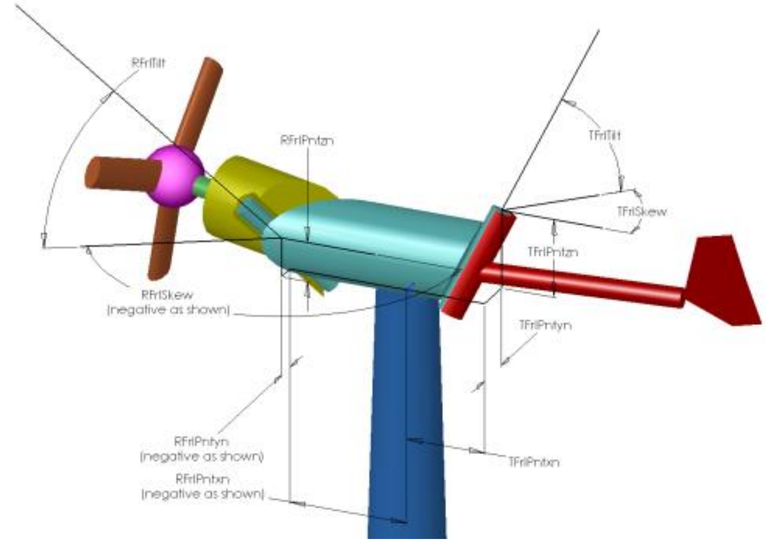


CAE Tools –E.G. FAST - & - ADAMS

- **Multi-body system dynamics with Aerodynamics packages**
- **FAST- Aero-Hydro-Servo-Elastic CAE Tool developed since 1996**
  - Open-Source – FREE!
  - Capable of simulating tail and furling dynamics for small wind
  - 24 DOFs HAWT only- VAWT aerodynamics captured in upcoming V8.xx
  - *Use for: Design to IEC load cases - Certification*
  - *V8 capable of blade torsional (twist) degree of freedom*
  - Can be used to prepare ADAMS input files and models

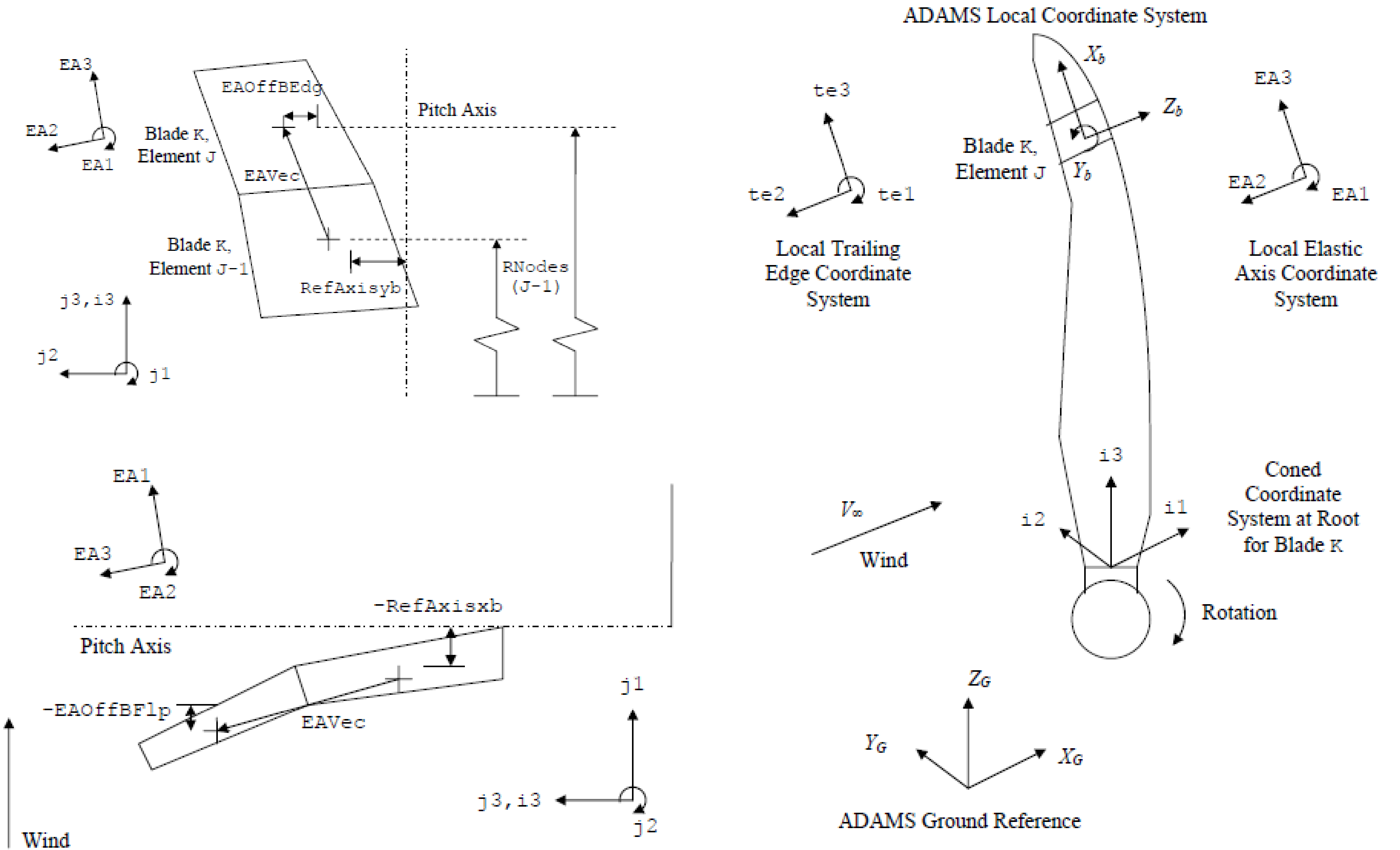
CAE Tools – FAST - & - ADAMS

- **MSC ADAMS – Multibody Dynamics**
  - Commercial Product
  - Can be coupled to Aerodyn (FAST module) – FAST2ADAMS available for FREE
  - Can be highly customizable with user's DLLs (requires a bit of programming)
  - Highly flexible – virtually any geometry you can think of
  - High fidelity – as many DOFs as user requires



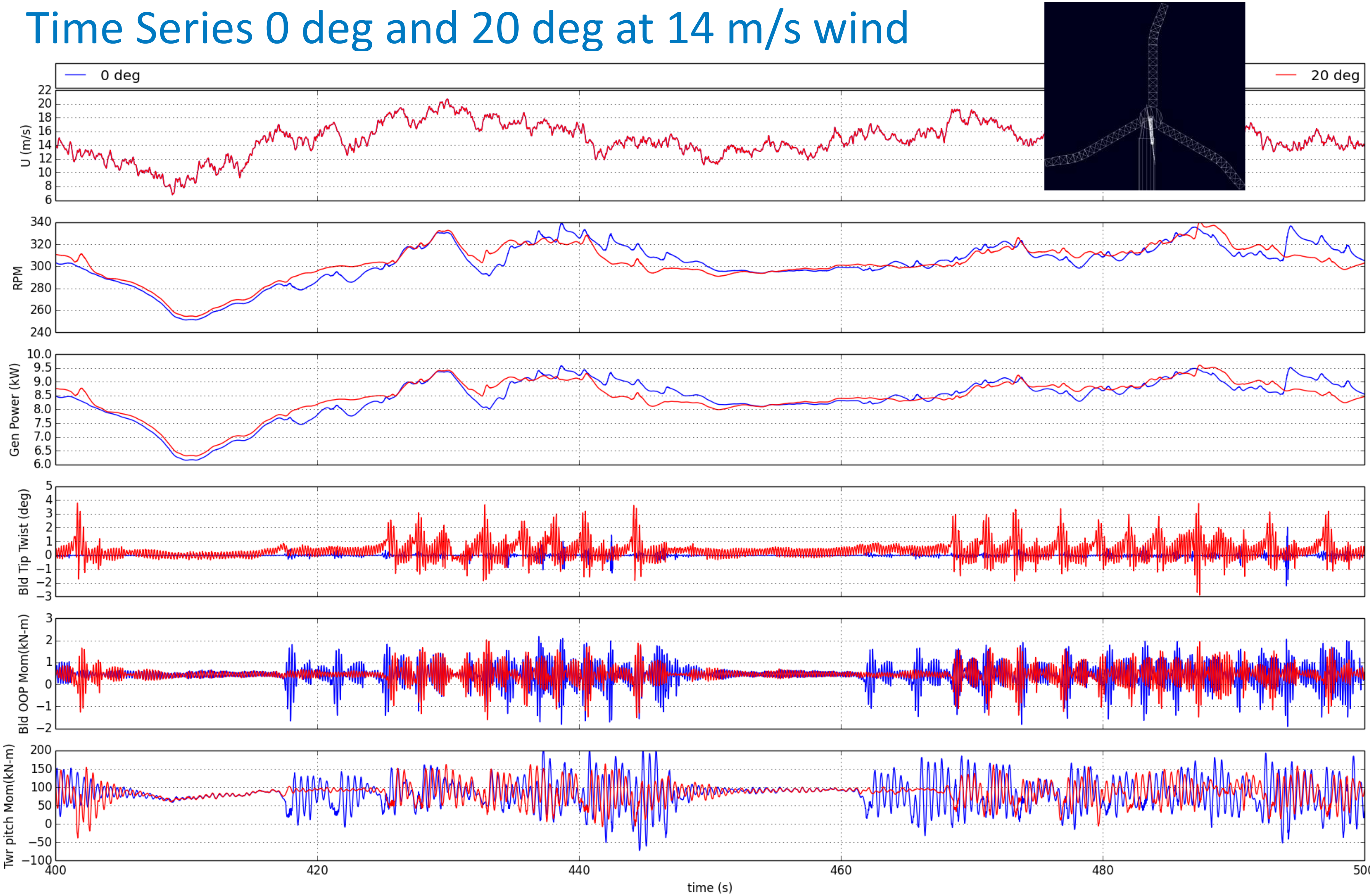
FAST-2-ADAMS

- **Elastic axis is now properly curved in both planes**

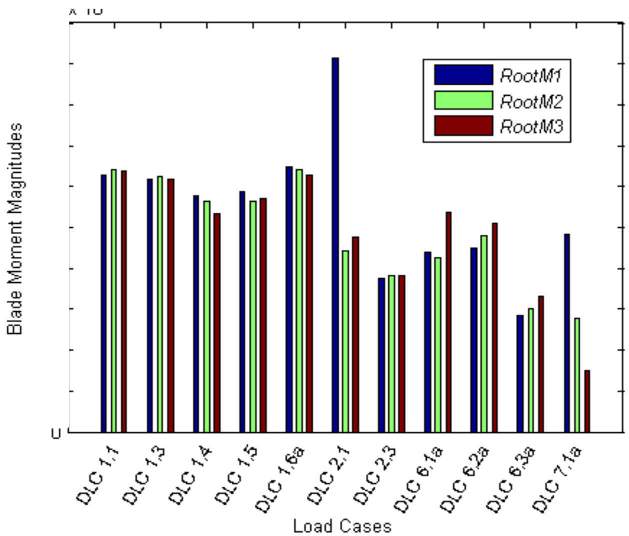


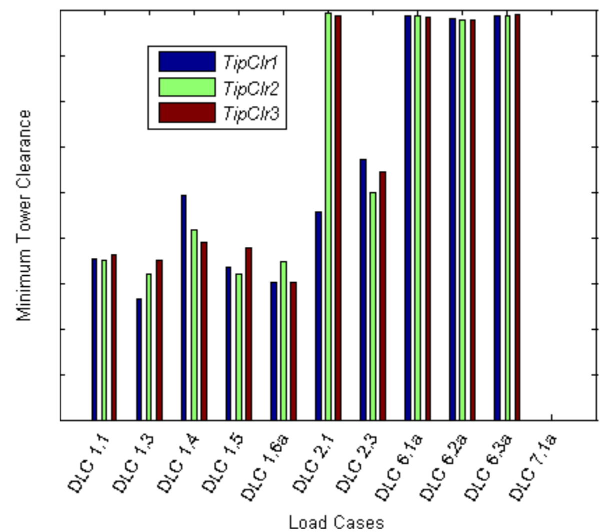
Example of time Series

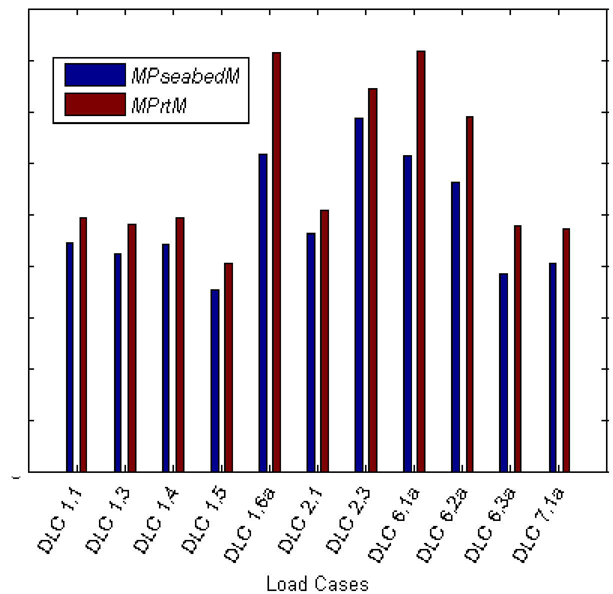
- Time Series 0 deg and 20 deg at 14 m/s wind



Example of Aeroelastic Loads Analysis Results







		RootFxc1	RootFyc1	RootFzc1	RootF1	RootMIP1	RootMOoP1	RootMzc1	RootM1	HorWindV	NacYawErr
Parameter	**Type**	**(kN)**	**(kN)**	**(kN)**	**(kN)**	**(kN·m)**	**(kN·m)**	**(kN·m)**	**(kNm)**	**(m/sec)**	**(deg)**
RootFxc1	**Minimum**	**- 3.4979E+2**	- 1.9859E+2	9.9347E+2	4.0223E+2	5.2299E+3	- 1.5579E+4	- 1.6011E+2	1.6433E+4	2.5470E+1	6.5600E+1
RootFxc1	**Maximum**	**9.7160E+2**	- 7.8098E+2	8.4294E+2	1.2466E+3	2.6042E+4	3.7638E+4	- 6.7028E+2	4.5769E+4	2.9600E+1	6.3190E+0
RootFyc1	**Minimum**	8.6049E+2	**- 8.0311E+2**	8.1608E+2	1.1770E+3	2.5218E+4	3.2643E+4	- 6.2546E+2	4.1249E+4	2.7500E+1	- 2.7570E+0
RootFyc1	**Maximum**	4.0414E+1	**6.9575E+2**	- 2.8116E+2	6.9692E+2	- 2.0691E+4	4.3043E+2	3.2538E+2	2.0695E+4	5.3440E+1	6.2700E+1
RootFzc1	**Minimum**	- 1.2606E+1	- 9.1335E+1	**- 4.2975E+2**	9.2201E+1	3.8880E+3	- 1.0035E+3	- 2.6325E+1	4.0154E+3	2.3170E+1	- 1.5240E+1
RootFzc1	**Maximum**	3.2100E+2	- 1.7475E+2	**2.2515E+3**	3.6548E+2	5.0475E+3	9.6990E+3	- 9.6345E+1	1.0934E+4	1.5140E+1	6.5070E+0
RootF1	**Minimum**	2.7049E-3	3.6927E-3	- 2.4266E+2	**4.5774E-3**	3.6817E+3	- 1.3376E+3	- 7.3579E+1	3.9172E+3	4.7640E+1	- 2.9020E+0
RootF1	**Maximum**	9.7119E+2	- 7.8219E+2	8.4146E+2	**1.2470E+3**	2.6096E+4	3.7625E+4	- 6.7028E+2	4.5788E+4	2.9600E+1	6.3190E+0
RootMIP1	**Minimum**	5.0017E+1	6.4955E+2	- 3.3803E+2	6.5147E+2	**- 2.2143E+4**	4.0315E+2	3.9149E+2	2.2147E+4	5.5520E+1	4.0960E+1
RootMIP1	**Maximum**	9.7119E+2	- 7.8219E+2	8.4146E+2	1.2470E+3	**2.6096E+4**	3.7625E+4	- 6.7028E+2	4.5788E+4	2.9600E+1	6.3190E+0
RootMOoP1	**Minimum**	- 3.4587E+2	- 2.3531E+2	1.0020E+3	4.1832E+2	6.0534E+3	**- 1.5822E+4**	- 1.3073E+2	1.6940E+4	2.5530E+1	6.5880E+1
RootMOoP1	**Maximum**	9.7065E+2	- 7.4372E+2	8.6765E+2	1.2228E+3	2.3031E+4	**3.7908E+4**	- 7.0376E+2	4.4356E+4	2.9320E+1	- 2.2490E+0
RootMzc1	**Minimum**	9.4095E+2	- 7.3211E+2	8.8398E+2	1.1922E+3	2.2599E+4	3.6504E+4	**- 7.2522E+2**	4.2933E+4	2.9480E+1	- 3.1590E+0
RootMzc1	**Maximum**	7.5889E+1	5.9664E+2	2.7280E+2	6.0145E+2	- 1.8887E+4	1.1407E+3	**4.3934E+2**	1.8921E+4	6.0530E+1	- 5.9690E+1
RootM1	**Minimum**	3.3583E+1	1.3640E+2	- 1.8315E+2	1.4047E+2	- 2.9480E-1	2.9634E-1	- 1.2309E+2	**4.1800E-1**	4.6540E+1	- 6.8960E+0
RootM1	**Maximum**	9.7119E+2	- 7.8219E+2	8.4146E+2	1.2470E+3	2.6096E+4	3.7625E+4	- 6.7028E+2	**4.5788E+4**	2.9600E+1	6.3190E+0

Examples from large WTG Loads Analyses

Turbine Design – Full Scale Load Measurements

- Load Measurements should be taken under conditions as close as possible to the aeroelastic model DLCs [61400-2]

- Load measurements for large turbines almost exclusively used for model validation. Determination of design loads is then done with the validated model.
- Extrapolation of measured loads shall occur in compliance with IEC/TS 61400-13.

Measurement Load Cases (MLCs)

- **Set of MLCs to match the DLCs of the standard.**

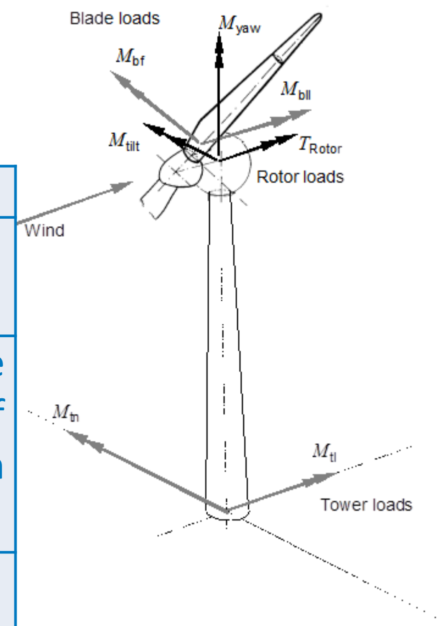
[IEC 61400-13]

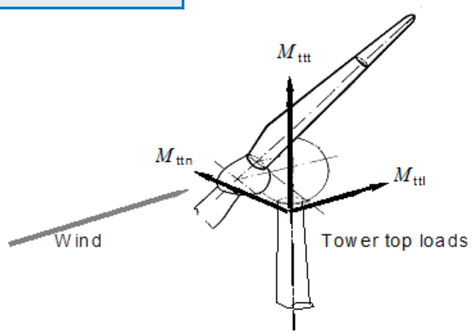
MLC number	Measurement load case MLC	DLC number (IEC 61400-1)	Wind condition at DLC	Remarks
1.1	Power production	1.2	Vin < Vhub < Vout*	In this mode of operation, the wind turbine is running and connected to the grid
1.2	Power production plus occurrence of fault	2.3	Vin < Vhub < Vout*	Any fault in the control or protection system, which does not cause an immediate shut-down of the turbine
1.3	Parked, idling	6.2	Vin < Vhub < 0.75 Ve1*	When the wind turbine is parked, the rotor may either be stopped or idling
* Has to be divided further into wind speed bins and turbulence bins.				

MLC	Measurement load case MLC	DLC	Target wind speed
2.1	Start-up	3.1	Vin and > Vr + 2 m/s
2.2.	Normal shut-down	4.1	Vin, Vr and > Vr + 2 m/s
2.3	Emergency shut-down	5.1	Vin and > Vr + 2 m/s
2.4	Grid failure	1.5	Vr and > Vr + 2 m/s
2.5	Overspeed activation of the protection system	5.1	> Vr + 2 m/s
Ideally the measurements should be taken at Vout. As this is impractical, the measurements are taken at wind speeds higher than Vr + 2 m/s.			

Load measurements – Mandatory Loads

Load quantities	Specification	Comments
Blade root loads	Flap bending Lead-lag bending	Blade 1: mandatory Other blades: recommended
Rotor loads	Tilt moment Yaw moment Rotor torque	The tilt and yaw moment can be measured in the rotating frame of reference or on the fixed system (for example, on the tower)
Tower loads	Bottom bending in two directions	





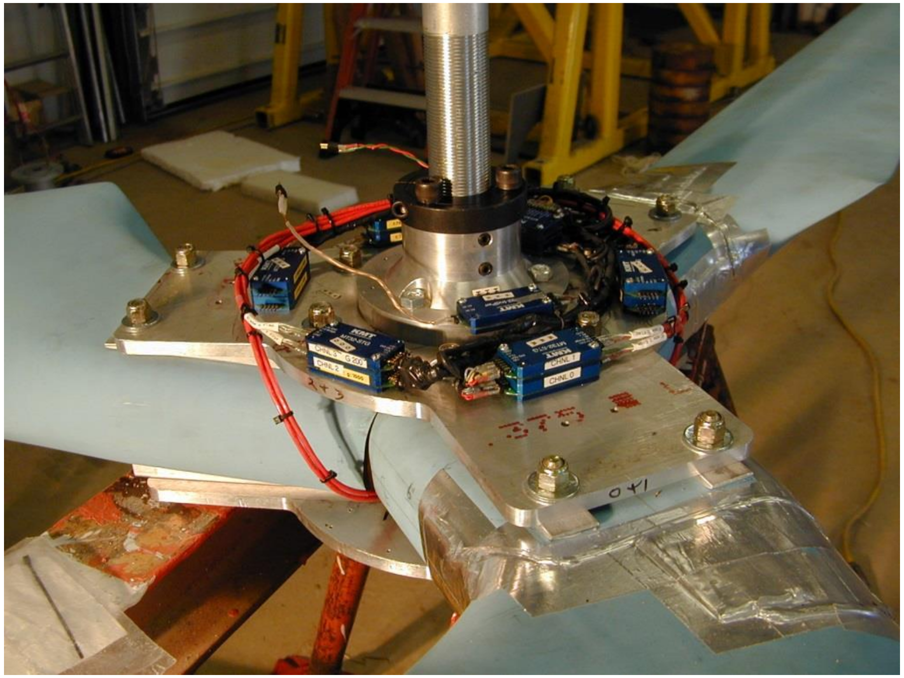
Load Measurements – Other Quantities

Meteorological Quantity	Importance level
Wind speed	Mandatory
Wind shear	Recommended
Wind direction	Mandatory
Air temperature	Mandatory
Temperature gradient	Recommended
Air density	Mandatory

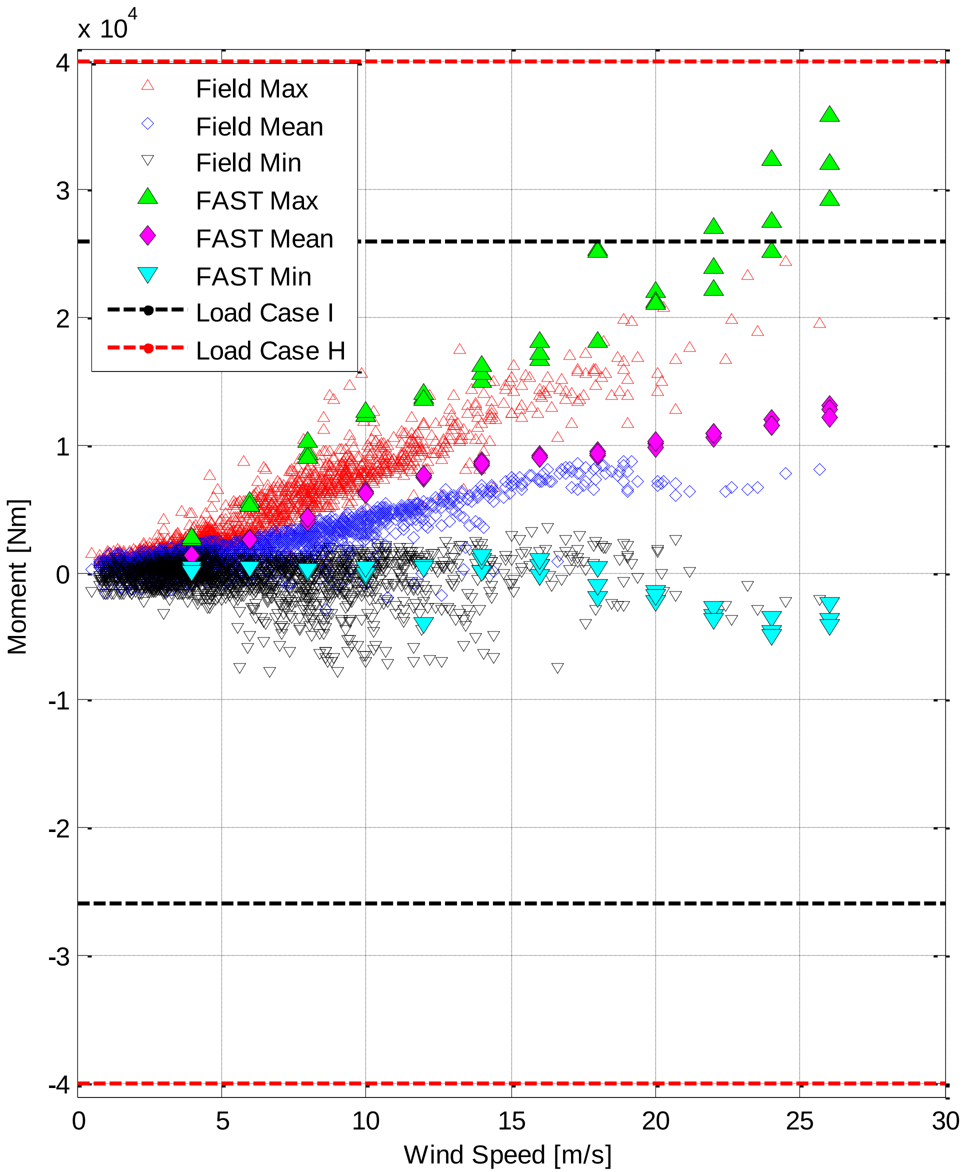
Turbine operational Quantity	Importance level
Electrical power	Mandatory
Rotor speed	Mandatory
Pitch angle	Mandatory
Yaw position	Mandatory
Rotor azimuth	Mandatory
Grid connection	Recommended
Brake status	Recommended
Wind turbine status	Useful

Load Measurements - SWT specific issues

- Small spaces & Instrumentation can alter behavior (mass, inertia) thus: $mall equipment
- Instrumentation exposed to elements
- Free yaw
- No guidance of VAWTs in IEC 61400-13
- Cost of SWT loads test similar to large turbine >$100k



Full Scale Load Measurements vs Aeroelastic Predictions



Load Measurements: IEC 61400-13 revision

- To become an IS (instead of Technical Specification).
- Scope changes to: "This part of the IEC 61400 describes the measurement of fundamental structural loads on wind turbines for the purpose of the load simulation model validation.".. "If these methods are used for an alternative objective or used for an unconventional wind turbine design, the required signals, measurement load cases, capture matrix, and post processing methods should be evaluated and if needed adjusted to fit the objective."
- Informative VAWT annex added.

Conclusions

- **IEC allows various approached to the structural design evaluation**
  - Load Measurements: difficult and expensive to accomplish – better left to model validation
  - Simplified Loads Equation: one model fits all, get advantages of a quick turn-around, but disadvantage of incomplete picture and conservatism in some cases
  - Aeroelastic modeling: requires attention to detail and model set-up, best overall approach from the physics point of view, and most versatile

….On the other hand, those who have mastered the disciplines often have no particular interest in wind turbines or commitments to their design.

-Eggleston & Stoddard (1987)