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TITLE

Reference-free displacement estimation for structural health monitoring of railroad bridges

AUTHORS

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ABSTRACT

This paper investigates a means for reference-free estimation of the displacements of railroad bridges under train loading. The authors carried out field monitoring campaigns for two class I railroad bridges using both wired and wireless sensors. This paper presents the goals, assumptions, and limitations found during each field experiment, including challenges found in deploying sensors to successfully collect data under both work trains and regular traffic. Use of the estimated displacement as a performance indicator for each bridge is also discussed. Results include data processing, displacement estimation experimental validations, and conclusions

suggesting additional work for developing structural health monitoring (SHM) of railroad bridges using wireless smart sensors.

INTRODUCTION

The railway community is paying increasing attention to structural health monitoring (SHM) to improve bridge safety and performance (Otter et. al. 2012). SHM means and methods have been substantially developed during the last 10 years. In particular, wireless smart sensor hardware and software are becoming more effective and affordable for infrastructure owners (Spencer et al. 2011). Bridge engineers are now interested in using these tools to provide useful information about the condition of their bridges. As a result of new federal regulations (FRA, 2010), AREMA has included a new section called "Guidelines for the Development of Bridge Management Programs" in their 2012 manual for railway engineering (AREMA, 2012).

In 2011, a survey of North American railroad bridge structural engineers determined that the top bridge research priority is to measure bridge displacements under train loads (Moreu and LaFave, 2011). Additionally, engineers are interested in determining which specific locations should be chosen to collect displacements, based on different railroad bridge types (Moreu et al. 2012). This paper presents displacement measurements for a timber bridge under different train loadings and provides preliminary results from data collected from a steel fixed Whipple truss; both bridges are for Class I railroads. Secondly, this paper presents experimental validation of a reference-free displacement estimation algorithm using measured accelerations. The potential for wireless smart sensors to collect and estimate displacements from accelerations is also discussed, as well as a description of their capabilities and potential for railroad bridge maintenance. Finally, results, conclusions, and future work are presented.

Importance of Measuring Reference-Free Displacements for Railroad Bridges

While the railroad bridge structural engineering community has demonstrated interest in using bridge displacements as an indicator of serviceability, such displacements are typically quite challenging to collect. Current displacement measurement methods require a fixed point from which to measure (e.g., using a linear variable differential transformer, LVDT) to provide a "relative" displacement with respect to the ground. Providing a fixed point is usually prohibitively expensive, and depending on the bridge type and site conditions (e.g., large spans over wide rivers), may even be impossible. On the other hand, accelerations are easy to collect (i.e., they do not require a fixed reference point from which to measure). Estimation of displacements from accelerations is proposed in this paper, and validation experiments for two Class I railroad bridges are presented.

Displacement estimation algorithm

Multiple attempts have been made in recent years to estimate displacements from accelerations for various applications in civil engineering (Yang et al., 2005; Gindy et al., 2008). Such studies typically estimate displacements from acceleration using double integration methods. This paper presents experimental validation of a displacement estimation method proposed by Lee et al. (2010). Their method estimates the displacement \ minimizing the difference between the double derivative of the displacement and the acceleration within a finite time interval. Validation of this method has been done in laboratory testing by using wireless smart sensors (Park et. al. 2011) and has the potential to be used in the field for direct estimation of railroad bridges deflections under train loadings. Consequently, this approach has been chosen to investigate herein.

Wireless smart sensors for acceleration collection and displacement estimation have numerous advantages for railroad bridge monitoring. Wireless smart sensors can be installed at multiple locations without the need of wires or an external power source as they have their own batteries. They can “sense” bridge accelerations, but can also collect bridge strains wirelessly. Consequently, this paper also presents displacement estimations from wireless acceleration collected under trains, as well as a brief description of the use of wireless sensors for bridge campaign monitoring. A description of the wireless sensors used for the bridge monitoring presented in this paper follows below.

Wireless Smart Sensor Description

SHM using wireless smart sensors is a promising alternative to the traditional wired approaches. The smart sensors are typically small, inexpensive, and capable of wireless communication and onboard computation (Spencer et al. 2004), addressing many of the concerns regarding wired monitoring. The Illinois Structural Health Monitoring Project (ISHMP 2012) has been developing hardware and software for the continuous and reliable monitoring of civil infrastructure using networks of Imote2-based wireless smart sensors. The open-source software library of customizable services, developed under the ISHMP, implements key middleware services necessary for high-quality sensing, synchronized and reliable network operation, as well as high-level application services, tools, and utilities (Rice and Spencer 2009). The developed sensor boards for the Imote2 platform provide high-sensitivity acceleration and strain measurements and accommodate signals from other analog/digital sensors (Jo et al. 2011). The Imote2 sensor platform, the Illinois SHM-A board, and the sensor enclosure assembly used for this experiments, are shown in Figure 1.

Figure 1. (a) ISM400 board stacked on Imote2, and (b) sensor enclosure assembly.

SHM OF A RAILWAY TIMBER TRESTLE

Bridge Description

The existing bridge consists of one 80 ft deck-plate girder supported on two reinforced concrete piers with eight panel timber ballast deck approach trestle on each end. The total length of the structure is 289 ft from abutment to abutment (see elevations of the bridge in Figure 2).

Figure 2. Bridge elevation view and picture.

Monitoring Opportunity and Planning

The CN railway planned to replace the old timber trestle bridge with three new deck-plate girders supported on new steel H-piles. Contractor forces and construction equipment and machinery were mobilized at the bridge site for a period of several months during the construction of the new bridge. Additionally, a flagman provided continuous track protection at the bridge. These circumstances created a good opportunity to access the old bridge and install appropriate instrumentation. The CN bridge personnel teamed up with the authors and collected displacements and accelerations with their equipment, as well as providing electricity and assistance to the Illinois team. The Illinois SHM team planned the monitoring campaign in coordination with the CN bridge construction personnel, bridge management, and the bridge testing team. The monitoring week was selected in conjunction with the construction schedule in order to have the best access window without interrupting bridge replacement work.

Monitoring Goal

The monitoring goal was to collect both displacements and accelerations from one bent cap under work trains of known speed, direction, and load. Displacements were taken from a fixed point on the scaffolding erected as a reference for this project. The scaffolding was connected to the adjacent concrete pier to increase its rigidity. Accelerations were collected from both wired and wireless smart sensors on the structure, as well as from wireless sensors on the scaffolding to measure the "fixity" of the reference point under train vibrations. Estimated displacements from the accelerometers were compared with the measured displacements for validation purposes. Figure 3 shows the elevation of the bent cap selected for the monitoring campaign. In this monitoring effort, this pier was called bent 1.

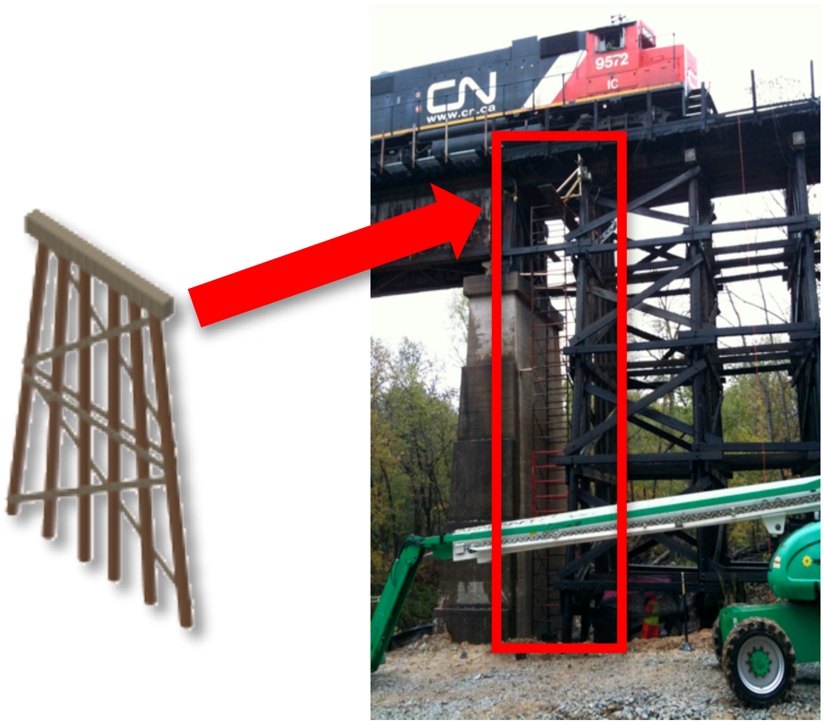


Figure 3. Bent cap location and scaffolding relative location.

Set-Up Instrumentation

Figure 4 shows the instrumentation installed for the monitoring of bent cap 1, including the following sensors:

- 2 LVDTs (1 vertical, 1 transverse) for displacements
- 1 biaxial accelerometer for accelerations
- 2 wireless tri-axial accelerometers (Imote2s) attached to bent cap 1
- 1 wireless tri-axial accelerometer (Imote2) attached to the scaffolding

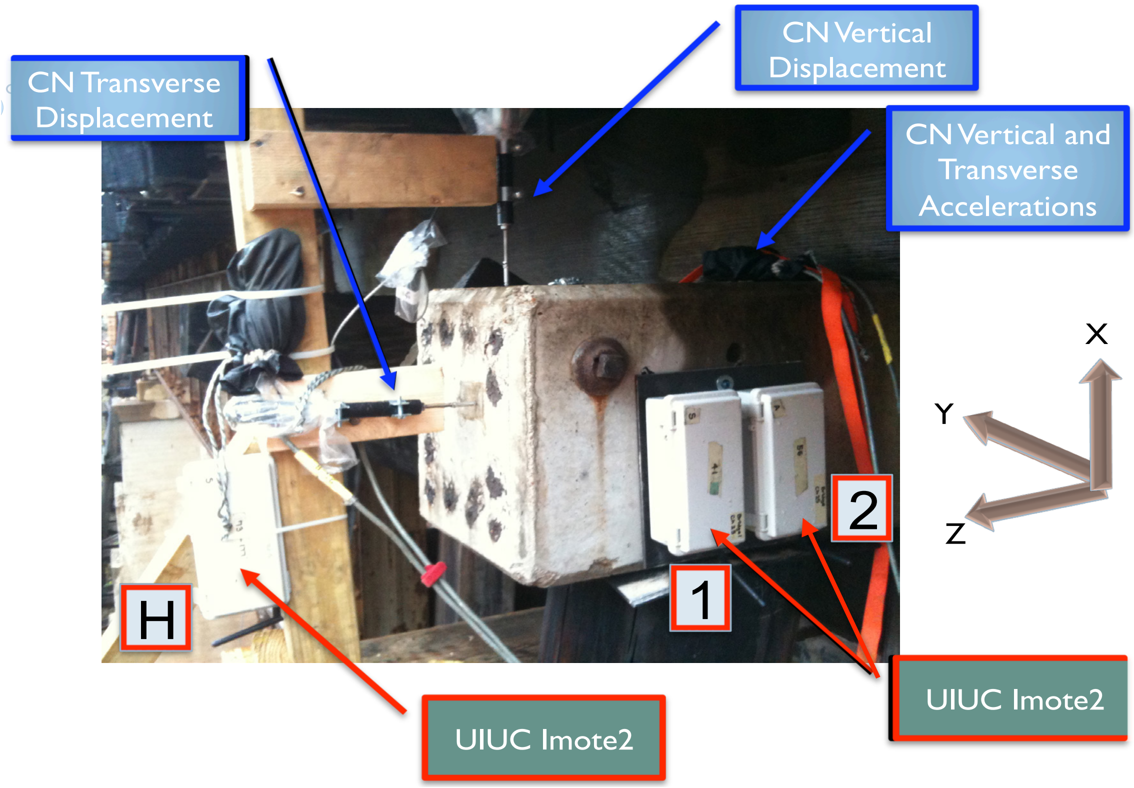


Figure 4. Instrumentation set-up.

Wired instrumentation collected responses in both vertical and transverse direction (*X* and *Z* in Figure 4). Wireless instrumentation collected responses in the three directions: vertical, longitudinal, and transverse directions.

Installation of wired instrumentation from the fixed reference point was executed the day before the monitoring. Installation of the wireless smart sensors on both the bent cap and the scaffolding was performed in a few hours prior to the monitoring. Before sensor installation on the bridge, different attachment tests were conducted in the Newmark Civil Engineering Laboratory. These experiments determined that the most efficient way to attach wireless smart sensors to concrete was by epoxying and bolting a ¼ in. steel plate to the concrete bent cap; this plate then became a base for the magnets of the sensor enclosures.

Raw Data

The monitoring of all bridge responses was conducted in one day. Work train orientation and layout are shown in Figure 5, with both South Bound (SB) and North Bound (NB) work trains. Table 1 shows the monitoring times for the 10 work trains. SB and NB responses are grouped independently, since: (1) the bridge configuration is non-symmetric and hence bridge responses will depend on the direction the traffic is crossing, and (2) SB and NB train configurations are opposite and their loading input patterns will affect bent responses differently (see Figure 5). Maximum displacements and accelerations in the vertical and transverse directions are plotted in Figure 6.

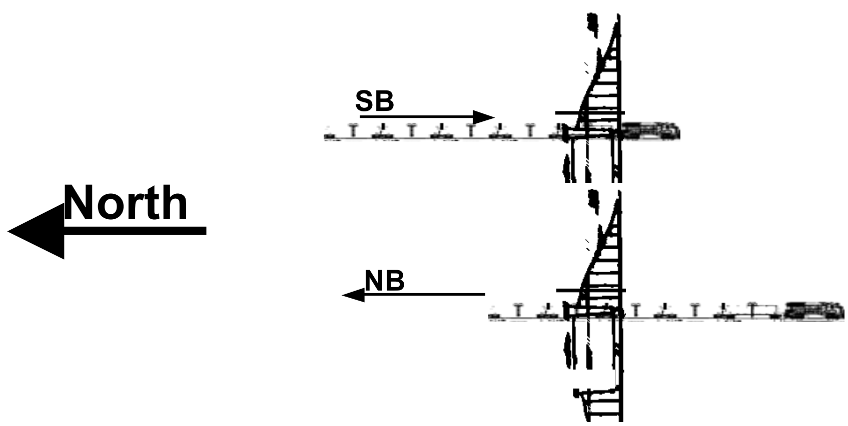


Figure 5. Work train orientation.

Table 1. Work train description.

Time	Work Train
9:55	Arrived to the site
10:40	5MPH SB
10:50	5MPH NB
11:00	10MPH SB
11:12	10MPH NB
11:17	15MPH SB
11:27	15MPH NB
11:32	20MPH SB
11:41	20MPH NB
11:47	25MPH SB
11:56	25MPH NB

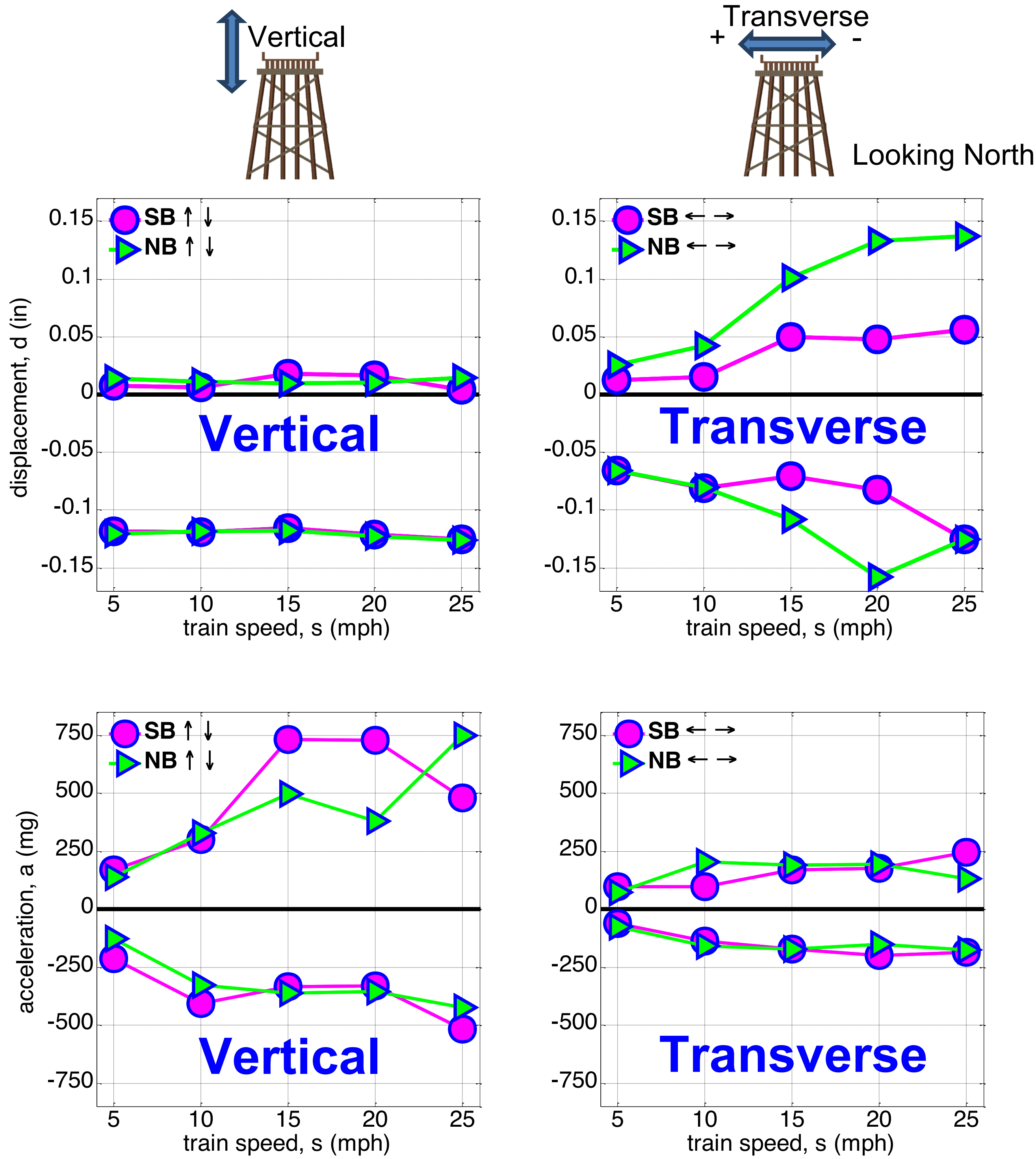


Figure 6. Maximum displacements and accelerations versus train speed.

By comparing both vertical and transverse responses, the following conclusions can be drawn:

1. The transverse displacements of the bent cap increased with the speed of the work train. Transverse accelerations did not increase with train speeds.
2. The vertical displacements of the bent cap did not increase with the speed of the train, while the vertical accelerations changed with speed trains.

Measured transverse displacements decreased with lower speeds, whereas vertical displacements did not. This could be partially caused because the weight of train cars stabilized the bent forced vertical vibrations regardless of train speeds; however, the vertical weight of the train cannot help controlling the transverse bent response; nevertheless, further research is needed to confirm/validate the cause of this phenomena. On the other hand, specific research on a bridge by bridge case is needed to assess correlations between measured displacements vs. measured accelerations and why accelerations cannot capture the trends found in displacements.

From the data for this timber bent, the transverse displacements appear to decrease with slower train speeds. Transverse displacement measurements could assist to quantify bridge serviceability under train traffic. For example, a maximum transverse displacement (threshold) could be determined by the bridge owner, and slower orders could be made when estimated transverse displacements of the bridge under train loadings would exceed this pre-determined "maximum" lateral displacement for that particular bridge. Additionally, estimating displacements could assist to compare timber bridges responses quantitatively. Based on these displacement comparisons within timber bridge populations, timber bridge replacements could be prioritized, choosing to upgrade those timber bridges with larger displacements under similar traffic loadings and speeds.

Data Analysis

Both Illinois and CN accelerations were used to estimate displacements. Using the accelerations measured by the Imote2, the scaffolding acceleration could be subtracted from the bent cap acceleration, as shown in Figure 7. From this analysis, the scaffolding vibration had negligible effect in the displacement estimation.

The total lateral (transverse) displacement in this experiment can be separated in two components: pseudo-static (low frequency) and dynamic (high frequency). The estimated displacement matches well the measured dynamic component of the transverse responses. Since the dynamic component was the most significant for this experiment, comparisons between the total measured displacements (prior to detrending) vs. estimated displacements showed good correlation. However, in sight of broader bridge applications, this study compared measured dynamic displacements versus estimated displacements.

The dynamic displacement caused by the 25 MPH NB work train has been estimated by detrending the measured data and comparing it to estimated displacement. Figure 8 compares the dynamic displacement estimation for both the CN and the Illinois Imote2 acceleration data. As can be seen, the reference-free displacements capture well the dynamic movement of the bent cap.

Railroad bridge managers are interested in the total displacement experienced in timber piles under train loads. A measured dynamic displacement range for each work train is defined by adding the maximum displacements in both directions (positive and negative) from the displacement. Figure 9 shows the summary of the 10 work trains of both measured and estimated maximum dynamic displacements range vs. train speeds.

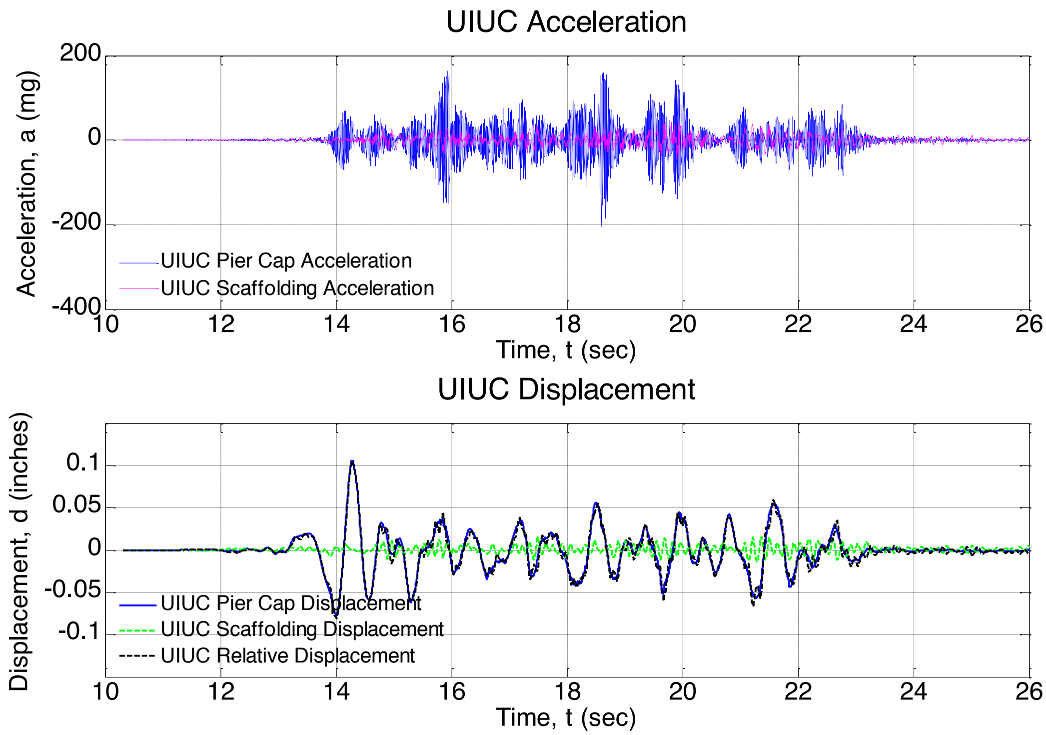


Figure 7. Illinois Imote2 acceleration correction and displacement effect.

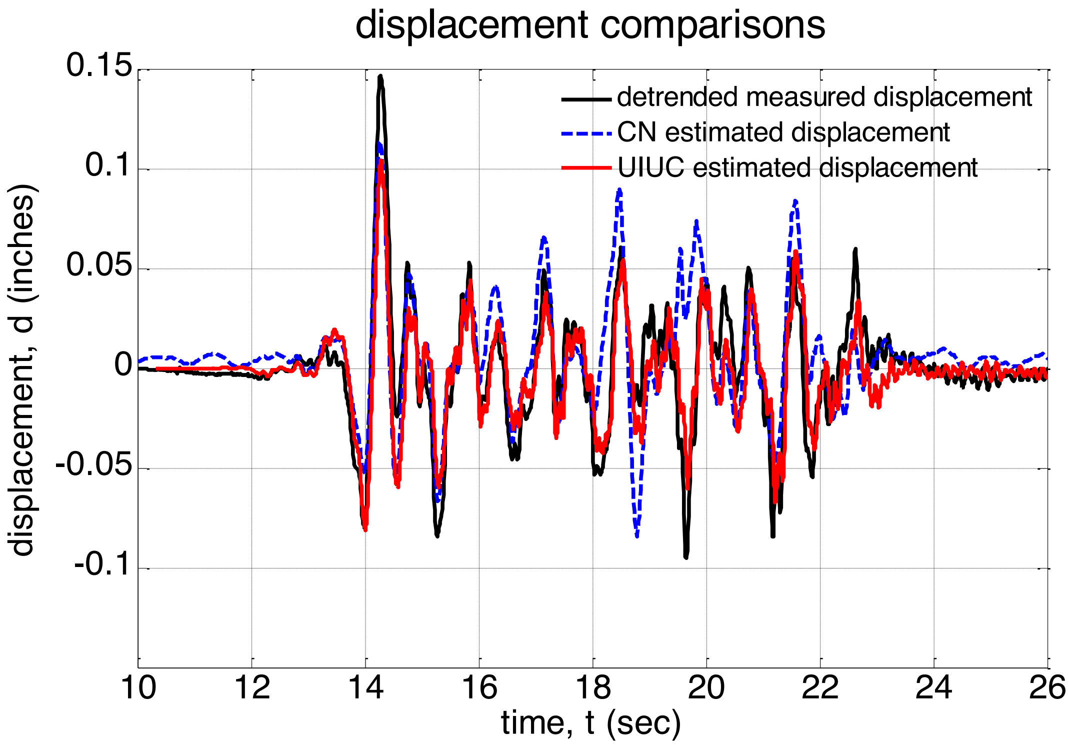


Figure 8. Displacement estimation vs. displacement measurement for 25 MPH NB work trains.

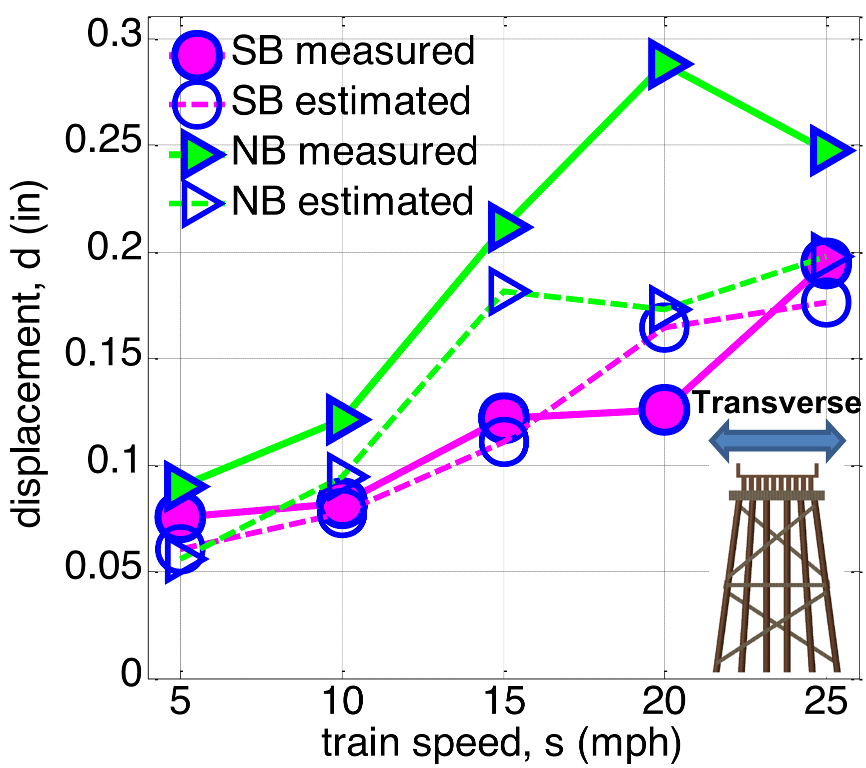


Figure 9. Summary of displacement estimations vs. train speed.

Additionally, 2 wired accelerometers were installed in two other bents further south from bent 1, called respectively bent 2 and bent 3. Bent 2 had less longitudinal bracing than bents 1 and 3. Their configuration and estimated maximum displacements in the transverse direction are shown in Figure 10.

Finally, dynamic displacements were also estimated from the in-service trains crossing the bridge during the test experiment, as shown in Figure 11.

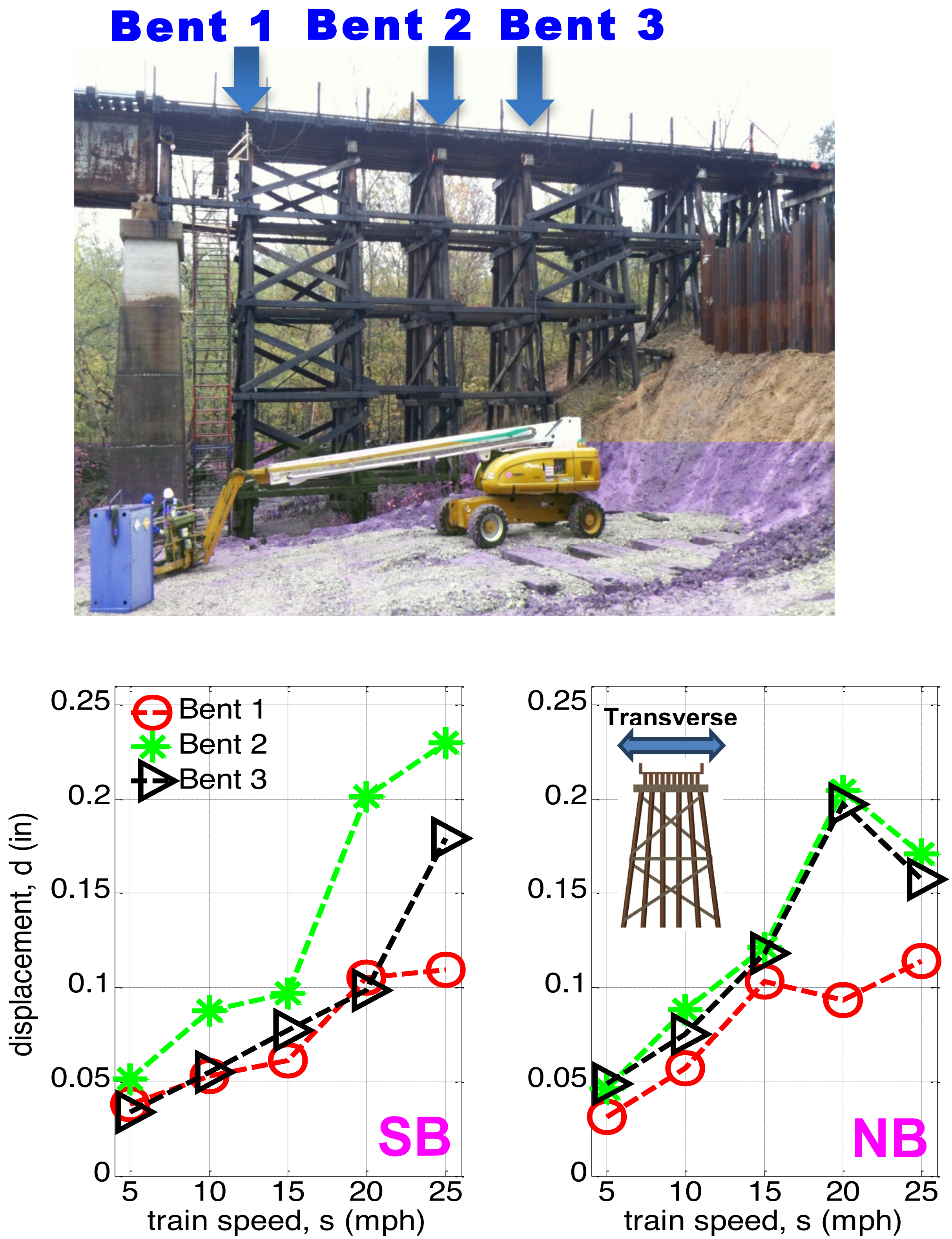


Figure 10. Estimated maximum transverse displacement vs. train speed for three bents.

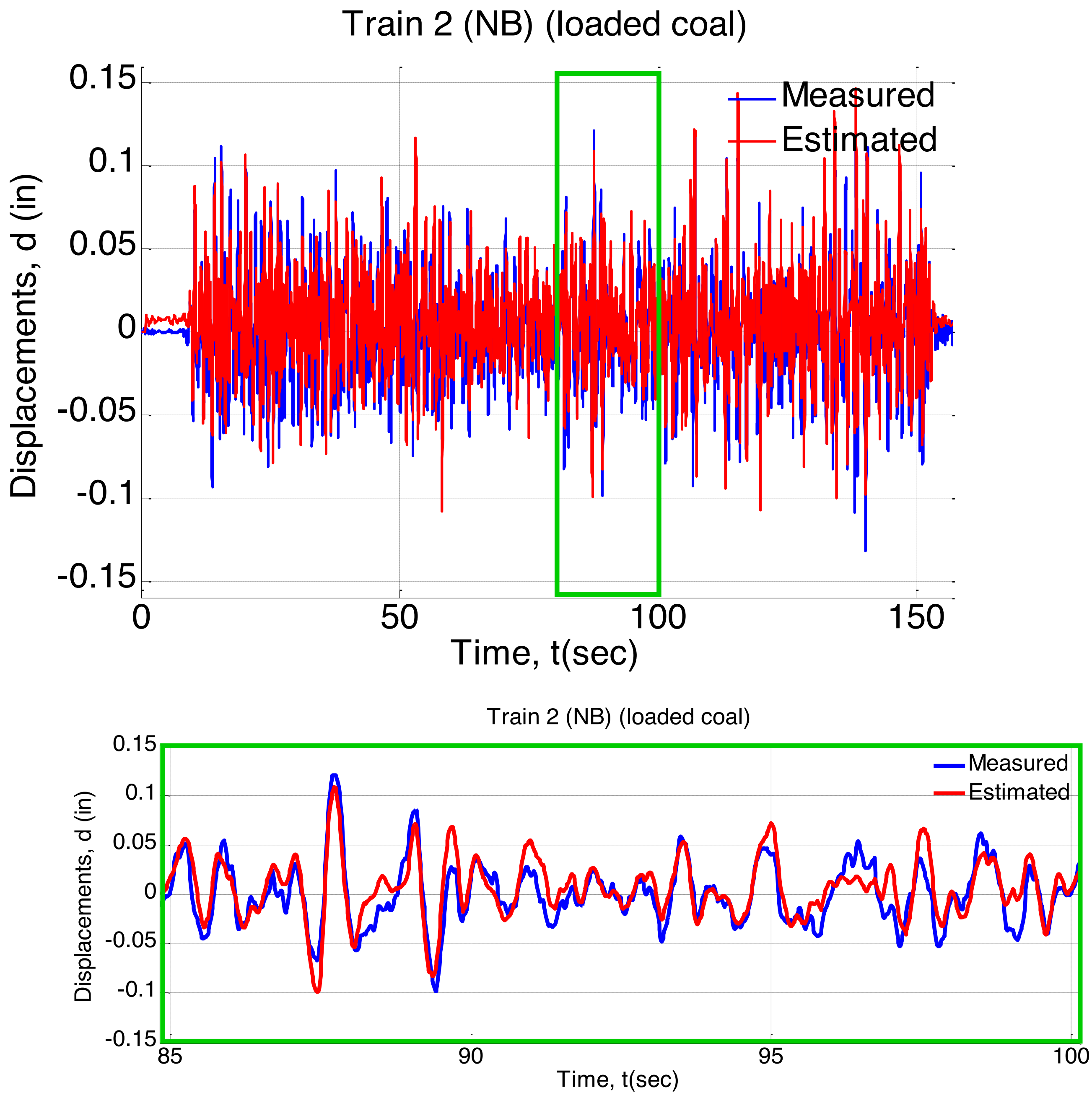


Figure 11. Measured vs. estimated displacement for loaded coal train.

RESULTS FROM THE STEEL TRUSS OVER THE MISSISSIPPI

A second monitoring campaign was conducted for the two-track Burlington Bridge over the Mississippi river that was to be replaced. Using the new pier cap as a reference, which was located only five feet from the bottom chord of the old span (see Figure 12), a very unique opportunity was provided to accurately monitor displacements of the steel span.

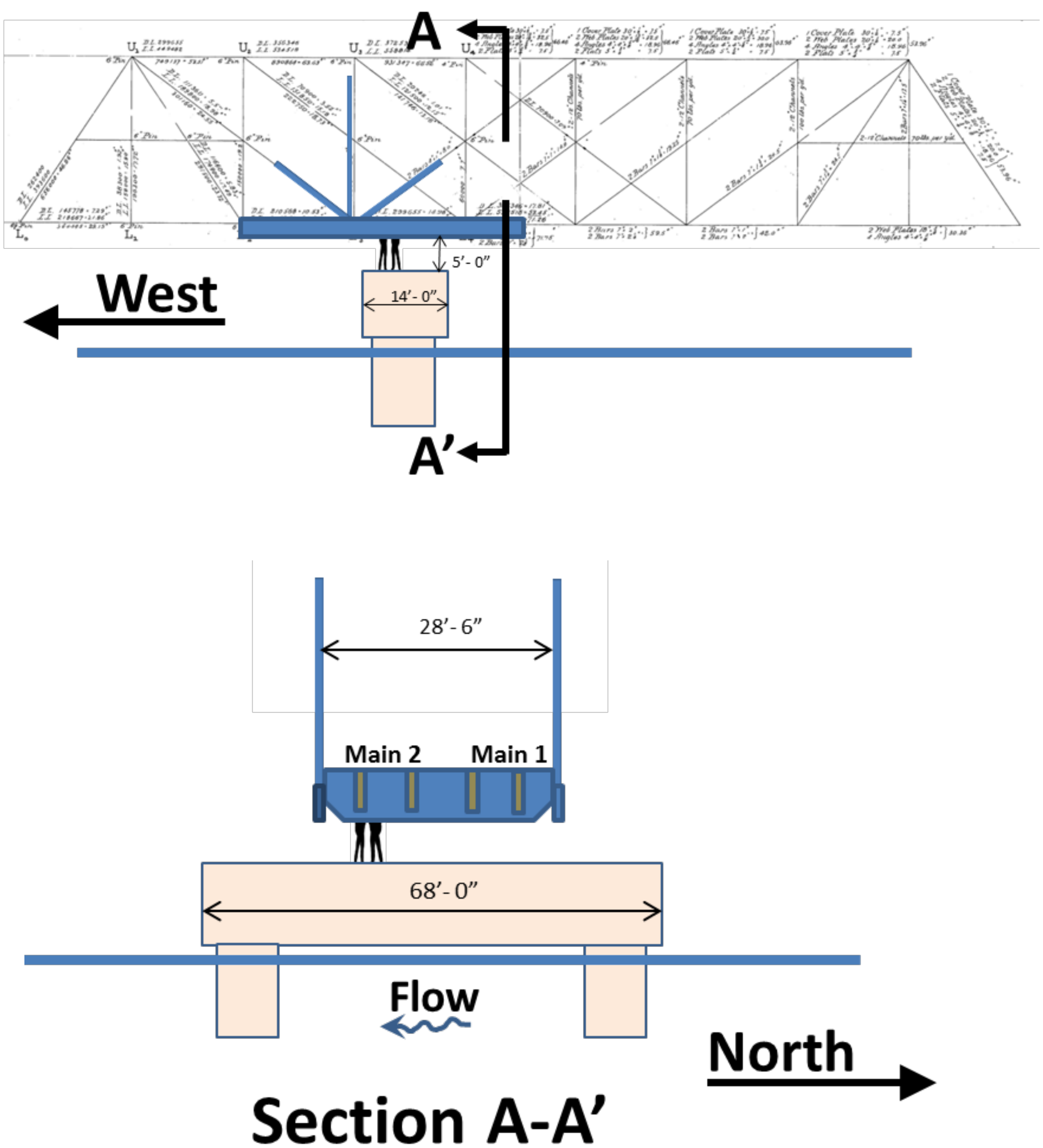


Figure 12. Monitoring access elevation and section sketch view.

Data was collected at about the third point of the span, next to one of the nodes of the truss. Figure 13 shows the location and view of the sensors. Wired sensors measured uniaxial displacements and accelerations with LVDTs and piezoelectric accelerometers, respectively. Wireless smart sensors were used to collect wireless strain data at the mid-point in-between nodes.

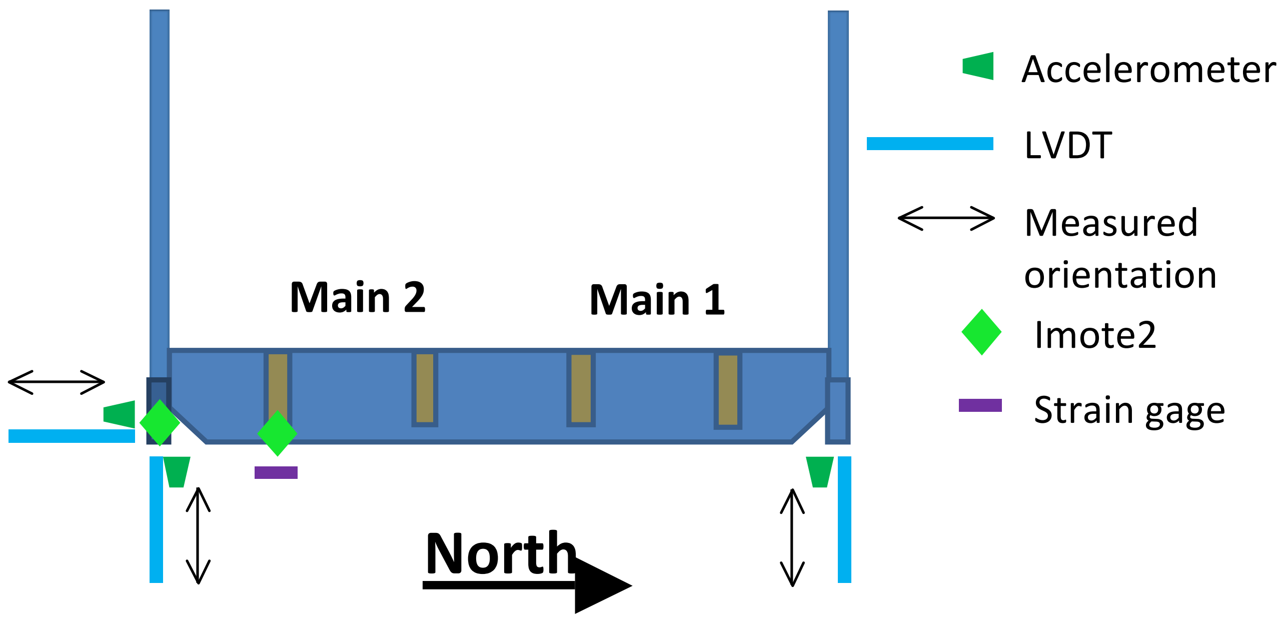
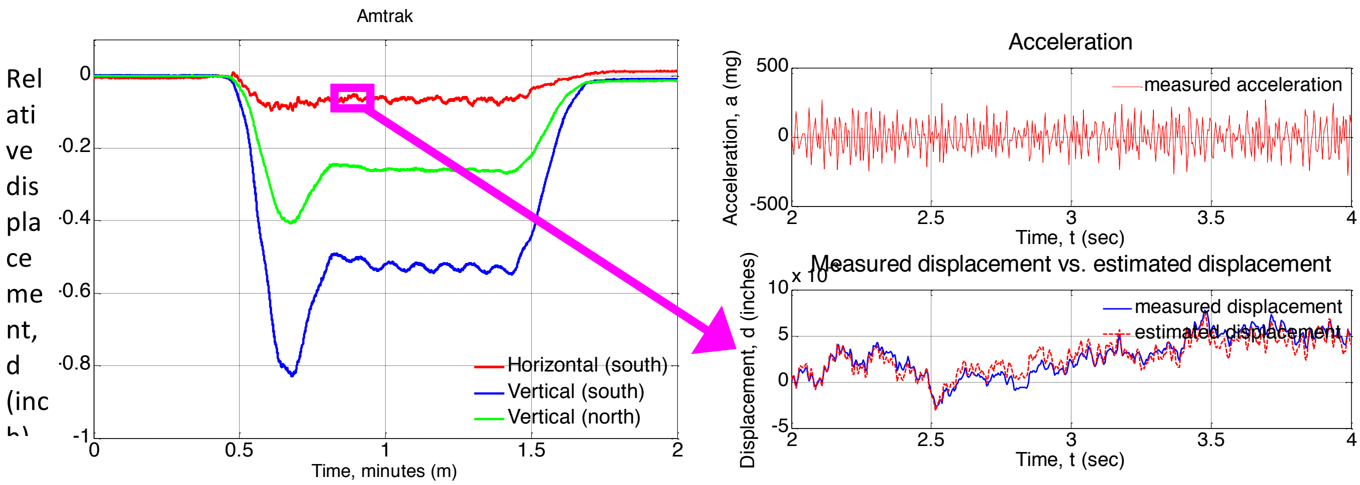


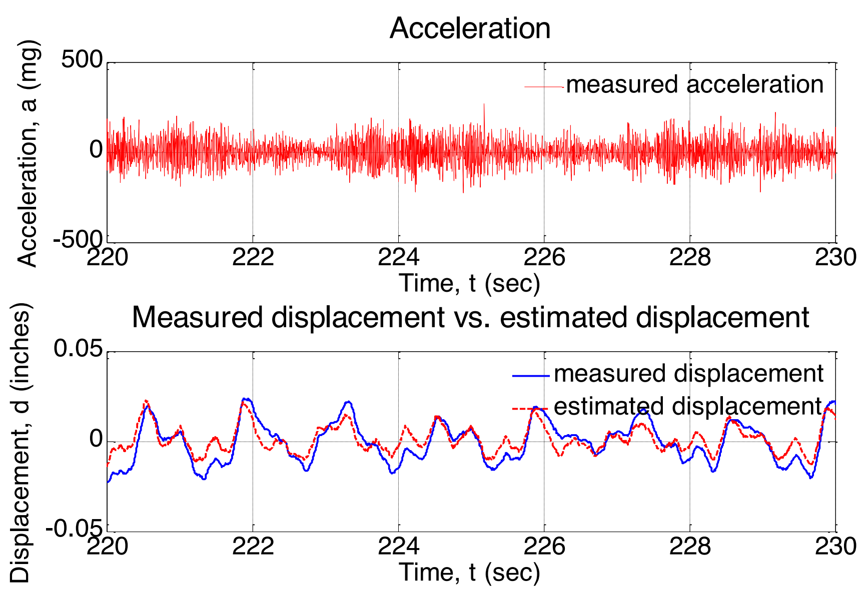
Figure 13. Wireless smart sensors location and view.

Lateral (transverse) displacements were estimated for all four trains, and compared to the actual measured transverse displacements. Results for the transverse displacements under trains are shown in Figure 14. Estimated dynamic displacements from accelerations match dynamic measurements collected with LVDTs.

Figure 15 shows strain measurements under different loading conditions. Strain measurements were recorded with wireless smart sensors. Results are shown for two different bridge responses under two different train loading levels, Amtrak train vs. loaded coal train. Both bridge displacements and strains measured under the crossing of the loaded coal train were larger than those collected under the Amtrak train. The ratio of both the strains and displacements collected matched closely for the two trains monitored.

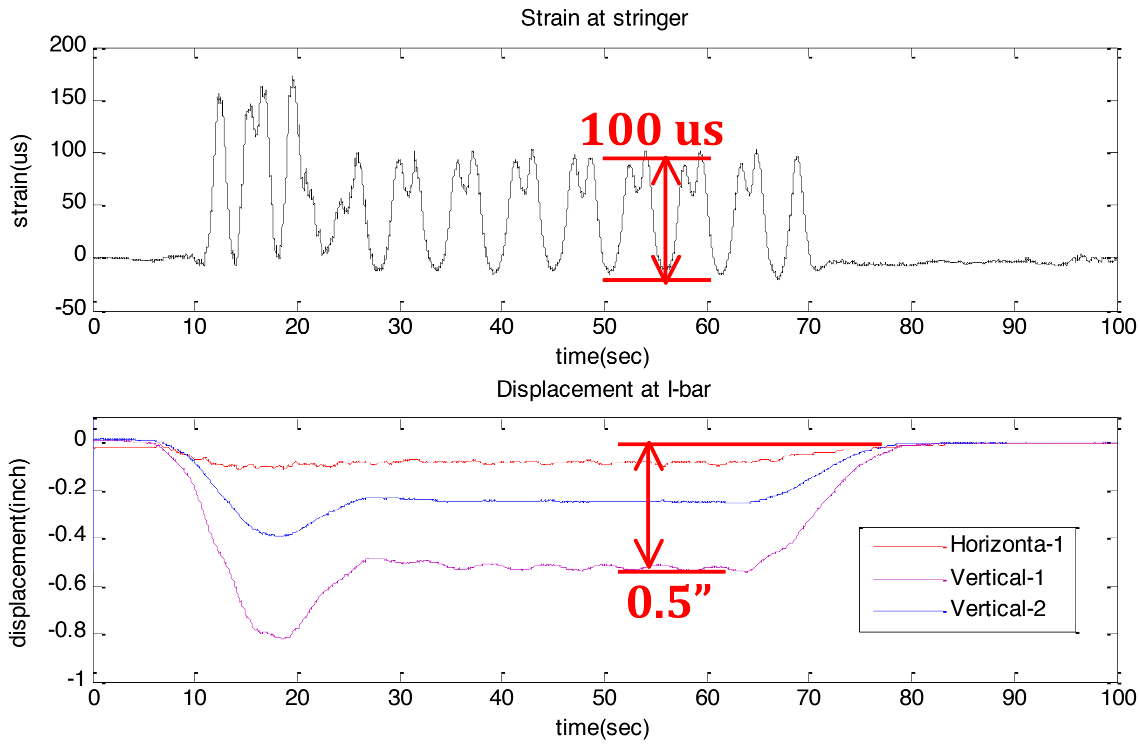


(a) Amtrak train

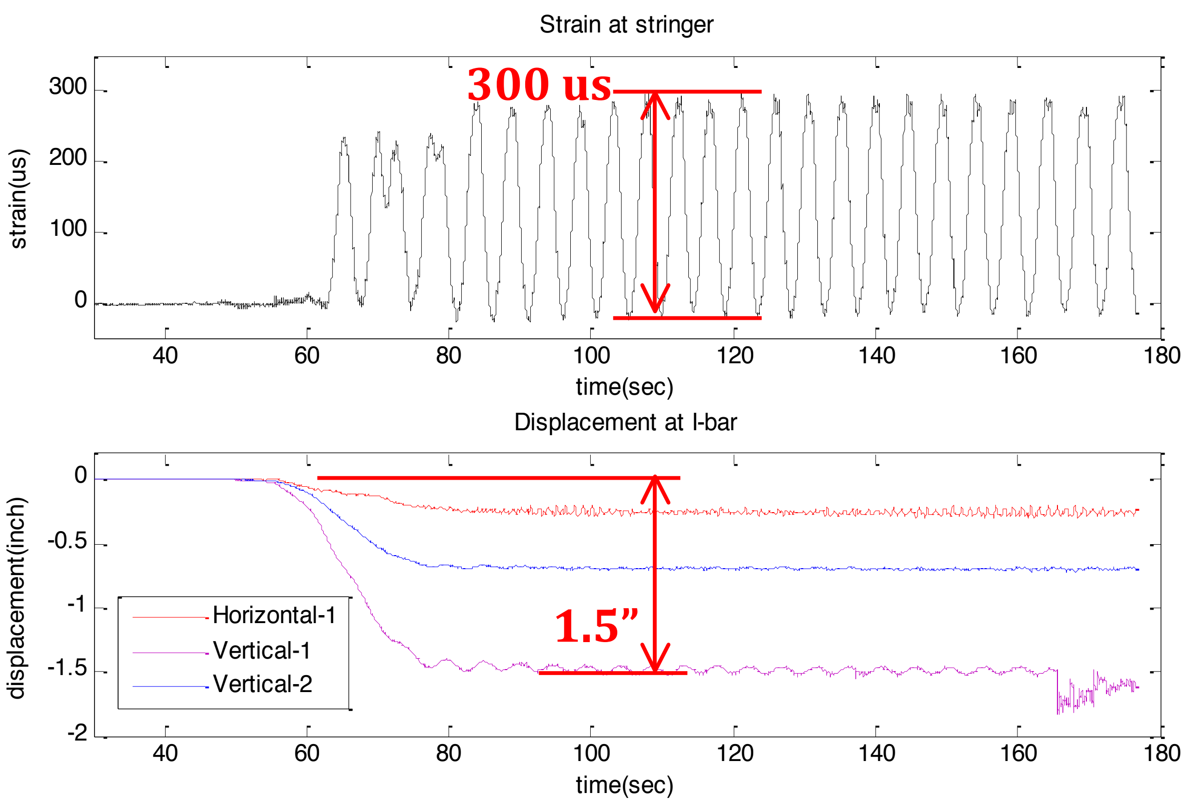


(b) Loaded coal train

Figure 14 Transverse estimated displacement vs. measured displacement



(a) Amtrak train



(b) Loaded coal train

Figure 15 Wireless strain measurements under train traffic

SUMMARY AND FUTURE WORK

This paper presented the experimental validation of a reference-free means to estimate the displacement for two Class I railroad bridges during train crossings. The first bridge was a timber bridge owned by CN, whereas the second bridge was a steel fixed Whipple truss owned by BNSF. For the timber bridge, the transverse and vertical displacements of a timber pile were measured under different work trains run at different speeds. Transverse displacements increased with the speed of the work trains, but the vertical displacements did not. Work trains running in the NB direction caused larger transverse displacements than work trains running in the SB direction. However, in this timber bridge experiment, measured transverse accelerations did not increase with the speed of the work trains while the vertical accelerations did.

Displacements have been estimated from acceleration records, with comparable results for the dynamic range of both work trains and in-service trains. Displacement estimations also appear to show how timber pier responses of piers without longitudinal cross bracing are larger than responses of timber piers with cross bracing. Finally, both measured and estimated displacements show how the displacement response of timber bridges at 20 mph is higher than the response of timber bridges at 25 mph.

Additionally, results from a 250 ft steel truss also showed good reference-free estimations of displacements from accelerations. Strain measurements collected with wireless smart sensors identified different train loading conditions at the bridge.

The future direction and ultimate goal of this research is to develop a comprehensive railroad bridge structural health monitoring system using wireless smart sensors that is tailored to the needs of the railroad industry. This system will provide railroads with new objective information about the in-service performance of their bridges that can improve railroad safety, increase structural reliability, enhance inspection quality, reduce maintenance costs, and help to improve prioritization of bridge repairs and replacement by the railroads.

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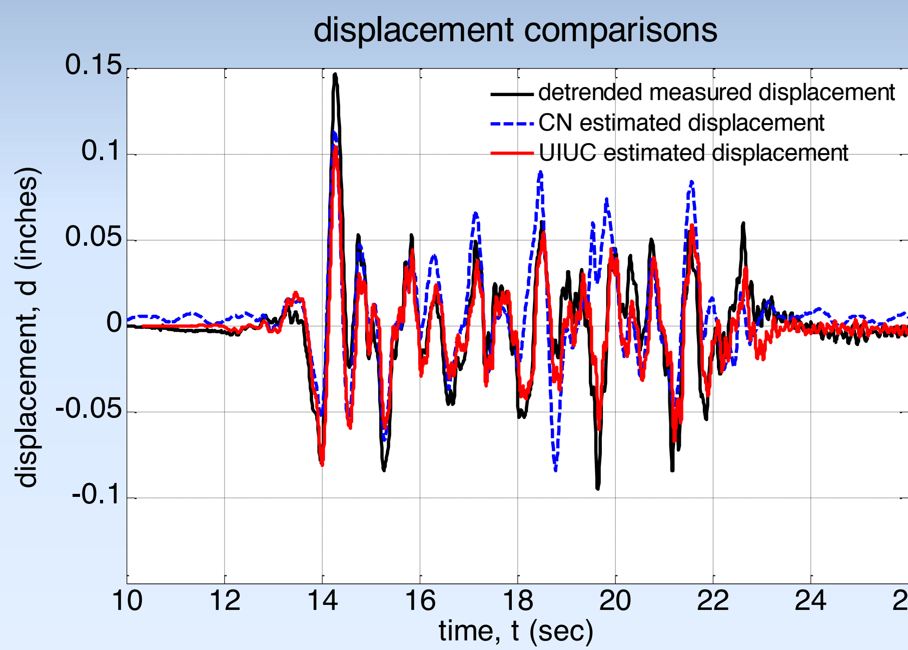


CN RAILTEC ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN SSTL SMART STRUCTURES TECHNOLOGY LABORATORY BNSF RAILWAY

Outline of Contents

Intro	Background and Goals
Experiment	Experimental Setup
Bridge Performance	Displacements Measurement
Analysis	Displacements Estimation
Other Results	Steel Truss Displacements
Discussion	Conclusions

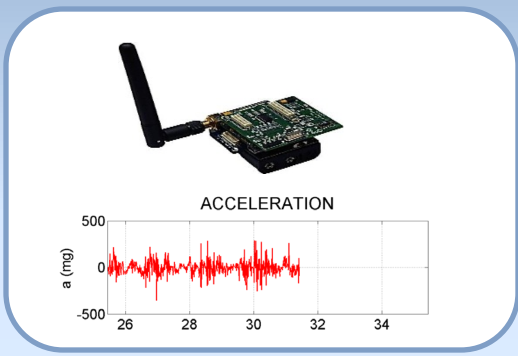
Displacement as a performance parameter

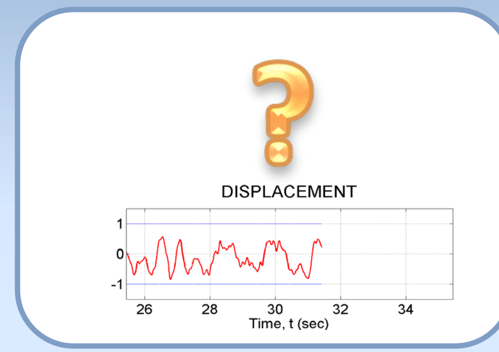
- *Monitoring bridge displacements can assess bridge performance*
- *Measuring peak displacements and time histories under trains*
- *Both for short and long term assessment*

Current methods to monitor displacement need a fixed point and are expensive

Motivation for reference-free displacement

- *Accelerations are easy to record, and don't require a fixed point*
- *Lee et al. (2010) proposed a displacement estimation from accelerations*
- *Laboratory experiments validated that wireless sensors can estimate displacements from accelerations*
- *Goal: a "reference-free" displacement estimation method for railroad bridges*



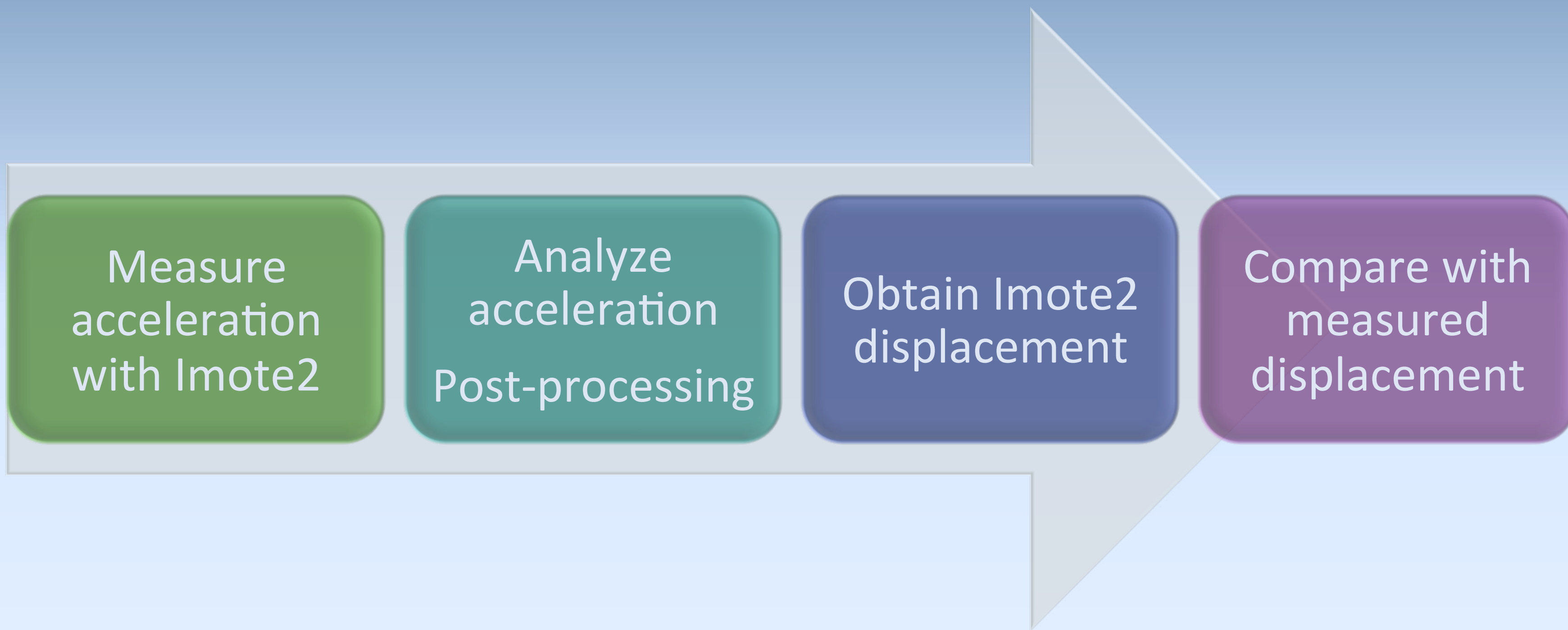


ISM400 board stacked on Imote2

Sensor enclosure assembly

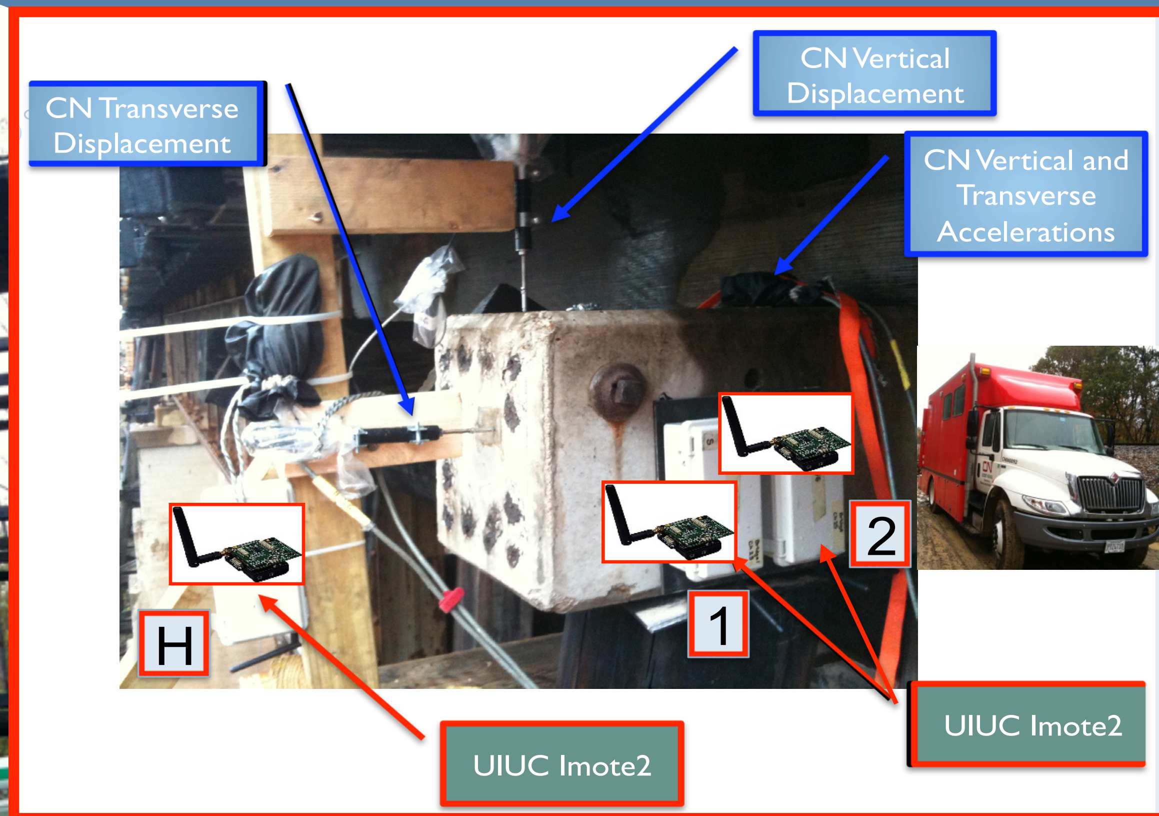
Research goal

Goal: Use of wireless sensors to obtain reference free measurement of displacements of railroad bridges under live-loads



Experiment: measuring Imote2 accelerations and LVDT displacements from 1 pier cap under trains

Experimental Setup



2 LVDTs (1 vertical, 1 horizontal) for displacements

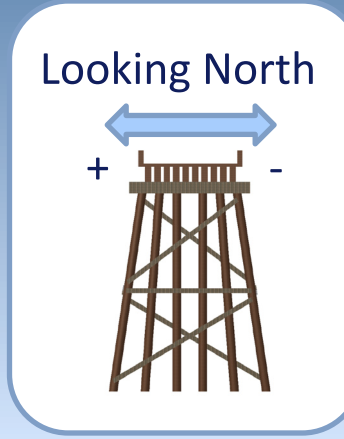
1 biaxial accelerometer for accelerations

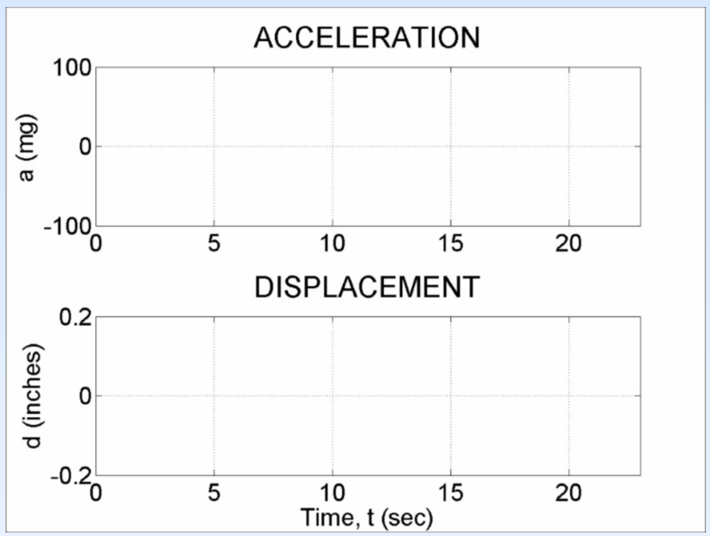
2 Imote2s attached to pier cap (tri-axial acceleration)

1 Imote2 attached to the scaffolding (tri-axial acceleration)

Measured 10 work trains (WT) and 4 regular trains

Measured Data





10 Work Trains Total

Time	Work Train
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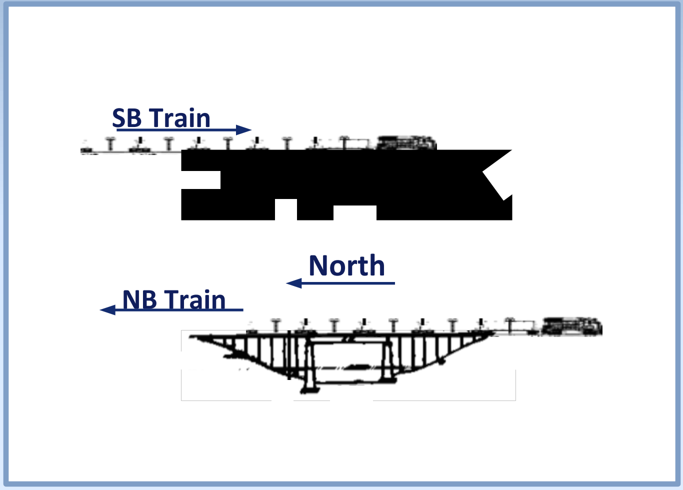
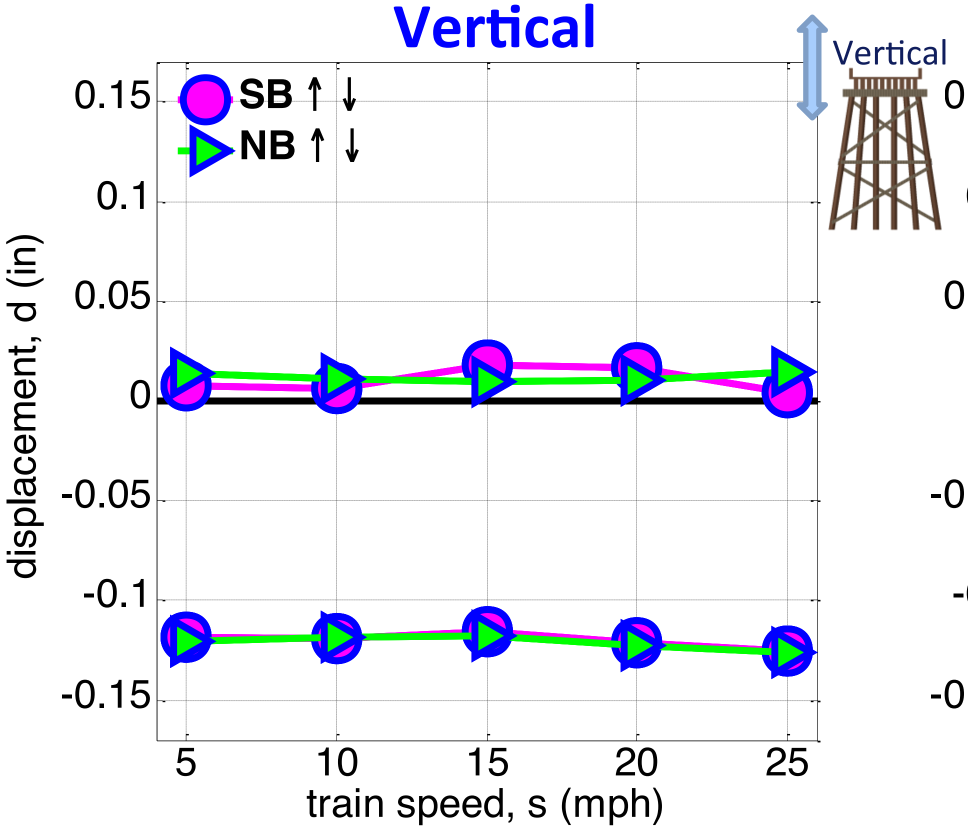
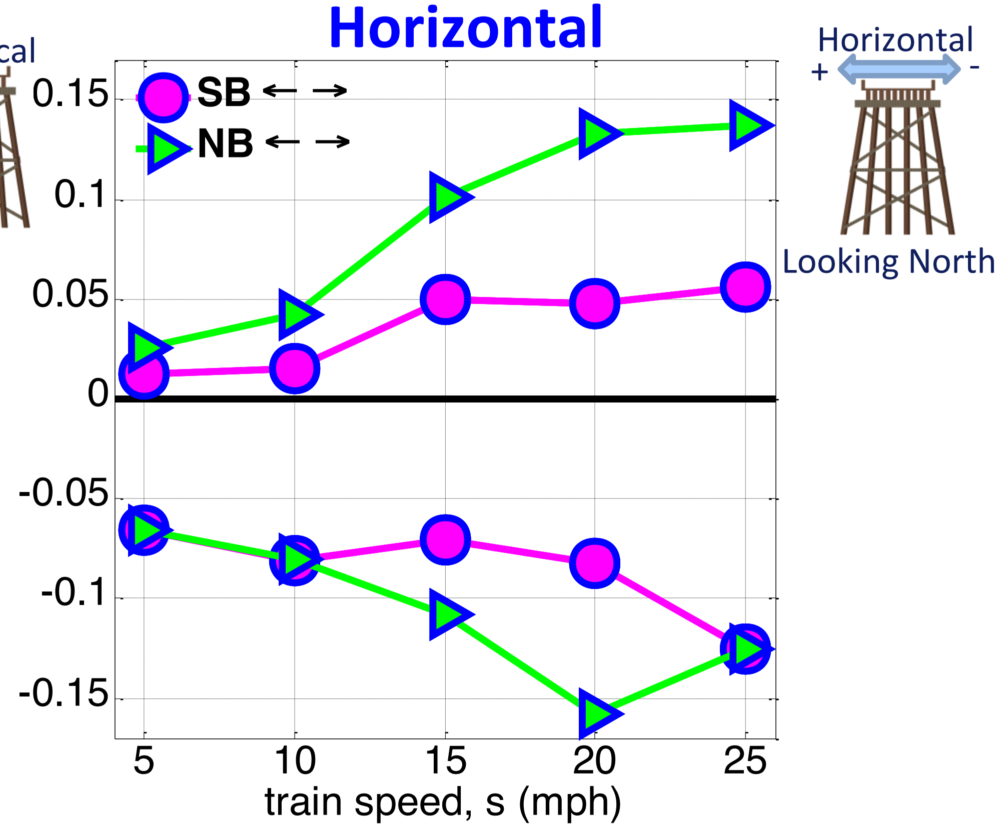


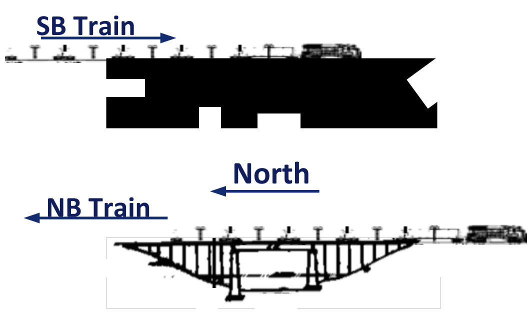
Measured maximum displacements vs. train speed

Vertical



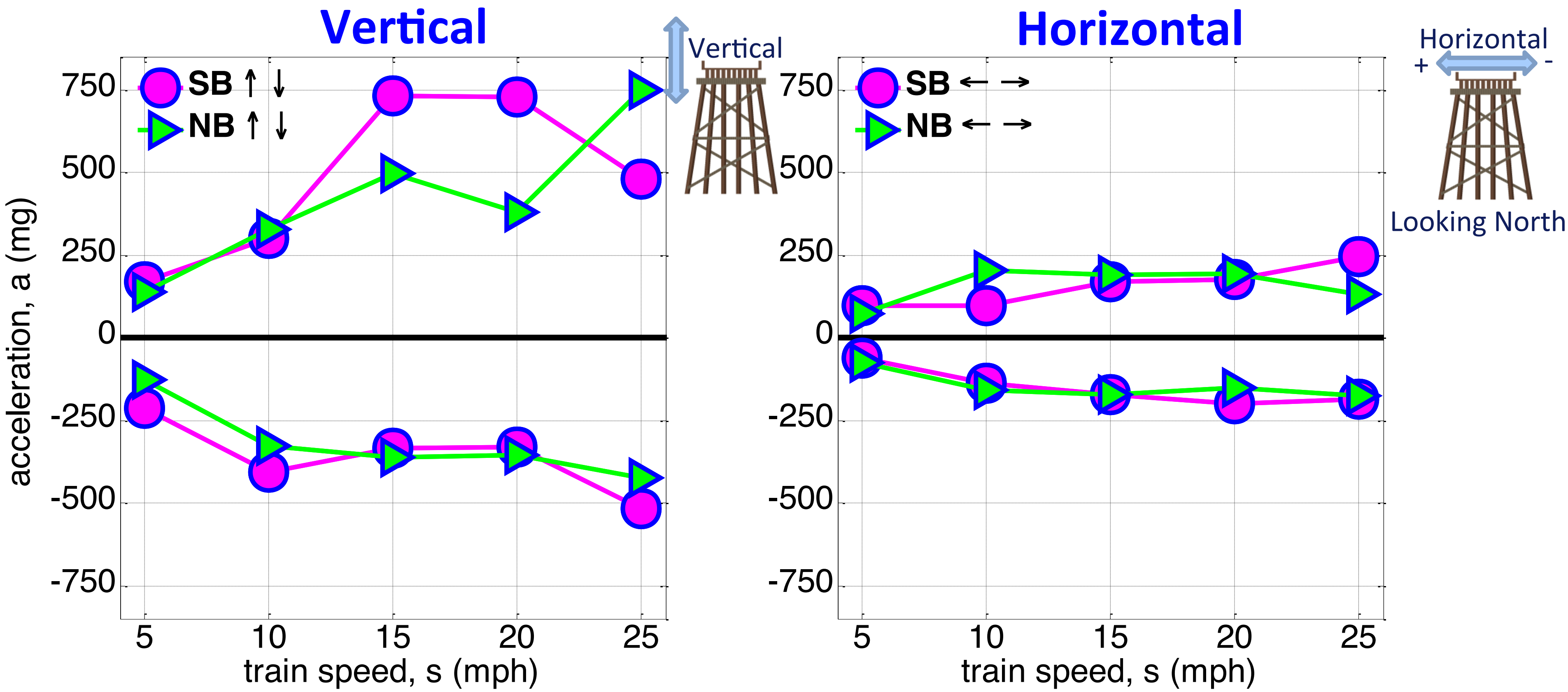
Horizontal

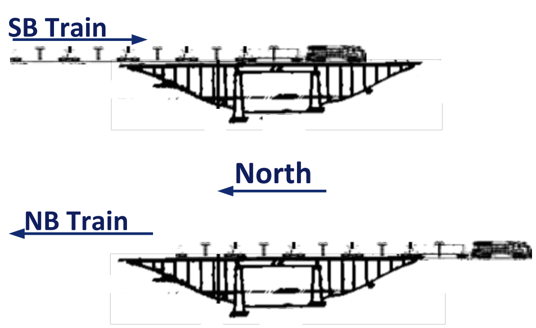




- Vertical displacements are independent of train speed
- Horizontal displacements increase with train speed
- Railroad bridges are managed with slow orders
- **Slow orders** are affected by lateral performance

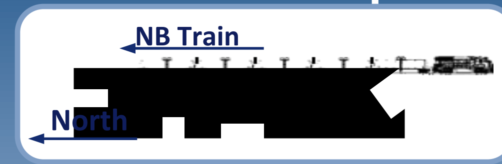
Vertical & horizontal accelerations vs. train speed

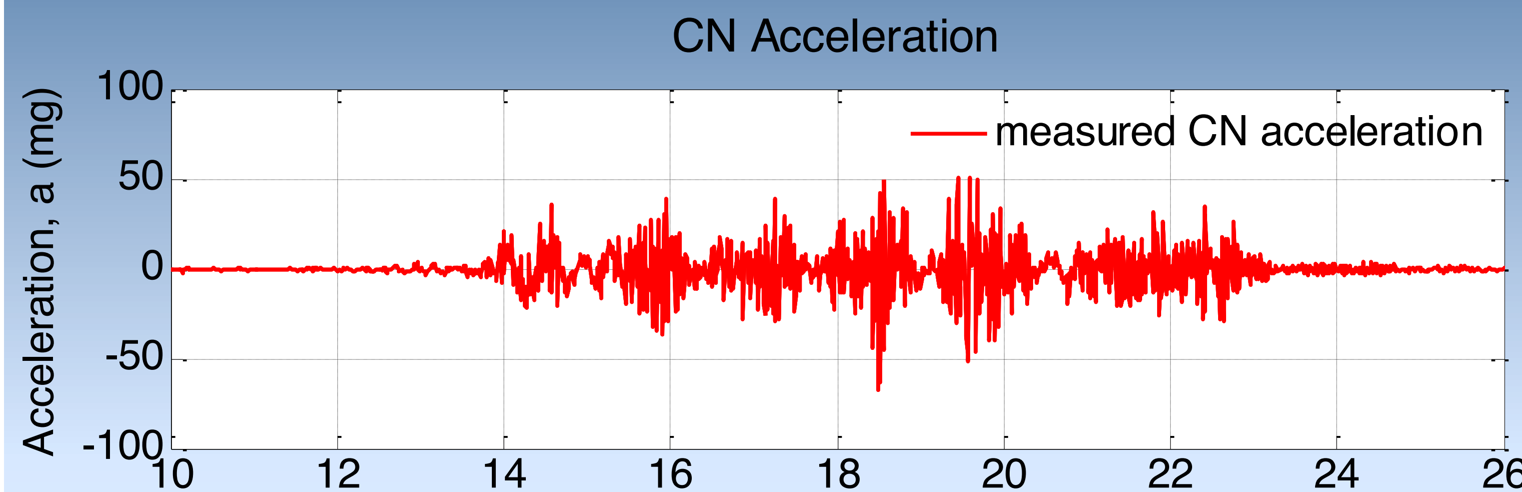


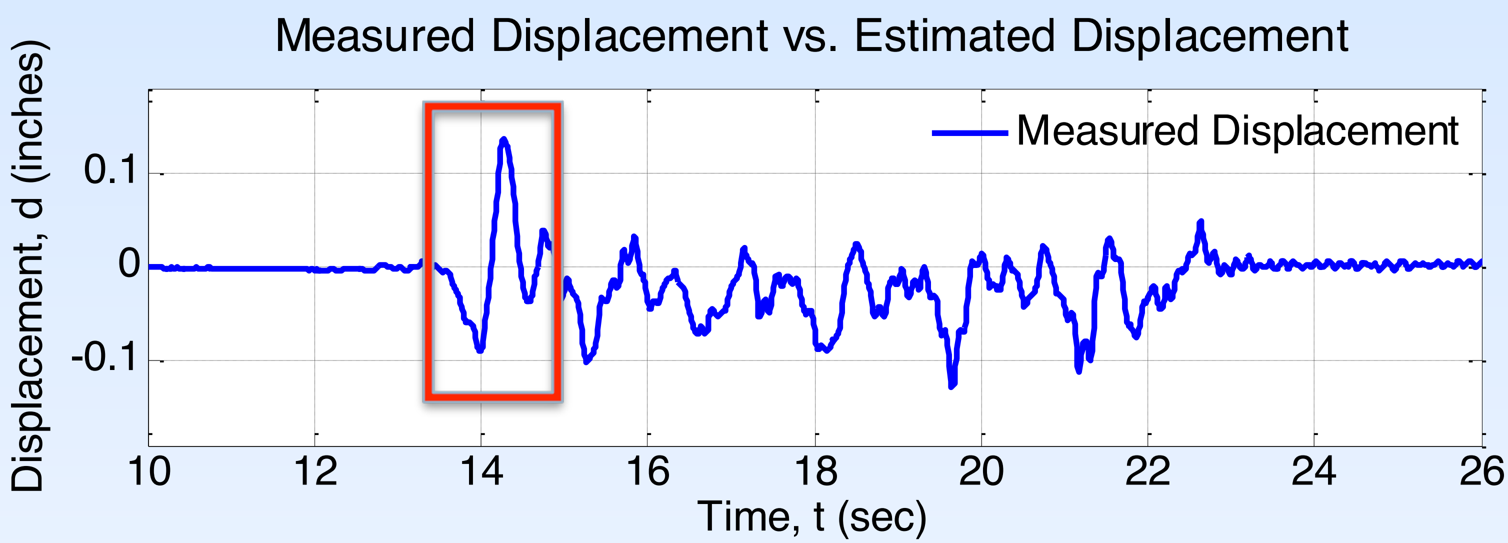


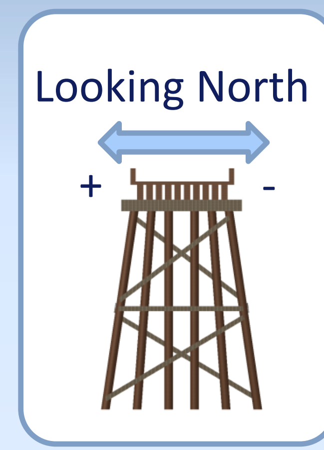
- ❑ Accelerations increase from 5 mph to 15 mph
- ❑ After 15mph, accelerations do not clearly increase
- ❑ Accelerations can't substitute displacements
- ❑ Lateral displacements alone measure performance

North Bound (NB) 25 MPH WT

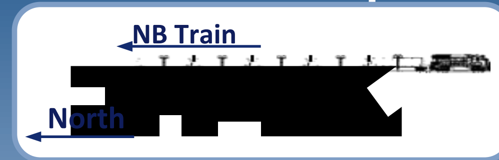


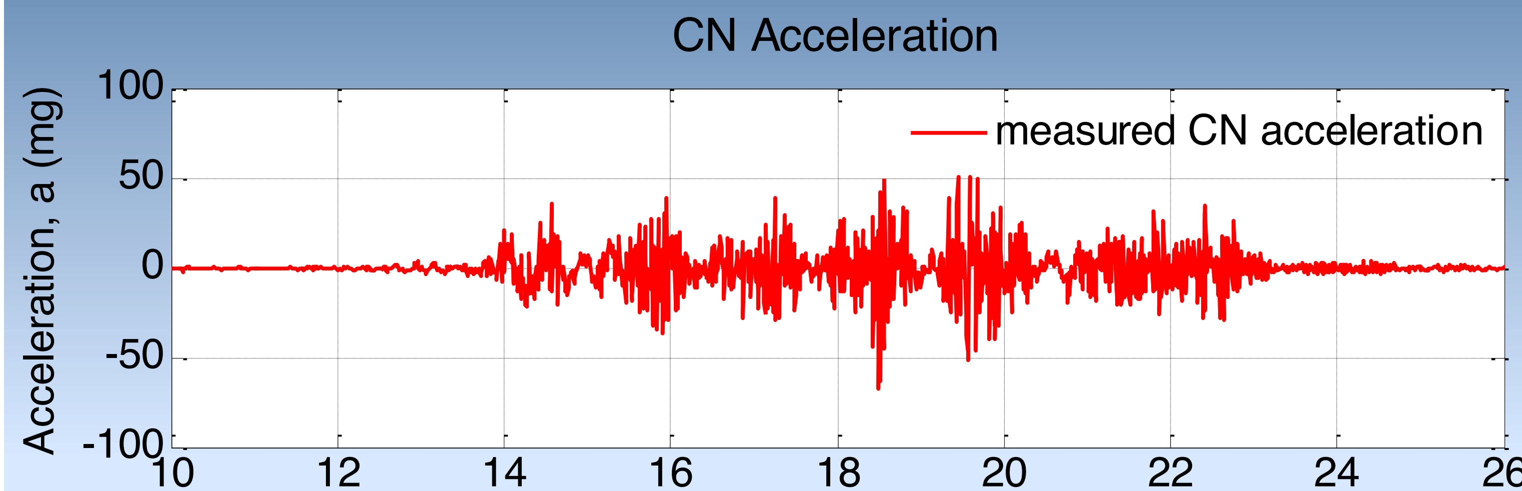


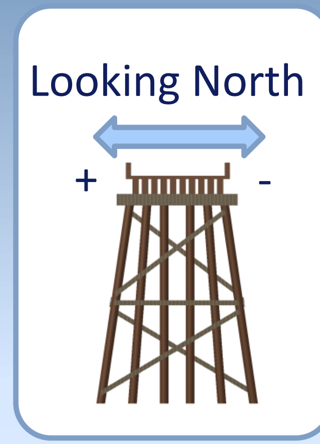


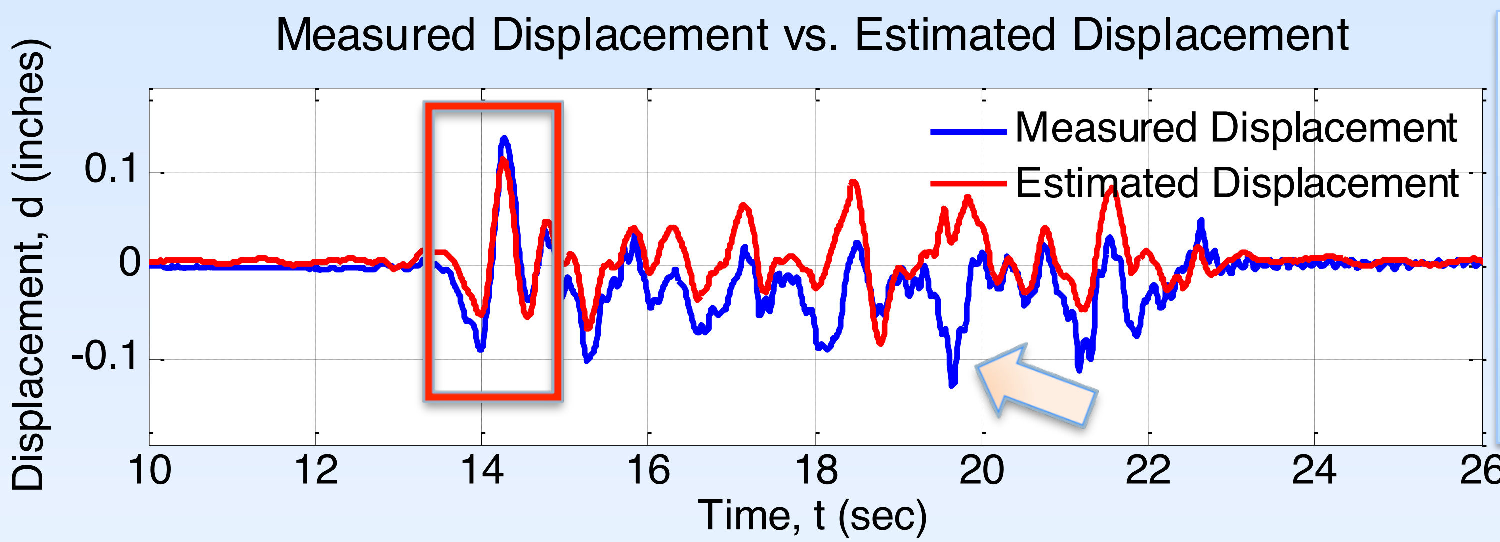


North Bound (NB) 25 MPH WT





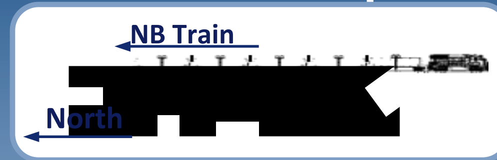


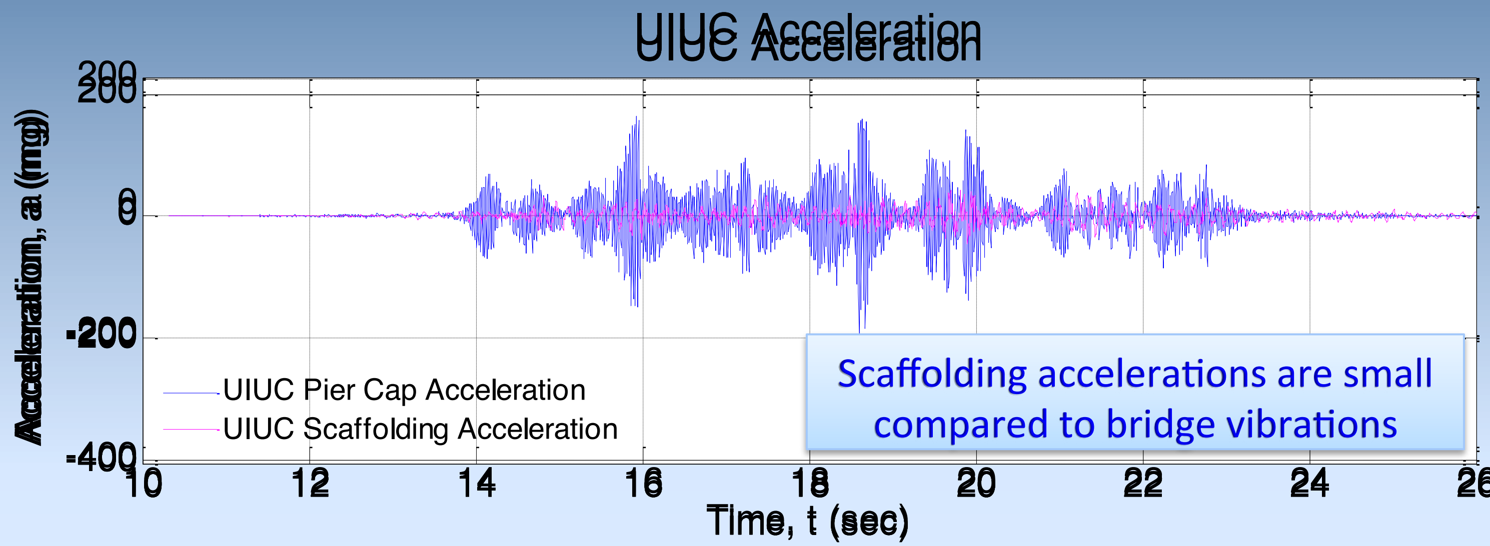


Measured Displacement has a pseudo-static trend (non-symmetric)

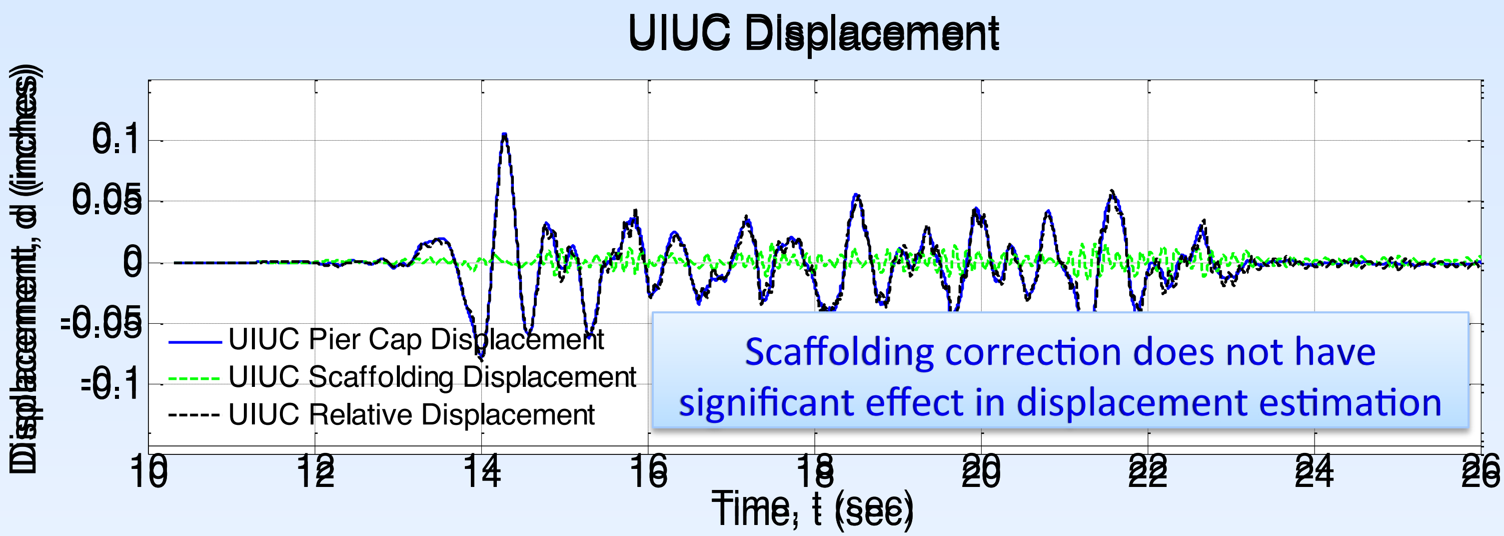
Estimated Displacement does not have a trend (symmetric)

North Bound (NB) 25 MPH WT



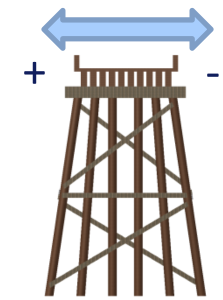


Scaffolding accelerations are small compared to bridge vibrations

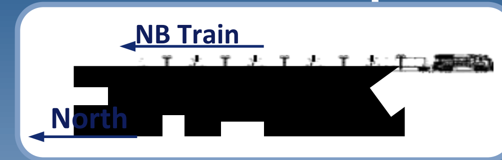


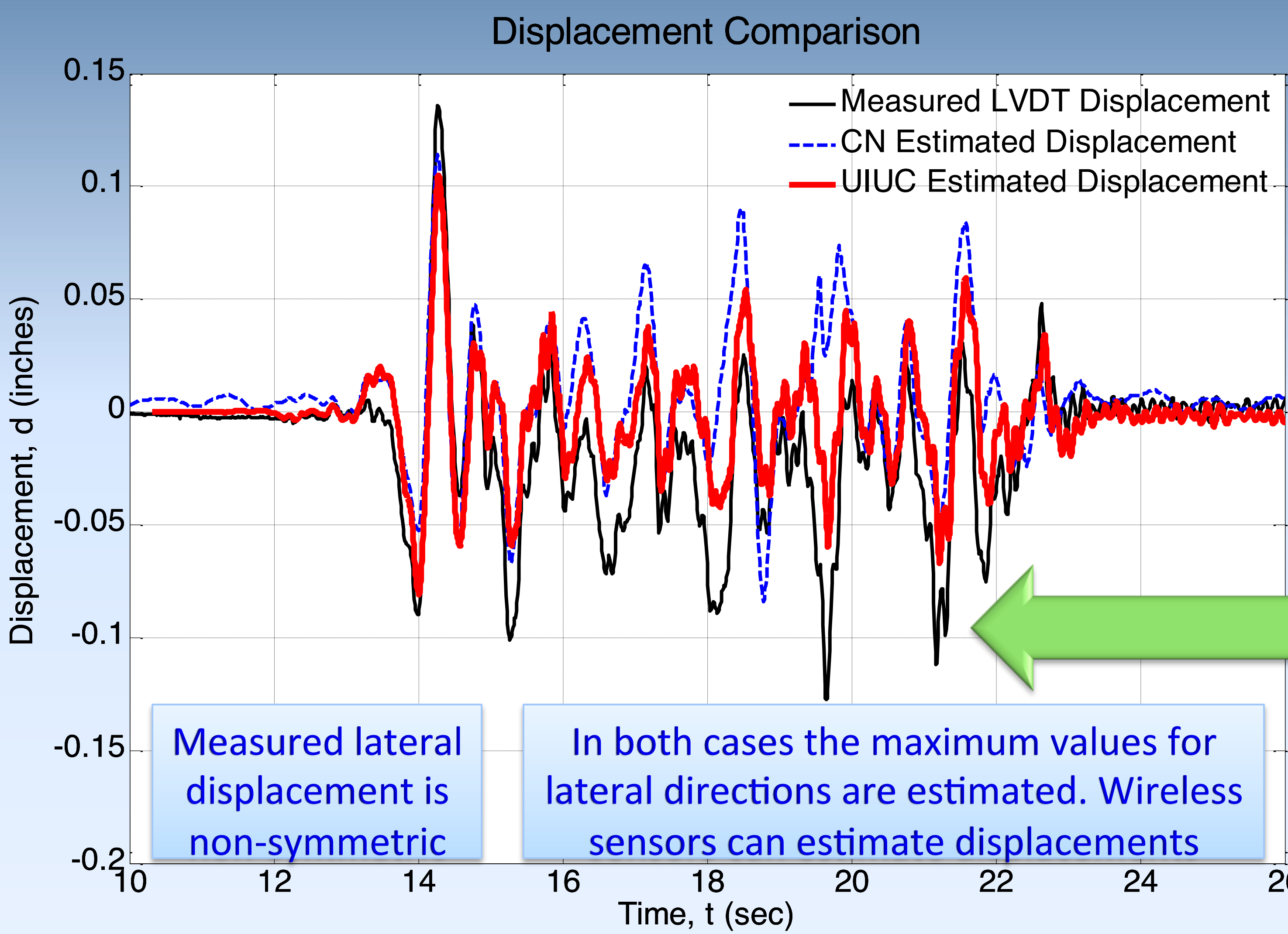
Scaffolding correction does not have significant effect in displacement estimation

Looking North



North Bound (NB) 25 MPH WT

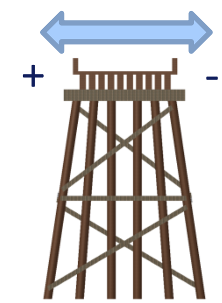




Measured lateral displacement is non-symmetric

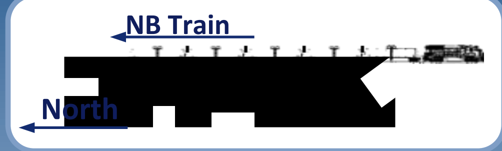
In both cases the maximum values for lateral directions are estimated. Wireless sensors can estimate displacements

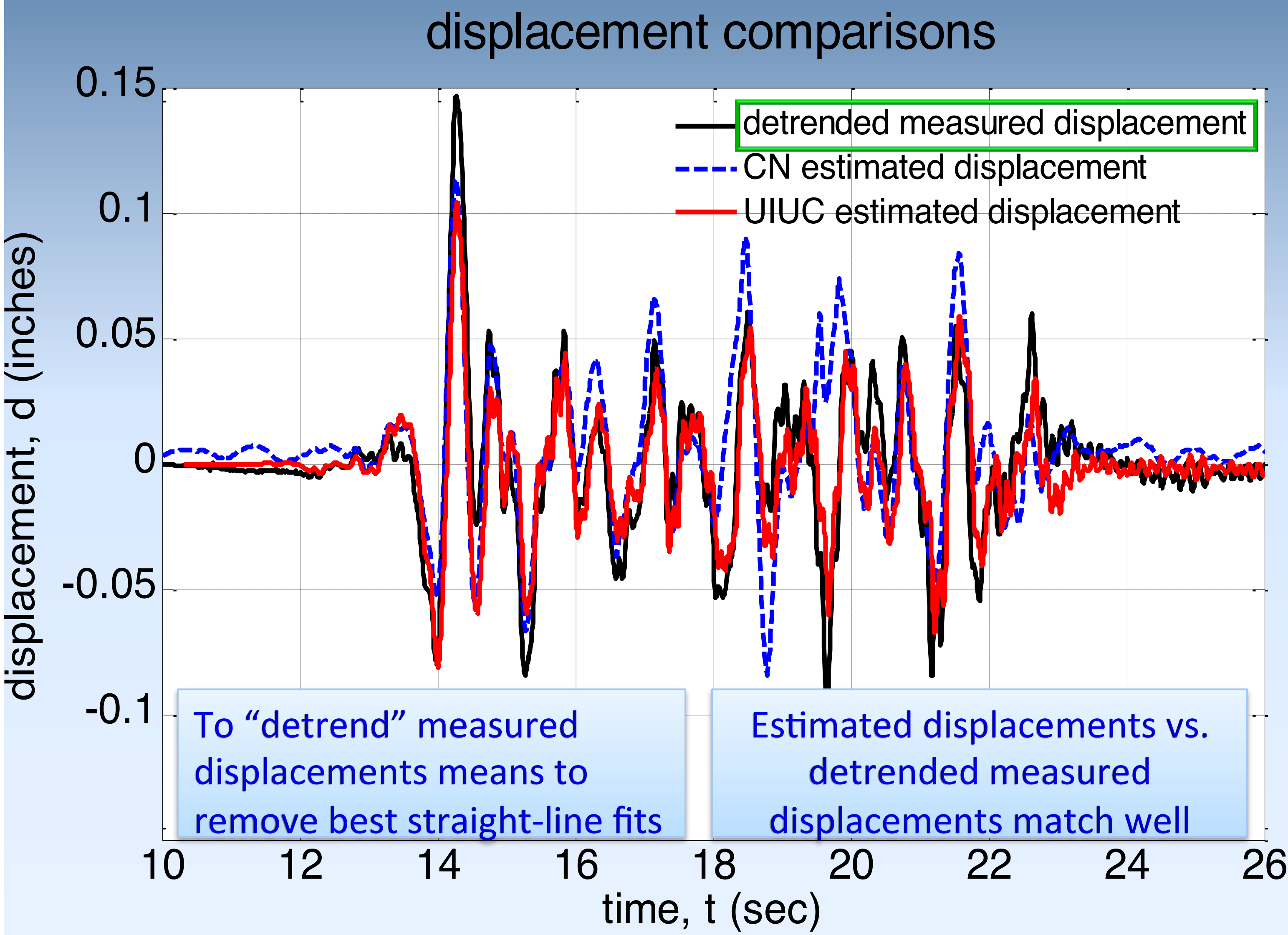
Looking North



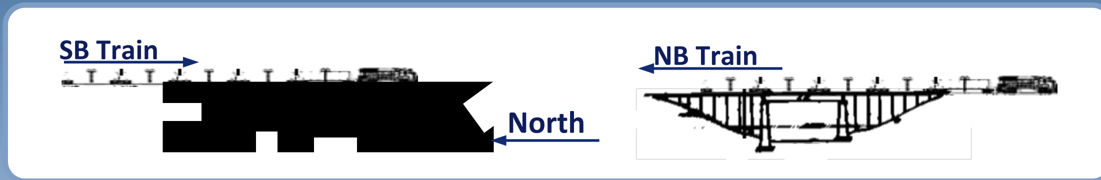
Measured pseudo-static trend could be removed by "detrending" measured displacements

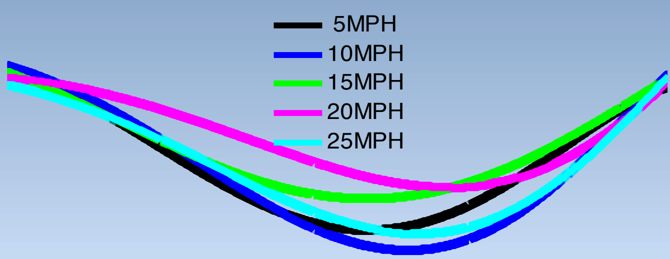
North Bound (NB) 25 MPH WT



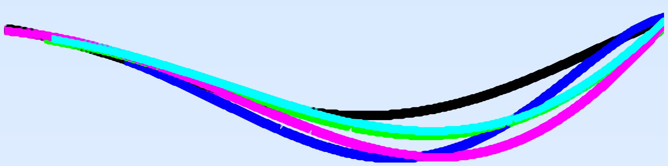


Total range displacement estimation

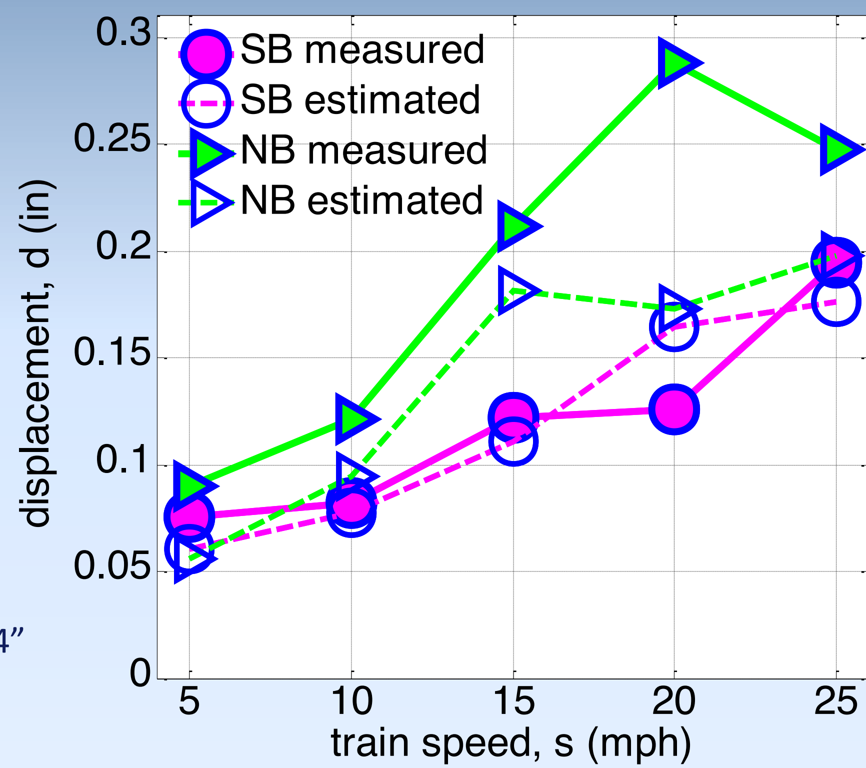


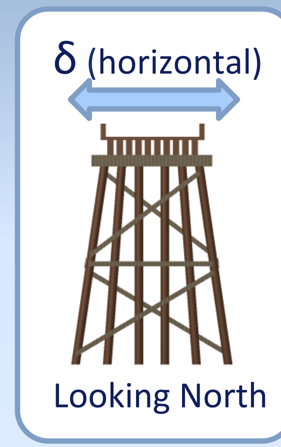


Max. **SB** pseudo-static horizontal = 0.05”



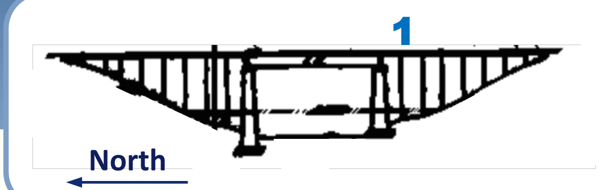
Max. **NB** pseudo-static horizontal = 0.04”



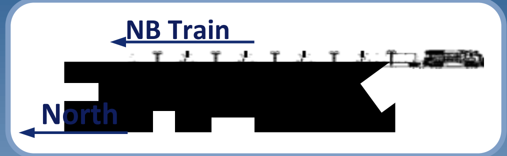


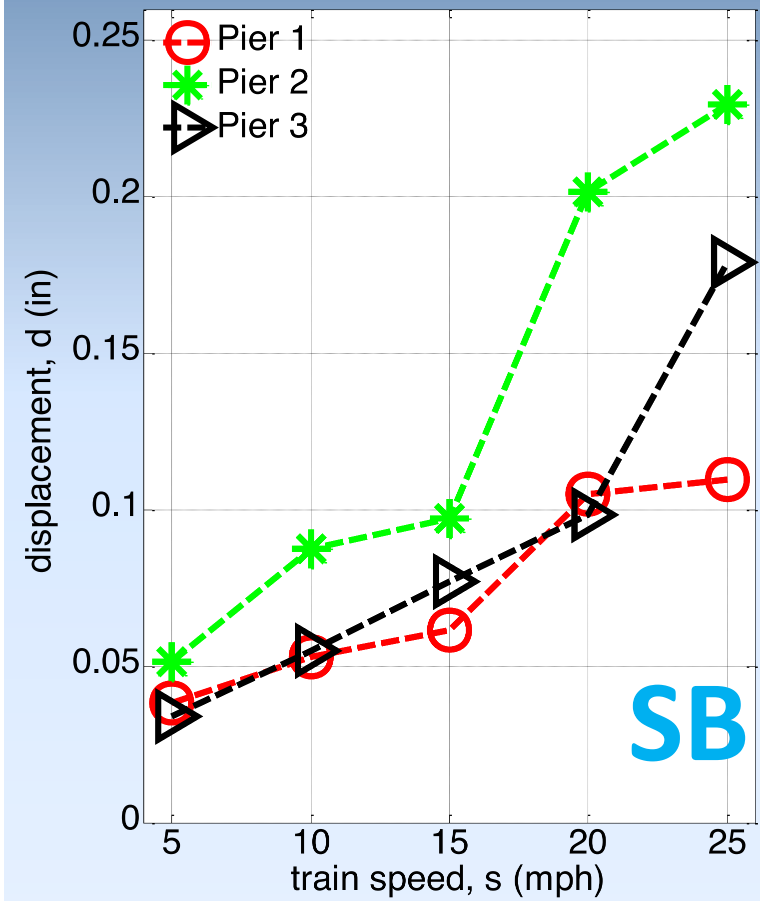
- ❑ Except for NB 20mph train, estimations improve with higher velocities
- ❑ The pseudo-static component significantly affects the lateral estimations

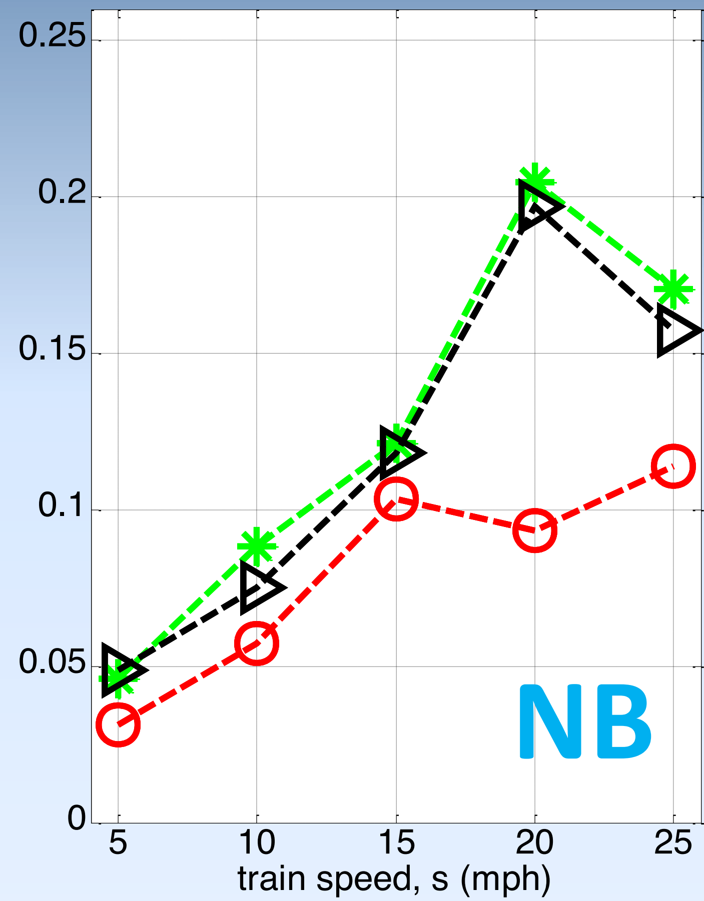
Piers 2 and 3 estimated displacements

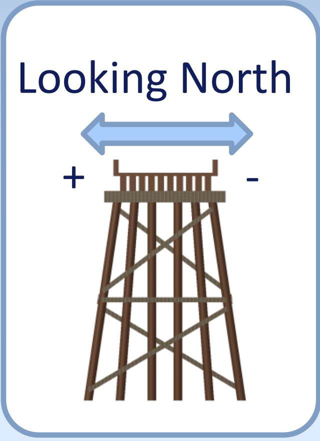


Displacement estimations for different piers



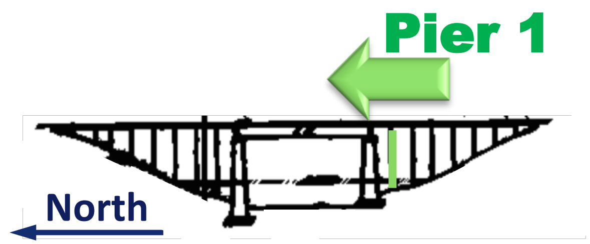






Estimated maximum displacements can assist identifying piers with larger displacements

Longitudinal displacements estimated from UIUC Imote2 accelerations

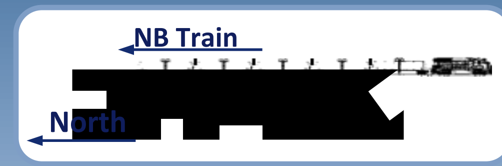


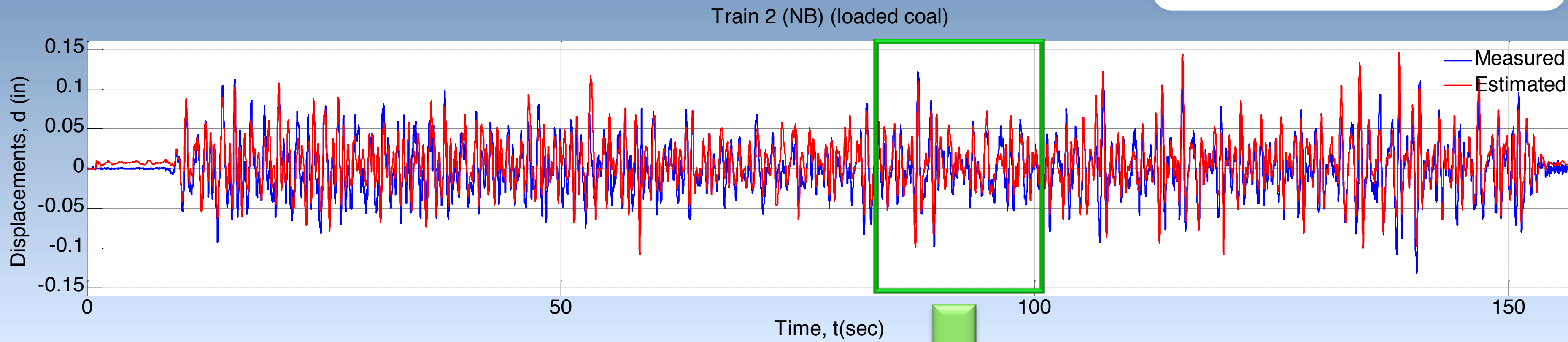
	5	10	15	20	25
SB	0.055	NA	0.257	0.207	0.197
NB	0.014	0.093	0.242	0.195	0.393

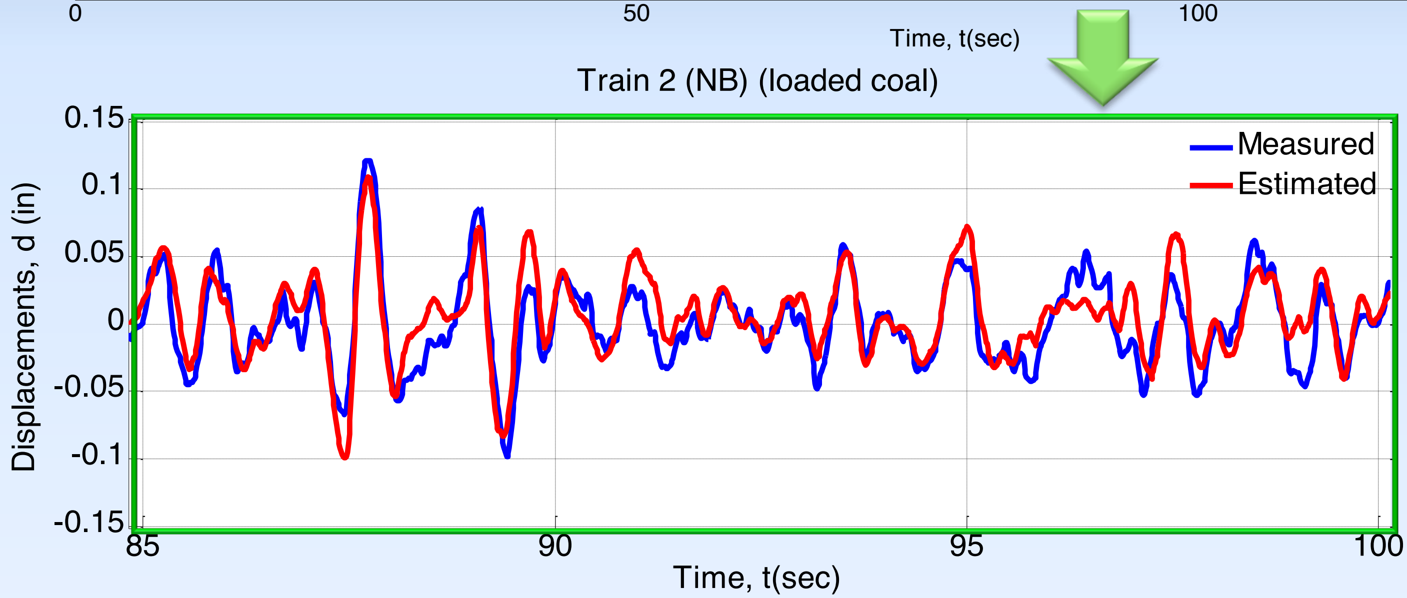
- Larger than measured transverse displacements
- Maximum estimated values always toward South (independent of traffic direction)

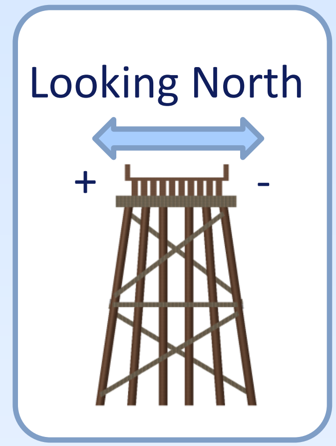
Loaded train measurements

Dynamic displacement estimates (train)



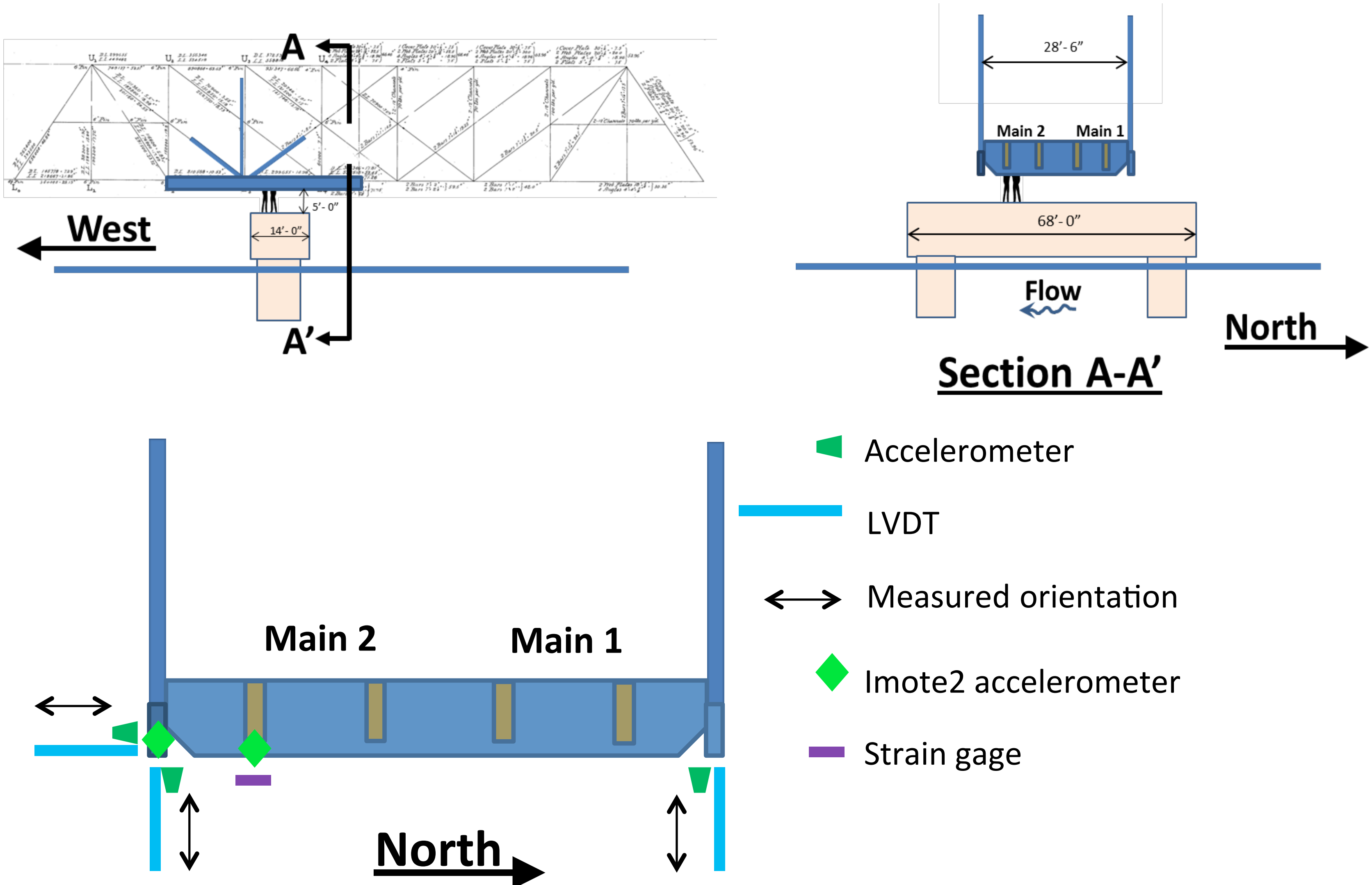






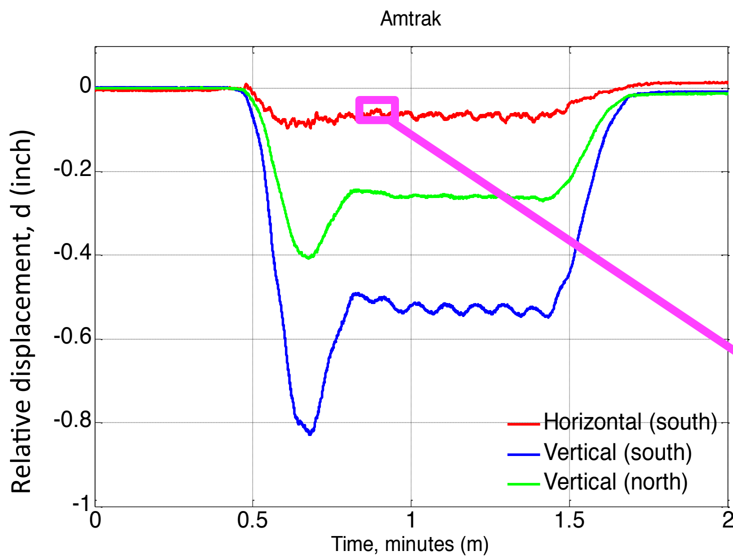
- The estimation of displacement from accelerations is also possible with in-service trains

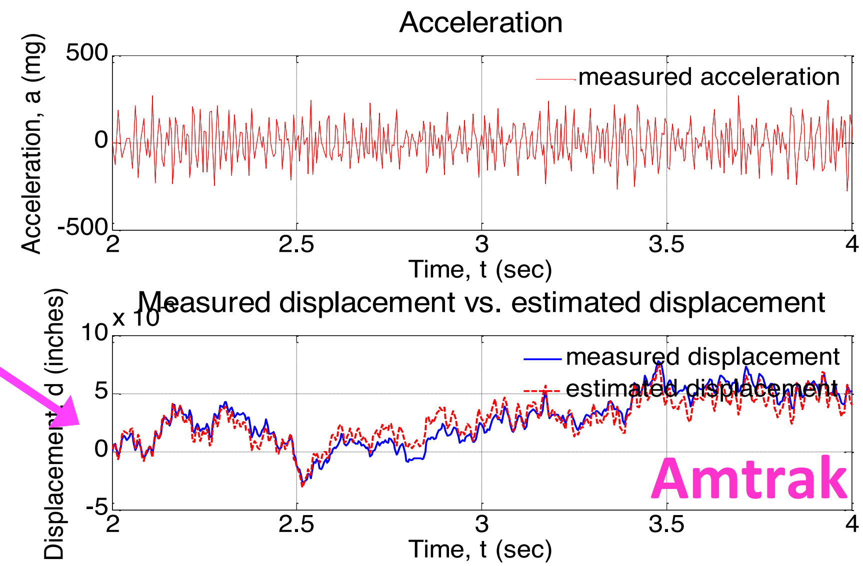
Other results: steel truss displacements

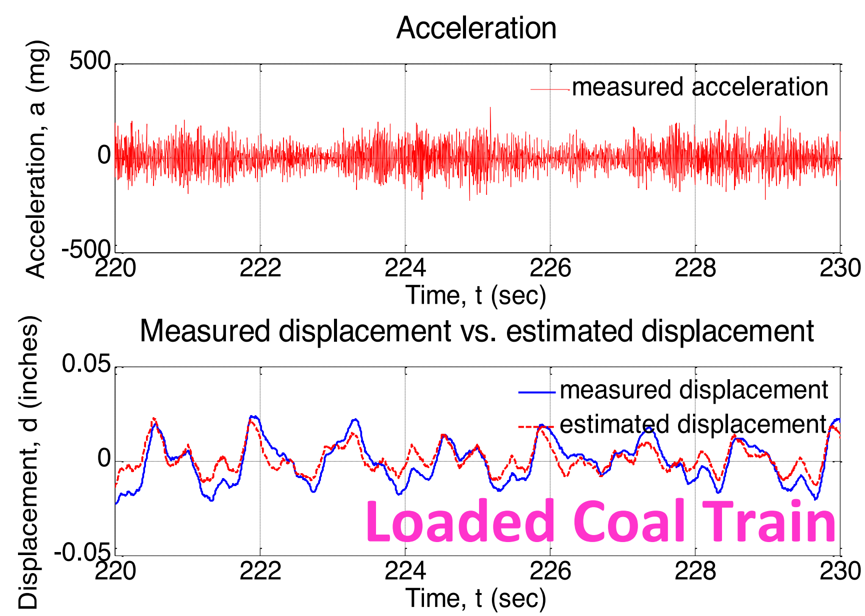


A very unique opportunity was provided to accurately monitor displacements of the steel span using a new pier cap as a reference

Estimated dynamic displacements



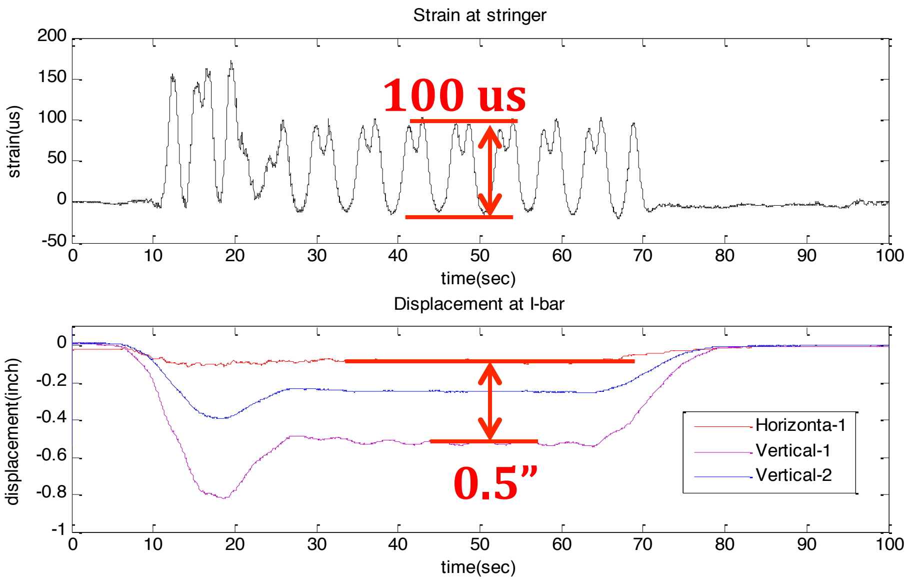




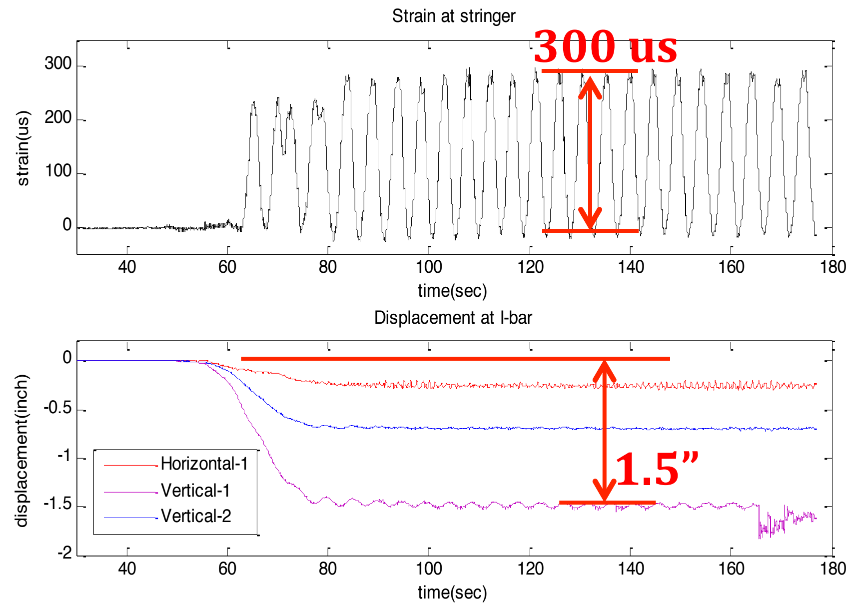
Estimated lateral (horizontal) dynamic displacements from accelerations match dynamic measurements collected with LVDTs

Wireless strain measurements

Amtrak



Loaded Coal Train



The ratio of both the strains and displacements collected matched closely for the two trains monitored

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Summary

- For the timber trestle measured under work trains, lateral displacements increased with speed
- Displacements have been estimated from accelerations, with comparable results for the dynamic range of both work trains and in-service trains
- Results from a 250 ft. steel truss also showed good reference-free estimations of displacements from accelerations
- Strain measurements collected with wireless smart sensors identified different train loading conditions at the bridge

Acknowledgements

- AAR Technology Scanning Program
- SEI ASCE O. H. Amman Research Fellowship
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- BNSF: José Mares, Trevor Altwood, and Fred Klesner
- ROW Consultants: Dan Painter

Thank you for your attention
Any questions?