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Total reference-free displacements for condition assessment of timber railroad bridges using tilt

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Abstract. The US railroad network carries 40% of the nation's total freight. Railroad bridges are the most critical part of the network infrastructure and, therefore, must be properly maintained for the operational safety. Railroad managers inspect bridges by measuring displacements under train crossing events to assess their structural condition and prioritize bridge management and safety decisions accordingly. The displacement of a railroad bridge under train crossings is one parameter of interest to railroad bridge owners, as it quantifies a bridge's ability to perform safely and addresses its serviceability. Railroad bridges with poor track conditions will have amplified displacements under heavy loads due to impacts between the wheels and rail joints. Under these circumstances, vehicle-track-bridge interactions could cause excessive bridge displacements, and hence, unsafe train crossings. If displacements during train crossings could be measured objectively, owners could repair or replace less safe bridges first. However, data on bridge displacements is difficult to collect in the field as a fixed point of reference is required for measurement. Accelerations can be used to estimate dynamic displacements, but to date, the pseudo-static displacements cannot be measured using reference-free sensors. This study proposes a method to estimate total transverse displacements of a railroad bridge under live train loads using acceleration and tilt data at the top of the exterior pile bent of a standard timber trestle, where train derailment due to excessive lateral movement is the main concern. Researchers used real bridge transverse displacement data under train traffic from varying bridge serviceability levels. This study explores the design of a new bridge deck-pier experimental model that simulates the vibrations of railroad bridges under traffic using a shake table for the input of train crossing data collected from the field into a laboratory model of a standard timber railroad pile bent. Reference-free sensors measured both the inclination angle and accelerations of the pile cap. Various readings are used to estimate the total displacements of the bridge using data filtering. The estimated displacements are then compared to the true responses of the model measured with displacement sensors. An average peak error of 10% and a root mean square error average of 5% resulted, concluding that this method can cost-effectively measure the total displacement of railroad bridges without a fixed reference.

Keywords: bridges; experiment; sensor/sensor placement; smart sensor; structural dynamics; structural health monitoring (SHM); serviceability; railroad bridges; tilt; displacements; accelerations

1. Introduction

The US railroad network is considered one of the most dynamic freight systems in the world (FRA 2012a), transporting nearly 40% of the nation's freight (FRA 2010). A 2014 study conducted by Towson University calculated the economic activity of the line haul freight railroads with an operating revenue of at least $457.91 million at 2015, also known as Class 1 railroads, to be $274 billion (AAR, 2016, 2017). There are seven Class I railroads in North America: BNSF Railway, CSX Transportation, Grand Trunk Corporation, Kansas City Southern Railway, Norfolk Southern Combined Railroad Subsidiaries, Soo Line Corporation, and Union Pacific Railroad. Additionally, CN and Canadian Pacific own railroad systems in the United States that qualify them to be Class I railroads (AAR 2017). The US railroad network is aging, however, the weight of cars has increased since 1970 by 70% (Unsworth 2010). Despite a doubling of investment in the railroad network since 1980 (see Fig. 1), Cambridge Systematics (2007) projected that the railroad network will exceed its train per day volume capacity by 2035. If current infrastructure is not upgraded, the future capacity will add accumulated strain on the infrastructure, accelerating its decay and decreasing its robustness. While a continuous source of funding is dedicated to keeping the railroads safe and profitable, investing in infrastructure for future capacities, resources are limited and railroads need to prioritize improvement and maintenance operations. Railroad bridges are one of the most critical components of this network. With an estimated 100,000 bridges connecting track every 1.4 miles on

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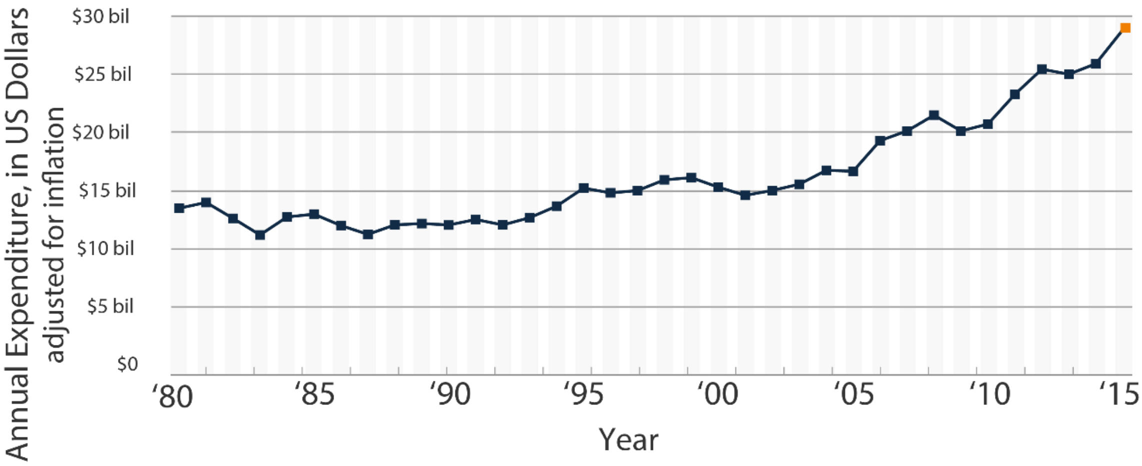

Fig. 1 Freight railroad investment per year since 1980, adjusted for inflation (AAR 2015)

average (Moreu 2015), being able to accurately and objectively measure bridge performance under traffic loading is essential for safety and replacement prioritization (Moreu and LaFave 2012).

Infrastructure managers are interested in collecting objective information to inform their decisions about maintenance, repairs, and replacement for those bridges within their network that need them the most. Multiple researchers have studied different techniques for assessing the structural health of bridges (Farrar *et al*. 1994, Zhang and Aktan 1995, Villemure *et al*. 1996, Nickitopoulou *et al*. 2006, Balageas 2006). Frangopol *et al*. (2012) claimed that the bridges of a network are very likely to: (i) have similar traffic loads; (ii) be designed with the same codes; (iii) have similar environmental conditions; and (iv) have experienced the same extreme events. If responses of bridges within a network could be easily measured, those measurements could inform the prioritization of management decisions within the network.

Railroad bridge transverse displacements relate directly to the structural condition of the bridge and can be used to determine a bridge's serviceability when train derailment is considered as the main concern (Moreu *et al*. 2015). Class I railroad bridge owners believe that the total transverse displacement of a railroad bridge under train crossing is one parameter of interest to quantify a bridge's ability to safely perform traffic (i.e., serviceability). For railroad bridges with poor track conditions, the transverse displacements can be amplified under heavy locomotive due to impacts between the wheel and the rail joints (Hussain *et al*. 1980, Xia *et al*. 2006, Xia *et al*. 2008). Under these circumstances, vehicle-track-bridge interactions could cause excessive bridge displacement, and hence, unsafe train crossings (American Railway Engineering and Maintenance-of-Way Association - AREMA 2014a, b). For this reason, FRA (2012b) considers harmonic roll as a train accident cause. If displacements during train crossings could be measured objectively, owners could repair or replace less safe bridges first.

Sensors, such as linear variable differential transducers (LVDTs), can measure displacements when placed in the direction of motion and provided a fixed reference point. Moreu *et al.* (2014) collected railroad bridge transverse displacements using LVDTs under varying traffic conditions to investigate the effect of different speeds and loads on bridge behavior. Uppal *et al.* (1990) also used LVDTs to measure the displacements of timber railroad bridges to show that different train speeds influence the deflections of the bridge deck. Sundaram *et al*. (2015) used LVDTs, among other sensors, to measure displacements of a pre-stressed concrete slab bridge and monitor responses under heavy axle freight wagons. Fanning *et al*. (2005) also used LVDTs for direct displacement measurements. A common problem of these studies is that they require a fixed reference point to attach the displacement sensor and measure the responses with respect to that position. However, building a scaffold as the fixed reference is often difficult, especially when bridges are spanning over big geographical obstacles, such as rivers, lakes or gaps between mountains. Other researchers have proposed contact-free methods to measure the displacements of railroad bridges. Psimoulis and Stiros (2013) proposed the use of a robotic total station (RTS) to measure the deflections of a short-span railroad bridge in response to passing trains. Nassif *et al*. (2005) utilized a Laser Doppler Vibrometer (LDV) to measure the deflection and vibration of bridges. The LDV measures the velocity and displacement of the vibrating object by detecting the frequency shift of the reflected light. These methods do not require a scaffold, however, they need to be placed on a flat and uniform reference. Proposing a new total reference-free method to measure bridge displacements under trains can assist managers in collecting valuable information in the field.

Researchers have used acceleration measurements to estimate reference-free displacements. Traditional methods successfully used in the past to obtain reference-free displacements include double integration of the acceleration readings and removal of the integration errors through filtering (Boore 2003, Yang *et al*. 2005, Gindy *et al.* 2008). Park *et al*. (2013) used a finite impulse response (FIR) filter to estimate zero-mean displacements from accelerations and validated it for earthquake signals using shake tables in the laboratory. Moreu *et al.* (2015) validated this approach by

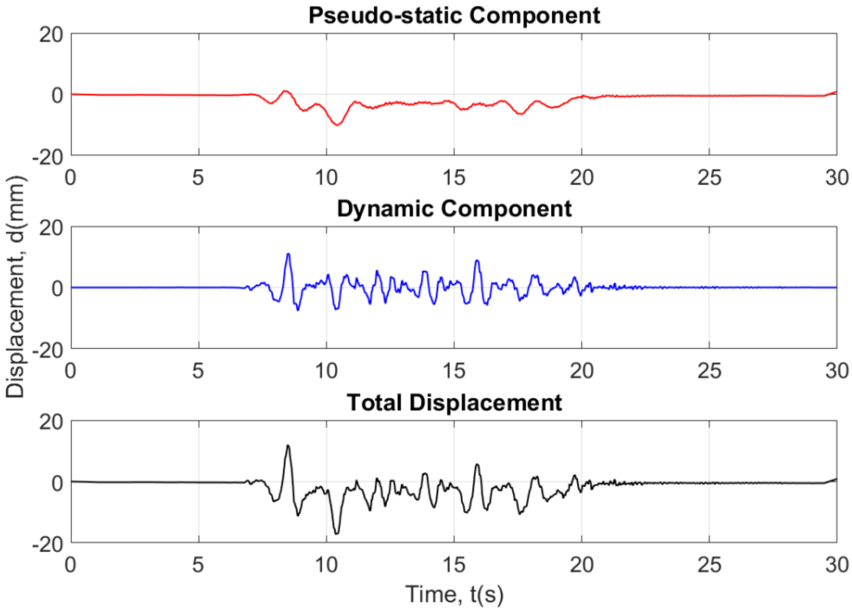

Fig. 2 Schematic representation of displacement components of railroad bridge

estimating the displacements of a real railroad bridge using wireless smart sensors (WSS) and comparing the estimations to LVDT readings. Cho *et al.* (2015) integrated acceleration data and strain measurement into finite element models to estimate bridge displacements. Likewise, Hoag *et al.* (2017) conducted experiments to obtain the displacements of a railroad bridge using digital image correlation (DIC) and accelerometers. Existing methods, however, cannot be directly applied to measure the total displacement of railroad bridges due to the nature of train loading, railroad bridge type, and their interaction. The displacement of a railroad bridge has two components: low frequency pseudo-static components due to the weight of the train; and high frequency dynamic displacements due to the vibrations of the bridge during the train crossing (Stephen *et al.* 1993). Fig. 2 shows the total displacement of a railroad bridge deck with its two differentiable components. The pseudo-static components can be described as the displacements that would be observed on the bridge if the train was not moving. The dynamic component is a zero-mean displacement that is produced by the impact of the train with the track, and it is related to the train-bridge interaction during bridge crossing events.

Accelerometers are inertial sensors and can only measure dynamic excitations due to their zero-mean nature. Based on past field monitoring efforts, measuring the pseudo-static component of the railroad bridge displacement with accelerometers are often challenging (Moreu *et al*. 2014). There is a need to provide both dynamic and pseudo-static displacements using reference-free sensors.

Researchers have investigated and validated several reference-free methods for measuring the total displacements of bridges. One of the most commonly utilized methods consists of measuring the inclination of the bridge deck to obtain vertical displacement. Hou *et al.* (2005) defined a method for calculating the vertical deflection by attaching several inclinometers along the span of a bridge and computing its angle of inclination over time. Then, they calculated the deflection of the span by differentiating the angular values and obtained the deflection curve. The precision of the method increases when more sensors are used. Yu *et al.* (2013) used inclination sensors to calculate the deflection of bridges to assess their structural health. However, the authors simplified their method to a centered point load and a uniform distributed load, hence only calculating the mid-span point. Zhang *et al*. (2016) presented a deflection and damage estimation method based on the relation between the forces and inclinations present in the bridge. They built a finite element model (FEM) of the bridge and combined it with the measured inclinations. The deflections were then reconstructed from the inclinations and the changes in the nodal loads were used as damage indicators. Although the studies discussed here estimated the total deflection of the bridges, they focused only on the vertical displacements and did not account for the interaction between the bridge and the service loads. Transverse displacement of a railroad bridge during train crossing has the equal importance and is acknowledged as an indicator for the structural performance when train derailment is considered as the main concern (Moreu *et al*. 2014). Railroad managers are interested in data-driven objective maintenance prioritization of railroad bridges for the efficient, cost-effective and safe operation of this infrastructure. Moreu *et al.* (2015) identified that transverse bridge displacement under train service load can inform bridge managers of structural performance levels. Collecting the total transverse displacement under trains can be an indication of the structural condition of railroad bridges.

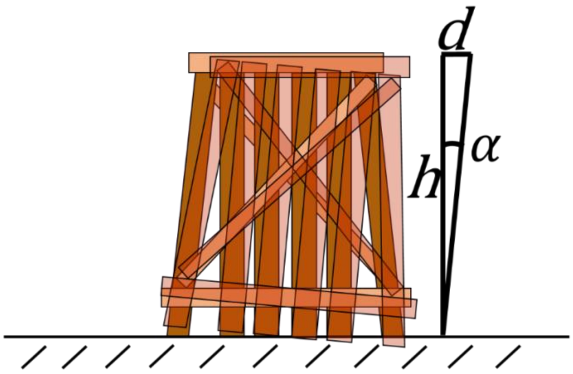

Fig. 3 Schematic relation between tilt and pseudo-static displacement of a railroad timber trestle

This paper proposes a new method to measure the total transverse displacements of railroad bridges, specifically timber trestles, under train traffic. This new method combines both the pseudo-static and the dynamic components of railroad bridge displacements through reference-free means. The pseudo-static component of the bridge displacement is attributed to the angle of inclination of the top of the exterior pile bents on standard timber trestles. In this method, the angle of inclination of the pile bent is obtained by measuring the time history of gravity components and relating them trigonometrically. The relation between the angle of inclination of the pile bent and the displacement is assumed linear. Researchers built a representative pile bent model on a shake table to run the train crossing simulations and validate the method under real railroad bridge displacement data collected in the field. An LVDT measured the displacement of the shake table to evaluate the accuracy of the system. Two accelerometers placed on the pier of the model measuring responses in the vertical and horizontal directions captured the angular data. A filter extracted the trend from the angle measurements taken from the pile bent of the model. Then, researchers transformed the angular data into displacement using a linear trigonometric relationship. In addition, another accelerometer was placed in the direction of motion of the shake table to capture the dynamic component of the displacement by applying a finite impulse response (FIR) filter to the acceleration data. Finally, researchers combined both components of the displacement (dynamic and pseudo-static) to obtain the total displacement estimation. Ten real bridge displacements were used to validate the method. The errors between the total displacement estimation and the real displacement were less than 15%, demonstrating the accuracy of the method and its ability to obtain the total reference-free displacement of a railroad bridge under trains.

2. Methodology

This section describes the methodology to estimate the displacements from the angular data of the pile bent. The first part defines the steps followed to record the experimental data. The subsequent part defines the characteristics of the filters used to obtain the displacements from the recorded accelerations. Finally, this section explains the significance of the errors of the estimation with respect to the LVDT.

2.1 Total reference-free displacement

The bridge displacement under train crossing events is composed of dynamic and pseudo-static components. The dynamic component is a zero-mean motion caused by the high frequency responses of the bridge under the vibration of the train. The deflection of the bridge at low frequencies caused by the non-symmetric boundary and train loading conditions governs the pseudo-static displacement component (Moreu *et al.* 2015). Although double integration of acceleration data is an alternative tool for capturing the pseudo-static component of the railroad bridge displacements, initial conditions on velocity and displacement are often unavailable for those integration methods (Hester *et al.* 2017). To solve this problem, this research estimates the pseudo-static component using the relation between the inclination angle of the pile bent and its displacement. For the preliminary validation of this experimental method, the pseudo-static displacement of the timber trestle piles is assumed to be governed by pure rocking under trains. This simplification of the pseudo-static response of timber railroad bridges has been determined by consulting Class I railroad bridge engineers concerned about the effect of displacement on the safety of operations. For this preliminary assumption and experimental validation, the time history of the angle will be directly proportional to the total displacement of the deck, which is the combination of pseudo-static and dynamic displacements. Eq. (1) defines the trigonometric relation and Fig. 3 illustrates its application to railroad bridges.

$$d = \tan\alpha \cdot h \quad (1)$$

where h is the known height of the pier, α is the inclination angle of the pier, and d is the displacement of the deck. Ozdagli *et al.* (2017) have proposed the

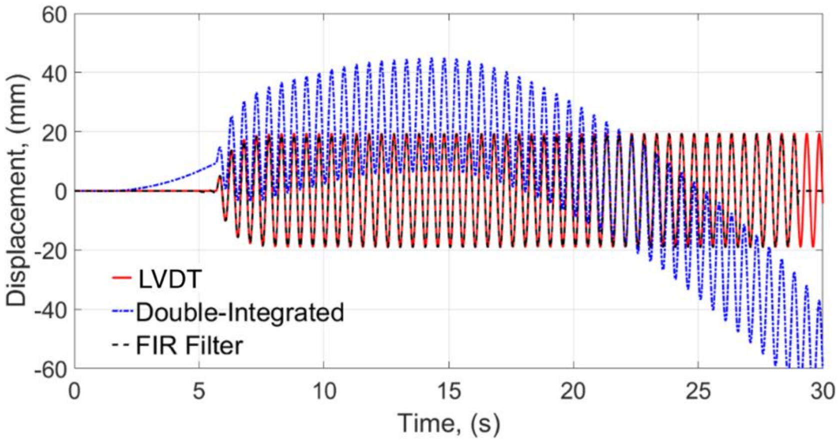

Fig. 4 Displacement estimations from acceleration double integration and FIR filter

theoretical validation of the estimation of the pseudo-static displacement by simulating the influence of tilt in railroad bridges caused by bending with OpenSees structural analysis software (OpenSees 2017). This paper validates both the estimation of pseudo-static displacement caused by pure rocking both theoretically and experimentally. Other contributions to pseudo-static displacements such as shear, local effects, or other nonlinear behavior are not included.

2.2 FIR filter for dynamic displacement estimation

Lee *et al*. (2010) developed a finite impulse response (FIR) filter to reconstruct displacements from accelerations. This algorithm allows the researchers to reduce the errors produced by the traditional double integration method. The problem is defined by introducing the minimization problem shown in Eq. (2)

$$\underset{u}{\mathrm{Min}}\, \Pi_E(u) = \frac{1}{2}\int_{T_1}^{T_2}\left(a\big(u(t)\big) - \bar{a}\right)^2 dt \qquad (2)$$

where u is the displacement that is being calculated, a is the theoretical acceleration for the double integration method and $\bar{a}$ is the measured acceleration. The acceleration is then discretized using the finite differences approximation method and the discretized acceleration is introduced in the minimization problem in Eq. (2). To avoid having an ill-posed problem, a Tikhonov regularization is performed with the addition of a regularization factor λ, as shown in Eq. (3)

$$\underset{u}{\mathrm{Min}}\, \Pi(u) = \frac{1}{2}\left|\left|Lu - (\Delta t)^2 L_a \bar{a}\right|\right|_2^2 + \frac{\lambda^2}{2}\left|\left|u\right|\right|_2^2 \qquad (3)$$

where L_a is a diagonal matrix with all the diagonal elements equal to one with the exception of the first and the last elements which are equal to $\frac{1}{\sqrt{2}}$, L which is the diagonal weighing matrix product of L_a and L_c (linear algebraic operator from finite differences method), u is the estimated displacement, Δt is the time increment, $\bar{a}$ is the measured acceleration and λ is the optimal regularization factor.

Eq. (4) gives the solution with respect to the unknown displacement u

$$u = (L^T L + \lambda^2 I)^{-1} \cdot L^T L_a \bar{a}(\Delta t)^2 = \mathrm{C}\bar{a}(\Delta t)^2 \qquad (4)$$

where I is the identity matrix and C is the coefficient matrix required for the displacement reconstruction. Multiple researchers have validated this algorithm for different applications (Park *et al*. 2013, Moreu *et al*. 2015).

Fig. 4 shows a graphical representation of the displacement estimation using traditional double integration, and the described FIR filter is shown. The LVDT signal is a sinusoidal wave acting as the reference displacement. The two estimations were taken during the same event. The double integration curve differs from the LVDT due to the unknown integration constants. On the other hand, the FIR estimation coincides accurately with the reference displacement.

2.3 Moving average filter for pseudo-static displacement estimation

This section describes the characteristics of the filter used to process the pseudo-static displacement measured from the inclination angle of the pile bent. A filtering technique was necessary due to the noisy nature of the collected data. The first proposed option was the use of a Kalman filter. The Kalman filter is a commonly used technique in guidance, navigation, and control of vehicles. However, the Kalman filter was found to be inadequate for the desired application. Therefore, a moving average filter was utilized to extract the trend from the displacement obtained from the inclination angle. The conceived idea was to obtain the trend by calculating the mean of a number of points contained inside a predefined window and move that window along the data array to create multiple means from each window at every point. After the calculation of all the means resulting from the windows, the pseudo-static displacement was obtained by averaging the means of the overlapping windows. Eq. (5) shows the calculations performed to obtain the values of the filtered signal

$$y(i) = \frac{1}{N}\sum_{j=0}^{N-1} x(i+j) \qquad (5)$$

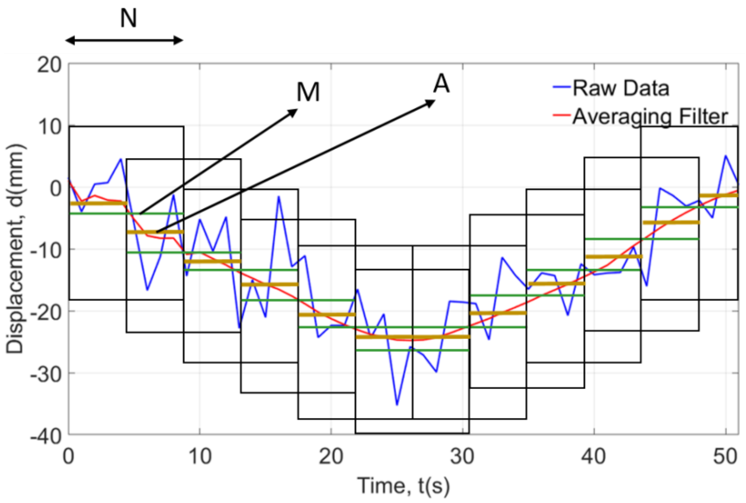

Fig. 5 Graphical illustration of moving average filter for tilt estimation

where x is the input data that is being filtered, y is the filtered output signal, i is the index of the analyzed point, N is the window size and j is the index of the point within the window. In Fig. 5, the behavior of the filter is illustrated.

The window size, N denotes the number of data points that are averaged. The size of this window corresponds to the half of the total data points sampled in one second, i.e., sampling frequency. The window overlap was *N-1*, although Fig. 5 shows a smaller overlap for illustrative purposes. The mean of the data points is contained inside the window, N is defined by M and the mean of all the overlapping M returns the filtered data A. Fig. 5 illustrates that the filter is capable of extracting the trend despite the noise of the signal.

2.4 Performance evaluation criteria

Researchers calculated three types of errors to assess the error between the true displacement measured by the LVDT and the estimations. Eq. (6) defines the average peak error (E_1)

$$E_1(\%) = \frac{\frac{\sum_{i=1}^{n}(A_i - B_i)}{n}}{\frac{\sum_{i=1}^{n} A_i}{n}} * 100 \tag{6}$$

where A_i is the ith maximum peak measured by the LVDT, B_i is the ith maximum peak of the displacement estimation and n is the number of peaks. This error value provides information regarding the overall behavior of the sensors when estimating the maximum points. This criterion computes the errors for the five most significant peaks (both maxima and minima) between estimation and the true displacement and averages them.

The second performance index (E_2) was the Root Mean Square (RMS) error, which indicates the capability of the proposed methodology in capturing the overall nature of the displacements. The RMS error is calculated in Eq. (7)

$$E_2 = RMSE = \sqrt{\frac{\sum_{i=1}^{n}(a_i - b_i)^2}{n}} \tag{7}$$

where a_i is the value of the true displacement at a certain point at ith time step, b_i is the value of the estimated displacement at the same point and n is the number of data points in the sample. Researchers in the past proposed a normalized RMSE obtained by dividing the RMSE over the peak displacement (Moreu *et al.* 2015). Accordingly, once the RMSE value is obtained, a third performance index (E_3) can be computed by normalizing the RMSE with respect to peak measured displacement, as given in Eq. (8)

$$E_3(\%) = \frac{RMSE}{A} \tag{8}$$

E_1 describes the ability of the estimation to determine the maximum displacements on the bridge. E_2 defines the performance of the estimation by comparing the estimation with the true displacement. E_3 defines an overall error percentage by normalizing the RMS error.

2.5 Implementation

The proposed method focuses on obtaining dynamic and pseudo-static displacements of timber pile bent cap individually and combining them together to compute the total transverse displacements. The dynamic component can be estimated from acceleration measured by an accelerometer sensor using FIR filter. Two accelerometers placed on the vertical and horizontal direction measures the tilt required for determining the pseudo-static component.

The success of this tilt measurement approach requires the utilization of DC-type accelerometers capable of measuring static gravity vector, or the projection of acceleration. The calculation of the angle involves the readings of the two accelerometers with the tangent of the angle with respect to gravity, as shown in Eq. (9).

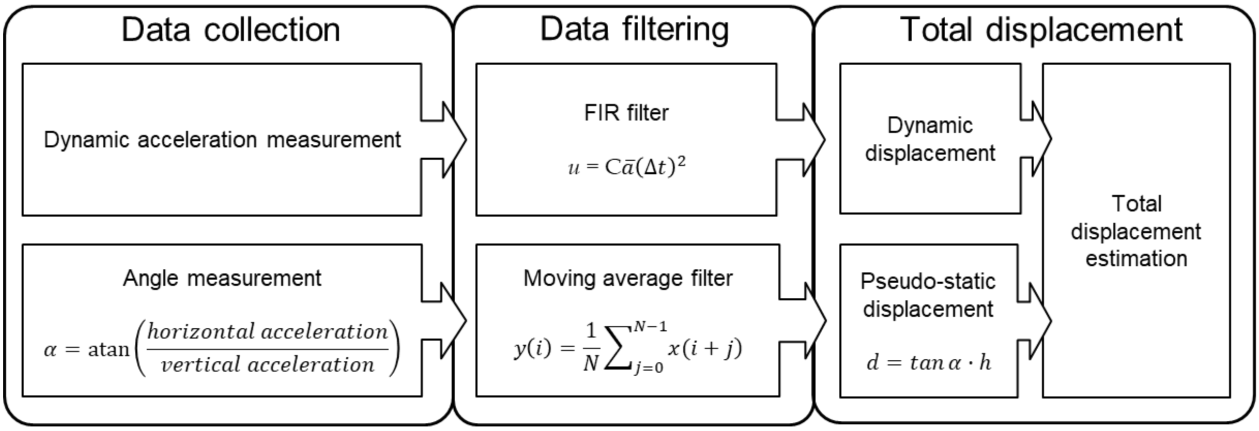

Fig. 6 Methodology of the tilt angle estimation from displacements

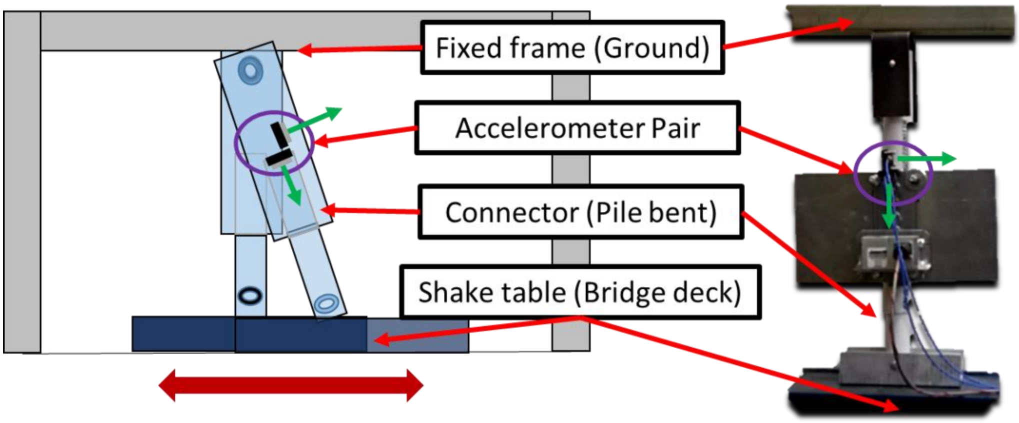

Fig. 7 Final set-up for railroad bridge tilt measurement

$$\alpha = \text{atan}\left(\frac{\text{horizontal acceleration}}{\text{vertical acceleration}}\right) \quad (9)$$

Eq. (9) combines the accelerations in the horizontal and vertical directions instead of relating only one of them with a sine or cosine function. The proof of this concept is shown in Eqs. (10) and (11)

$$\alpha = \text{atan}\left(\frac{\text{horizontal position}}{\text{vertical position}}\right) = \text{atan}\left(\frac{X = A \cdot \cos(wt)}{Y = B \cdot \cos(wt)}\right) = \text{constant} \quad (10)$$

$$\alpha = \text{atan}\left(\frac{\text{horizontal acceleration}}{\text{vertical acceleration}}\right) = \text{atan}\left(\frac{X = -Aw^2 \cdot \cos wt}{Y = -Bw^2 \cdot \cos wt}\right) = \text{constant} \quad (11)$$

Upon obtaining the inclination angle, moving average filter described in Eq. (5) extracts the pseudo-static trend. The pseudo-static responses are usually concentrated between 0-0.5Hz, as reported by Park *et al.* (2005) and Hester *et al.* (2015). Additionally, frequency analysis conducted by Moreu *et al.* (2015) has shown that the dominant dynamic characteristics of train-bridge interaction are above 0.5 Hz.

As a result, to effectively extract the pseudo-static trend, researchers use a moving average filter and its number of data points to be averaged corresponds to the half of the sampling rate. The authors verified that the number of data points for the moving average filter is independent of the sampling rate and the type of accelerometer used. Finally, Eq. (1) computes the pseudo-static displacement from the inclination. Fig. 6 shows the schematic methodology flow chart divided into three stages: data collection, data filtering, total displacement estimation.

3. Experiment

This section describes the experimental set-up used to replicate the railroad bridge conditions in the laboratory. The first part explains the used experimental model in the validation of the proposed method. Then, this section describes the technical specifications of the instruments used. Finally, the section defines the characteristics of the utilized railroad bridge displacement.

3.1 Railroad bridge testing layout

This research proposes a new upside-down railroad bridge configuration to simulate the effect of train crossings on pile bents. The shake table acted as the vibrating railroad bridge deck. In order to provide a fixed ground for the base of the pile bent, researchers designed and built a steel frame on top of the shake table. The final design consisted of two tubes with different diameters that fitted inside one another allowing the differential elongation of the pile with respect to the frame. The tubes were pinned and fixed to the shake but were free to rotate with respect to the frame and the shake table. Fig. 7 shows the final set-up for the measurement of tilt angles and the locations of the relevant accelerometer sensors.

3.2 Instrumentation

Two 3711B1110G capacitive accelerometers manufactured by PCB Piezotronics (PCB Piezotronics 2015) measured the tilt of the pile bent. The 3711E1110G is a capacitive MEMS DC accelerometer that can achieve true DC response for measuring uniform (or constant) acceleration. It has a sensitivity of 200 mV/g, a measurement range of ±10 g and a frequency range from 0 to 1000 Hz. Additionally, another 3711B1110G accelerometer was attached to the shake table in the direction of motion to record the dynamic component of the displacement.

A linear variable differential transducer (LVDT), DCTH3000A manufactured by RDP Electrosense (RDP Electrosense 2016) collected the displacement of the shake table. This LVDT has a small linearity error (0.5%) and a measurement range of ±75 mm, which provides accurate readings to be used as the reference displacement. Output signals of all the sensors were sampled at a frequency of 1024 Hz with an 8-channel VibPilot DAQ system manufactured by M+P International (M+P International 2015). A USB cable connected the VibPilot to a laptop computer which controlled the sensing parameters, such as the sensitivity of the sensors and their sampling frequency. The shake table used was a QUANSER Shake Table II (Quanser 2016), which allows a maximum displacement range of 15.2 cm.

Table 1 Train characteristics description

Train	Speed, km/h (mph)	Direction
1	8.7 (5.4)	SB
2	8.7 (5.4)	NB
3	16.2 (10.1)	SB
4	17.8 (11)	NB
5	23.3 (14.5)	SB
6	24.9 (15.5)	NB
7	33.9 (21)	SB
8	31.1 (19.3)	NB
9	41.5 (25.8)	SB
10	41.0 (25.5)	NB

3.3 Railroad bridge displacement data

In order to prove the efficiency of the method, ten real bridge displacements were introduced with the shake table. Bridge displacements were taken in the transverse direction from a pile bent of a timber bridge, the Bluford Bridge near Edgewood, Illinois during train crossings running at different speeds (ranging from 8.7 km/h (5.4 mph) to 41 km/h (25.5 mph)) and directions (northbound (NB) and southbound (SB)) (Moreu *et al*. 2014, Moreu *et al*. 2015).

Table 1 shows a detailed description of the train crossing parameters. A frequency-domain analysis conducted by Moreu *et al.* (2014) shows that the frequency content of the transverse responses is concentrated in the range of 0 - 1.4 Hz and is associated with the harmonic roll of the passing train.

4. Results

The ten different bridge displacement signals from the various train crossings described in the previous sections were input into the shake table. Researchers obtained the inclination angle of the pile bent by relating the components of the acceleration with a simple trigonometric relation, as shown in Eq. (9). The angular data was then used to calculate the displacement relating it to the height of the pier, as shown in Eq. (1). A moving average filter with a window size of 512 samples extracted the pseudo-static component from the total displacement. Finally, the researchers combined the estimations of the dynamic and pseudo-static components to retrieve the total displacement estimation.

Fig. 8 displays the efficiency of estimated total reference-free displacements under Train 8 (31.1 km/h NB). This train illustrates the effect of the harmonic rock and roll in the displacements. The harmonic rock and roll is an oscillatory motion associated with heavy cars and speeds around 24 km/h (15 mph) (Hussain *et al.* 1980). Railroad managers are interested in using displacement measurements to detect resonance of large trains (up to two miles in length) crossing timber trestles (Moreu *et al*. 2015).

The repetitive loading of heavy loaded cars on long timber trestles can enhance the rock and roll phenomena. According to the railroad, if total displacements could be measured with reference-free mean, those measurements could be used to inform railroads of the rock and roll resonance under different trains and speeds. The results shown in Fig. 8 demonstrate the accuracy of the proposed method, step by step.

Researchers followed the same process for the ten different train crossing events. Fig. 9 shows the pseudo-static displacement obtained from the tilt angle of the pile bent for all the trains. Fig. 10 presents the dynamic displacement estimations obtained from the displacement reconstruction algorithm explained in section 2.2. Finally, Fig. 11 shows the total displacement estimation after the combination of both components.

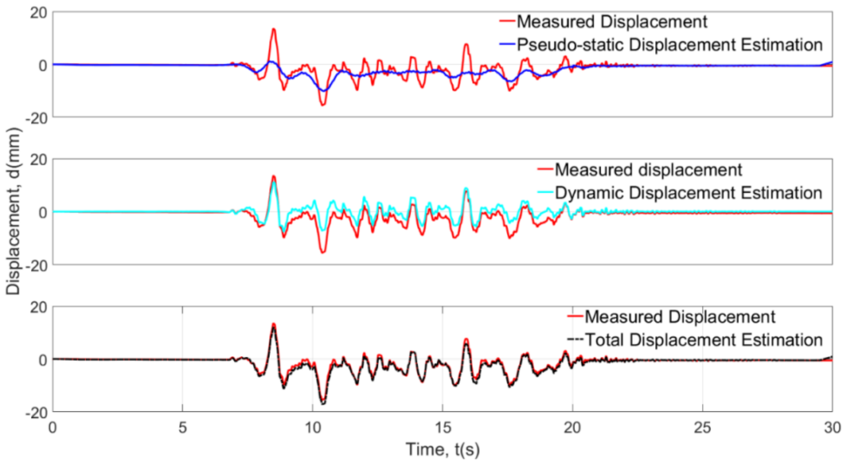

Fig. 8 Bridge displacement estimation under Train 8 (31.1 km/h NB)

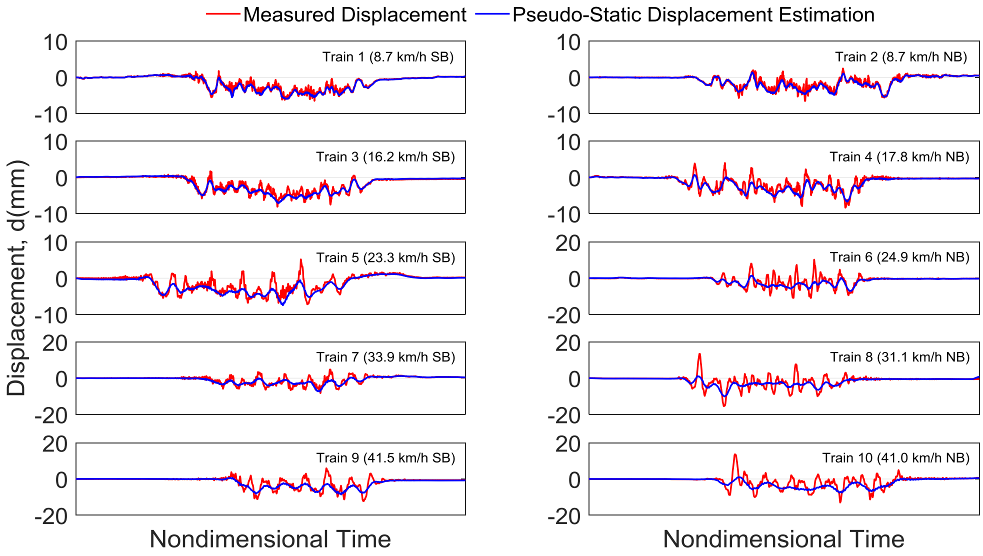

Fig. 9 Pseudo-static displacement estimation

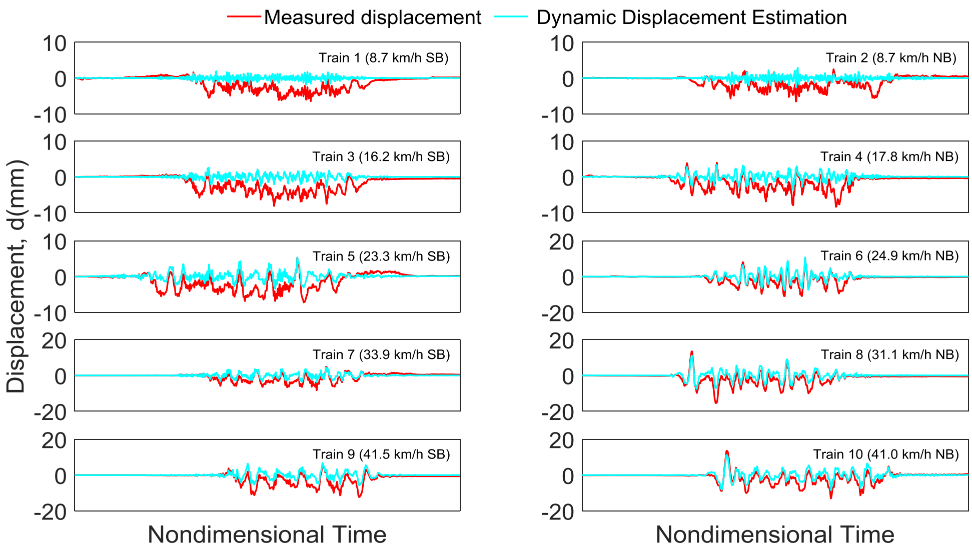

Fig. 10 Dynamic displacement estimation

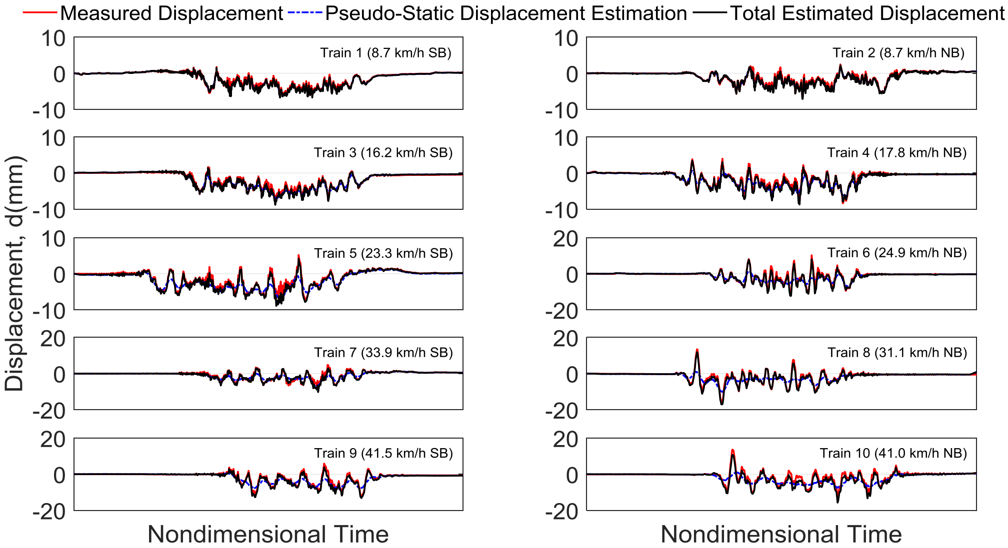

Fig. 11 Total displacement estimation

Table 2 Estimation errors

Trains	E_1(%)	$E_2(mm)$	E_3(%)
1	11.65	0.33	5.14
2	6.06	0.33	4.98
3	3.26	0.37	4.60
4	12.68	0.44	5.22
5	10.03	0.56	7.78
6	10.73	0.89	8.06
7	10.89	0.76	9.21
8	7.84	0.65	4.17
9	7.21	0.88	7.14
10	14.87	0.77	5.61

After the time histories of the displacements were obtained, errors were calculated to quantify the accuracy of the implemented method. Table 2 displays the error values for the three calculated performance parameters. It is observed that all the E_1 errors are below 15%. In the case of the E_2 performance index, all the error values are below 10%, with an average of 6.2%. The results show that the method is accurate and that it can effectively measure the transverse displacement of a railroad bridge without a fixed reference. Moreu *et al.* (2015) estimated the dynamic displacements of the same railroad bridge obtaining a 20% error, on average. The reference-free total displacement estimation method proposed in this paper obtained an average peak error of 9.52% and a normalized RMS error of 6.2%. These results show that the proposed methodology is experimentally validated and total reference-free displacement can be obtained with non-reference sensors with relatively small errors. The results obtained and the experiment can be further expanded to increase the variability of structural systems and train crossing events.

However, the results presented under the assumed bridge behavior allow for reference-free experimental displacement estimation with acceptable error margins for railroad bridges under train crossing. The ten experiments show that the proposed method is independent of the speed and direction of the train. Similarly, the assumption of the pile bent is the first effort to expand the proposed approach for field validation for different railroad bridge types. Fig. 12 displays the all-peak and normalized root mean square errors in percentage obtained from the estimations of the ten train crossings.

5. Future work

While this paper focuses on obtaining total displacements of timber trestles under rocking behavior, the method explained here can be extended to measure vertical responses of railroad bridges at the midspan. For this purpose, a 4 m (13 ft.) long timber bridge span between two pile bents is isolated from a timber bridge structure illustrated in Fig. 13. This span is modeled in OpenSees as simply supported beam (see Fig. 14), and a distributed load simulating train traffic is applied on the beam as prescribed in Ozdagli *et al.* (2017). The accelerations obtained from midspan is converted to dynamic displacements with FIR filter. The moving average filter extracts pseudo-static components from the rotations at the beam supports. The general Euler-Bernoulli beam equations for simply supported beams under uniform distributed force can be rewritten such that the filtered rotations can be translated to pseudo-static displacements without prior knowledge on material and section properties as given below

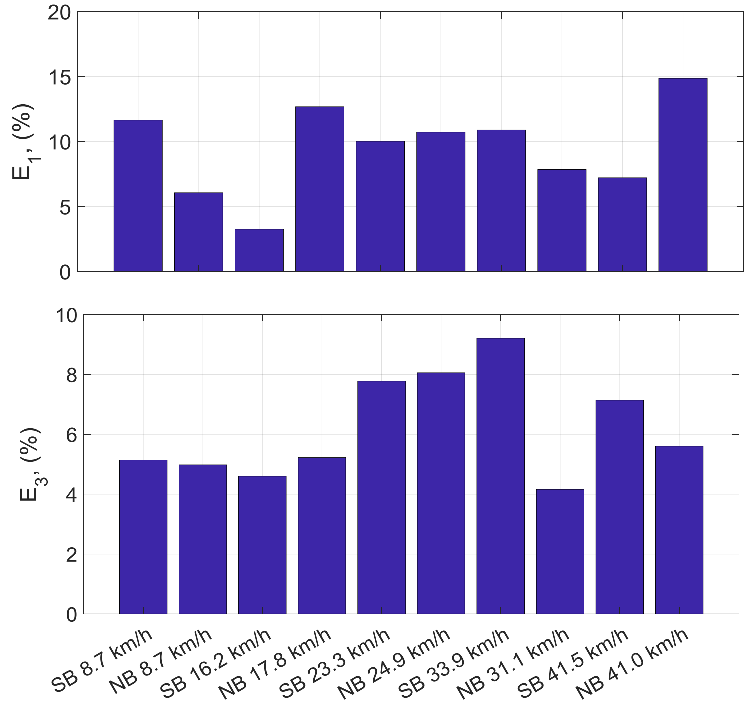

Fig. 12 Error values of the total displacement estimation

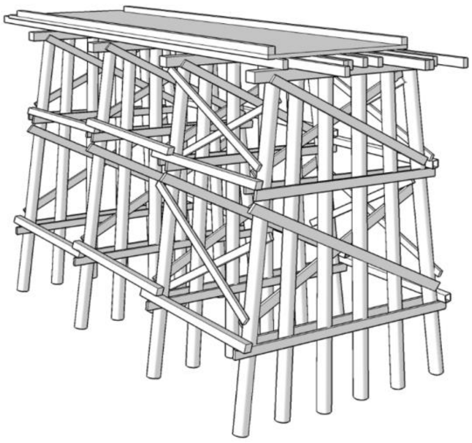

Fig. 13 Partial view of a timber railroad bridge

$$\delta_{midspan}^{pseudo-static} = \frac{5qL^4}{384EI} \quad (10)$$

$$\theta_{beam\ end}^{pseudo-static} = \frac{qL^3}{24EI} \quad (11)$$

$$\delta_{midspan}^{pseudo-static} = \theta_{beam\ end}^{pseudo-static}\frac{5L}{16} \quad (12)$$

The resulting dynamic, pseudo-static and total vertical displacements are compared to the total measured responses in Fig. 15. The outcome of this comparison demonstrates that the proposed method can be potentially used for other applications related to performance assessment of railroad structures and critical infrastructure.

In future, authors will extend the capabilities of the proposed method to estimate pseudo-static displacements of railroad bridges under transverse bending by testing a timber trestle idealized as a cantilever column model in the laboratory (see Fig. 16). The model is inverted such that the free end of the cantilever is excited by a shake table capable of reproducing bridge deck response to train crossings. Similarly, the fixed end of the model is secured to a rigid frame which represents the stiff ground condition.

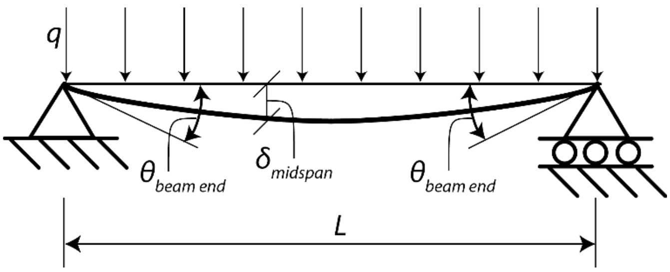

Fig. 14 Idealized model of the timber railroad bridge span

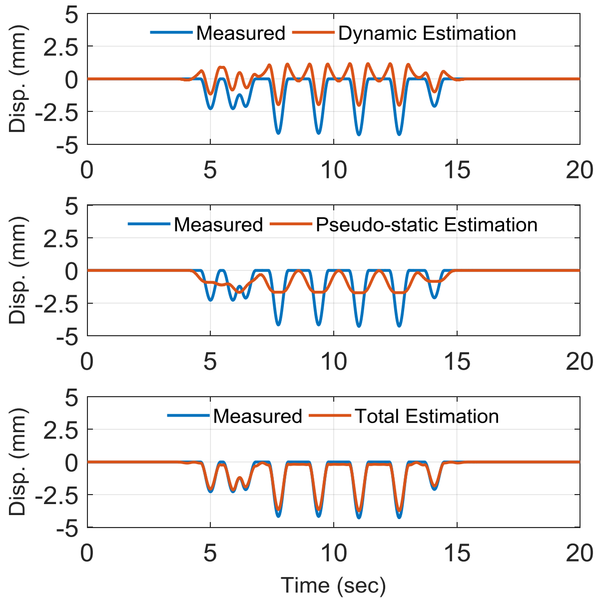

Fig. 15 Partial view of a timber railroad bridge

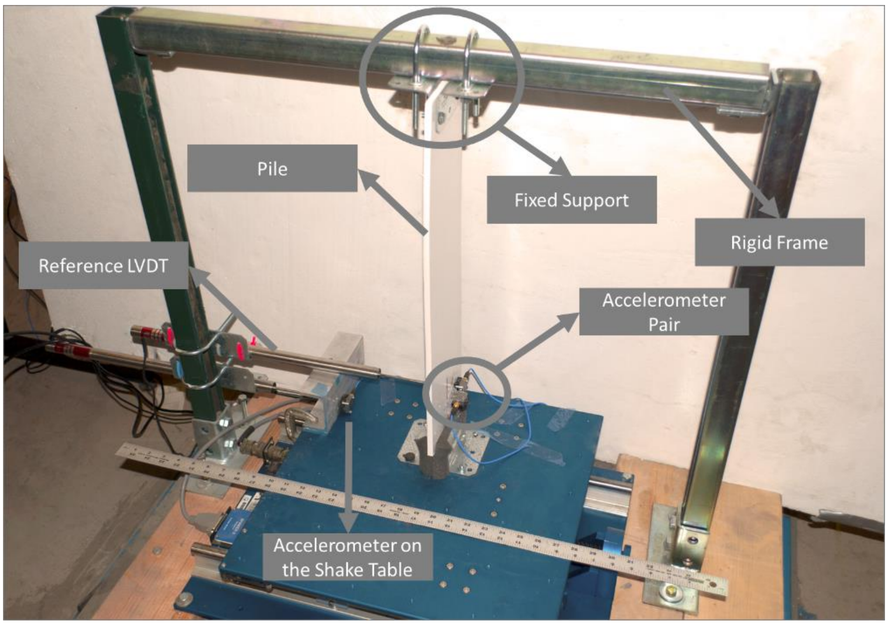

Fig. 16 Future experiment setup

6. Conclusions

The efficient maintenance of railroad bridges is of crucial importance in order for the railroad network to continue providing effective delivery of goods across the nation. Due to limited maintenance budgets, prioritizing bridge maintenance using objective data is necessary for cost-effective, informed decisions of their serviceability. However, most bridge inspections are conducted visually and are unable to assess the dynamic performance of bridges under service loading. Monitoring the displacements of bridges can help to provide accurate and objective information about their serviceability. Direct displacement is often difficult to collect in the field due to the lack of a fixed reference point. This paper proposes a reference-free displacement estimation method based on the estimation of the pseudo-static and dynamic components of the displacement separately. A pile bent model was built on a shake table and was excited with displacements measured on-site from a bridge during train crossings. This estimation method uses the tilt angle of the pile bent to obtain the pseudo-static component of the displacement and the deck accelerations for the dynamic component estimation. Data filtering techniques transform accelerations into displacements. The estimated values were then compared to the real displacement and the error between them were calculated. This paper shows an average peak error of 10% and a root mean square error average of 5%. Therefore, the method presented in this research allows the estimation of the total displacement of the railroad bridge that takes into consideration both the dynamic and the pseudo-static componenst of the displacement. The findings of this research show that this method can be effectively used for structural health monitoring of railroad bridges. For further validation of the proposed method, it should be applied in the field to test its accuracy and to compare it with the results obtained in the laboratory. Additionally, low-cost wireless systems can be used to lower the cost of the sensing systems, making the proposed method more widely available for development and implementation. Providing a wireless connection would improve the value of the method and facilitate its implementation on a large scale.

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