A Data-driven Approach for Damage Detection in Wind Turbine Blades using a Dense Array of Soft Elastomeric Capacitors

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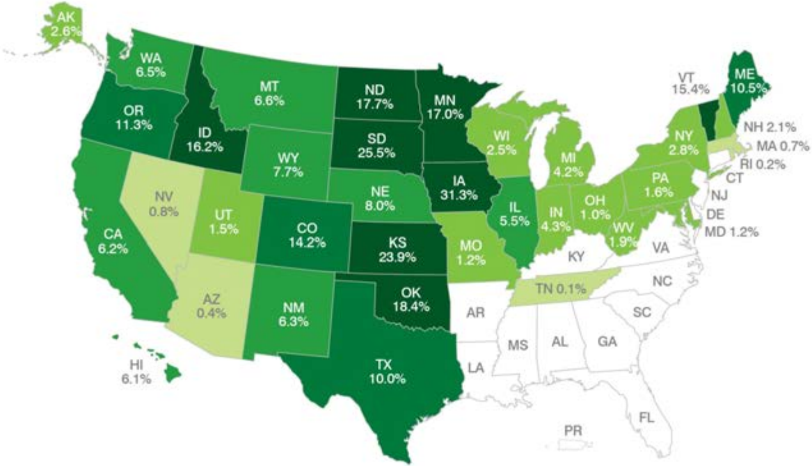
June 6th 2017

Overview

Contents

Failure of a 49 meter wind turbine blade wind-watch

Iowa, a center for wind



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

Towards 50% wind energy


FUTURE TENSE THE CITIZEN'S GUIDE TO THE FUTURE.

FROM SLATE, NEW AMERICA, AND ASU

The Most Impressive State for Clean Energy

It's Iowa. Really!

By Daniel Gross

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

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


MidAmerican Energy To Invest $3.6 Billion In 2 GW Wind Project

April 19th, 2016 by Joshua S Hill

US energy company MidAmerican Energy has announced a commitment to invest $3.6 billion to build the 2 GW Wind XI project in Iowa.

The MidAmerican Energy Company announced last week that it had filed a request with the Iowa Utilities Board to build the 2 GW Wind XI, a project that will add 2 GW of wind energy capacity to Iowa. The project, which will cost a proposed $3.6 billion, is the largest economic development project in the state's history, and the largest wind project MidAmerican Energy has ever undertaken, and the company hopes to avoid increasing customer rates or seeking financial assistance.

The project is a big step towards the company's goal of 100% renewable energy for all its Iowa customers.

"We have a bold vision for our energy future," said Bill Fehrman, CEO and president of MidAmerican Energy. "We don't know of another US energy provider that has staked out this

The project is a big step towards the companys goal of 100% renewable energy for all its Iowa customers. cleantechnica.com

Taller towers

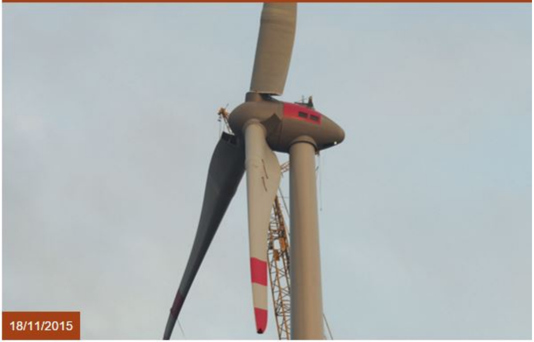
Iowa has the tallest land-based (US) wind turbine (115 meter hub height) Donnelle Eller

Iowa State University is working on the development of hexagon concrete towers. news.iastate.edu

Bigger blades

HOME > ONSHORE WIND > ENERCON ADDS LOW-WIND TURBINES

Enercon adds low-wind turbines

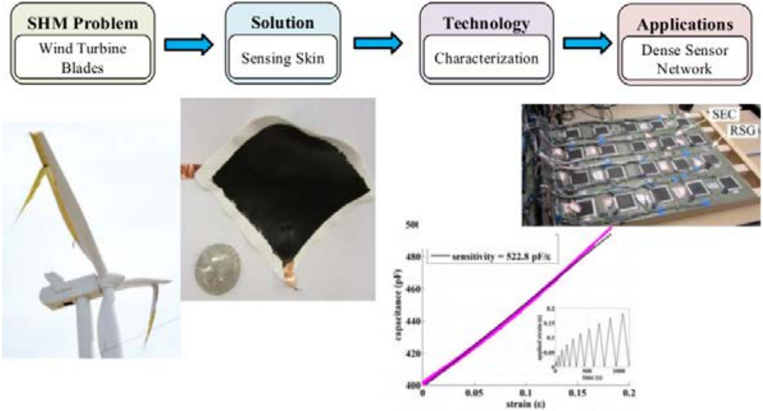


Enercon has introduced low-wind speed versions to its 4MW and 2MW onshore wind turbine platform.

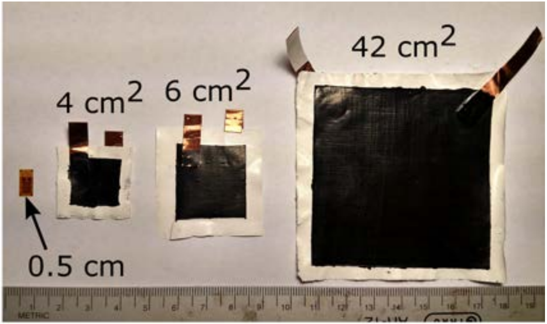
Enercon 73 meter blade Wind Energy

Structural health monitoring of wind turbine blades

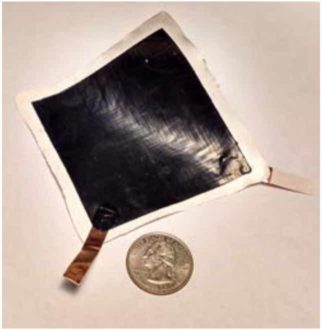
Utilizing large area electronics for global coverage



Soft Elastomeric Capacitor (SEC)



SECs of varying size compared to a resistive strain gauge (RSG).



Highly elastic sensing membrane.

SEC model

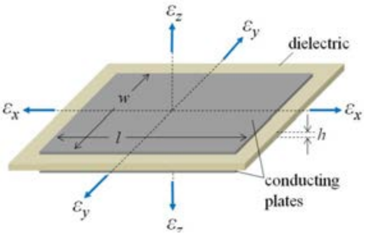
Parallel plate capacitor

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

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

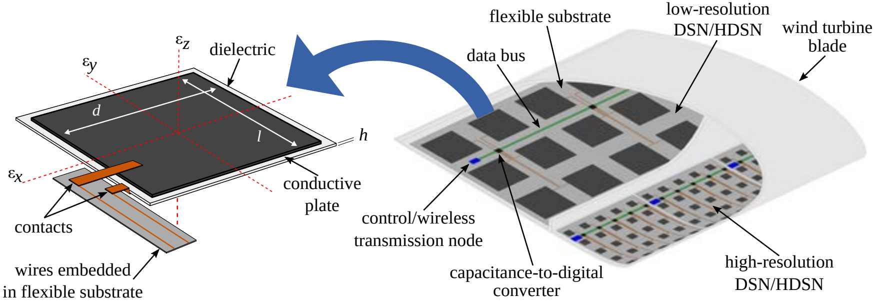
$$\frac{\Delta C}{C} = \lambda(\varepsilon_x + \varepsilon_y) \qquad (2)$$

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



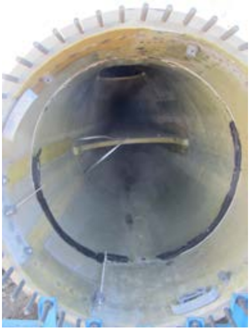
SEC sensor

Fully integrated SEC based sensing skins for mesosystem monitoring



Implementation

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

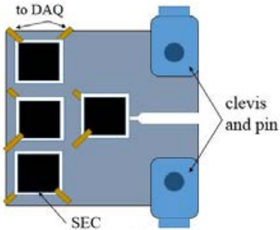


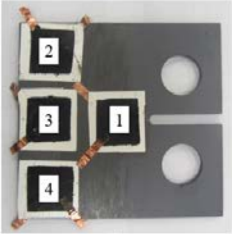
Inside a 45 meter GE blade Austin Downey

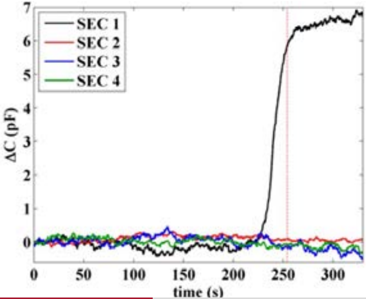
Damage cases

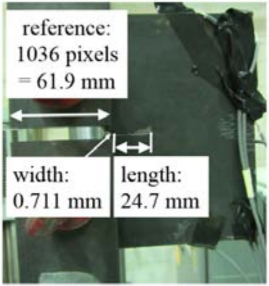
Typical damage cases: 1) through crack; 2-3) edge split; 4) impact. Austin Downey

Dense sensor network for fatigue crack detection





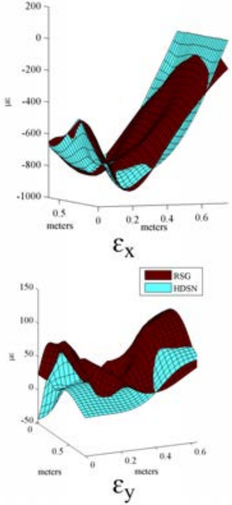




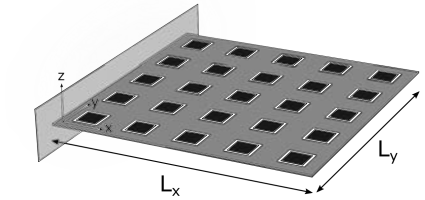
Decompose the additive strain signal into unidirectional strain maps

Develop a model for creating unidirectional surface strain maps:

- Assume a shape function.
- Impose boundary conditions.
- Calculate function parameters via a least square estimation.



Shape function

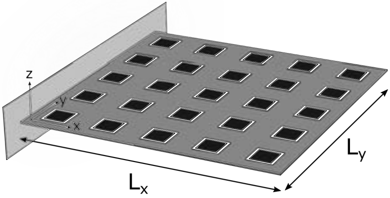


schematic representation of cantilever plate with SEC array

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

Pascals Triangle for displacement function

Shape function



schematic representation of cantilever plate with SEC array

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

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

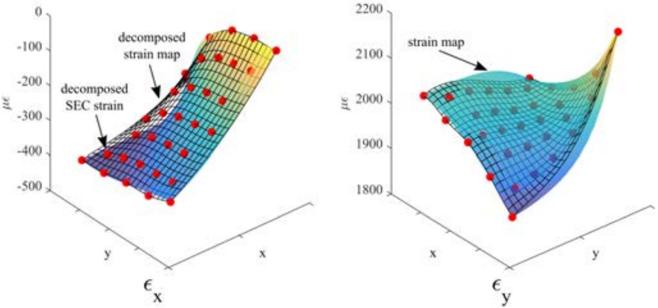
$$\hat{\varepsilon_x}(x,y) = \hat{b}_1 + \hat{b}_2 x + \hat{b}_3 y + \hat{b}_4 x^2 + \hat{b}_5 xy + \hat{b}_6 y^2$$
$$\hat{\varepsilon_y}(x,y) = \hat{b}_7 + \hat{b}_8 x + \hat{b}_9 y + \hat{b}_{10} x^2 + \hat{b}_{11} xy + \hat{b}_{12} y^2$$

Unidirectional strain maps

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

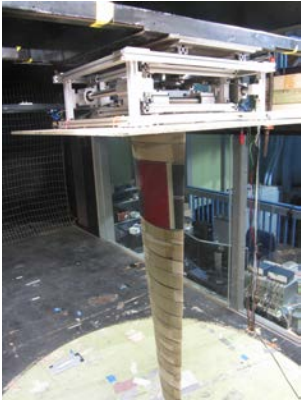
solve for b using least squares estimator (LSE):

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



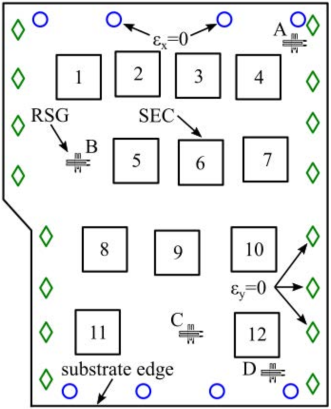
Real-time unidirectional strain maps

Wind Tunnel Testing



Link

Strain Maps

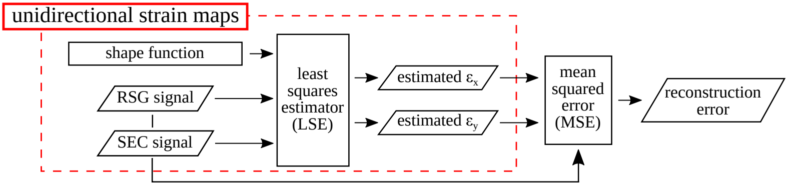


Link

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

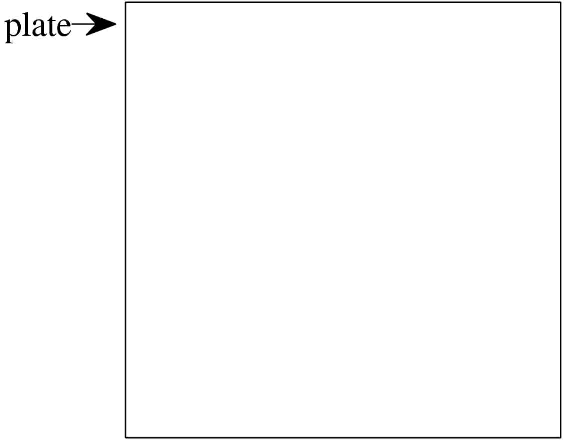
Damage detection and localization through a Network Reconstruction Feature (NeRF)

1. Data fusion of the additive SEC signal and unidirectional RSG 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.



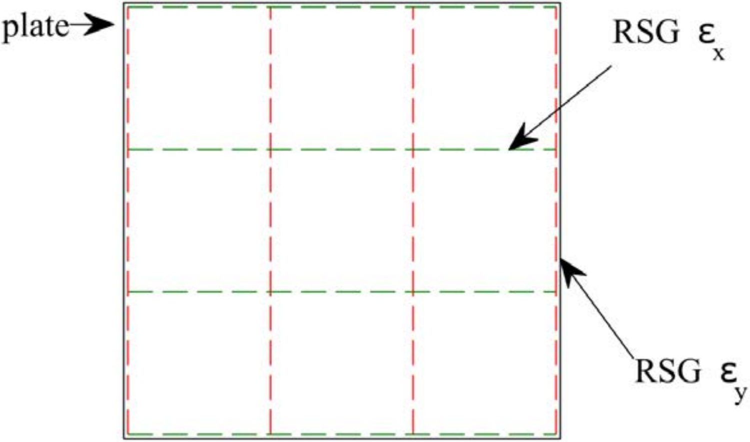
Extract damage features based on the fit of a shape function

Building a HDSN



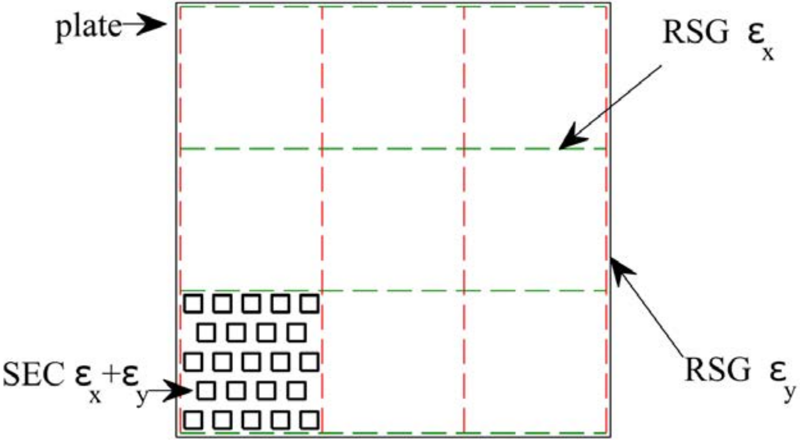
Deploying HDSN of SECs and RSGs onto a plate.

Building a HDSN



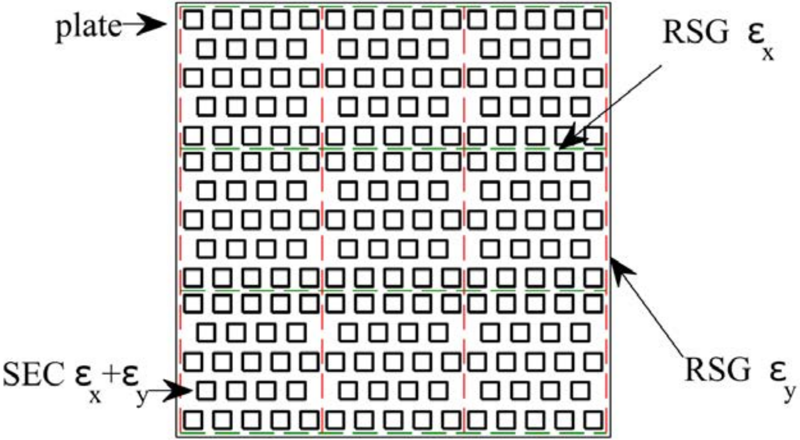
Deploying HDSN of SECs and RSGs onto a plate.

Building a HDSN



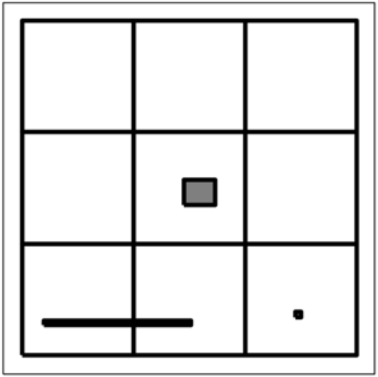
Deploying HDSN of SECs and RSGs onto a plate.

Building a HDSN



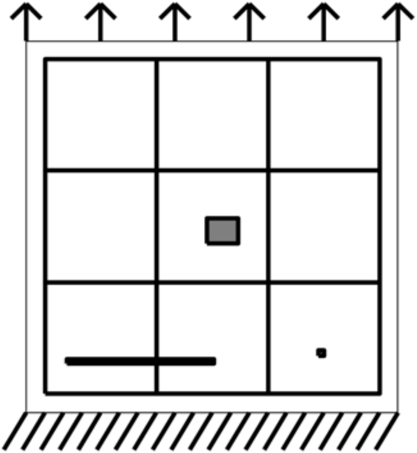
Deploying HDSN of SECs and RSGs onto a plate.

Damage cases



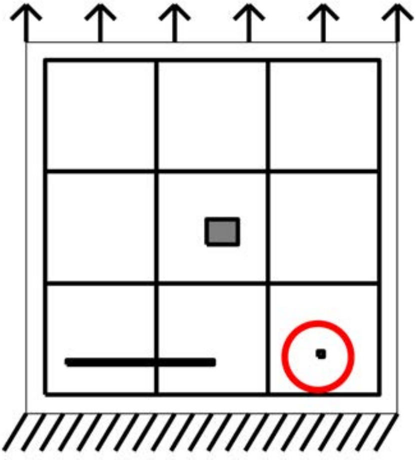
Cantilever plate with damage induced as reduction of stiffness.

Damage cases



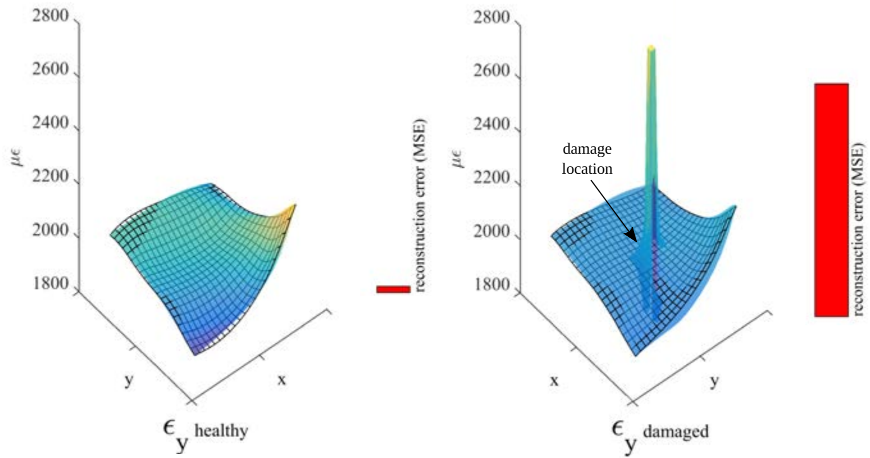
Cantilever plate with damage induced as reduction of stiffness.

Damage cases



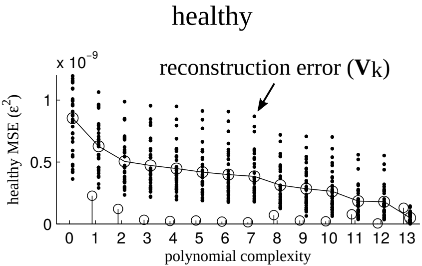
Cantilever plate with damage induced as reduction of stiffness.

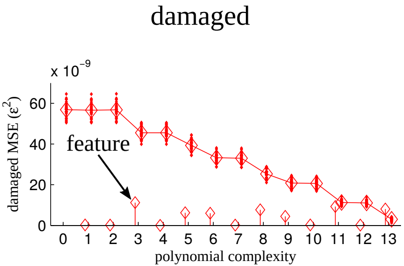
Error detection



Error in strain map reconstitution measured at sensor locations.

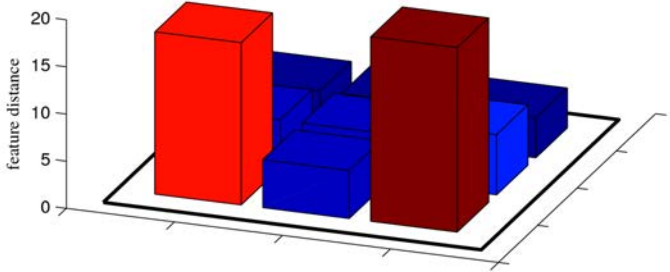
Feature extraction

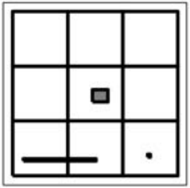




Features extracted from change in fit with increasing shape function complexity

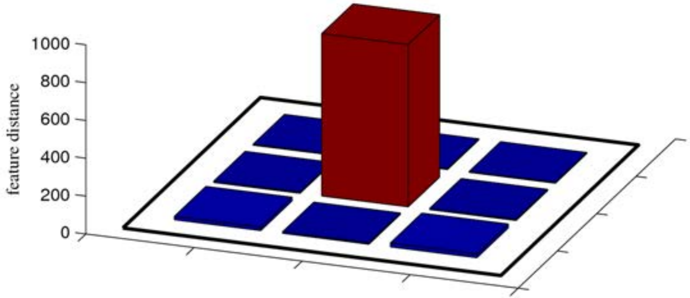
Damage localization

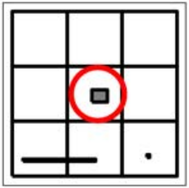




Damage localization on cantilever plate with damage induced as reduction of stiffness.

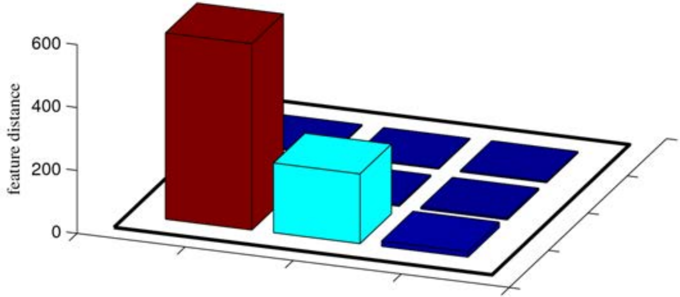
Damage localization

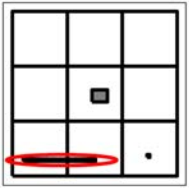




Damage localization on cantilever plate with damage induced as reduction of stiffness.

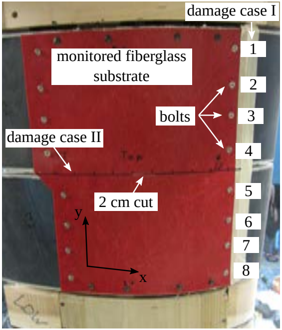
Damage localization

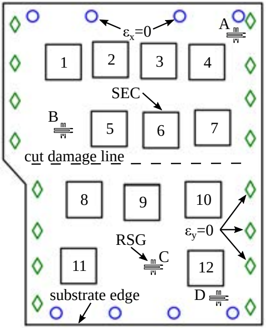


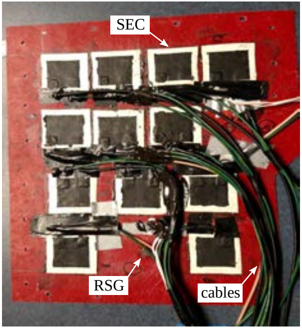


Damage localization on cantilever plate with damage induced as reduction of stiffness.

Experimental wind tunnel validation

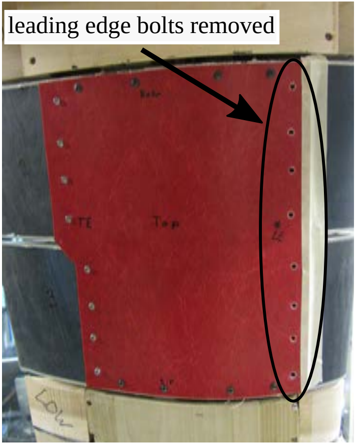


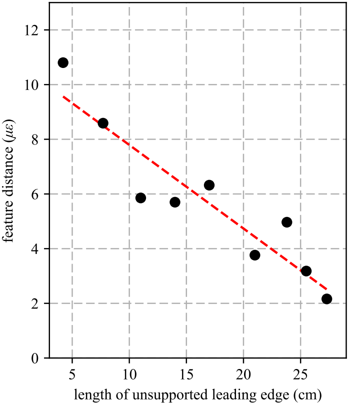




Wind turbine blade shaped cantilever plate with damage induced as reduction of stiffens, pressure loading on face.

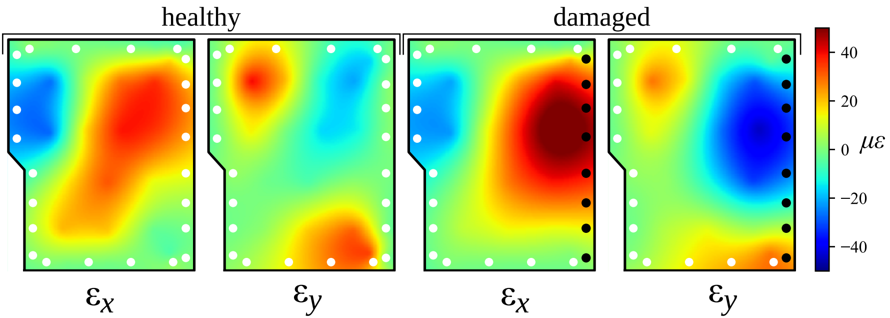
Leading edge damage



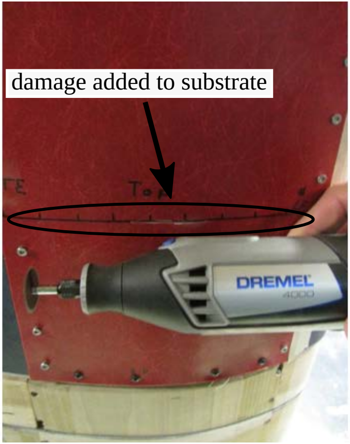


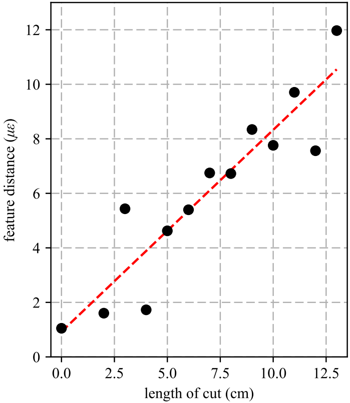
NeRF algorithm results for changing boundary conditions on the leading edge of the monitored substrate.

Changing load paths caused by damage



Cut damage





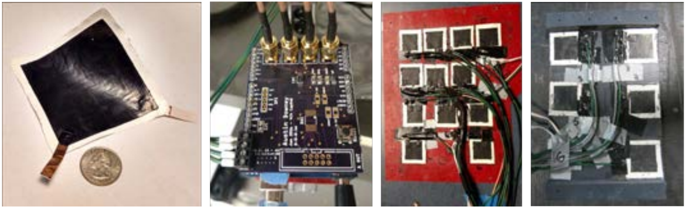
NeRF algorithm results for cut damage induced into the center of the monitored substrate.

Conclusion

- Low cost measurement system for mesoscale structures.
- Demonstrated capability to detect and localize damage.

Limitations

- Can be difficult to distinguish damage for complex loading.



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

Thank you

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