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A Comprehensive Structural Study of Offshore Wind Turbine Foundation and Non-Model Based Damage Detection using Effective Mass with Application to Small Components/ Cables and a Truss Wind Turbine Tower

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- Offshore Wind Turbine
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  - Methodology
  - Sample Cases
- Damage Detection
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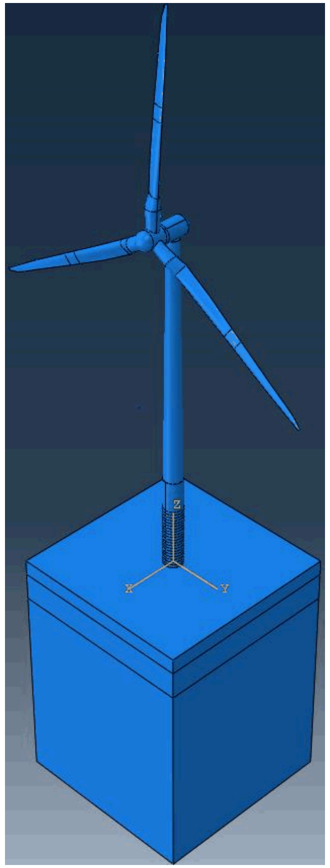
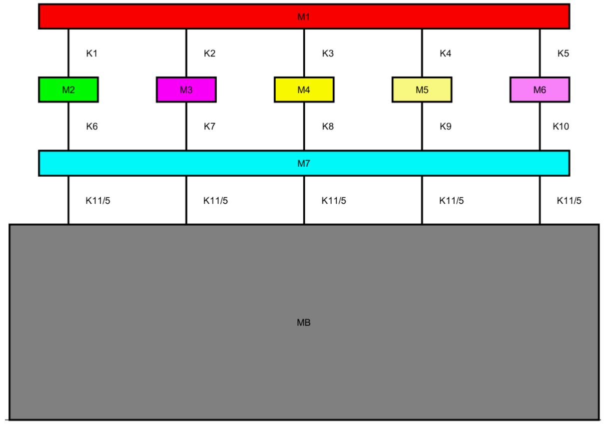
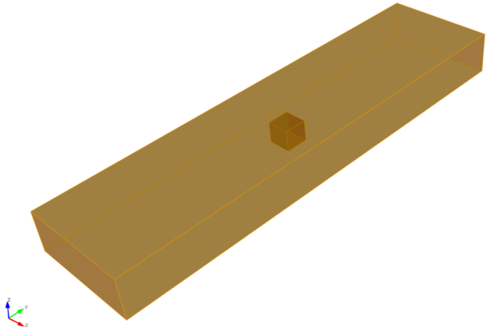
  - Methodology
  - Sample Cases
- Tasks and Timeline







Offshore Wind Turbine: Background

- With the increase of fossil fuel consumption the US Department of Energy released the "20% Wind Energy by 2030" report in 2009
  - Set a goal for having 20% of all energy produced in the US be from wind energy
  - 4 years later Maryland passed the Offshore Energy Act of 2013 to achieve this goal by 2022.
- Due to Maryland ranking 42nd for total area compared to other states
  - Wind farms would end up near residential areas which limit the aesthetics of the turbine
  - Offshore Wind Turbine (OWT) have:
    - Relaxed aesthetic constraints
    - Higher investment
    - Harsher Environment

Offshore Wind Turbine: Background cont.

- Failure more likely for OWT
  - Installed on saturated soil
  - Under complicated load from:
    - Wind
    - Wave
    - Ice
    - Ship Impacts
  - No well developed code in US
    - Some for large multi-pile structures and other offshore structures
    - Can result in an over designed system
    - Increasing cost of a part of the system that is already 13% of the cost of the whole system
  - Can fail from vertical and/or lateral directions
    - Vertical failures include: pile buckling and shear failure of the soil
    - Lateral failures include: pile bending and ultimate lateral resistance of the soil being exceeded

Offshore Wind Turbine: Background cont.

- For OWT soil-foundation interactions (SFI) is important in predicting fail
- There are several techniques
  - Elastic analysis, ultimate subgrade reaction, elastic subgrade, and p-y curve
  - May result in erroneous response due to
    - Stiffness and damping received by static methods
    - As well as modeled as springs and dampers
  - Continuum technique can yield more accurate results due to formulation of stiffness and damping
- SFI are important because
  - Lateral cyclic loads affect foundation in lateral and axial directions
  - Need for fatigue life studies, foundation be permanently rotate, and scouring effects

Offshore Wind Turbine: Methodology

- Resonance of OWT is important due to continuously applied cyclic loads
  - Rotation of the turbine
  - Wave loading
  - Ocean Currents
  - Wind
- A linear modal analysis will be performed to get the frequencies of tower-foundation modes
- Due to resonance issues with some soil-foundation interaction models the continuum approach is used
  - To reduce the computational cost of the model
    - Dampers are applied to the boundary of the continuum
    - Only the foundation, tower and soil are considered elastic
    - The turbine blades are assumed to rigid and balanced removing the need for rotating bodies

Offshore Wind Turbine: Methodology cont.

- The dampers are defined to absorb the stress waves that propagate through the soil

$$C_{\perp} = \rho V_c A, \qquad C_{\parallel} = \rho V_s A$$

Where A is the tributary area of the surface node, V_c is the compressive wave velocity, and V_s is the shear wave velocity

- The stress wave velocities are calculated using the material properties of the soil:

$$V_c = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}}, \qquad V_s = \sqrt{\frac{E}{2\rho(1+\mu)}}$$

- The interaction between the soil continuum and the foundation is not “stuck”
  - Friction is applied using the friction angle approach

$$\nu = tan\left(\frac{2\phi}{3}\right)$$

Where ϕ is the friction angle, which is internal friction angle

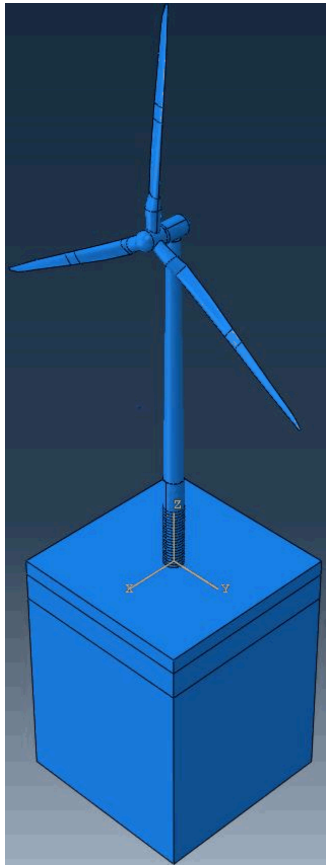
Offshore Wind Turbine: Case Study

- The NREL 5 MW reference OWT is modeled
- Aerodynamic loads calculated in CFD simulation and hydrodynamic loads from the Morison equation are applied to the model
- The Morison equation is given as:

$$F(t) = \frac{\pi}{4}\rho C_m D^2 \dot{u} + \frac{1}{2}\rho C_D D u|u|$$

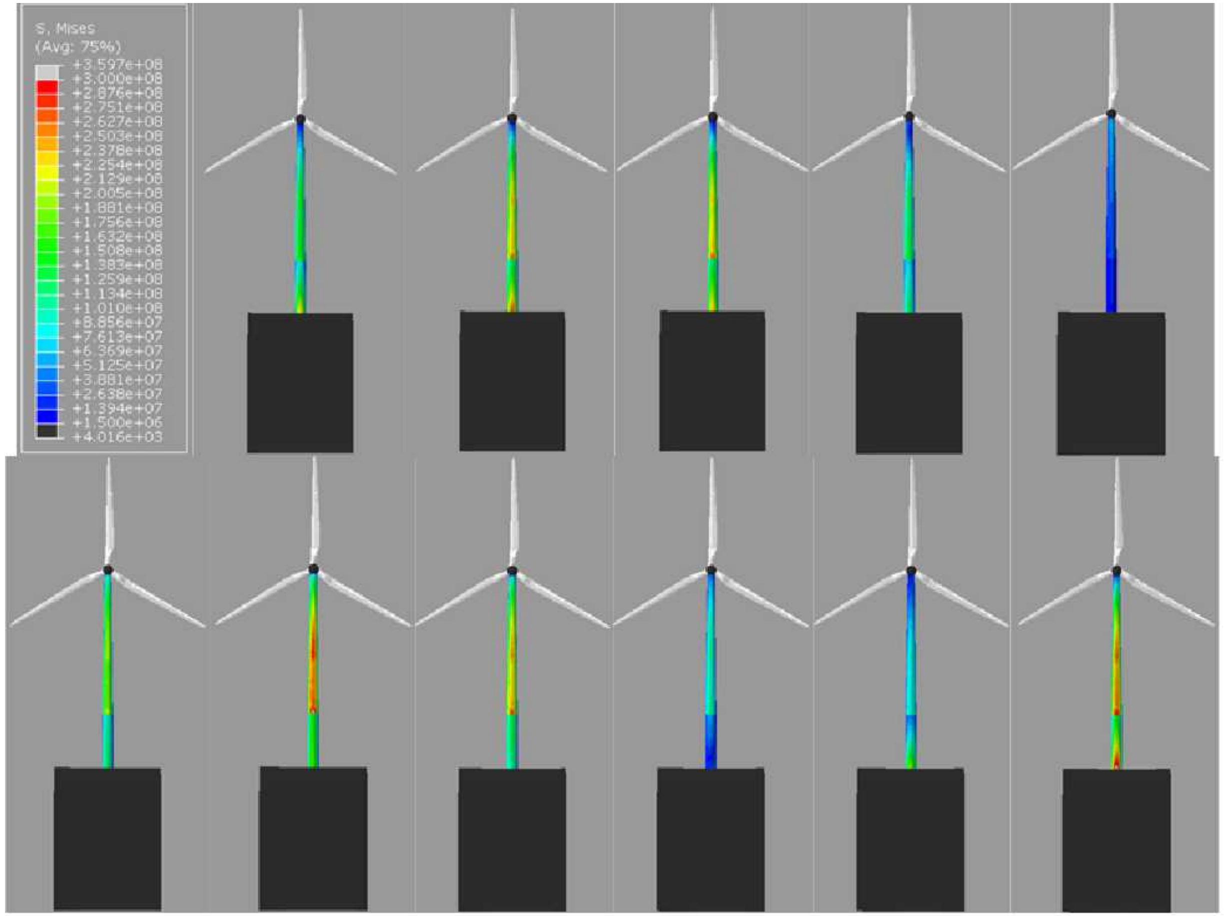
Where C_m is the inertia coefficient (2 for the purpose of this study), D is the diameter of the foundation, u is the time varying speed of the wave, overdot denotes the first time derivative, and C_D is the drag coefficient (0.744 for flow perpendicular to a circular cross section).

- The Morison equation is force per meter and is applied in a line on the surface facing the fluid flow



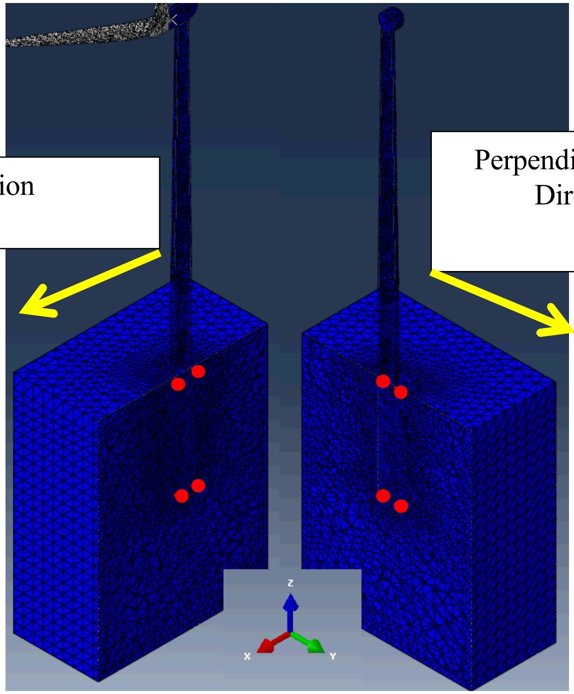
Offshore Wind Turbine: Case Study cont.

- Mises Stress for 5 seconds
- Starting at 10 seconds
- Every 0.5 seconds



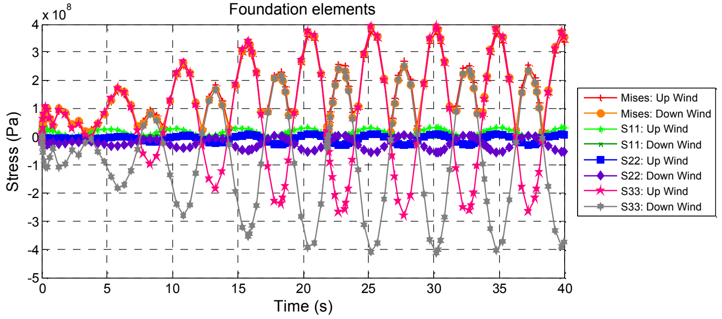
Offshore Wind Turbine: Case Study cont.

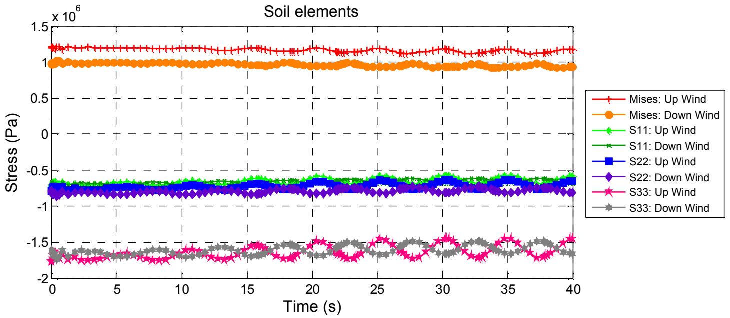
- Time histories of the principal and Mises Stresses of the foundation and soil

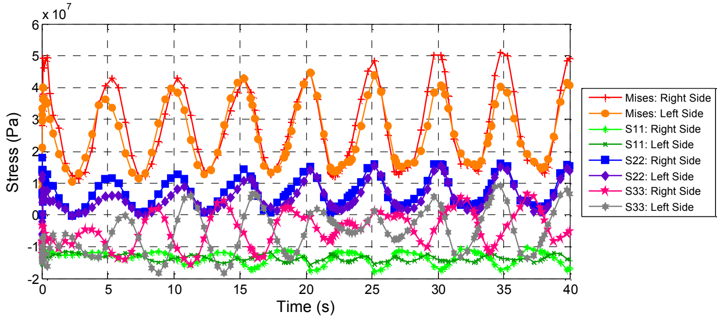


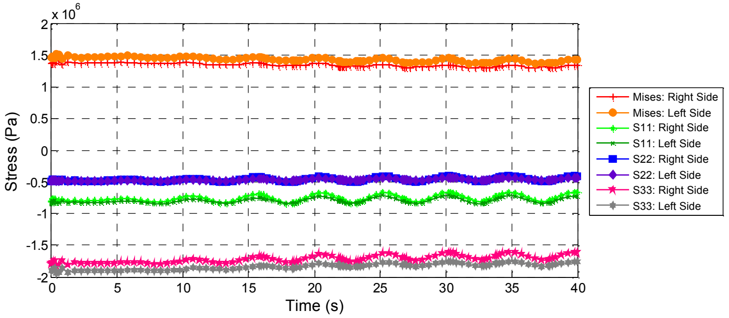
Wind Direction

Perpendicular Flow Direction









Damage Detection: Background

- Structural health monitoring is a focus in the engineering community for the last few decades
- Various studies has made use of vibrations to detect damage because stiffness and mass are contained in the calculation of the vibration problems
  - The advantage of using vibrations is that it is a non-destructive method
  - The disadvantage to current techniques is that they require precise models or fine measurement grids
- Failure of electrical cables are of interest to the vehicle and aeronautic industries
  - Loss of signal quality and signal are of concern
- Currently not many researchers are focused on damage of electrical cables
  - Most are focused on fretting corrosion of pins
  - There is a study on electrical components under earthquake loading
- None of the studies look at the housing of the electrical connector
  - The cyclic loading on the connector causes fatigue on the pin solder
  - When cable is 90^o to the connector even higher stress can be seen

Damage Detection: Methodology

- Effective mass is proposed
- It interpolates the modal reaction force at the boundary
- Characteristics:
  - Directional dependent
  - Summing all effective mass gives the mass of the structure
  - Unique for each mode in each direction
- The direction dependence requires the effective mass to be calculated in each direction to receive the whole picture
  - This can be used as an advantage because damage may not show up in one direction or another
- There are two ways to calculate the effective mass
  - Place force cells in between the specimen and the boundary condition at each attachment location
  - Constrain fixture modes to contain only rigid body modes in the desired direction and calculate the pseudo-participation factor

Damage Detection: Methodology cont.

- To perform an effective mass calculation

1. Perform “free-free” modal testing on fixture
2. Attached structure and perform modal analysis again
3. Mass normalize the mode shapes
4. Constrain system to have one rigid body mode
    1. Take pseudo-inverse of modes to be constrained
    2. Multiply the pseudo-inverse by the system modes
    3. Find null matrix of the product
    4. Recalculate Eigen-solution of
    5. Get fixed base modes by multiply $L\Gamma$, where Γ is the Eigen-vector of the previous sub-step

$$\Psi = \phi * diag(\sqrt{\left(diag(\phi^T M\phi)\right)^{-1}}$$

$$B^+ = (B^*B)^{-1}B$$

$$L = null(\Theta_c^+\Psi_c)$$

$$L^T\begin{bmatrix} \backslash & & \\ & \omega_n^2 & \\ & & \backslash \end{bmatrix}L\{q_L\} - \omega^2 L^T[I]L\{q_l\} = 0$$

$$\Psi_{fixed} = \Psi_c L\Gamma$$

Damage Detection: Methodology cont.

- To perform an effective mass calculation

5. Calculate the Pseudo-Modal Participation Factor
    1. Grab the parts of the vector that only have to do with the motion of the fixture, ignore any measurements on the test article
    2. The rest of the $pmpf$ are associated with the modes of the fixture
6. Constrain last rigid body mode
7. Calculate Participation Factor
8. Calculate the effective mass

$$pmpf = \Phi^T M \Psi^k$$

$$pmpf(1) = m_{TA} \Psi_B^1$$

$$pmpf(k) = -M_B \sum_{Bi=1}^{n} \Psi_{Bi}^k / n = -M_B \Psi_B^k$$

$$P_k = \Phi^T M \, \Psi_{fixed}^k / mm_k$$

$$\rightarrow P_k = pmpf * L \, \Gamma / mm_k$$

$$m_{eff,k} = P_k^2 mm_k$$

Damage Detection: Methodology cont.

- Now that the Effective mass is calculated how will this information be used?
- An energy method using FRFs has been used
  - However for lightly damped structures the area under a peak may over shadow other modes
- The effective mass method separates the modes into a series of single degree of freedom systems, representing each mode
- The damage index is calculated by
  - Calculating the average energy over one cycle
  - Sum the average energy in one direction
  - Compare to a know “healthy” measurement

$$E = m_{eff}\frac{x_o^2\omega_n^2 + v_o^2}{2}$$

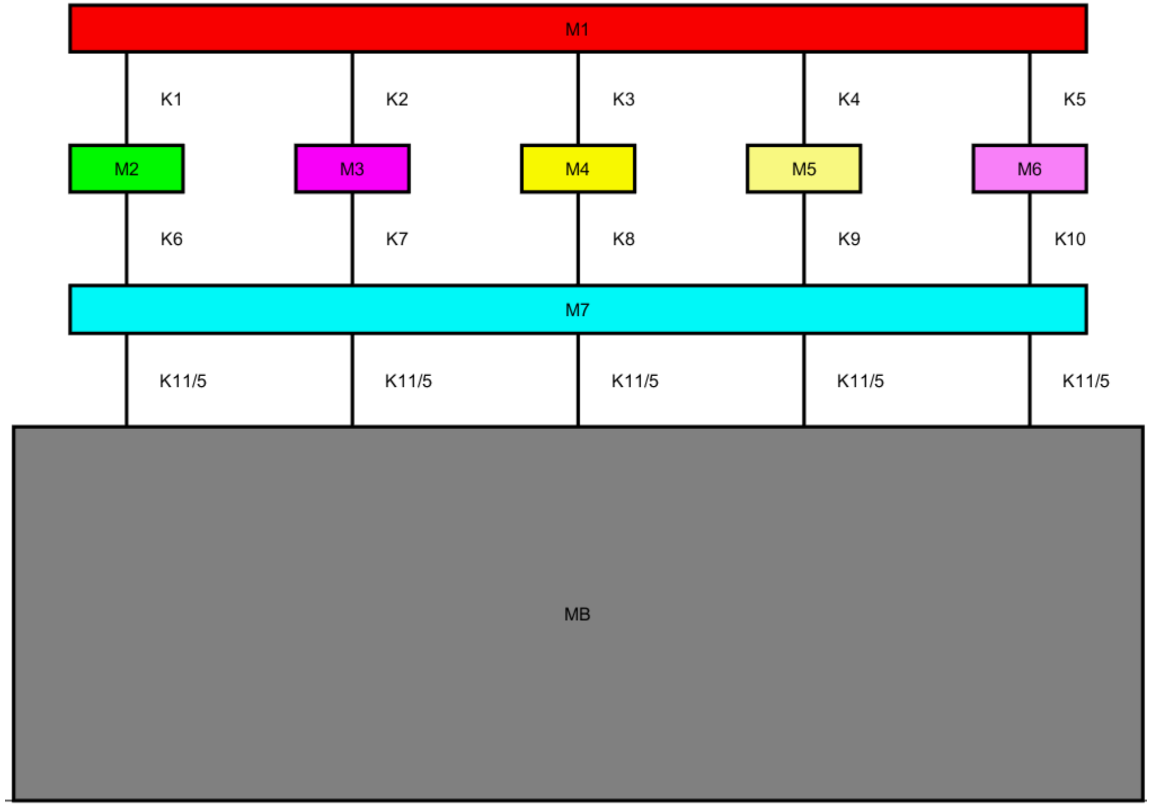
- The energy of certain modes maybe larger than others
  - Weighting function maybe useful to have all energy of the modes used have same order

$$E_{weight} = E_{ave} * 10^{ORD} \qquad ORD = \frac{\left\|\log\left(\max(E_{ave})\right) * 2\right\|}{2} - \frac{\|\log(E_{avei}) * 2\|}{2}$$

Damage Detection: Case Studies

- Simple Case
  - The mass of M1 and M7 are 10 kg,
  - M2 through M6 are 2 kg, and MB is 900 kg
  - Stiffness of K1 through K10 are 100 N/m
  - K11 is 500 N/m

Case	Item Changed	Change
Healthy	None	Healthy
1	M3	50% Reduction
2	M4	50% Reduction
3	M5	50% Reduction
4	M6	50% Reduction
5	Springs touching M3	50% Reduction
6	Springs touching M4	50% Reduction
7	M3 and springs	99% Reduction
8	M4 and spring	99% Reduction
9	Boundary spring	50% Reduction



Damage Detection: Case Studies cont.

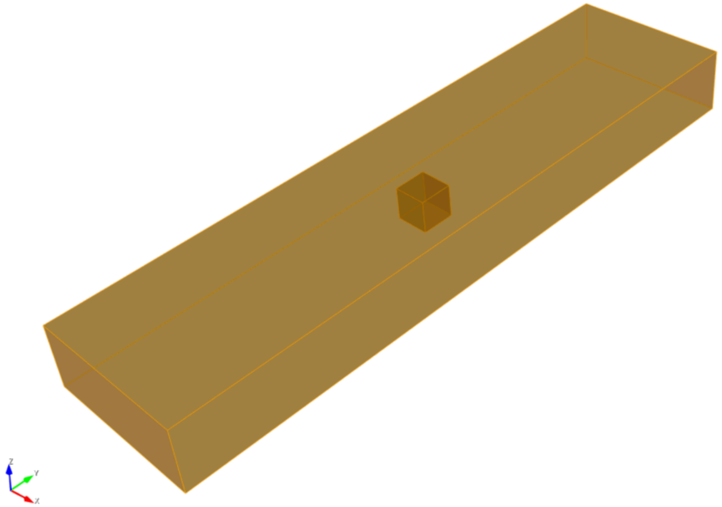
Case	Item Changed	Change
Healthy	None	Healthy
1	M3	50% Reduction
2	M4	50% Reduction
3	M5	50% Reduction
4	M6	50% Reduction
5	Springs touching M3	50% Reduction
6	Springs touching M4	50% Reduction
7	M3 and springs	99% Reduction
8	M4 and spring	99% Reduction
9	Boundary spring	50% Reduction

Relative Effective Mass

Case	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7
Healthy	91.4080%	7.4877%	0.0000%	0.0000%	0.0000%	0.0000%	1.1044%
1	91.0183%	7.7952%	0.0000%	0.0000%	0.0000%	1.0074%	0.1791%
2	91.0183%	7.7952%	0.0000%	0.0000%	0.0000%	1.0074%	0.1791%
3	91.0183%	7.7952%	0.0000%	0.0000%	0.0000%	1.0074%	0.1791%
4	91.0183%	7.7952%	0.0000%	0.0000%	0.0000%	1.0074%	0.1791%
5	90.2159%	0.0586%	8.5345%	0.0000%	0.0000%	0.0000%	1.1911%
6	90.2159%	0.0586%	8.5345%	0.0000%	0.0000%	0.0000%	1.1911%
7	87.8530%	10.9053%	0.0000%	0.0000%	0.0000%	0.0000%	1.2417%
8	87.8530%	10.9053%	0.0000%	0.0000%	0.0000%	0.0000%	1.2417%
9	96.8472%	2.9436%	0.0000%	0.0000%	0.0000%	0.0000%	0.2092%

Case	Weighted Energy	Damage Index
Healthy	13.4468	--
1	13.8484	2.987
2	13.8484	2.987
3	13.8484	2.987
4	13.8484	2.987
5	11.9273	11.300
6	11.9273	11.300
7	185.9267	1282.684
8	195.9267	1282.684
9	5.8315	56.633

Damage Detection: Case Studies cont.



Case	Size of Void Cube (m)	Location of Void Center (m)
1	0.05	0.000, 0.000, 0.000
2	0.05	0.000, 0.100,0.000
3	0.05	0.000, 0.250, 0.000
4	0.05	0.000, 0.400, 0.000
5	0.05	0.000, -0.250, 0.000
6	0.05	0.075, 0.000, 0.000
7	0.05	0.075, 0.100, 0.000
8	0.05	0.075, 0.250, 0.000
9	0.05	0.075, 0.400, 0.000
10	0.025	0.000, 0.000, 0.000
11	0.025	0.000, 0.100, 0.000
12	0.025	0.000, 0.250, 0.000
13	0.025	0.000, 0.400, 0.000
14	0.025	0.075, 0.000, 0.000
15	0.025	0.075, 0.250, 0.000
16	0.025	0.075, 0.400, 0.000
17	0.025	0.000, 0.000, 0.025
18	0.025	0.000, 0.250, 0.025
19	0.025	0.000, 0.400, 0.025
20	0.025	0.075, 0.000, 0.025
21	0.025	0.075, 0.250, 0.025
22	0.025	0.075, 0.400, 0.025
23	0.025	0.000, 0.000, -0.025
24	0.025	0.000, 0.250, -0.025
25	0.025	0.000, 0.400, -0.025
26	0.025	0.075, 0.000, -0.025
27	0.025	0.075, 0.250, -0.025
28	0.025	0.075, 0.400, -0.025

Case	Damage Index	Case	Damage Index
1	22.54	15	12.99
2	30.15	16	13.27
3	14.72	17	5.95
4	26.01	18	2.39
5	14.72	19	1.74
6	9.19	20	7.96
7	8.40	21	9.84
8	9.73	22	2.11
9	36.70	23	10.54
10	7.26	24	6.38
11	8.64	25	6.56
12	14.07	26	10.02
13	13.66	27	6.73
14	7.47	28	7.87

Work Plan and Timeline

OFFSHORE WIND TURBINE

- Run the tower under full computational fluid dynamic loads
  - Compare results to simplified models
- Model and Simulate tower in NREL Fast
  - Use only aero-hydrodynamic loads
  - Expand study to include other loads as well
- Study model with nonlinear soil properties
  - Compare results from Abaqus and Fast
  - Compare results to linear models

Task\Month	1	2	3	4	5	6	7	8	9	10	11	12	13
OWT 1	🟧	🟧											
OWT 2		🟧	🟧	🟧									
OWT 3				🟧	🟧	🟧	🟧	🟧	🟧	🟧			
DD 1.1	🟨	🟨											
DD 1.2		🟨	🟨	🟨	🟨								
DD 1.3		🟨	🟨	🟨	🟨								
DD 1.4					🟨	🟨	🟨	🟨	🟨	🟨			
DD 1.5										🟨			
DD 2							🟨	🟨	🟨	🟨	🟨	🟨	🟨

Damage detection of Electrical Cables and Wind Turbine Towers

Damage detection of electrical cables

- A 3D Finite Element model of the cable-connector-fixture assembly will be created
  - The fixture will be impacted at the same locations as the real structure
  - Effective mass calculations will be performed on this data
  - Volumes of lower density and stiffness will then be placed at different locations in the model one at a time and Steps a-c will be repeated
  - The effective masses will then be studied to determine if a void exists
- Five “nominal” connectors will then be manufactured and tested to determine the variation band for “nominal” connectors
- Five “damaged” connectors will then be tested and the effective mass will be determined
- The effective mass will then be compared to the “nominal” data and studied for changes to detect the voids.

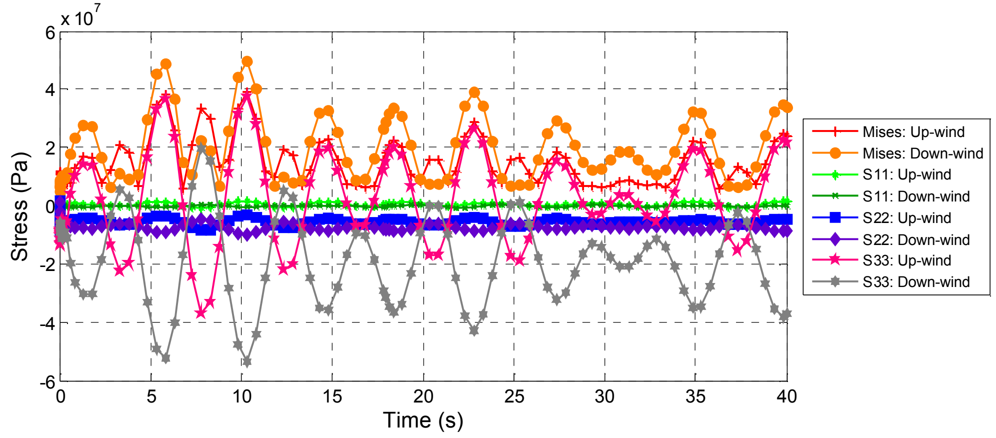
Damage detection of wind turbine tower

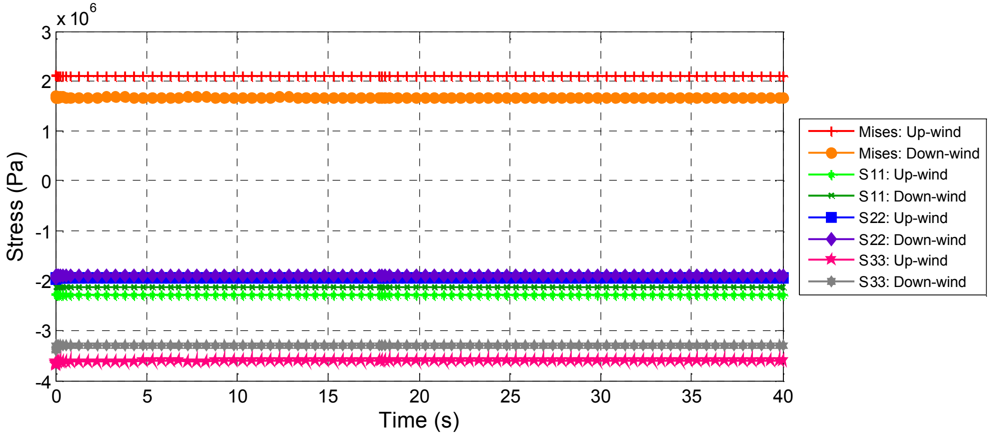
- Simplify model to be one section and fixed boundary
- Create different case studies to determine the minimum damage that can be detected
- Expand study to whole model of tower
- Use experimental data to determine if loosened bolts in the actual tower can be determined

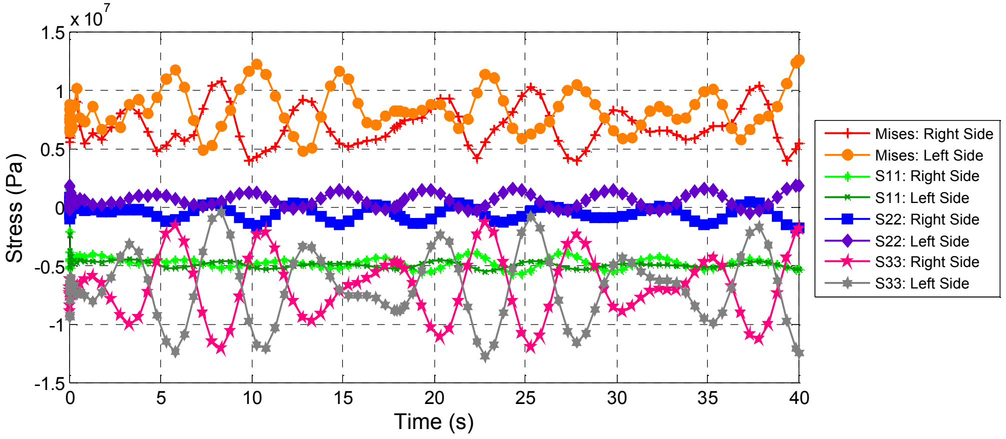
Questions?

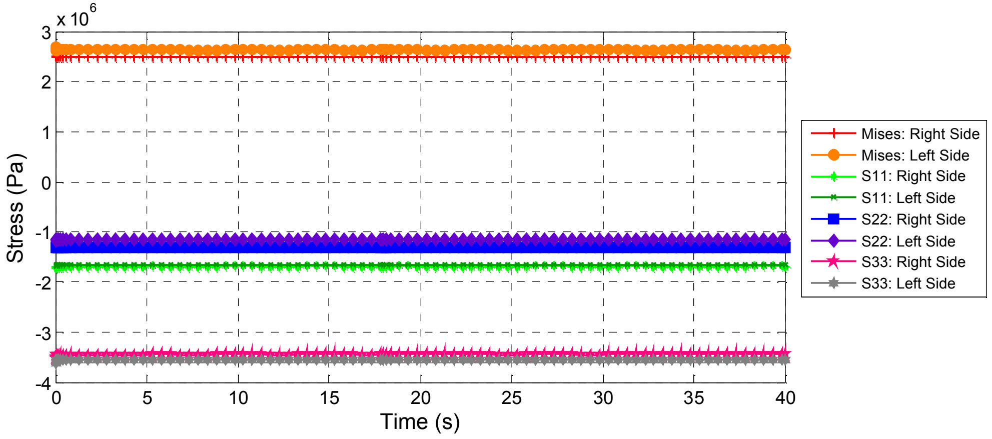
Additional slides

OWT under CFD wave load

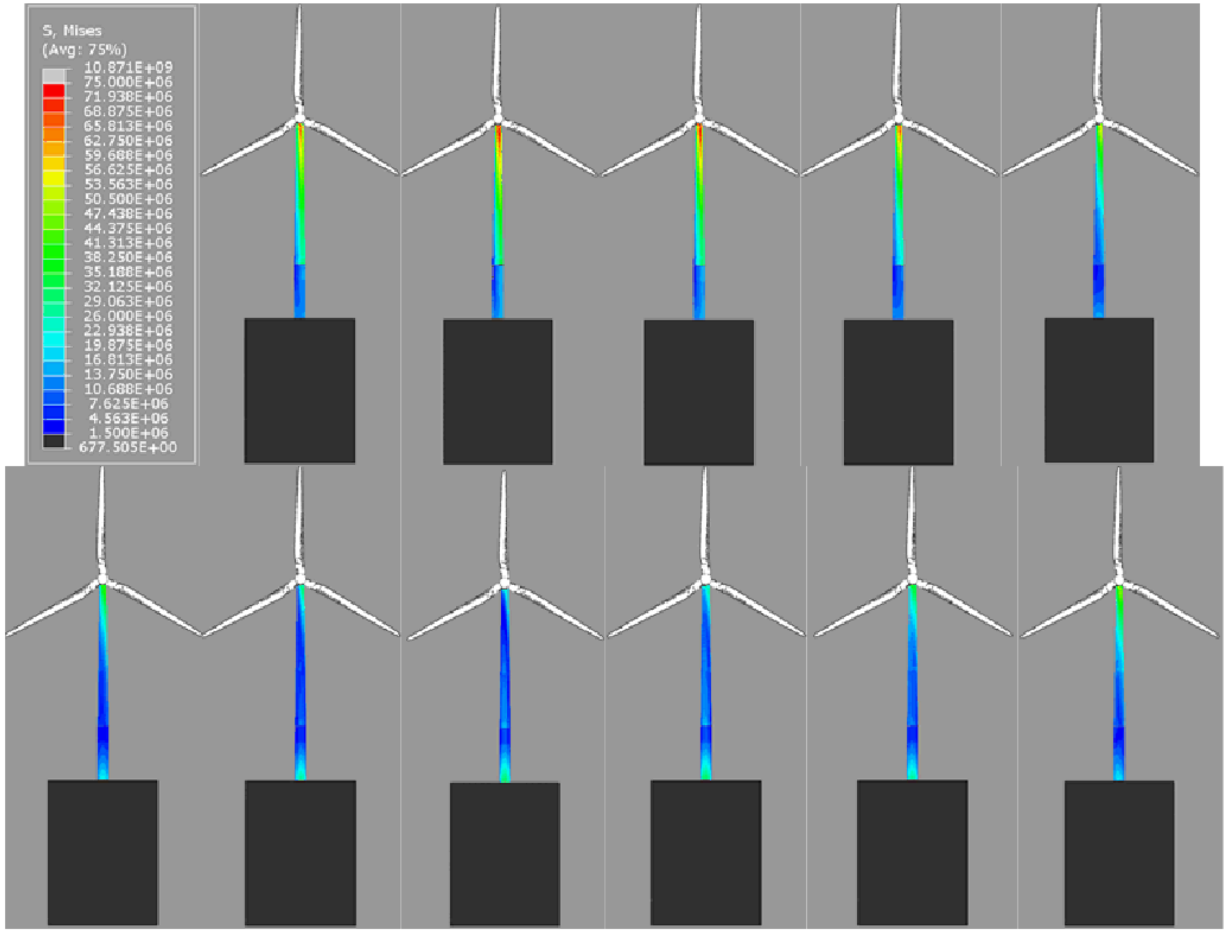




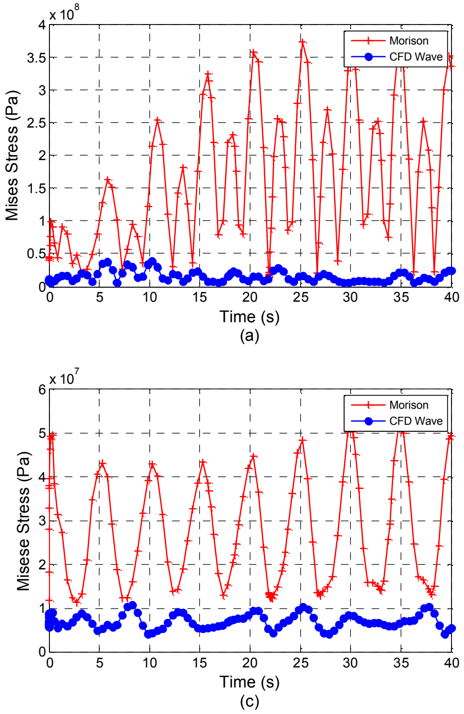




OWT under CFD wave load



OWT method comparison

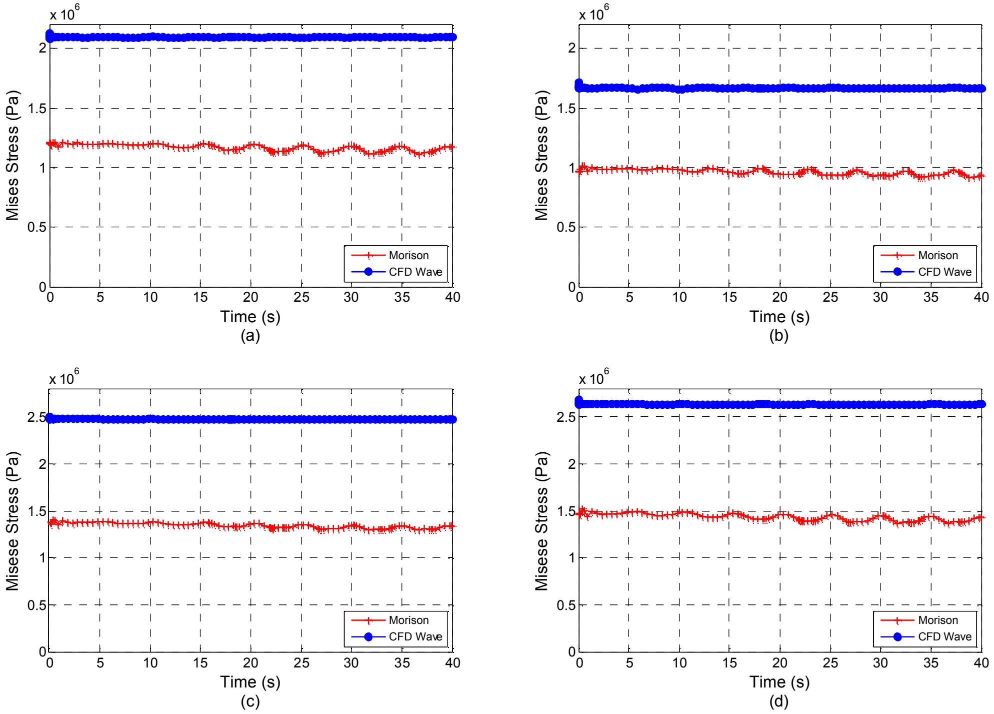


(a)

(b)

(c)

(d)



(a)

(b)

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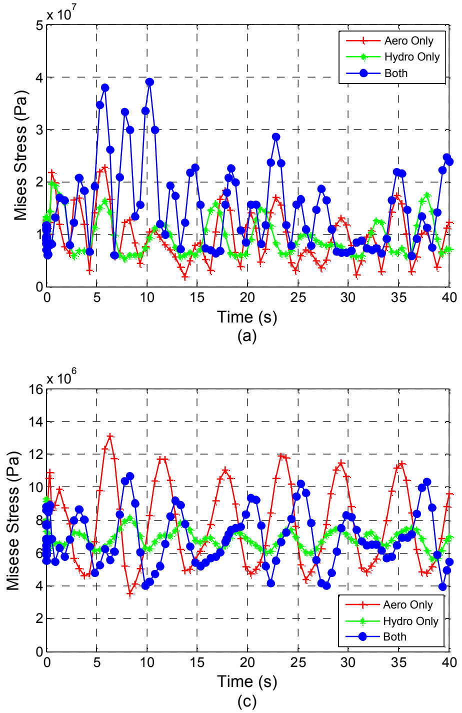
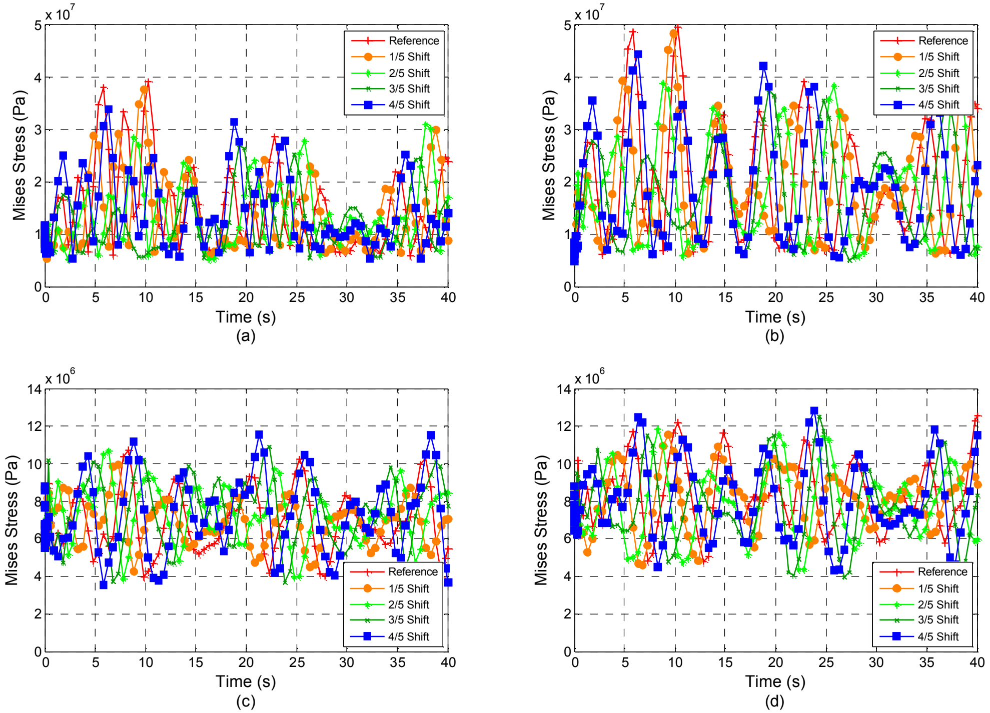
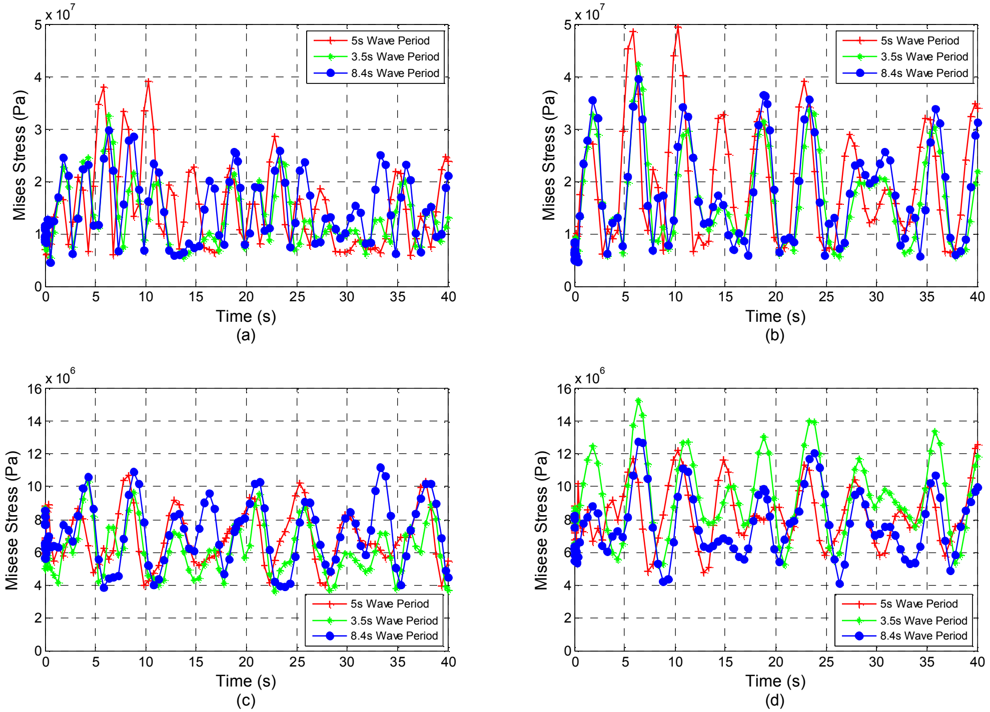
OWT other studies

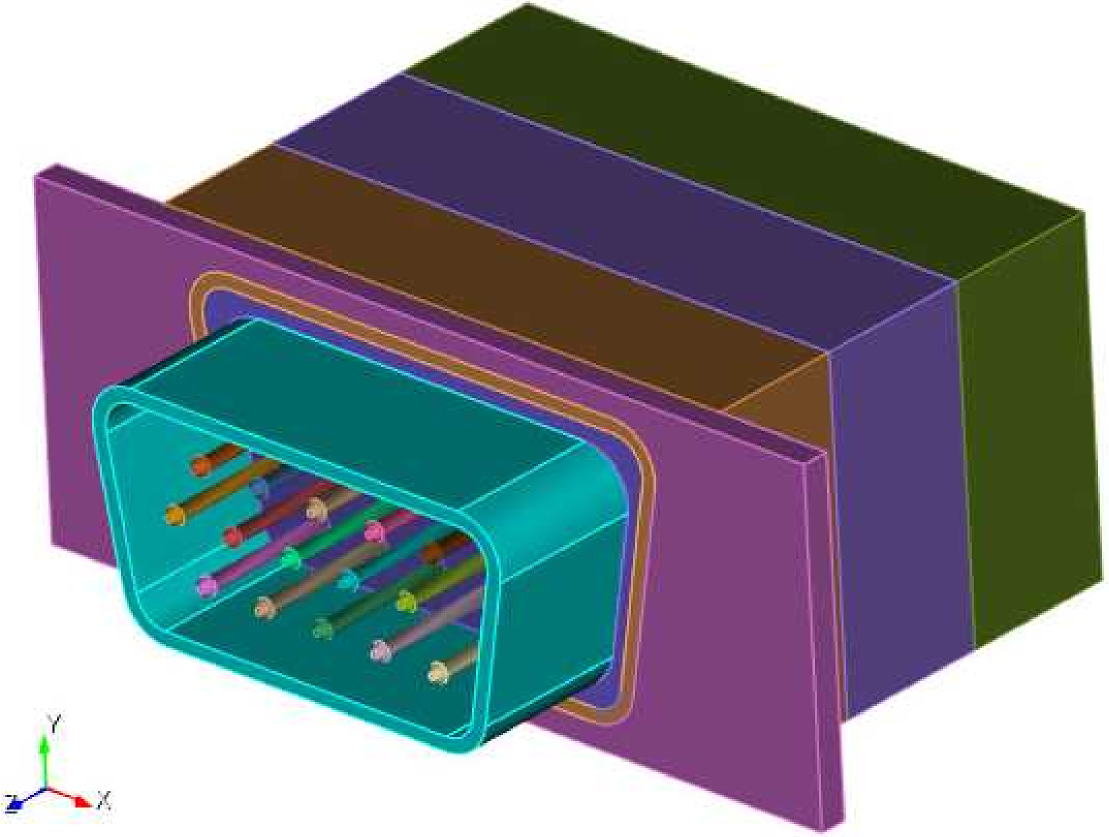




OWT other studies



Damage Detection VGA



Case	Location of Void Center (m)			Comment	Damage Index
1	-0.0003	0	-0.0094		2.44
1B	-0.0003	0	-0.0094	Acrylic and ABS 1 GPA Softer	110.06
1C	-0.0003	0	-0.0094	Acrylic and ABS 0.2 GPA Softer	18.27
1D	-0.0003	0	-0.0094	Acrylic and ABS 1% Softer	3.84
2	-0.001	0	-0.0094		4.93
3	-0.0025	0	-0.0094		34.96
4	-0.005	0	-0.0094		2.53
5	-0.008	0	-0.0094		202.05
6	-0.0003	0.002	-0.0094		2.97
7	-0.001	0.002	-0.0094		34.92
8	-0.0025	0.002	-0.0094		35.03
9	-0.0003	0	-0.008		1.95
10	-0.001	0	-0.008		34.80
11	-0.0025	0	-0.008		34.87
12	-0.0003	0.002	-0.008		5.51
13	-0.001	0.002	-0.008		34.94
14	-0.0025	0.002	-0.008		35.11
15	-0.0003	0	-0.0109		2.62
16	-0.001	0	-0.0109		6.78
17	-0.0025	0	-0.0109		35.86
18	-0.005	0	-0.0109		4.22
19	-0.008	0	-0.0109		35.14
20	-0.0003	0.002	-0.0109		3.15
21	-0.001	0.002	-0.0109		35.81
22	-0.0025	0.002	-0.0109		35.99
23	-0.0003	0	-0.013		173.49
24	-0.001	0	-0.013		173.35
25	-0.0025	0	-0.013		173.66
26	-0.005	0	-0.013		173.32
27	-0.008	0	-0.013		173.08
28	-0.0003	0.002	-0.013		174.00
29	-0.001	0.002	-0.013		173.73
30	-0.0025	0.002	-0.013		173.93
31	-0.0003	0	-0.015		173.18
32	-0.001	0	-0.015		173.44
33	-0.0025	0	-0.015		173.69