NHDOT SPR2 PROGRAM
RESEARCH PROGRESS REPORT

INSTRUCTIONS:

Project Managers and/or research project investigators should complete a progress report at least every three months during the project duration. Reports are due the 5th of the month following the end of the quarter. Please provide a project update even if no work was done during this reporting period.

Project # 26962G	**Report Period** Year: 2018 ☐Q1 (Jan-Mar) ☐Q2 (Apr-Jun) ☐Q3 (Jul-Sep) XQ4 (Oct-Dec)	
Project Title: The Living Bridge: A Benchmark for Bridge Monitoring The Living Bridge: Tidal Turbine Deployment System		
Project Investigator: Erin S. Bell Project Co-Investigators: Martin Wosnik, Kenneth Baldwin **Phone: (603)862-3850** **E-mail: erin.bell@unh.edu**		
Research Start Date: sample July 1, 2016	**Research End Date:** May 30, 2019	**Project schedule status:** ☐ X On schedule ☐ Ahead of schedule ☐Behind schedule

Brief Project Description:

This project is a collaborative project between the civil and environmental engineering, mechanical and ocean engineering programs at UNH, the NHDOT and several industrial partners to install of an array of structural health monitoring, environmental and estuarine sensors on the Memorial Bridge in Portsmouth, New Hampshire that will be powered by a tidal turbine attached to one of the bridge piers. The funding for the Tidal Turbine Deployment System is leveraged with funding provided by the National Science Foundation's Partnerships for Innovation (PFI) Program, The Living Bridge: The Future of Smart, Sustainable User-Centered Transportation Infrastructure, and funding provided by the US Department of Energy (DOE) to the UNH Center for Ocean Renewable Energy.

Progress this Quarter (include meetings, installations, equipment purchases, significant progress, etc.):

Benchmark for Bridge Monitoring:

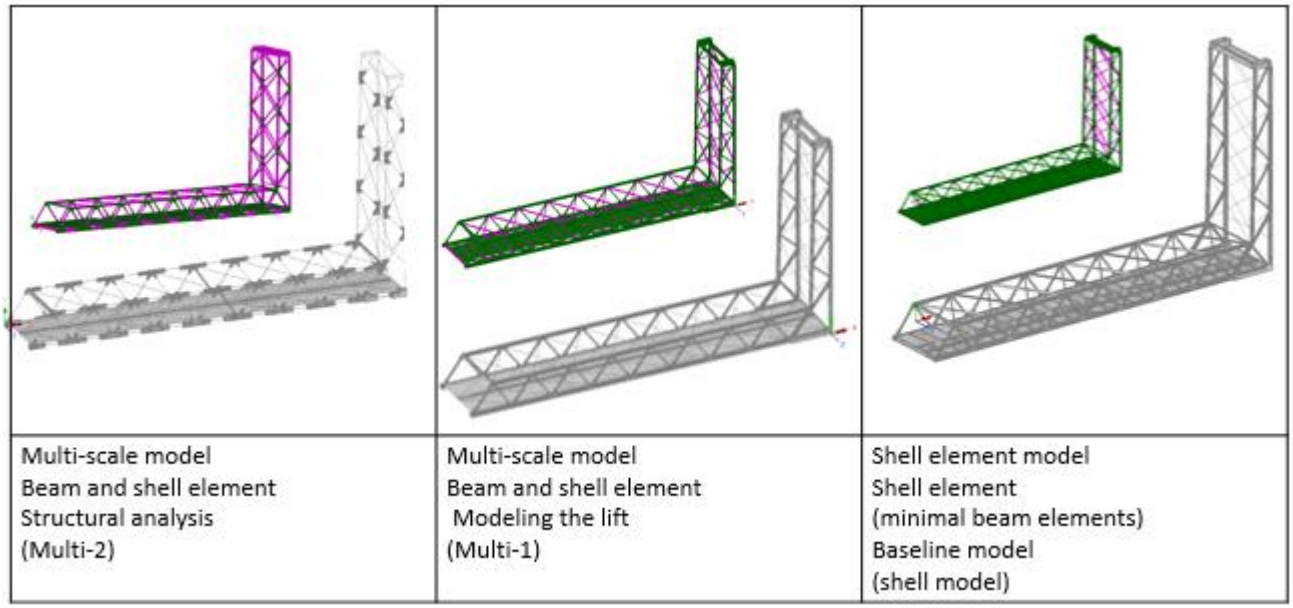
The final instrumentation plan for the structural health monitoring was discussed at the June 28th 2016 technical advisory group meeting in Concord, NH, and was approved on July 18 2016. The structural sensors were installed on the bridge structure in March 2017. The installation was complete on March 8 2017. The sensors are operational. The marine sensors are installed on the turbine support platform and the collected data is integrated with the structural information, mechanical performance information and environmental information. The structural sensors on the vertical guide posts were installed in late October 2017. These sensors are temporary collecting data followed by the installation of the tidal turbine in June 2018. The sensors will be permanently installed to the database when the droop cable is installed to the main connector.

A pseudo-static load test was conducted on October 27th 2017. This load test used a NHDOT truck loaded with concrete barriers. The test location was the Portsmouth side of the bridge. A NHDOT truck carrying Jersey barriers was used. A total of five runs (5 mph) were conducted: three (3) runs on the northbound side and two runs on the southbound side. Each static run included two stops. In addition, five dynamic runs (15-30 mph) were conducted: two runs without traffic (one on the northbound side and one on the southbound side) and three runs with traffic (two on the northbound side and one on the southbound side). This collected data is being used to validate the multi-scale structural models of the Memorial Bridge.

Progress in FE modeling;

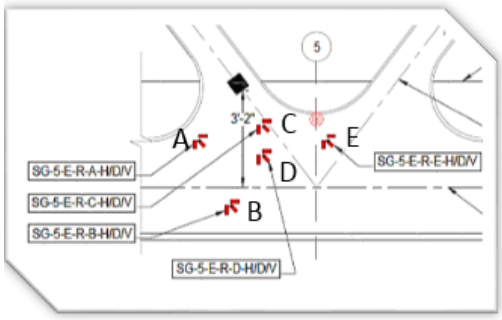
A set of full-scale and multi-scale finite element models of the bridge was developed at UNH in Lusas® by PHD candidate Maryam Mashayekhizadeh, See Figure 1. This program was chosen to mirror the modeling done during bridge design by HNTB. Also, the structural model of the Memorial Bridge in SAP2000® is complete. A comparison of Lusas® models with the SAP® model shows that they are in good agreement with each other in preparation for calibration with collected field data from the October 2017 load test. The models are for the Portsmouth span and lift tower only. The models were validated with respect to the collected data specifically focusing on stiffness of the connection elements, See Figure 2. Additional model updating algorithms are under development to refine the connection stiffness values based on load test data.

The developed multi-scale FE models of the bridge calibrated using the field data during the load test are going to be applied to inform the health status of the critical locations, see Figure 3. She gave a presentation, titled "Data Validated Multi-Scale Finite Element Modeling Protocol for Complex Connections of a Movable Bridge" in June 2018 in Engineering Mechanics Institute Conference, MIT. This work was also published in the Journal of Computer-Aided Civil and Infrastructure Engineering (https://doi.org/10.1111/mice.12424)



Multi-scale model Beam and shell element Structural analysis (Multi-2)	Multi-scale model Beam and shell element Modeling the lift (Multi-1)	Shell element model Shell element (minimal beam elements) Baseline model (shell model)

Figure 1 Multi-Scale Finite Element Model of the Memorial Bridge, Portsmouth, NH



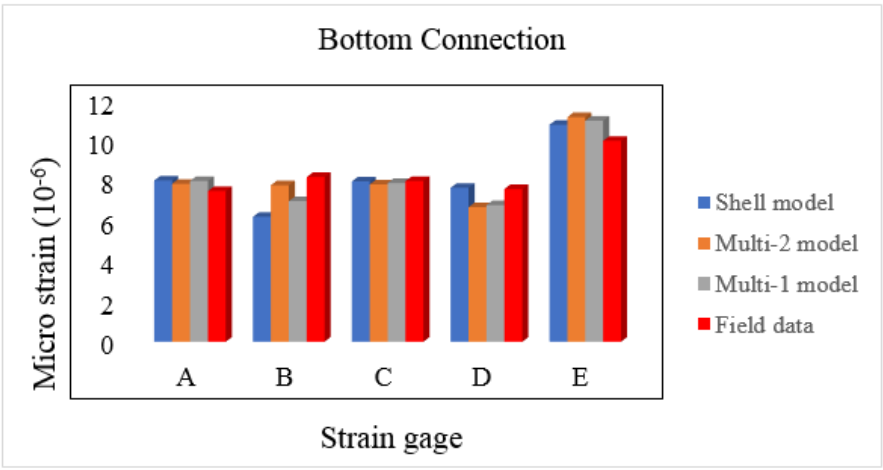
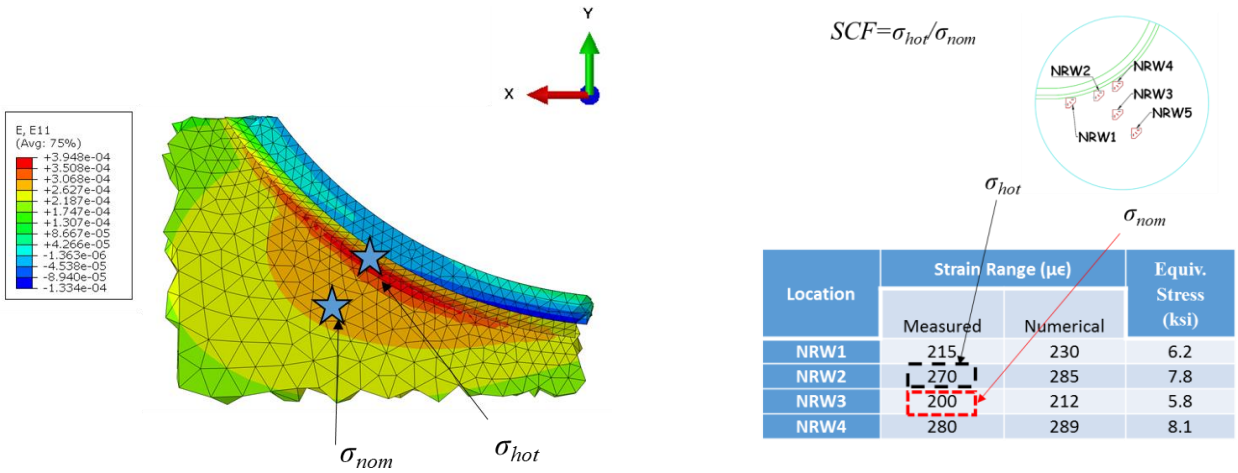


Figure 2 Verification of the Structural Models of the Memorial Bridge as compared to Load Test Data

A detailed finite element model of the connection was also developed as part of this project, see Figure 3a. This model was verified with both data collected at the Memorial Bridge, as shown in Figure 1 and data collected through the Gussetless Connection Project (26962M). This comparison is presented in Figure 2B.



Location	Strain Range (με)		Equiv. Stress (ksi)
	Measured	Numerical	
NRW1	215	230	6.2
NRW2	270	285	7.8
NRW3	200	212	5.8
NRW4	280	289	8.1

Figure 3 Verification of the Structural Model (a) of the Memorial Bridge as compared to Laboratory Data (B) collected via NHDOT Project 26962M

A detailed model of the gusset-less truss connection in ABAQUS® is completed. The response from this model is the basis for a quantitative set of stiffness values (stiffness matrix) to represent the connection in the structural SAP® model. This model was manually verified with respect to the collected data and the analytical responses from this model will be to determine the stiffness value of the super-element that will represent the gusset-less connection in the SAP2000® model.

Graduate student, Timothy Nash, conducted a study of wind loads developed from AASHTO, ASCE7-10 and European codes to predict the structural response of the lift tower. Tim defended his thesis and graduated with his masters degree in December 2016. In June2018, part of his results were presented by Milad Mehrkash, PhD candidate, in the Engineering Mechanics Institute (EMI) conference in Boston, MA. This predicted information will be compared to the measured structural response of the tower, as a data set is collected over time under varying environmental conditions.

Graduate student, Chao Yang, conducted a probability-based environmental demand assessment of the wind and wave loads on the tidal turbine deployment platform, specifically with respect to the anchorage capacity. Chao defended his thesis and graduate with his masters' degree in December 2017. In June 2018, part of his results is presented by Vahid Shahsavari, postdoctoral research scholar, in the Engineering Mechanics Institute (EMI) conference in Boston, MA. A senior capstone project for the 2018-2019 academic year is continuing this work using data collected from the vertical guide posts.

PI Bell continues to communicate with bridge designer, Ted Zoli, both in live and virtual meetings. The last conference call as held in September 2018 with Professor Ricardo Medina to discuss this project and program 26962M. The most recent live meeting was a live meeting in New York on November 20th 2018. We are planning a conference call in January 2019 to discuss this project and project 26962M.

Progress of Fatigue assessment of the critical components at the Memorial Bridge

Doctoral candidate, Maryam Mashayekhizadeh, has performed fatigue assessment of the critical gusset-less connection at the Memorial Bridge using the long-term high-speed monitoring data to determine the remaining life of the bridge's components. The most critical areas showing less remaining life can be identified for further inspection and maintenance activities. It is planned to characterize the monitoring data into the meaningful categories including the structural and environmental impacts to determine the most deteriorative factors that can threaten the remaining life of the gusset-less connection for the further bridge's management programs. See Figure 4 for rain fall data collected at the Memorial Bridge to be used for fatigue damage assessment of the gusset-less connection. Also, the remaining life of the non-instrumented critical components of the bridge will be determined using the analytical response of the FE models. Part of her work has

produced a scale factor, stress concentration factor (SCF) to scale the stress value collected along the web to predict the stress at the weld toe.

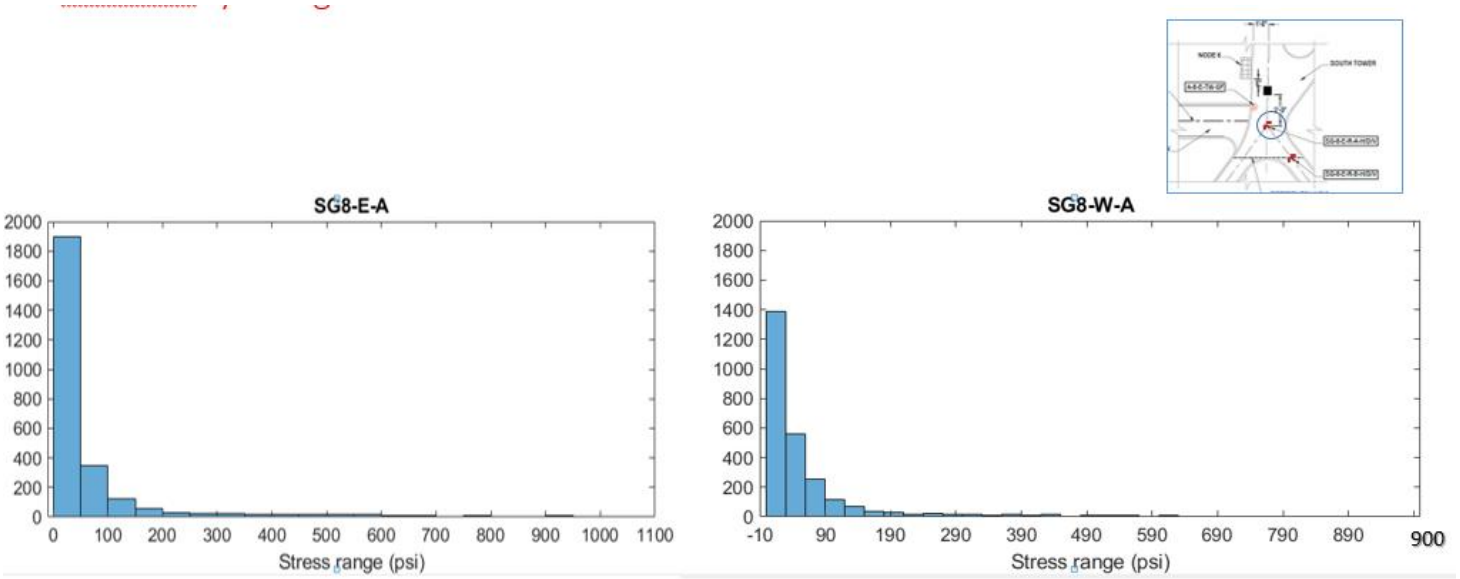


Figure 4 Stress Histograms for Fatigue Damage assessment at the Memorial Bridge

The fatigue damage response at the bridges measured through the field collected data has a variable property due to the variable amplitude of the traffic load and environmental excitations. Figure 5 show the variability in fatigue damage index over a six months data collection period. Acquiring variable fatigue damage responses from the multiple periods varying in time interval and duration, can make the method less reliable. Also, the application of the long periods of data collection for fatigue damage assessment, makes the method less-attractive for the short-term decision making programs on the fatigue life of the bridges. A framework is under development to for data collection for repeatable and reliable fatigue performance assessment. The framework will be completed by the end of this project.

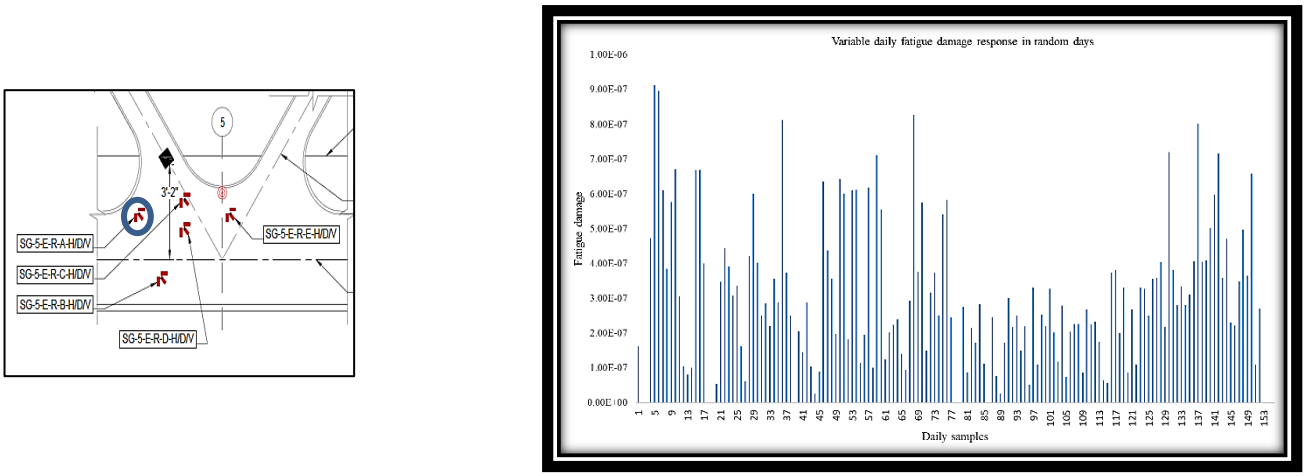


Figure 5 Fatigue Damage Index for the fatigue assessment at the Memorial Bridge

Progress of model updating, parameter estimation and condition assessment of the Memorial Bridge;
PhD candidate, Milad Mehrkash, developed an API MATLAB-based code to estimate the stiffness parameters of structures. At this step, this code can be used for updating the small-scale and mid-size structures. However, it is in progress to be able

to update stiffness parameters of the gusset-less connection of the Memorial Bridge at the end of the project. Also, the potential structural damage to the gusset-less connection of the Memorial Bridge was simulated in ABAQUS® model of the connection and LUSAS® model of the bridge, and the capability and robustness of the SAP2000® model updating procedure for the damage detection, localization and identification will be verified. Milad attended TRB 2018 Conference in Washington, D. C., January 2018 to present a literature review about modeling of complicated connections in structural and mechanical systems and propose a methodology for simplified modeling of the Memorial Bridge gussetless connections. Milad and Vahid developed a modal system identification program in MATLAB for extraction of the Memorial Bridge modal parameters from the monitoring data. In May 2018, Milad presented the results of this study in the Engineering Mechanics Institute (EMI) conference in Cambridge, MA. Milad's paper about local model updating of the Memorial Bridge gussetless connection was presented at the SMT & NDT-CE 2018 conference in New Brunswick, NJ in September 2018.

Postdoctoral research scholar, Vahid Shahsavari, developed an objective decision-making protocol for future condition assessment of the Memorial Bridge. The focus of this research is on long-term monitoring of the bridge behavior to train a baseline model in the early age of the bridge when the condition is undamaged. In January 2018, Vahid presented the preliminary results of his findings at the 97th Annual Meeting of Transportation Research Board (TRB), Washington D.C. The proof of concept is analytically verified to detect the change in structural performance due to abnormal events using finite element model of the Memorial Bridge in SAP2000®, resulting in a conference paper at the 27th American Society for Nondestructive Testing (ASNT) Research Symposium, Orlando, FL, presented by Vahid. In the last three months, Vahid and Milad collaborated on this subject and proposed a new approach to predict as accurately and efficiently as possible the degraded load carrying capacity of the bridge using the calibrated analytical model of the bridge in SAP2000®. A journal paper was submitted on this topic in August 2018. Vahid and Milad attended the 2018 ASNT Annual Conference in Houston, TX, October 2018 to present on the effect of simulated damaged members on the load carrying capacity of the Memorial Bridge. The proposed approach provides a realistic means to determine the members that are key to the overall system strength and should receive more attention by bridge owners and instrumentation engineers. According to this study, the top chords and diagonals of the Memorial Bridge were deemed crucial to keep the bridge remaining in service due to damaged-induced changes to its structural members.

Selected List of peer-reviewed publications:

1. Mashayekhi, M. and **Santini-Bell, E**.*(2018) "Developing three-dimensional multi-scale finite element model for in-plane service performance assessment of bridges" Computer-Aided Civil and Infrastructure Engineering, Published online 11/22/2018. https://doi.org/10.1111/mice.12424

Selected List of submissions and presentations:

- Milad Mehrkash and Erin Santini-Bell, Local Condition Assessment and Damage Detection of Gusset-less connections Used in a Vertical Lift Truss Bridge, 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure, St. Louis , MO, 2019 (full paper is under review).
- Milad Mehrkash and Erin Santini-Bell, System Identification of a Bridge Gusset-less Connection by Simplified and Detailed Local Analytical Models, NDE/NDT for Highway and Bridges: Structural Materials Technology (SMT 2018) and the International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE 2018), New Brunswick, NJ, 2018.
- Milad Mehrkash, Vahid Shahsavari and Erin Santini-Bell, Instrumentation Sufficiency of a Vertical Lift Bridge for Modal System Identification by Frequency Domain Analysis, Engineering Mechanics Institute Conference, Cambridge, MA, 2018
- Maryam Mashayekhizadeh, Erin Bell "Data Validated Multi-Scale Finite Element Modeling Protocol for Complex Connections of a Movable Bridge", Engineering Mechanics Institute Conference, Cambridge, MA, 2018
- Timothy Nash, Erin Santini-Bell, Milad Mehrkash and Vahid Shahsavari, "An Objective Decision Making Protocol for Lift Bridge Operation Subjected to High Wind Loads", Engineering Mechanics Institute Conference, Boston, MA, 2018.
- Chao Yang, Erin Santini-Bell, Vahid Shahsavari and Milad Mehrkash, "Probability-Based Demand Evaluation of the Bridge Tidal Turbine Deployment System Subject to Environmental Events", Engineering Mechanics Institute Conference, Boston, MA, 2018.
- Maryam Mashayekhizadeh, Milad Mehrkhash, Vahid Shahsavari, and Erin Bell, "Multi-Scale Finite Element Model Development for Condition Assessment of Vertical Lift Bridge", ASCE Structures Congress 2018, Fort Worth, TX, April 19-21, 2018.

- Milad Mehrkash and Erin Santini-Bell, “Modeling and Characterization of Complicated Connections in Structural and Mechanical Systems as Applied to a Gusset-less truss connection”, 97th Annual Meeting of Transportation Research Board (TRB), Washington D.C, 2018.
- Maryam Mashayekhizdeh and Erin Santini-Bell, “Influence of temperature on vibration-based structural health monitoring of a vertical bridge”, 27th ASNT Research Symposium, Orlando, FL, 2018.
- Vahid Shahsavari, Milad Mehrkash and Erin Santini-Bell, “Structural Health Monitoring of a Vertical Lift Bridge Using Vibration Data”, 27th ASNT Research Symposium, Orlando, FL, 2018.
- Vahid Shahsavari, “Long-Term Monitoring of Bridges under Operational and Environmental Variations”, The Transportation Research Board (TRB) 97th Annual Meeting, Washington, D.C., January 7-11, 2018.
- Vahid Shahsavari, Milad Mehrkash, Erin Santini-Bell, “Effect of Damaged Structural Members on Performance Degradation of a Vertical Lift Truss Bridge,” ASNT Annual Conference, Houston, TX, October 28-31, 2018.
- Milad Mehrkash, Vahid Shahsavari and Erin Santini-Bell, Instrumentation plan verification for damage detection of a vertical lift steel truss bridge, to be presented at SPIE Smart Structures and Nondestructive Evaluation, Denver, CO, March 3-7, 2019.
- Milad Mehrkash and Erin Santini-Bell, Finite element model updating of the UCF Grid benchmark connections using experimental modal data, to be presented at 37th International Modal Analysis Conference (IMAC-37), January 28-31, 2019, Orlando, FL.
- Milad Mehrkash and Erin Santini-Bell, Investigation of mode shape expansion and reduction techniques for model updating of a steel grid using experimental incomplete modal data, 2019 SEM Annual Conference, Reno, NV, June 3-6, 2019 (abstract is under review).
- Milad Mehrkash, Vahid Shahsavari and Erin Santini-Bell, Monte Carlo sensitivity analysis for local finite element model updating of a gusset-less steel truss bridge, ASNT Research Symposium, Garden Grove, CA, April 1-4, 2019 (abstract is under review).
- Vahid Shahsavari, Milad Mehrkash and Erin Santini-Bell, Progressive damage detection of a vertical lift steel gussetless truss bridge by wavelet analysis, ASNT Research Symposium, Garden Grove, CA, April 1-4, 2019 (abstract is under review).
-

Tidal Turbine Deployment System

The tidal turbine deployment system consists of vertical guide posts (VGPs) attached to the Portsmouth-facing side of Pier No.2 and a floating turbine deployment platform (TDP) on which a tidal turbine is installed and operated from.

The turbine was installed during June 6-8, 2018, and was operated for the first time in off-grid mode on the afternoon of June 8th. The UNH team spent the remainder of the summer operating the turbine in an off-grid mode while the team was present. The turbine was always removed from the water, when the team left the TDP. These tests were being performed to gain confidence in system operation to eventually operate the turbine in an unattended, on-grid mode. In August and September 2018, the adapter bracket was redesigned, fabricated and installed based on concerns related to excessive movement during turbine operation, see Figure 4 for original and revised adapter bracket. Bolts connecting the two piece generator housing were replaced with stronger bolts during the bracket replacement in October 2018.

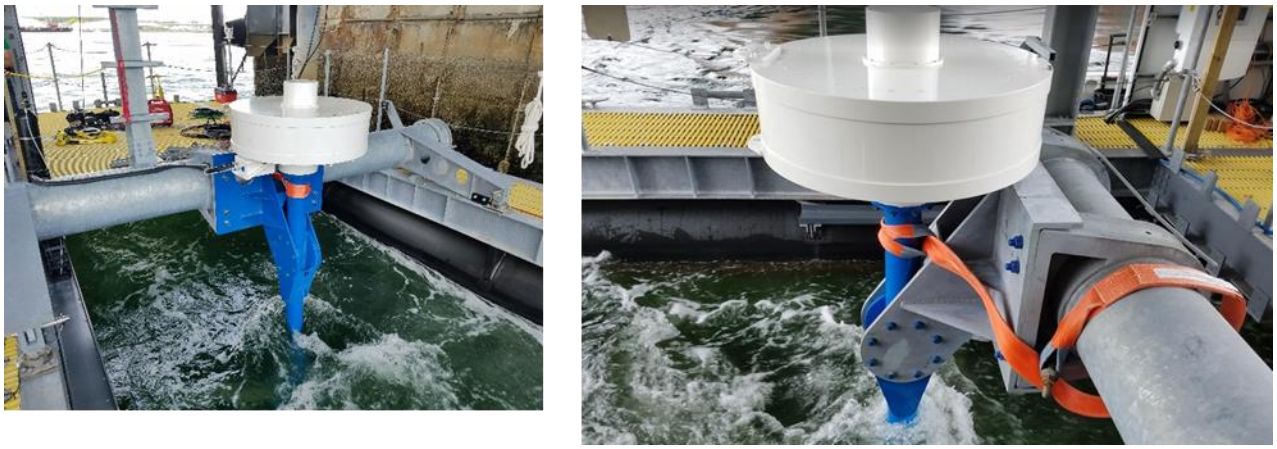


Figure 6: Turbine Operation at the Memorial Bridge (L) with original adapter bracket and (R) with the revised adapter bracket.

The grid connection application required by Eversource ("Interconnection Standards for Inverters Sized up to 100kVA: Simplified Process Interconnection Application and Service Agreement") was completed by UNH with all technical information, and sent to NH-DOT. The application was signed by NH-DOT and sent to UNH on 26 Sep 2018. The completed and signed application, together with the turbine interconnection electrical drawings, the technical specifications of the UL-1741 certified grid-compliant inverter (Solis), a photo of the inverter label with serial number (shown in Figure 7), a photo pf the Memorial Bridge electric meter, and the UL508-A turbine interface panel certification report were transmitted to Eversource on 27 Sep 2018.

The turbine was first connected to the bridge grid to test grid-connected operation on 25 October 2018. Jeff Stevens, Master Electrician, of Northeast Integration (NEI), the electrical contractor for Memorial Bridge, inspected and measured outputs on all connections and then connected the inverter to the bridge grid. Several settings on the rectifier and inverter needed to be customized for the application, these adjustments were made over the next few test runs of the turbines on follow-on dates in November and December. Trouble-shooting of inverter errors led to the discovery of a faulty relay; the inverter will need to replaced with a new one supplied by the inverter manufacturer under warranty. This process has been initiated and is being managed by NEI.

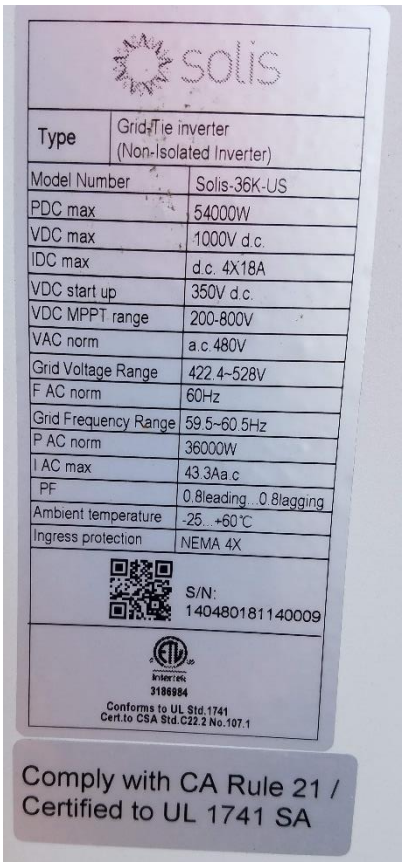


Figure 7: Label of the UL-1741 certified grid-compliant inverter (made by Solis), with serial number.

Items needed from NHDOT (i.e., Concurrence, Sub-contract, Assignments, Samples, Testing, etc):
UNH will need access protocols for the data closet at the bridge for maintenance of the data acquisition system.

UNH would like to repeat the load test again in March/April 2019 and will require the NHDOT approval and support for the load test.

NHDOT has provided approval for the grid connection of the tidal turbine. Martin Wosnik is work with Robert Spinney at for connection.

Anticipated research next 3 months:

Benchmark for Bridge Monitoring:
The integration of the structural health, mechanical operation and environmental instrumentation the sensors for remote access is complete. A trigger program has been established in March 2018 to trigger tentatively mechanical information. The proposed trigger protocol has been working efficiently so far. The event data files will be evaluated to refine the trigger limits.

The validation of the structural models of the Memorial Bridge in Lusas® as well as local model of selected gusset-less connections at the Memorial Bridge with respect to collected data in Fall 2017. Calibration of the structural models for condition and performance assessment with respect to design verification. These models have been preliminarily verified and are being used for condition assessment and operational decision making protocols.

Tidal Turbine Deployment System
The deployment of the tidal turbine deployment platform (TDP) with estuarine sensors at the Memorial Bridge occurred in June 2017. The TDP was move to the UNH Pier for installation of the pitch mechanism in late 2017. The installation of the tidal turbine on the deployment platform was completed in June 2018, with power and communication connection installed in June 2018 by NEI.

NHDOT SPR2 PROGRAM
RESEARCH PROGRESS REPORT

The New Energy turbine was delivered in June 2018. It was mounted to TDP and then towed to the bridge. Strain data are being collected from the sensors on the vertical guide posts. Commissioning and initial testing was started in June 2018 and gird connection was planned for October 2018 due to a faulty inverter this connection was delayed and is planned for Spring 2019. The inverter was returned to the manufacturer for repair and is expected to be replaced in early February 2019. UNH will operate this particular turbine for the duration of approximately one year as part of this project, provided operation and maintenance through the seasons prove feasible at reasonable effort and cost

NHDOT SPR2 PROGRAM

RESEARCH PROGRESS REPORT

Circumstances affecting project: Describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope, and budget, along with recommended solutions to those problems.

As described in the "Progress this Quarter" section of this report, the schedule delay and increased cost related to the electrical conduit negatively impact this project.

Tasks (from Work Plan)	Planned % Complete	Actual % Complete
Living Bridge: Creating a Benchmark for Bridge Monitoring		
Project Coordination	**100**	**100**
Structural Model Creation	**100**	**100**
Design the instrumentation Plan	**100**	**100**
Sensor Deployment	**100**	**100**
Data Collection and Model Calibration	**95**	**95**
Trigger Protocol	**100**	**100**
Incorporation of collected data and model into NHDOT protocols	**90**	**90**
Final Report and Adoption Recommendation	**0**	**0**
Tidal Turbine Deployment Structure		
Deployment Structure Design	**100**	**100**
Project Permitting	**100**	**100**
Installation of Support Posts	**100**	**100**
Procurement of the Turbine deployment platform	**100**	**100**
Site Installation	**100**	**100**
Electrical Connection	**100**	**90**
Final Report and Poster	**0**	**0**