Optimization of Optical Frequency-domain Reflectometry for Dynamic Structural Health Monitoring using Distributed Optical Fiber Sensors

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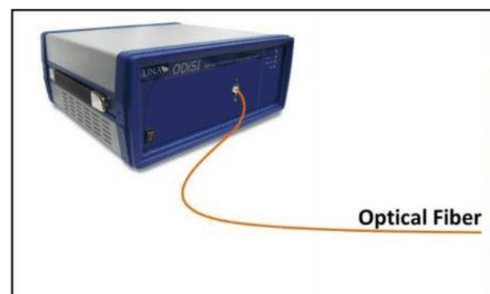
Introduction

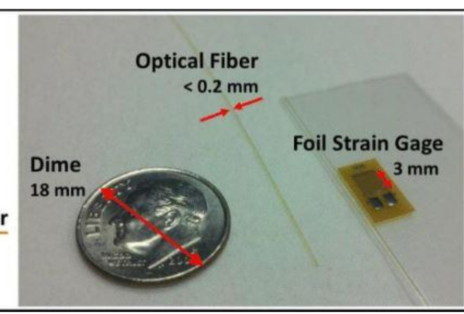
The goal of this project is to optimize the existing optical frequency-domain reflectometry (OFDR) method to facilitate dynamic structural health monitoring using Distributed Optical Fiber Sensors (DOFS) under field conditions. These sensors offer a cost-effective solution that reveals temperature, strain, and vibration information from any point along the entire length of an optical fiber. However, one of the biggest challenges that hinder the wide implementation of DOFS is the dynamic monitoring capability under field conditions. Although several efforts have been made to improve the dynamic monitoring capability of DOFS using polarization-optical time-domain reflectometry (OTDR), OTDR is limited to a spatial resolution of ~1m.

The cost to improve the spatial resolution of OTDR is very high and limits its suitability. On the other hand, optical frequency-domain reflectometry (OFDR) technique offer high spatial resolution. If similar performance can be achieved under dynamic monitoring conditions, OFDR can be implemented in virtually any SHM application. To date, only preliminary studies have been performed under laboratory conditions to evaluate dynamic measurements using OFDR. Thus, this study aims at developing an optimized OFDR for dynamic monitoring using DOFS under field conditions. A laboratory experimental program and field monitoring program has been developed to validate static and dynamic measurements with conventional sensors, respectively. The research team has established collaboration with the Florida Department of Transportation and other industrial partners/agencies. The research related to distributed optical fiber sensing is still in the early stages of development. Successful execution of this project will give ERAU a great advantage in our signature SHM field.

Structural Health Analysis Data Collection Equipment

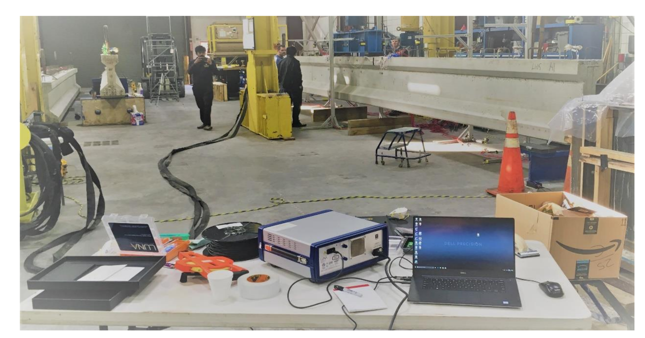


Luna DOFS System



Fiber Optic Sensor

Luna Fiber Optic Sensor along with BDI STS Data Acquisition system to verify results

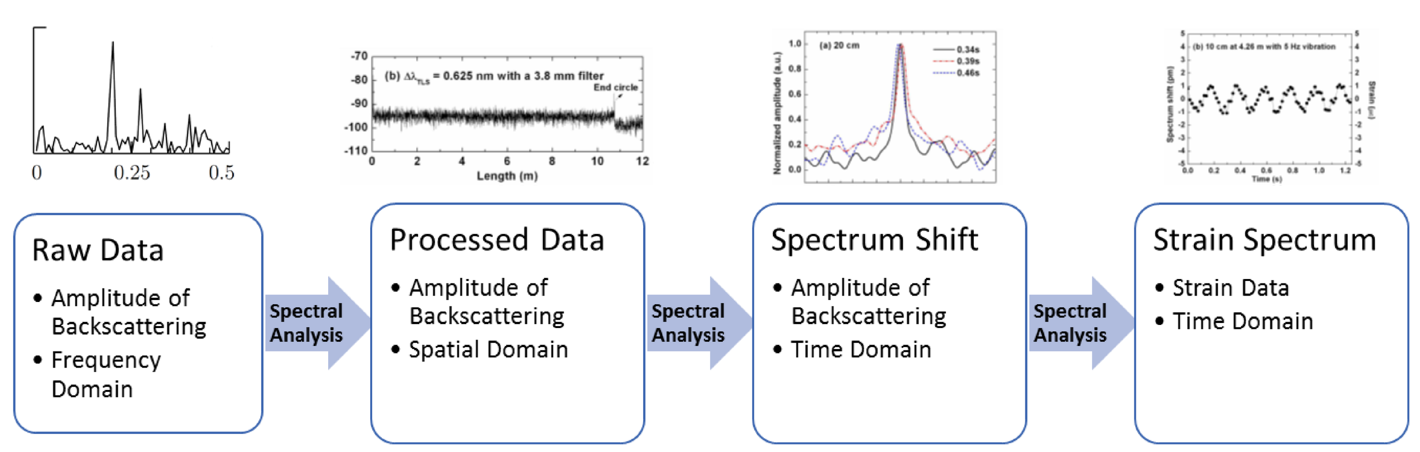


FDOT Structural Research Center Reinforced Girder Test

Development of Spectral Analysis Algorithm

Because Rayleigh scattering is independent of temperature and strain, the Rayleigh backscatter profile of an optical fiber depends on its heterogeneous permittivity, which varies randomly along the length of the fiber. Thus, when the external stimulus causes a shift of permittivity, it consequently causes a spectral shift. Considering a single-mode optical fiber in which the permittivity of the core varies along the axis, based on Maxwell equation, the steady-state propagation can be described as

$$\frac{\partial^2 E}{\partial z^2}+\beta^2\left[1+\frac{\Delta\varepsilon(z)}{\varepsilon}\right]E=0$$



Flowchart of Spectral Analysis Processes

$$E=E_0\exp(i\beta z)+\Psi(z,\beta)\exp(-i\beta z)$$

$$\frac{\partial^2\Psi}{\partial z^2}-2i\beta\frac{d\Psi}{dz}+\beta^2\frac{\Delta\varepsilon(z)}{\varepsilon}E_0\exp(2i\beta z)+\beta^2\frac{\Delta\varepsilon(z)}{\varepsilon}\Psi=0$$

E_0 is the constant amplitude of the forwarding traveling wave;
$\Psi(z,\beta)$ is the spatially varying amplitude of the backward-traveling wave.

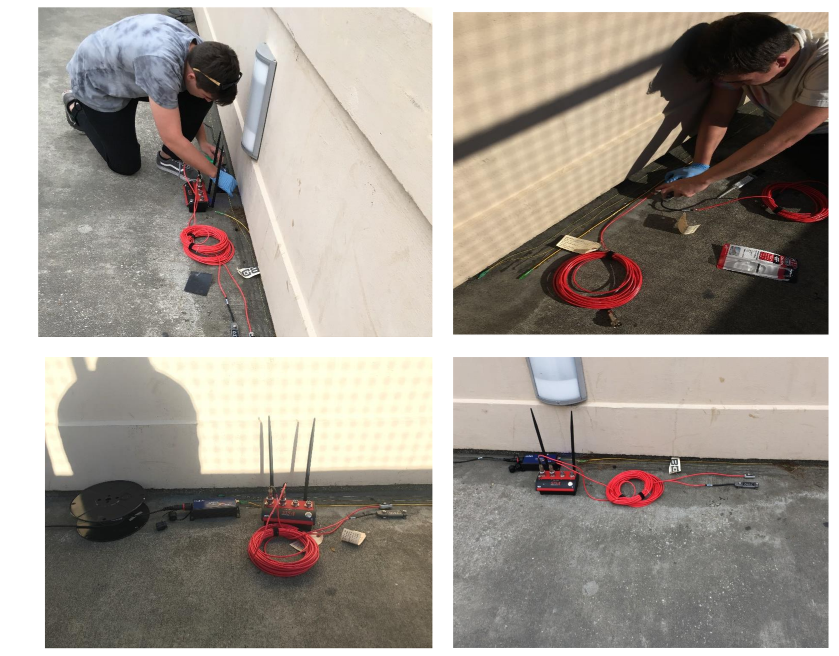
Development of New De-noising Method

- The interference of sinusoidal waveforms with random amplitudes generates fading noise. Fading noise presents a fantastic debacle for dynamic monitoring using Rayleigh-based OFDR.
- The result of fading noise is that the total amplitude fluctuates, which strongly restricts the possibility of detecting small reflections in the fiber.
- A new de-noising method is proposed to remove fading noise and optimize the signal strength. Singular-spectrum analysis (SSA) has been proven in many previous studies to be an efficient method to address the noise level of the sample.
- In this study, a Monte-Carlo based SSA method will be developed to minimize the noise effects. Compared to ordinary SSA, Monte-Carlo SSA (MC-SSA) takes the statistical significance of the signal into consideration.
- A new MC-SSA method will not only minimize the noise effects but will also enhance the quality of spectrum reconstruction.

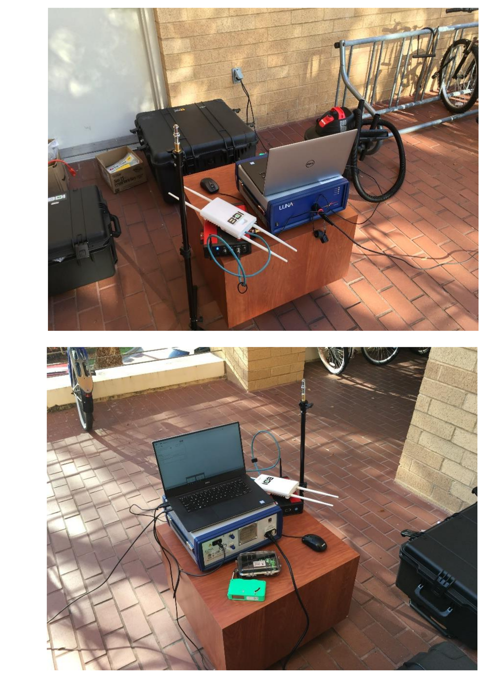
Acknowledgements: ERAU The Office of Research and Graduate Studies
ERAU Faculty Innovative Research in Science and Technology (FIRST) program
Florida Department of Transportation (FDOT)
LUNA Inc.

Field Data Collection

The field experimental study was performed on Student Village Pedestrian Bridge. Strain data was collected at peak traffic hours using both DOFS and STS strain transducer system. The data collected from DOFS was compared and validated with STS data. The data collected also used to develop spectral analysis algorithm.



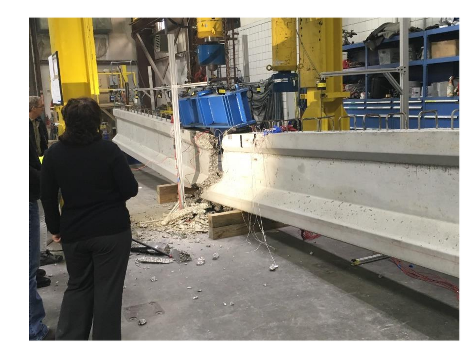
Sensor Installation

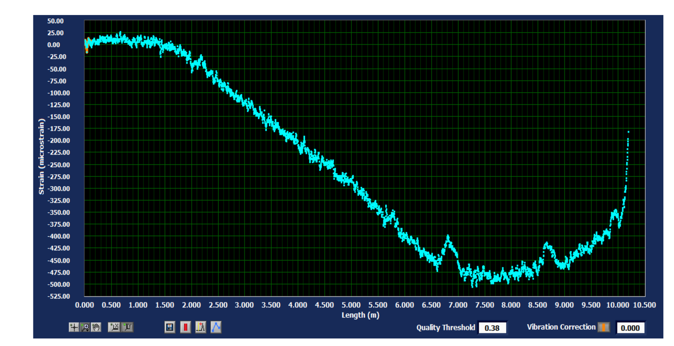


Mobile Data Collection Station

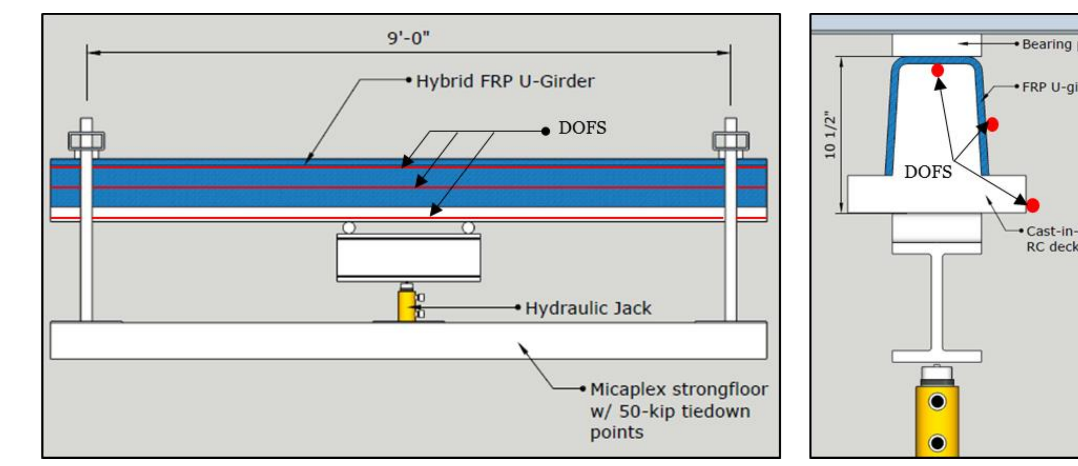
Laboratory Data Collection

The experimental test conducted at FDOT structure laboratory was **first time** applying OFDR-based distributed optical fiber sensor (DOFS) to a full size prestressed concrete girder flexural test





FDOT Structural Research Center Reinforced Girder Test

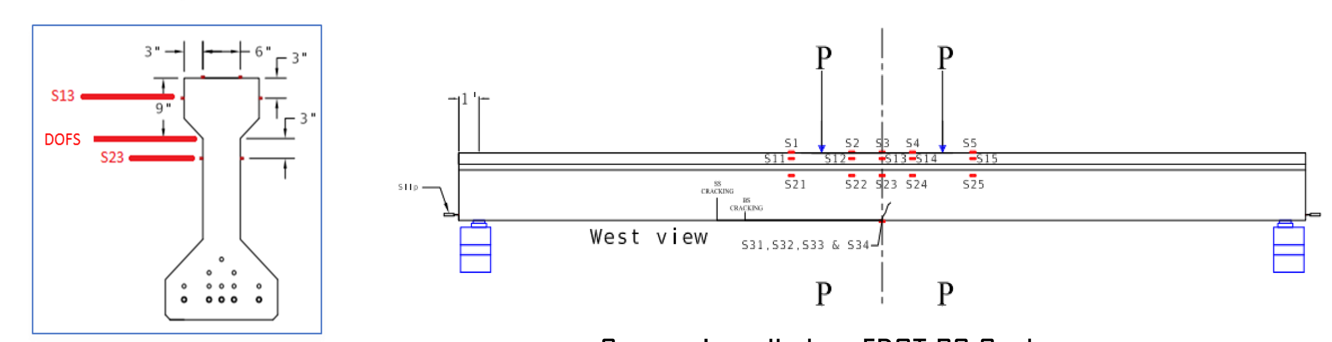


Measurement concept for distributed/continuous strain measurements

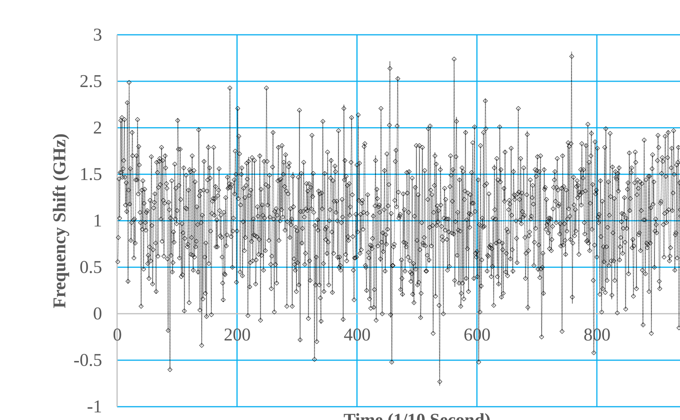
the research team proposes to instrument a series of DOFS on two quarter-scale FRP U-girders with span lengths of 8 ft. Strain gauges will also be installed to collect strain data at midspan location at the same heights as the DOFS.

Signal Processing and Data Analysis

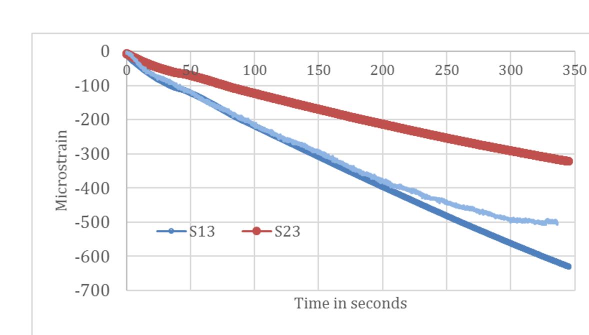
Once the data collection procedure has been completed, the data can be processed and analyzed.



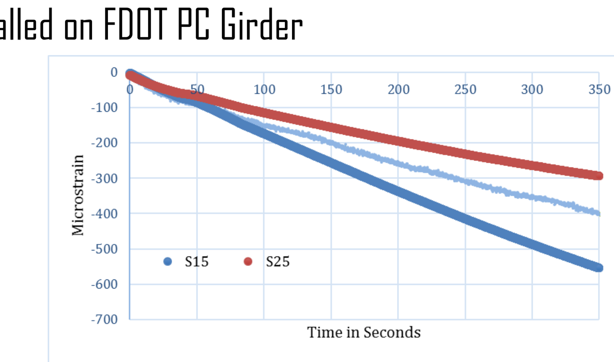
Sensor Installed on FDOT PC Girder



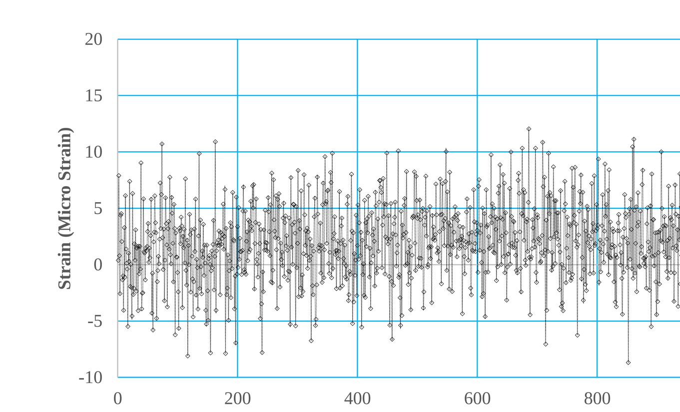
Raw Frequency Data (Pedestrian Bridge)



Strain Data Collected at the Midspan of the Girder



Strain Data Collected at 4ft 6in from the Midspan of the Girder



Processed Stain Data (Pedestrian Bridge)

Summary and Conclusions

- The research related to OFDR-based dynamic monitoring is still in the early stages of development. Successful execution of this project will give ERAU a great advantage in our signature SHM field.
- The contribution of this project will significantly elevate the applicability and dynamic monitoring capability of Rayleigh-based OFDR. The new optimized OFDR-based DOFS will be the first to achieve dynamic monitoring under field condition.
- The research group is currently expanding this research effort into several new scopes: (1) Self-sensing Carbon Fiber Reinforced Polymer (CFRP) composite with distributed sensing capability, and (2) Design and Development of Prestressed Concrete Girder with Embedded Distributed Sensing System

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