Algorithm for Damage Detection in Wind Turbine Blades using a Hybrid Dense Sensor Network with Feature Level Data Fusion

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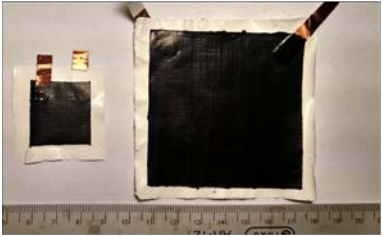
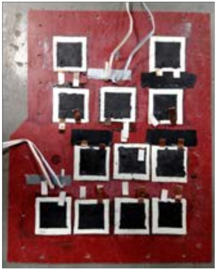
IOWA STATE UNIVERSITY

Hybrid Dense Sensor Network for Damage Detection on Wind Turbine Blades

Soft Elastomeric Capacitor (SEC)
Fiber Bragg Grating (FBG)
Resistive Strain Gauge (RSG)



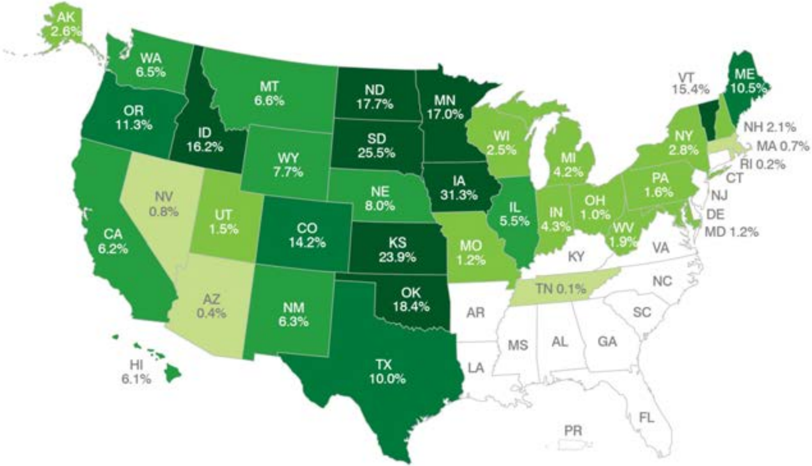


Overview

Contents

Failure of a 49 meter wind turbine blade wind-watch

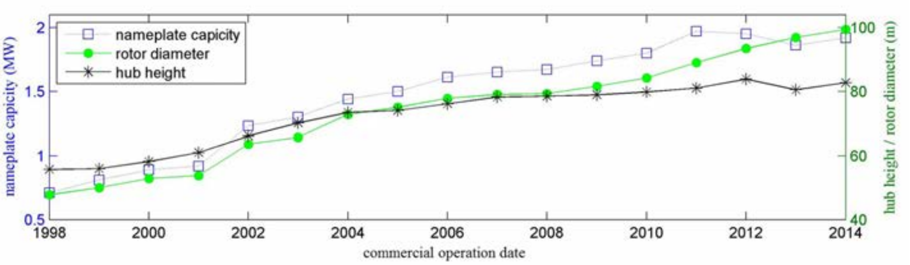
Center for wind



US wind energy share of electricity generation during 2015 iowa.gov

Motivation

- In 2015 the United States was the world's number one producer of wind energy.
- In total, domestic wind energy provided 181.79 terawatt-hours or 5.1% of the nations end use electricity demand in 2015. NREL



Largest wind project (building)

FUTURE TENSE THE CITIZEN'S GUIDE TO THE FUTURE. SEPT. 1 2016 2:38 PM

FROM SLATE, NEW AMERICA, AND ASU

The Most Impressive State for Clean Energy

It's Iowa. Really!

By Daniel Gross

7.9k 190 112

Iowa has been one of the epicenters of America's wind boom.

DarcyMaulsby/Thinkstock

Wind XI will add 1000 2-megawatt machines. slate.com

Taller towers

MidAmerican building tallest land-based (US) wind turbine (115 meter hub height) Donnelle Eller

Bigger Blades

HOME > ONSHORE WIND > ENCERCON ADDS LOW-WIND TURBINES

Enercon adds low-wind turbines

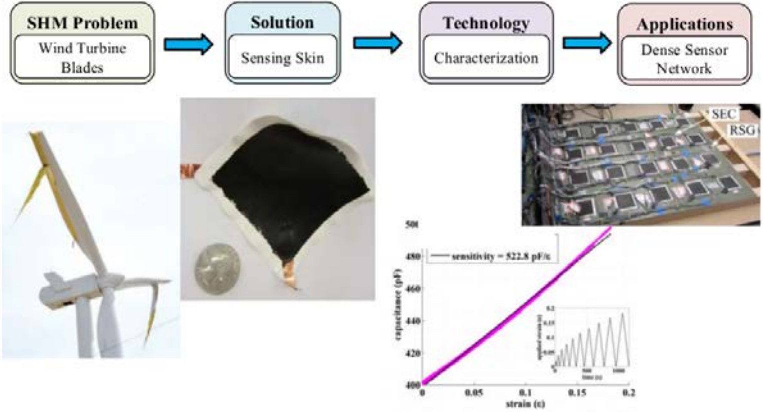
Enercon has introduced low-wind speed versions to its 4MW and 2MW onshore wind turbine platform.

Remote and Extreme Conditions

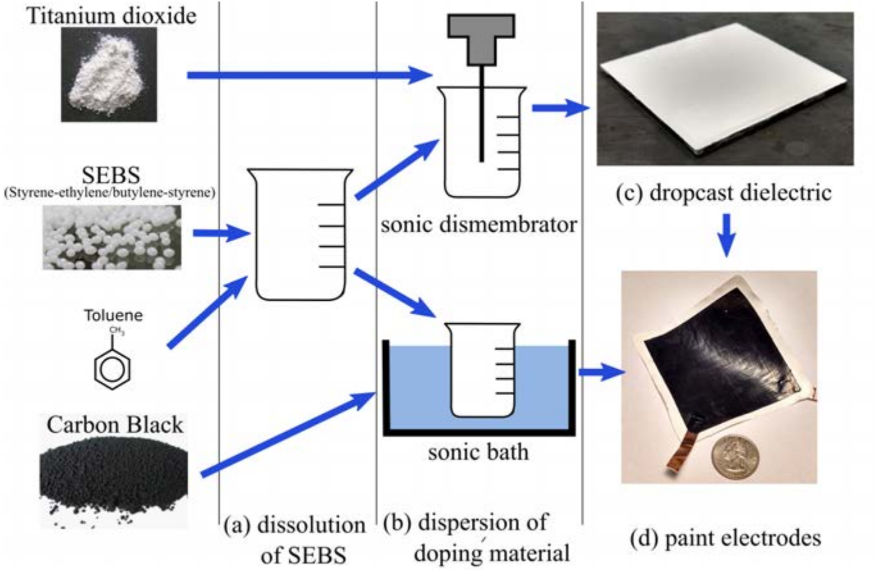
Blade installation in Kotezbue Alaska, used with permission KEA

Structural Health Monitoring of Wind Turbine Blades

Utilizing large area electronics for global coverage



Soft Elastomeric Capacitor (SEC)



SEC Model

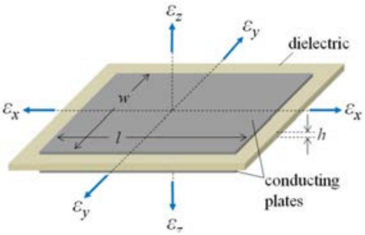
Parallel plate capacitor

$$\Delta C = \epsilon_r \epsilon_0 \frac{\Delta A}{t} \quad (1)$$

ϵ_r is the relative static permittivity and ϵ_0 is the dielectric constant. Using hooks law;

$$\frac{\Delta C}{C} = \lambda(\varepsilon_x + \varepsilon_y) \quad (2)$$

where ε_x is the strain in the x direction, ε_y is the strain in the y direction and λ is the sec's gauge factor ≈ 2 for mechanical excitation under < 15 hz



SEC sensor

Advantages of SEC for Mesosystem Monitoring

When arranged in an array the SEC's offer several advantages over current state-of-the-art strain sensors.

Accelerometers

- Measures strain results in direct and and simple signal processing
- Damage detection is simplified as the sensor measures discrete areas.

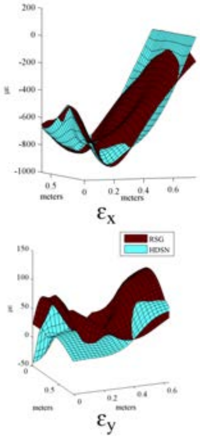
Resistive Strain Gauges

- Can be easily deployed over large surfaces.
- Capacitor-based strain gauges require a lower excitation energy.
- Easy manufacturing of complex 2D Shapes.

Unidirectional strain maps

Develop a bi-directional surface strain map:

- Assume a model.
- Build a shape function.
- Impose boundary conditions.
- Introduce sensor signals.
- Calculate function parameters via a least square estimation.



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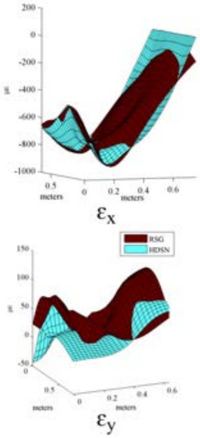
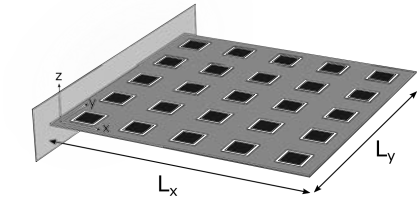


Selected models, shape function and the method of imposed boundary conditions vary from system to system.

Shape Function

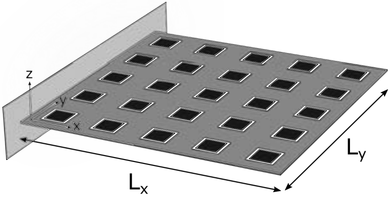


schematic representation of cantilever plate with SEC array

$$
\begin{array}{c}
a \\
x + y \\
x^2 + xy + y^2 \\
x^3 + x^2y + xy^2 + y^3 \\
x^4 + x^3y + x^2y^2 + xy^3 + y^4
\end{array}
$$

Pascals Triangle for displacement function

Shape Function



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\end{array}
$$

Pascals Triangle for displacement function

Kirchroff's theory of thin plates

$$\varepsilon_x(x, y) = -\frac{c}{2}\frac{\partial^2 z}{\partial x^2} = -\frac{c}{2}\left(2a_2 + 2a_5 y + 6a_6 x + 2a_9 y^2 + 6a_{10}xy + 12a_{11}x^2\right)$$

$$\varepsilon_y(x, y) = -\frac{c}{2}\frac{\partial^2 z}{\partial y^2} = -\frac{c}{2}\left(2a_3 + 2a_4 x + 6a_7 y + 6a_8 xy + 2a_9 x^2 + 12a_{12}y^2\right)$$

Unidirectional strain maps

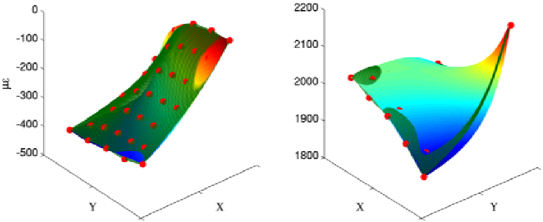
$$\hat{\varepsilon_x}(x,y) = \hat{b}_1 + \hat{b}_2 x + \hat{b}_3 y + \hat{b}_4 x^2 + \hat{b}_5 xy + \hat{b}_6 y^2$$
$$\hat{\varepsilon_y}(x,y) = \hat{b}_7 + \hat{b}_8 x + \hat{b}_9 y + \hat{b}_{10} x^2 + \hat{b}_{11} xy + \hat{b}_{12} y^2$$

Unidirectional strain maps

$$\hat{\varepsilon_x}(x,y) = \hat{b}_1 + \hat{b}_2 x + \hat{b}_3 y + \hat{b}_4 x^2 + \hat{b}_5 xy + \hat{b}_6 y^2$$
$$\hat{\varepsilon_y}(x,y) = \hat{b}_7 + \hat{b}_8 x + \hat{b}_9 y + \hat{b}_{10} x^2 + \hat{b}_{11} xy + \hat{b}_{12} y^2$$

solve for b using least squares estimator (LSE):

$$\hat{\mathbf{B}} = \frac{1}{\lambda}(\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{S}$$

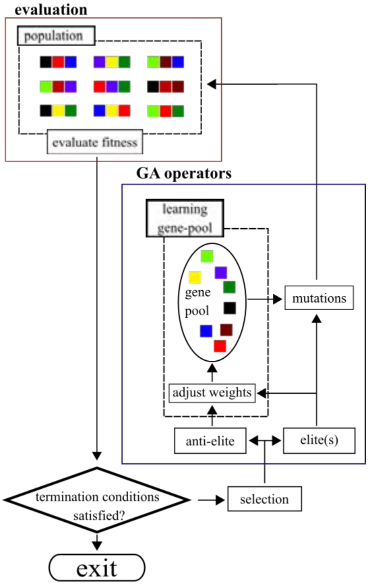


Unidirectional strain maps, ε_x and ε_y.

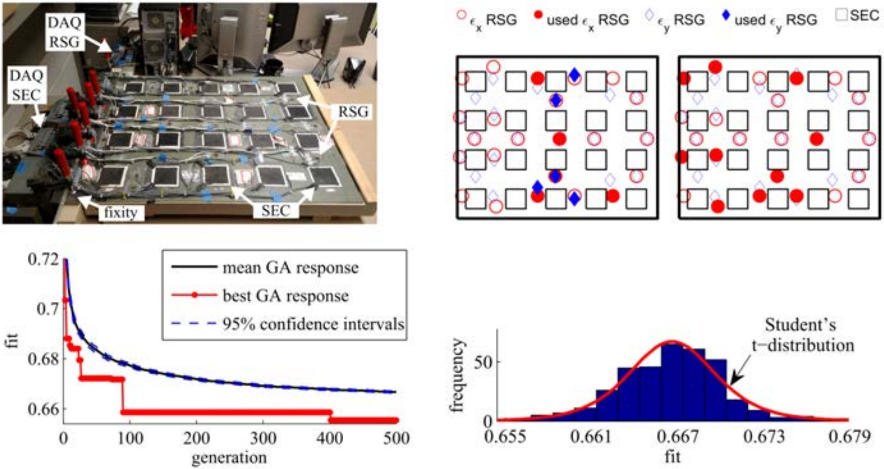
Adaptive Genetic Algorithm for Optimal Sensor Placement

Optimal placement of RSG sensors:

- Not all potential sensor locations contain the same level of information.
- Learning gene pool teaches subsequent generations.
- Finds key locations needed for unidirectional strain inputs.



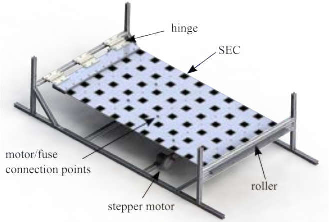
Generational improvements



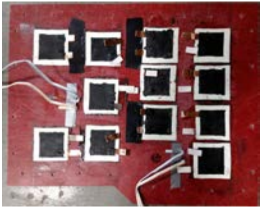
Generational improvement archived on a 20 SEC HDSN

Hybrid Dense Sensor Networks (HDSN)

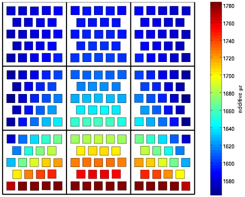
HDSN: 20-SEC, 46-RGSs. Austin Downey



HDSN: 40-SEC, 10-RGSs Austin Downey



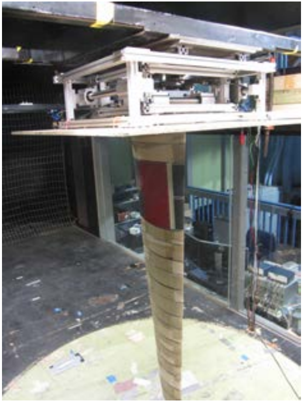
HDSN: 12-SEC, 8-RGSs. Austin Downey



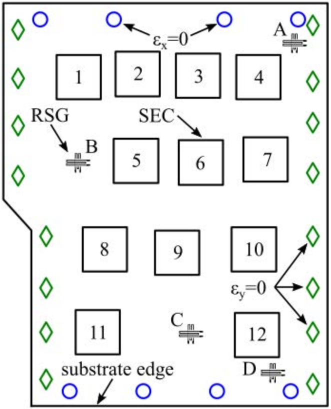
HDSN: 276-SECs and 140-FBG nodes. Austin Downey

Wind Tunnel Testing

Wind Tunnel Testing

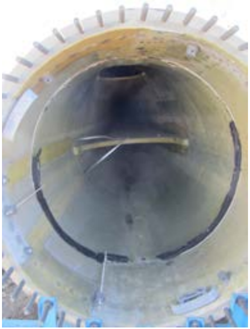


Strain Maps



Implementation

1. Deployable inside wind turbine blades.
2. Retrofit or OEM.
3. Useful for other large structures, e.g. buildings, bridges, aircraft.

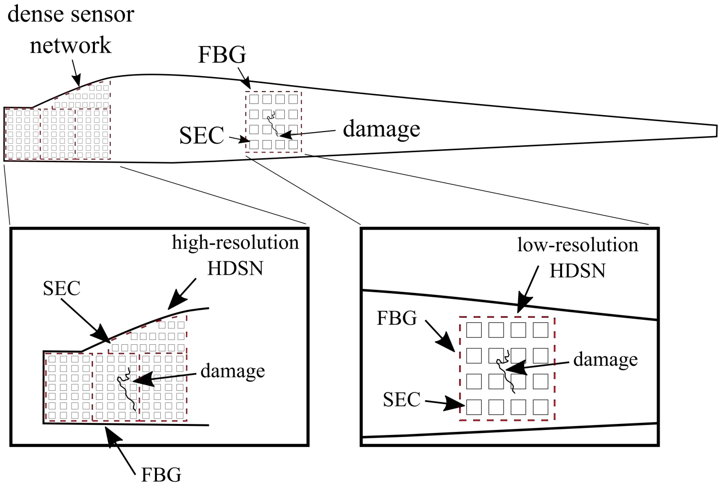


Inside a 45 meter GE blade Austin Downey

Damage Cases

Typical damage cases: 1) through crack; 2-3) edge split; 4) impact. Austin Downey

Deploying Hybrid Dense Sensor Networks

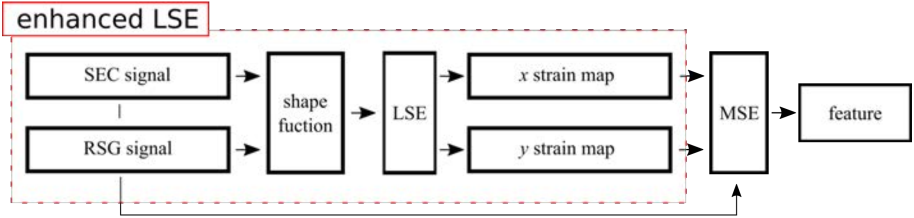


Subdividing a wind turbine blade's complex geometry into independent sections of different resolutions

Damage detection and localization through a Network Reconstruction Feature (NeRF)

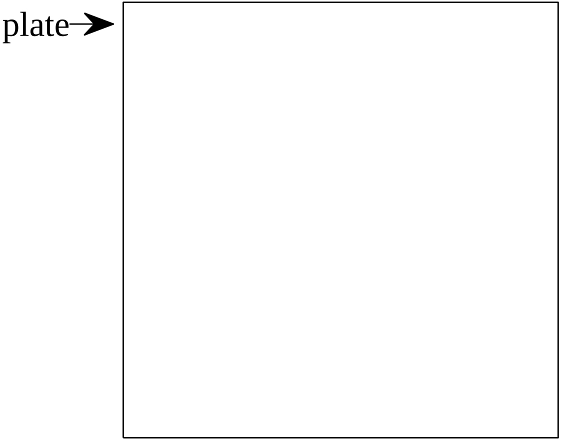
Damage detection and localization through a Network Reconstruction Feature (NeRF)

1. Data fusion of the additive SEC signal and unidirectional FBG signal.
2. Distinguish healthy states form possibly damaged states.
3. Capable of damage detection, quantification and localization.
4. Can function without historical data set or external models.



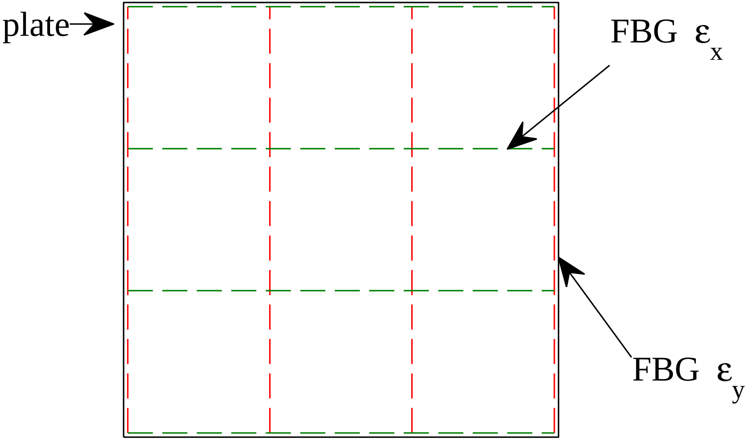
Extract damage features based on the fit of a shape function

Building a HDSN



Deploying HDSN of SECs and FBG onto a plate.

Building a HDSN



Deploying HDSN of SECs and FBG onto a plate.

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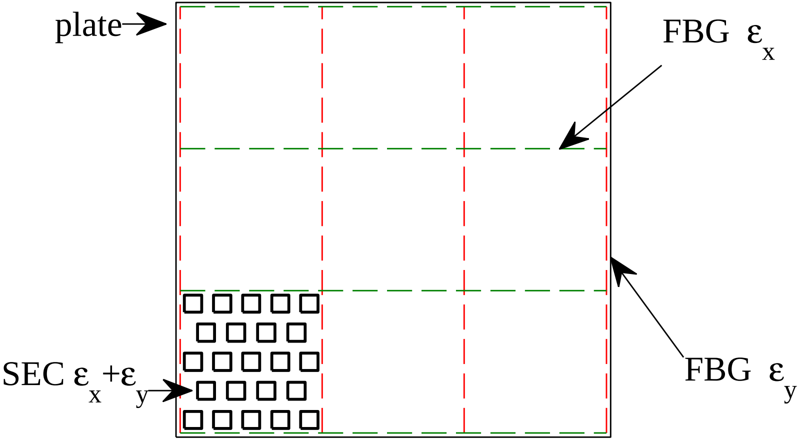
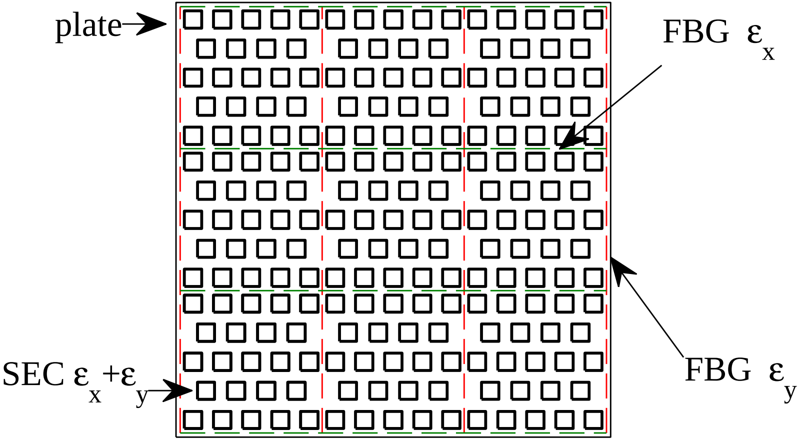


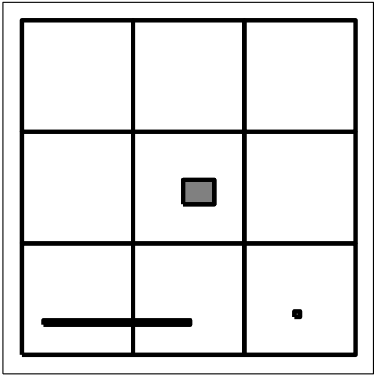
Deploying HDSN of SECs and FBG onto a plate.

Building a HDSN



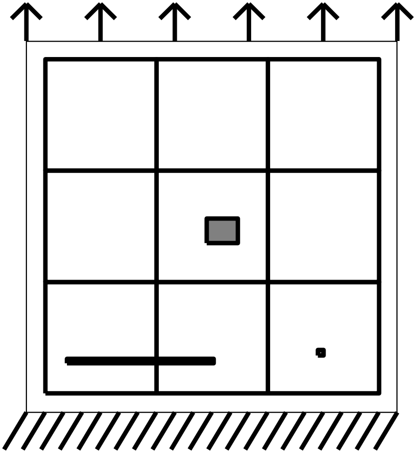
Deploying HDSN of SECs and FBG onto a plate.

Damage Cases



Cantilever plate with damage induced as reduction of stiffness.

Damage Cases



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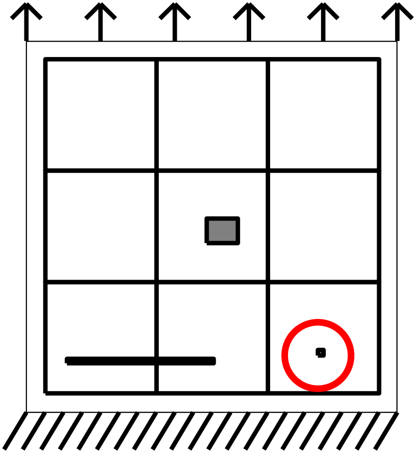
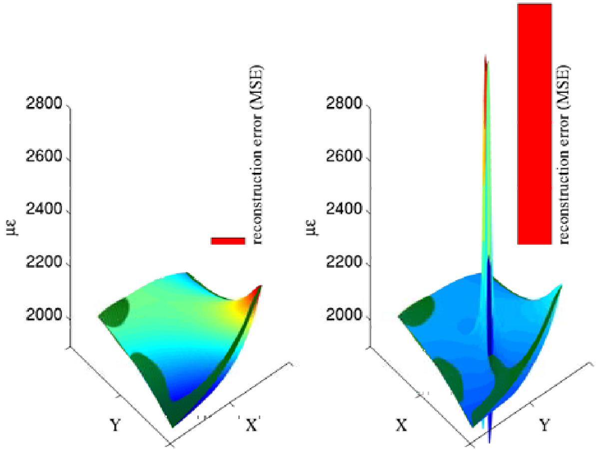


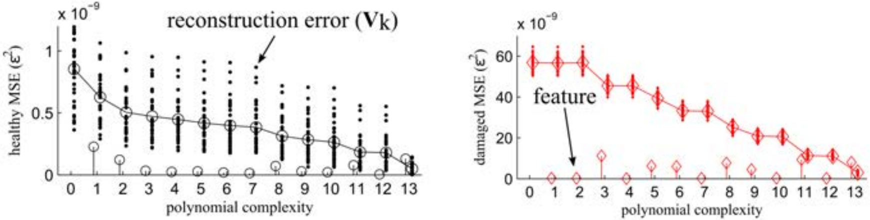
Cantilever plate with damage induced as reduction of stiffness.

Error Detection



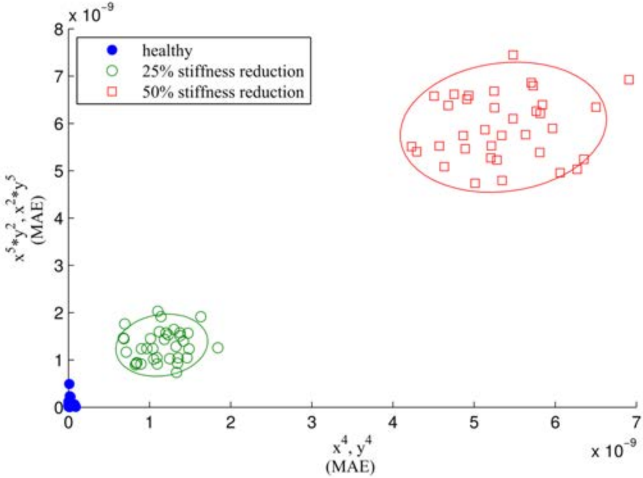
Error in strain map reconstitution measures at sensor locations.

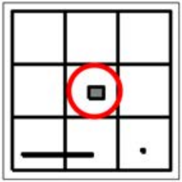
Feature Extraction



Features extracted from change in fit with increasing shape function complexity

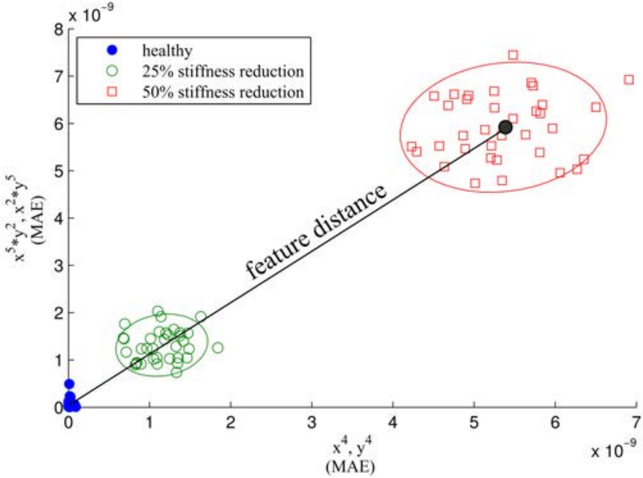
Damage Quantification

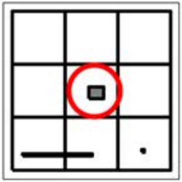




Different damage levels in a feature-feature plot.

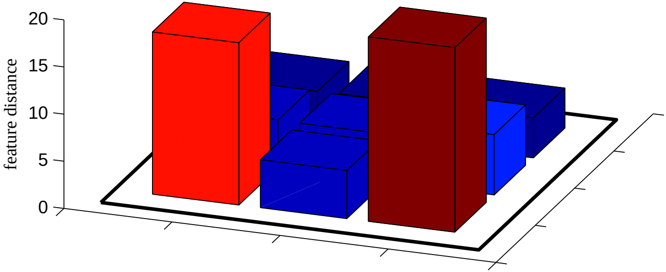
Damage Quantification

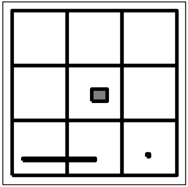




Different damage levels in a feature-feature plot.

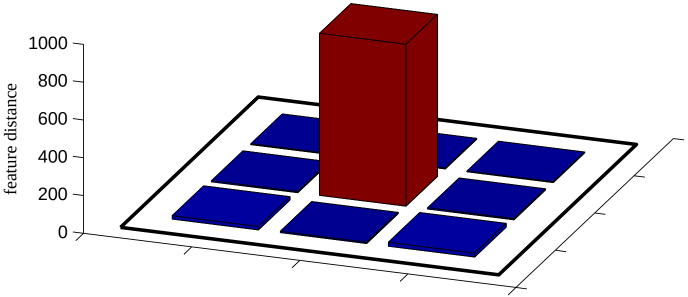
Damage Localization

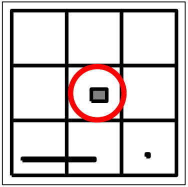




Damage localization on cantilever plate with damage induced as reduction of stiffness.

Damage Localization





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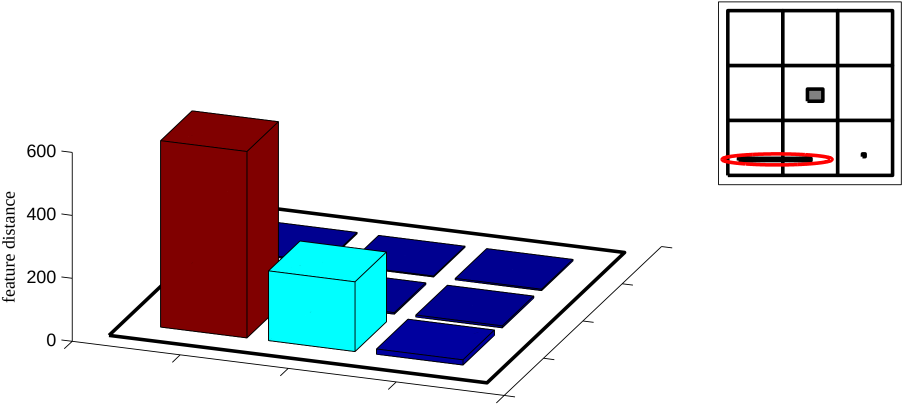

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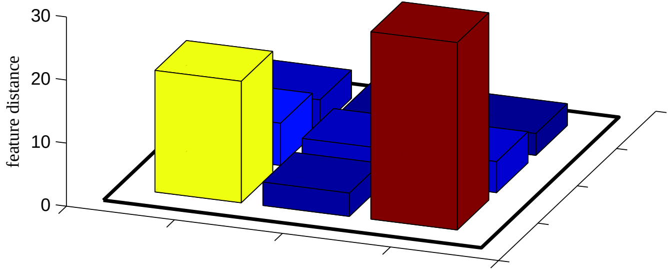
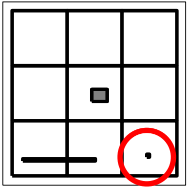
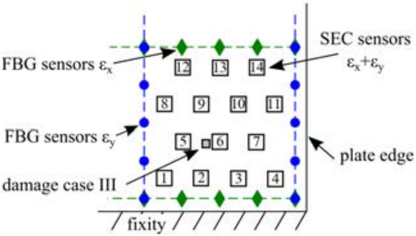
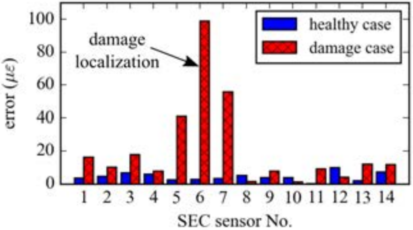




Damage localization on cantilever plate with damage induced as reduction of stiffness.

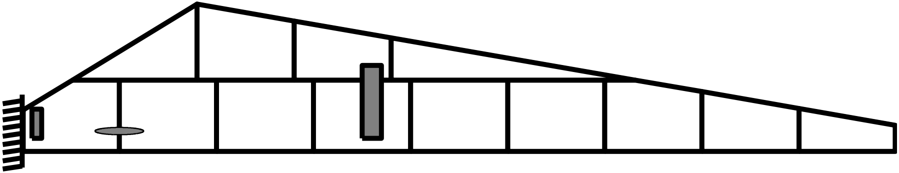
Damage localization within an HDSN





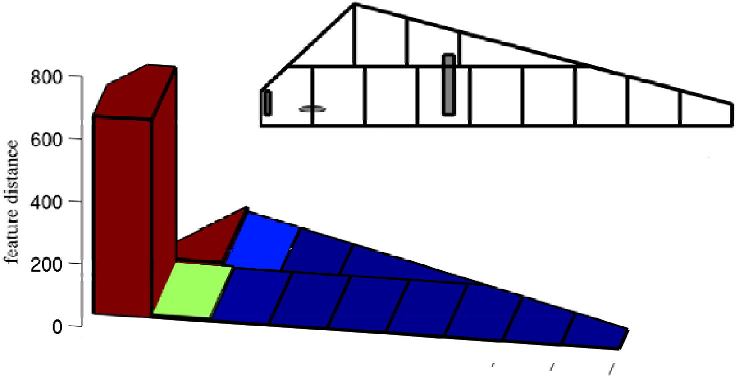
Damage localization within an HDSN: left) damage case III and associated HDSN; right) absolute difference (error) between the estimated and measured strain for SECs within the HDSN

Wind Turbine Blade Example



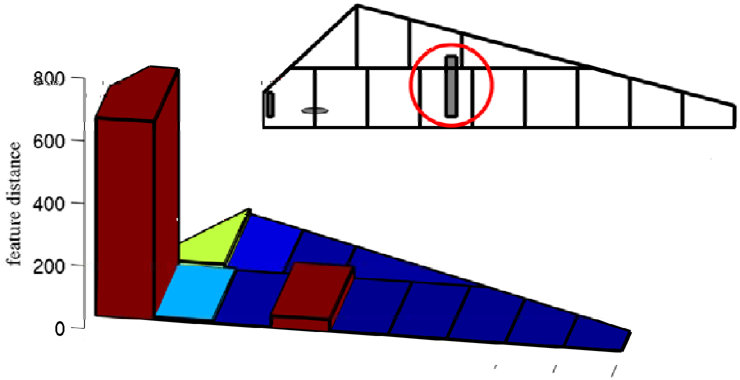
Wind turbine blade shaped cantilever plate with damage induced as reduction of stiffens, pressure loading on face.

Damage Localization



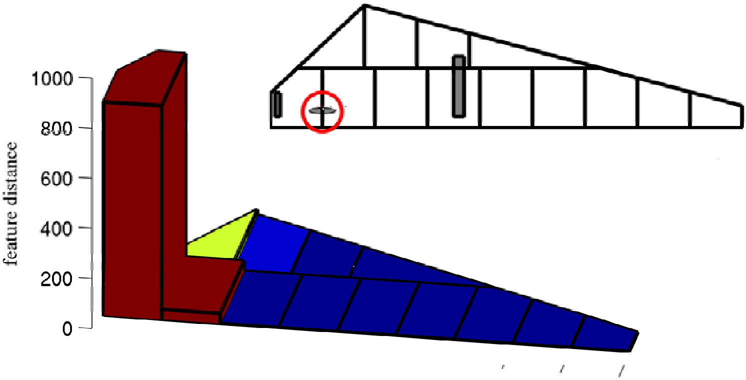
Damage localization on wind turbine shaped cantilever plate.

Damage Localization



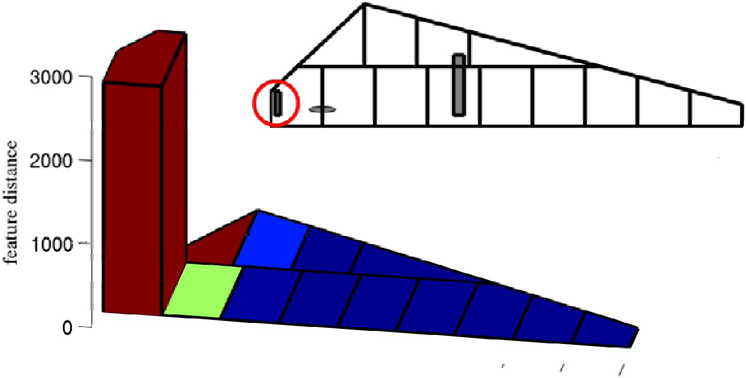
Damage localization on wind turbine shaped cantilever plate.

Damage Localization



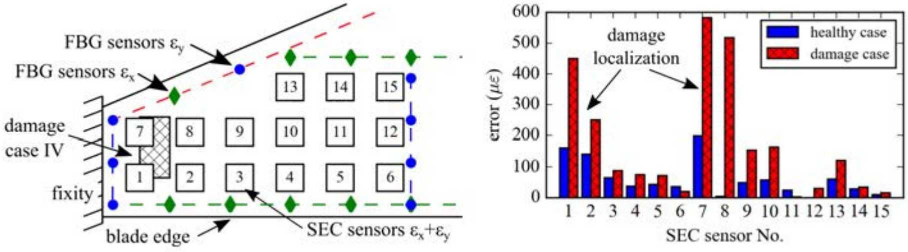
Damage localization on wind turbine shaped cantilever plate.

Damage Localization



Damage localization on wind turbine shaped cantilever plate.

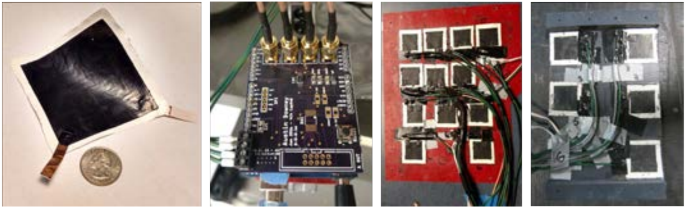
Damage localization within an HDSN



Damage localization within an HDSN: left) damage case IV and associated HDSN; right) absolute difference (error) between the estimated and measured strain for SECs within the HDSN

Conclusion

- Low cost measurement system for large area structures.
- Developed a damage detection technique using a HDSN.
- Demonstrated its ability to detect and localize damage.
- Developed basic understanding of the methods limitations.



SEC technology: 1) SEC sensor; 2) 4 channel DAQ; and 3) HDSN; 4) HDSN.

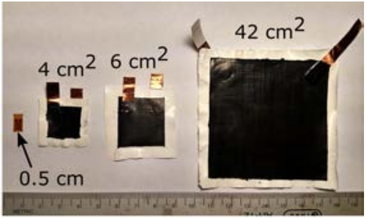
Conclusion

Benefits

- No need for a external model or prolonged monitoring.
- Computationally efficient way to categorize HDSNs as healthy or possibly damaged.

Limitations

- Can be difficult to distinguish damage from complex loading.



SECs of varying size.

Thank you

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