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Virtual Laboratory for leveraging technology for bridges and constructed systems

Emin Aktan[1], Ivan Bartoli[1], Franklin Moon[2], Marcello Balduccini[3], Kurt Sjoblom[1], Antonios Kontsos[4]
Hoda Azari[5], Matteo Mazzotti[1], John Braley[2], Charles Young[1], Shi Ye[1] and Andrew Ellenberg[4]

[1] Civil, Architectural and Environmental Engineering Department, Drexel University - Philadelphia, PA, USA.
[2] Civil and Environmental Engineering Department, Rutgers University - Piscataway, NJ, USA.
[3] Computer Science Department, Drexel University - Philadelphia, PA, USA
[4] Mechanical Engineering and Mechanics Department - Philadelphia, PA, USA
[5] Federal Highway Administration

ABSTRACT

The writers are exploring the development of an innovative and adaptive resource for highway bridge owners, managers, engineers as well as technicians from non-destructive testing (NDT) and structural health monitoring (SHM) industries and the public. The primary objective is an official Federal Highway Administration (FHWA) website offering guidance and training on how technology tools may be selected and applied with sufficient depth to generate reliable and actionable information. Currently a large number of technology tools in the realm of "information, communication, computing and data technology," "software for modelling and analysis of multi-physics phenomena and civil engineering systems," "sensing, imaging and non-destructive probing," and, "uncertainty and risk analysis and decision-making" are available for off-the-shelf purchase or applications by consultants. However, there are very few institutions that offer an ability for an integrative leveraging of such tools and the resulting data in conjunction with engineering heuristics for meaningful, feasible and effective solutions to infrastructure performance problems.

Users will be exposed to the challenges of designing field experiments, integrating, visualizing and interpreting data, information, simulation results as well as heuristic knowledge for identifying and understanding the root causes of condition defects and deterioration as well as performance shortcomings. Explanations will feature both case studies and computational simulation tools that employ multi-physics software to generate more interactive and in-depth visualizations than possible with field data alone. How various probes may offer information regarding invisible defects and deterioration will be shown along with training exercises for aspiring NDT and SHM engineers.

Given that vibration analysis is a common approach to SHM, and that many NDT techniques leverage vibrations caused by different physics at multiple scales, this paper will focus especially on vibration analysis case studies that are being developed as content for the website.

Keywords: Virtual Laboratory, bridge assessment, vibrations, structural health monitoring, non-destructive testing, training

INTRODUCTION

There is a growing consensus on the need to make a transition to data driven objective decision making in the realm of managing highway infrastructures. Achieving this will require the use of sensing, simulation, and information technologies to obtain, visualize and interpret quantitative performance data. Furthermore, robust and effective leveraging of technology demands proper policy, best practice standards, and also presupposes a profession with the requisite education/training. Along with these prerequisites, there is also an opportunity for a "gathering place" to help develop a community of highway infrastructure researchers, practicing engineers and professionals in technology to exchange ideas and contribute to best practices.

Within this context, the FHWA Exploratory Advanced Research Program has sought the development of an interactive Virtual Nondestructive Evaluation Laboratory for Highway Structures with the following overarching goals:

- Permit users to explore various NDT and SHM technologies in a holistic manner - inclusive of fundamentals of field experiment design, data collection and archival logistics, data processing, visualization, and interpretation.
- Offer realistic NDT and SHM case studies that expose users to decision scenarios related to the design and deployment of various NDT and SHM applications following best practices
- Provide a platform for the development of training and certification programs for the deployment of NDT and SHM technologies.

BACKGROUND

The authors are particularly interested in how constructed systems such as bridges should be inspected and their condition and performance measured objectively by technology leveraging. Objective data will enable condition and load capacity evaluation, maintenance, repair, retrofit or renewal decisions and designs to be integrated in the context of asset management. However, decision making by objective data from technology leveraging can be challenging and requires a systems approach and integration of more than one technology domain (for instance knowledge in bridge behavior, NDT, field testing using sensing and imaging, information technology, modelling and simulation, decision theory, organizational and consultant qualifications).

From the authors' perspective, the following items are offered as a set of prerequisites needed for comprehensive applications of technology:

(a) **Bridge heuristics** – i.e. observation-based understanding of how bridges are loaded, behave, carry their loads, and how various elements of a bridge work as a system. It takes a solid engineering education followed by many years of apprenticeship in design and field inspections to accumulate reliable heuristics. In the last several decades the community has lost many engineers whose heuristic knowledge was not captured and archived by proper applications of knowledge engineering.

(b) **Experimental arts, information technology, and logistics** – To deploy technology, inspectors must have the physical and engineering skills required for climbing a bridge safely, and the ability to install sensors and cameras for capturing critical responses over various time scales to understand the operational responses and live load environment. Current developments with wireless sensing and imaging appear likely to offer reliable measurements of loads and responses over days and even years within the near future.

Progress in Digital Image Processing (DIP) in mapping deterioration and cracks invisible to naked eye and attempts to integrate such advances in robotic platforms (unmanned aerial systems) will affect bridge assessment in the near future. Similarly, inspectors will have increasing access to portable technology (google glass or other advanced tools) and be able to share in real time information on the deterioration and defects they are observing to discuss possible causes and implications with an experienced engineer with heuristics.

The prerequisites to perform the next generation of bridge inspections include a grounding in experimental arts in the laboratory, and an ability to collect measurement data from the correct members and locations. Ideally, inspectors should be engineers, likely with an advanced degree. However, since it will be hard to have such qualifications for each bridge inspector, it would be desirable to take advantage of bridge "type-specific" inspections once every five years, unless warranted by the importance, design and construction details of a structure. Type-specific inspections would be designed and executed after collecting information on bridges that carry their loads by similar structural systems and mechanisms, such as "simply-supported" or "continuous multi-span" or "integral-abutment" RC deck on steel-girders.

(c) **Modeling and Simulation** – Current bridge engineering applications are not always grounded in a correct understanding of how structures should be modeled, and how these models may be calibrated by a number of images and strategically measured responses from the field. However, it is expected that every bridge engineer in the near future will be able to perform 3D FE modeling and analysis, which is essential for design of sensing, and interpretation of measured responses. Software for quick and complete 3D geometry capturing of actual as-built bridge geometry (LIDAR, Photogrammetry, etc.) is also becoming widely available, and this should make having a virtual twin of every bridge possible even today.

(d) **Decision Theory** – Decision theory includes reliability, uncertainty and risk analysis as well as optimization and decision-making under uncertainty. Engineering design skills are critical and necessary in addition to decision theory for making sound and prudent decisions involving economics and public safety.

(e) **Business Case, Organizational and Consultant Qualification** – Organizational leadership and culture are especially critical if the community wishes to transition from the current empirical approaches to one that properly leverages heuristics and relies on objective measurements for bridge management. Currently there are signature bridges that cost billions of dollars and with many performance concerns that are not leveraging technology, while other structures are monitored without a valid business case, and without any value to the bridge owner.

The principal objective of the Virtual Laboratory is therefore to facilitate technology leveraging by proper integration of the domains discussed above and by providing scenarios including a business case. The integration may be carried out by considering the framework represented in Figure 1.

The primary fields of the framework (Table columns) are:

1. **Objective + Heuristic inspection and evaluation of condition and performance** of a bridge. Clear understanding of operational loads and responses, in addition to boundary conditions and continuity between spans, superstructure and substructures. If warranted, foundation diagnostics should be included.

2. Objective and Quantitative Capturing of **Geometry and Material Properties**.
3. Structural-Foundation-Soil Modeling and **System Identification (i.e. model validation and calibration)** by leveraging measured data from operational monitoring, NDT and controlled testing.
4. Prognosis, Condition, Capacity and **Risk Assessment and Design of Corrective Actions**.
5. **Performance and Health Monitoring** – including Operational, Serviceability, Durability, Security, Safety and Resilience Monitoring.

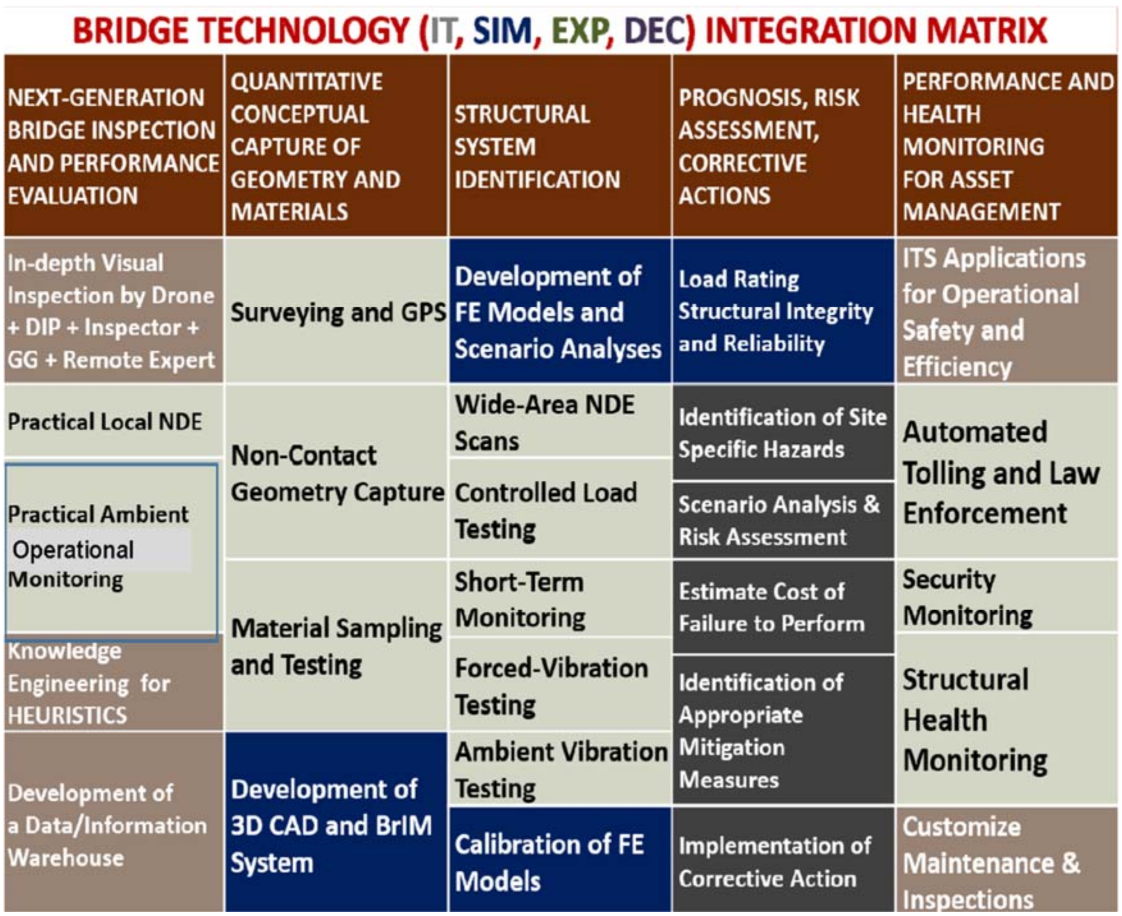

Figure 1. Integration of technology to support the decision making process for highways structures preservation (this figure outlines the proposed framework in a chronological order (from left to right))

Each application may require some or all of the steps illustrated in Figure 1, depending on the business case. If a Department of Transportation (DOT) is interested in a bridge type-specific study on a sample of a large population of bridges, each and every step may be justified. A one-time application to a one-of-a-kind bridge may not require many of the steps. A major toll crossing may justify the investment into the application of the entire set of steps in Figure 1.

The writers have explored the challenges and advantages of technology leveraging by applications to both long-span signature crossings as well as bridge type-specific applications [1-7], and aim to design and construct the proposed virtual laboratory based on these experiences.

VIRTUAL LABORATORY FOR LEVERAGING BRIDGE ASSESSMENT TECHNOLOGY

A mock-up of the envisioned gateway to the Virtual Laboratory website is shown in Figure 2. To provide some structure the website is organized into three areas that represent the different users and their distinct ways of interacting with the website. First, decision-makers would enter the website through the "decision scenarios" pathway that would present realistic scenarios (inclusive of goals, constraints, etc.) to illustrate the potential trade-offs and strategies that can be employed when contemplating a technology deployment. Second, the technical details associated with the four primary categories of Non Destructive Evaluation (NDE) approaches and their integration is provided. This will include general descriptions of various methods within each category with references to the NDE Web Manual (see fhwaapps.fhwa.dot.gov/ndep/) [8], interactive lab experiments, and interactive field applications. Third, the "Simulation and Sensor Lab" pathway will provide technical details for the various tools and methods as a reference for all users.

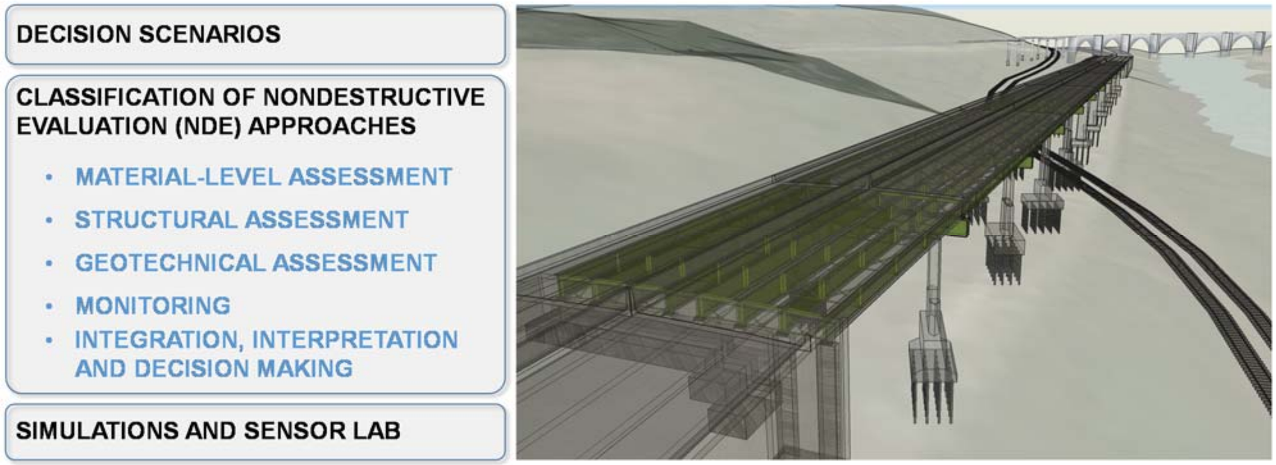

Figure 2. Mock-up portal of the Virtual Laboratory

Case studies with applications of SHM and NDE will be included in the Virtual Laboratory. An example is provided here showing the Operational Monitoring Application to a Reinforced Concrete (RC) Deck-on-Steel Girders Viaduct.

Decision Scenario: Operational Monitoring Application to a RC Deck-on-Steel Girders Viaduct

The viaduct carrying I-76 approaching Philadelphia (Figure 3) was first constructed in 1952, and the superstructure was replaced in 1986. The structure has 11 spans running alongside the banks of the Schuylkill River, carrying two lanes of traffic in each direction. The viaduct is congested during daytime, and it has been reported to carry about ~100,000 vehicles per day with ~4% being trucks. The DOT has been exploring whether it is possible to reconfigure the lanes and shoulders to fit 6 traffic lanes during rush hour. Meanwhile, there have been many calls from motorists reporting unusual levels of vibration on the viaduct. The District Bridge Engineer has been concerned about the performance of the viaduct and when the opportunity arose, requested the research team to evaluate the structure.

Figure 3. Operational Monitoring Application to a RC Deck-on-Steel Girders Viaduct

Structural System

The Viaduct was designed to leverage existing piers (from a previous bridge) which were supported on piles except for some directly supported by pre-existing masonry structures underneath. Pier heights were adjusted by pouring extensions where needed, and rectangular closed steel box cross-girders were placed on piers to serve as pier-caps. Each traffic direction is carried by 4 built-up steel girders that are supported on the cross-girders as shown in Figure 4, while the two directions of the bridges feature separate RC composite decks that are NOT laterally connected. The girders are continuous over every other pier but are simply supported at the other piers, creating a sequence of two span continuous sections (Figure 4).

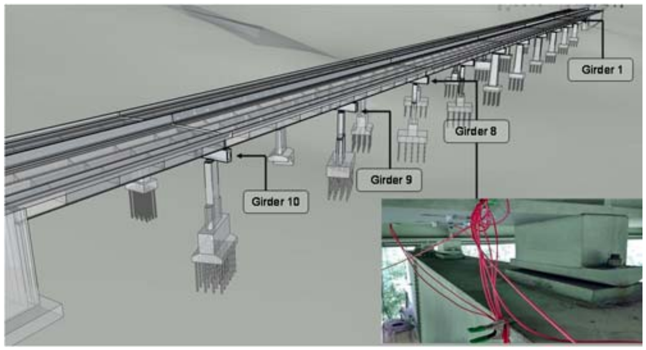

Figure 4. RC Deck-on-Steel Girders Viaduct geometry

Structural Assessment

Given the difficulty of accessing the driving lanes of the viaduct which could not be closed to traffic during the day, researchers decided on monitoring the operational responses of the superstructure, cross-girders and piers to identify the spans with the largest vibration. This study indicated that the superstructure elements (deck and girders), the cross-girders and the piers all exhibited varying levels and nature of vibration. The largest vertical vibrations at the cross-girder and superstructure were measured under Spans 7 and 8 exceeding 0.1g at the cross-girder and about 0.3g under the superstructure. Therefore, a longer duration of monitoring with a dense array of 30 accelerometers under Spans 7 and 8 as well as 12 Vibrating-wire strain gages was undertaken. The instrumentation plan is shown in Figure 5.

A finite element (FE) model of the bridge was constructed to assist in the design of the sensing system. Locations of maximum acceleration for the structure's natural modes of vibration were determined by running a linear dynamic solver on the model. The sensor layout was designed based on these locations so that the major modes of vibration could be uniquely captured. This resulted in a dense sensor layout on one of the instrumented spans. A power line running beneath the other span restricted access to much of the span, and thus a sparse sensor layout was employed.

Several sensors were also installed on the piers and box cross girder to investigate any relationship between the substructure and superstructure motion (Figure 5).

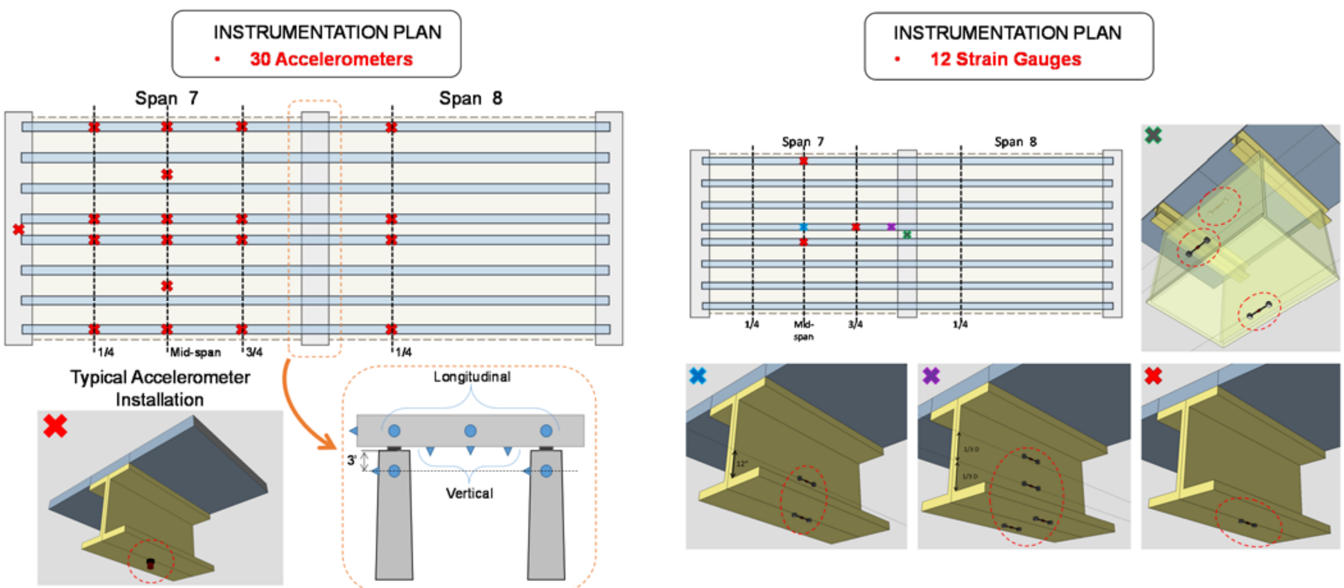

Figure 5. Viaduct vibration study instrumentation plan consisting of dense array of accelerometers and strain gages

Acceleration data was sampled at 200 Hz which allows for identification of modes of vibration as high as 100 Hz. The acceleration data was analyzed using Fourier transformation methods to extract information about the acceleration at specific frequencies. Several modes of vibration were found at frequencies below 5 Hz.

Figure 6(a) shows the power of each frequency. The peaks in the plots are poles where a mode of vibration is located, and for this structure, a natural frequency. In some instances, poles are at very similar frequencies and the separate peaks cannot be easily distinguished. This is due to the geometry of the structure (high degree of symmetry) and the fact that there are essentially two identical bridges adjacent to one another. The main modes identified consisted of bending and torsional modes. For these modes, the mid-span degrees of freedom are experiencing the greatest acceleration.

The vibration of the box cross girder shown in Figure 6(b), which is of principle concern due to its fracture critical designation, experiences several modes of vibration between 10 and 15 Hz. However, the magnitude of vibration is much less than that experienced by the superstructure, and the box girder participates very little at the superstructure modes of vibration.

A total of 12 strain gauges were installed and data recorded for more than 24 hours. Gauges were sampled at 50 Hz which allowed us to characterize the dynamic strain that the structure experiences under operational conditions.

Strain gauges located at the center of the span frequently recorded strain levels in excess of 100 microstrain (~3 ksi) throughout the 24 hour recording session, even during the middle of the night. Occasional responses as high as 200 microstrain (~6 ksi) were recorded in the bottom flange of longitudinal girders at mid-span. In comparison, the expected strain from an AASHTO HL-93 truck (with lane load) is 150 microstrain (~4.5 ksi), based upon finite element modeling and analysis of the structure.

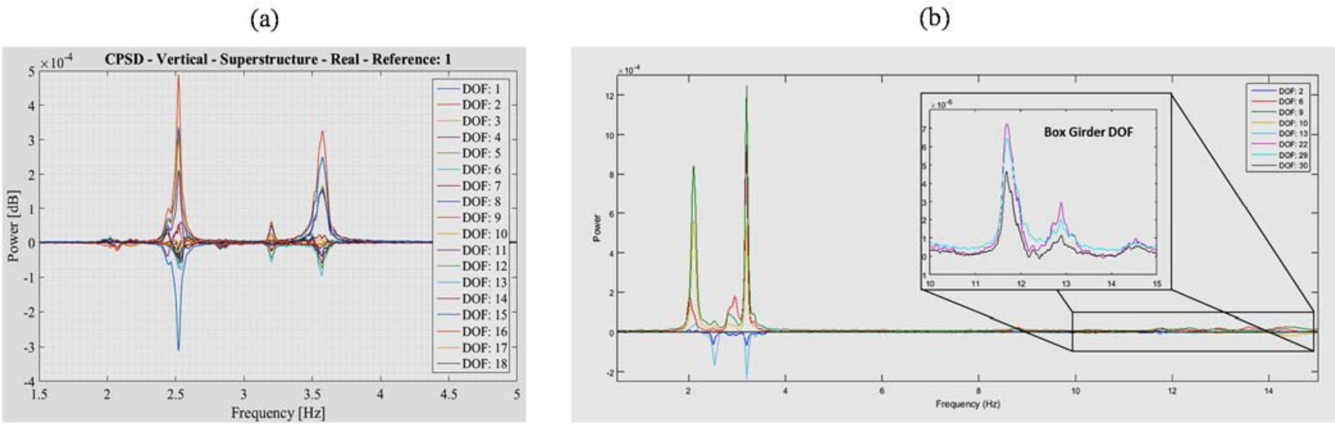

Figure 6. (a) Cross Power Spectral Density of Superstructure Degree of freedoms (DOFs); (b) CPSD of Box Girder DOF and Select Superstructure DOF

The maximum response recorded on the box cross girder was -92 microstrain (~2.7 ksi) on the top and 92 microstrain (~2.7 ksi) on the bottom. While no gauges were installed on the concrete deck, in two locations multiple gauges were installed at varying heights on the girder cross section, allowing the strain profile to be captured to extrapolate the deck strains assuming composite behavior. It was found that the deck in the positive moment region may be frequently experiencing tension as high as 100 microstrain which would correspond to a stress in excess of 300 psi. This level of frequent and cyclical stress in concrete could potentially cause cracking. These cracks would allow faster chloride ion intrusion, hastening corrosion of the reinforcement.

The strain data was further analyzed by applying a low pass filter to remove the response associated with frequencies above 1.5 Hz, thus permitting the dynamic response of the bridge to be removed from the data and only the static response of the bridge to be estimated. The plot of both the full response and the static (filtered) response is provided in Figure 7. The portion of strain due to the dynamic response of this structure is significant. Figure 7 time history was recorded during a large event. The static response accounts for over 100 microstrain, but the vibration of the structure causes the total response to exceed 200 microstrain. For this event, an amplification of the static response by approximately 75% is observed. In comparison, the amplification applied for bridge design is, at most, 33%. This level of amplification is on the upper end of what researchers and transportation organizations have measured. However, the fact that the high amplification occurs regularly and even with large events, makes the nature of this bridge's response quite novel.

Discussion

The relatively high magnitude of vibration experienced by this structure is likely due to a number of factors. The long span length and continuity create a flexible bridge that can be excited for a longer period of time by the vehicles crossing it. The dynamic characteristics of the structure may also be playing a role, where the loading frequency applied by the traffic is close to some of the bridge’s natural modes of vibration. Furthermore, the viaduct spans leading up to the monitored spans may be experiencing an amplifying vehicle-bridge interaction, effectively conditioning the frequency of the vehicle loading to be in tune with the structure.

The high levels of vibration are not considered a safety concern unless they impact drivers. The operational strains, while larger than predicted and greatly magnified by dynamic effects, are still well below stress and fatigue limit states. However, even though the bridge has sufficient capacity, the long term durability of the structure is questionable. The tensile stresses in the concrete deck at mid-span are close to the tensile capacity of the material, and thus may be causing cracking, accelerating corrosion and degradation.

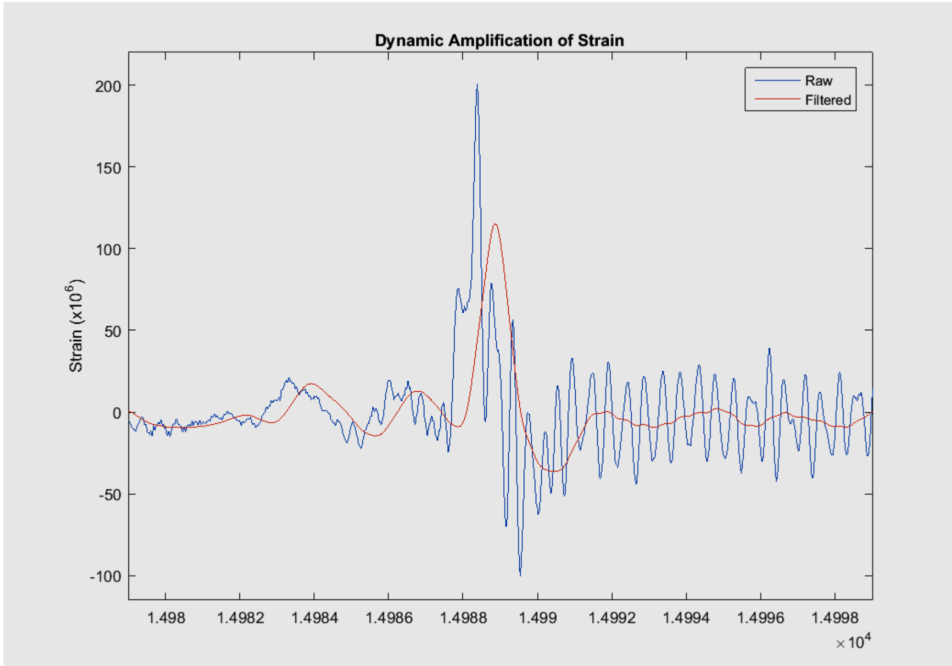

Figure 7. Dynamic Amplification of Strain

Visual inspection of the viaduct was conducted in April 2017 and researchers were able to perform NDE scans to check the deck for cracks and possible delamination during the inspections. The NDE results will be presented in the Virtual Laboratory as a case study.

Material Level Assessment

In the presentation of NDE methods and results obtained from field applications as discussed in the previous section, the Virtual Lab will often refer to the FHWA NDE Web Manual (see fhwaapps.fhwa.dot.gov/ndep/) that provides a powerful way to select NDE technology based on type of material, structure element and target of investigation as well as a description of the different NDE techniques [8].

The NDE portion of the virtual lab will give the users a progressive exposure to the concepts and physics behind each relevant NDE method using Multiphysics simulations, experiments executed in the laboratory and NDE data collected in the field. An additional component of the lab will also look into strategies to perform NDE data integration/fusion (meaning the fusion of data coming from different NDE methods), to facilitate asset management strategies and asset owners decision making.

Simulations of NDE applications often require the solution of complex sets of differential equations with numerical techniques such as Finite Element Method (FEM), Finite Difference method (FDM) and others. Any simulation that will appear on the Virtual Laboratory will be validated with ad hoc experimental testing following strategies similar to the ones used in structural identification.

As an example, finite element method simulations have been used to demonstrate the effect of heat transfer in bridge structural elements such as bridge decks to observe the presence of damage (i.e. delaminations). For instance, to introduce the concept of heat transfer and infrared (IR) thermography to Virtual Laboratory users, the heat transfer is predicted using Abaqus on a 20cm thick square concrete specimen (60cmx60cm) including delaminations simulated by 3mm thick foam inserts (15cmx15cm in plan dimensions) subject to controlled heat radiation (similar to sun radiation). Figure 8 shows the reinforced concrete block with the 3 foam delaminations depicted (Figure 8a).

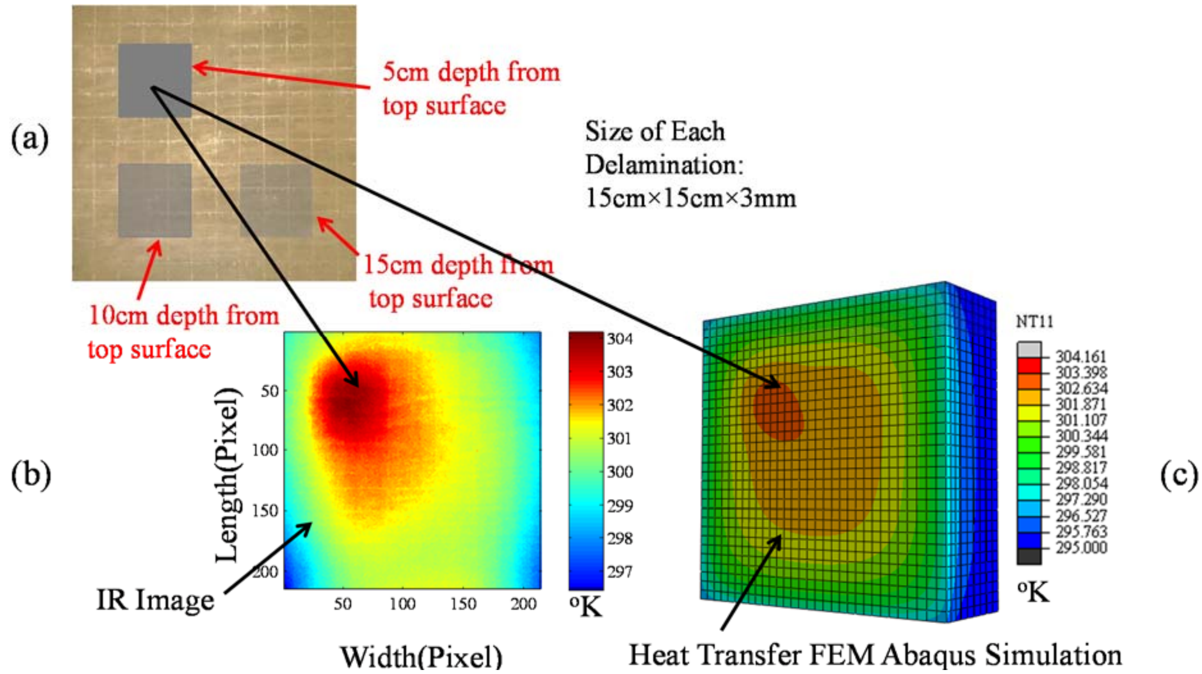

Figure 8. NDE Simulations: IR and Heat Transfer (FEM simulation example and experimental validation)

After 2 hours of heating provided by a set of heat lamps, only the shallow delamination is visible in both the validation experiment, where heat maps are extracted using a FLIR SC325 infrared camera (Figure 8b) and in the Abaqus FEM simulation (Figure 8c). The effect of the shallow delamination (5cm deep) is a small increase of the surface temperature above the foam inclusion (that slows the heat transfer process occurring inside the block). From this experiment and simulation, the Virtual Laboratory user can: (1) begin to understand the difficulty to observe deep delaminations within such a specimen using IR, (2) appreciate the delay between the initiation of the heating process when the lamps are turned on (or when the sun begins irradiating the surface of the bridge deck), and the appearance of temperature gradients on the deck surface, and (3) comprehend the 3D nature of the heat transfer process.

Another NDE approach that is commonly considered to unveil delaminations in bridge decks is the impact echo (IE) method. In this approach, a small impactor generates high frequency vibration in the concrete material (few tens of kHz). The stress waves induced are a combination of surface waves, P waves and S waves traveling within the material [8]. A sensor placed in the impact position is used to record the local displacement or acceleration. The presence of delaminations significantly alter such responses since the principle resonance observed, caused by the repeating reflection of the P (longitudinal wave), and observed in the frequency domain, changes. In fact, due to the mismatch in impedances at the delamination locations, the wave scatters when it reaches the delamination and the P wave path increases, increasing the round trip of the P wave (and decreasing its resonance frequency). Also, a P wave reflected by the delamination (with a short round trip time) causes a higher frequency peak to appear in the frequency domain. Furthermore, for large delaminations, a plate mode (where the plate is the region of concrete between the delamination and the surface) is excited, and appears in the frequency domain as low frequency resonance.

These phenomena are the core of the IE method and while it is well accepted by the industry and researchers, the Virtual Laboratory will attempt to introduce it to DOT personnel. To achieve this goal, simulations such as the one shown in Figure 9 will be leveraged to explain the physics behind the approach and gradually introduce the users to approach. Specifically in Figure 9 the response of a displacement sensor during an IE test is simulated together with the stress distribution created by the IE wave travelling within the thickness of a concrete slab that has a 10cm delamination at 5cm from the deck surface.

A large number of simulations such as the one shown here, will allow the users to comprehend the IE approach, get familiar with common signals recorded during a test, visualize the effect of geometry, size and location of the delaminations, and appreciate the effects of different probes and their location.

Simulations will be only a portion of the Material Level assessment NDE Virtual laboratory and will be extended to a number of methods such as the ground penetrating radar [8] and other NDE techniques. For each NDE method, after an introduction to simulated ideal NDE scenarios created using FEM tools, the user will be exposed to experiments of progressively increased difficulty in the laboratory. In the laboratory, specimens of known characteristics with defects of known properties will be used and actual NDE signals will be recorded. Finally, Virtual Laboratory users will be exposed to NDE data collected in the field, where the presence of operational variability and environmental factors can make the application of any NDE technique increasingly complicated and reduce its effectiveness.

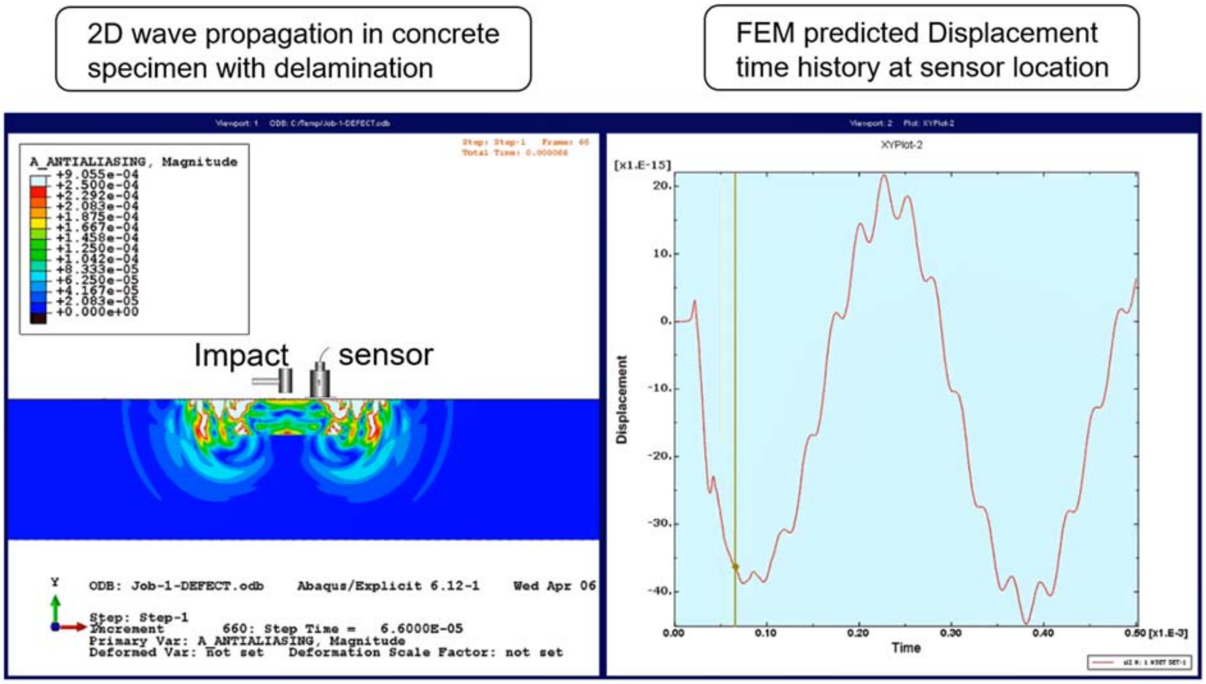

Figure 9. FEM simulation showing the response of a displacement sensor during an IE test (right plot) and acceleration amplitude induced by the IE wave travelling within the thickness of a concrete slab that has a 10cm delamination at 5cm from the deck surface

CONCLUSIONS

This paper discusses the development of a Virtual Laboratory to expose its users to the application of NDE and SHM into asset management of highway bridges. If successful, the resulting Virtual Laboratory website will serve infrastructure stakeholders such as highway asset owners, DOTs, industry users and researchers.

A "decision scenarios" pathway will present realistic scenarios (inclusive of goals, constraints, etc.) to illustrate the potential trade-offs and strategies that can be employed when contemplating a technology deployment in highway bridges. Second, the technical details associated with four primary categories of NDE approaches (material, structural and geotechnical assessments as well as monitoring strategies) will be provided in the Virtual Laboratory. This will include general descriptions of various methods within each category, interactive lab experiments, and interactive field applications. Finally, the "Simulation and Sensor Lab" pathway will provide technical details for the various tools and methods as a reference for all users.

In this paper an introduction to the Virtual Laboratory concept is provided, by first showing an example of decision scenario where a DOT may leverage technology to assess vibrations on a viaduct, presenting the results from the vibration monitoring of the structure and finally introducing selected NDE approaches that could assess the consequences of deterioration as well as performance deficiencies in bridges.

The virtual lab will provide an environment to train and educate the direct users of NDE technologies (technicians, engineers, etc.) as well as guide the decision-makers that will integrate technology deployments within their management practices (to better meet agency goals). In addition to these distinct, but related, educational objectives, the Virtual Lab could offer the base to develop universal certification programs to enhance QC related to technology applications.

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