Nothing-on-Road Axle Detection Strategies in Bridge-Weigh-in-Motion for a Cable-Stayed Bridge: Technical Paper

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Abstract

In this paper, field test investigations of a cable-stayed bridge have been carried out in order to address the challenges of axle identification for Bridge-Weight-in-Motion systems. Various structural members of the bridge including cables, girders and the deck have been instrumented with strain gauges at different locations to measure the axial, bending or shear strain responses. Numerous field testings have been conducted by running light and heavy vehicles travelling at different speeds, different traffic directions, and different lateral locations on the bridge. Since identification of the closely-spaced axles is a key to ensure true classification of the vehicles, therefore, vehicles with tandem and tridem axle configurations have been adopted in the field test. This paper then aims to identify the sensor arrangement through which the closely-space axles can reliably be detected regardless of the vehicle's speed, travelling direction and lateral location of the vehicle on the bridge. It is demonstrated that the axial strains on the cables and bending strains in the girders provide the global response of the structure, hence, unable to identify the closely-spaced axles. In contrast, it is demonstrated that the longitudinal strains under the deck can identify the closely-spaced axles, provided they are accurately positioned under the wheel path. Finally, it is illustrated that the shear responses at the end of the span are able to identify the closely-spaced axles irrespective of the travelling direction and lateral location of the vehicle. In order to fully automate the process of axle identification, Continuous Wavelet Analysis has been utilised using the Haar mother wavelet. Successful identification of axles, even the closely-spaced axles, can be reliably obtained by integrating the wavelet analysis on the measured shear responses at the end of the bridge.

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1 Introduction

Cable-stayed bridges have been widely used as one of the key components of transportation links across the world over the last fifty years. Cable-stayed bridges are aesthetically pleasant, structurally stable, and economically cost effective (Chang et al., 2001). The structural configuration of the cable-stayed bridges mainly encompasses three sub-structures; stiffening girders, towers, and inclined cables which make these bridges suitable as long span structures. Cable-stayed bridges are classified as indeterminate structures as the influence lines of any resultant action such as flexural strains under the girders produce nonlinear curves (Walther, 1999).

In addition to the research works undertaken about static behaviour of the cable-stayed bridges, substantial attentions have been taken to better understand their dynamic behaviour under moving loads (Wang and Huang, 1992). For a comprehensive study of the structural behaviour of a bridge, the knowledge of the applied loads is necessary. Since direct identification of the applied dynamic loads by the passing vehicles is not readily available, indirect algorithms have been developed by many researchers (Law and Zhu, 2000; Chan et al., 2000; Law et al., 1999; Chan et al., 1999; Law et al., 1997). In direct approach, the force applied by the wheels is directly measured by the force transducers placed on the pavement. Installation and maintenance of transducers in the direct approach cause interruption to traffic. Moreover, to continuously capture the dynamic force along the bridge applied by an axle, successive series of transducers are needed, which is not practical.

The concept of Bridge Weigh-in-Motion (BWIM) has been put forward to indirectly identify the weight of the passing vehicles utilising the responses captured by the strain gauges underneath the bridge (Moses, 1979; OBrien et al., 2009; O'Brien et al., 1999; Ojio et al., 2000;

Peters, 1984; Znidaric and Baumgartner, 1998). BWIM is a technique of converting a bridge into a scale by which the vehicles are weighed as they cross at normal speed. The bridge is instrumented with sensors which are placed off the road; making the system non-intrusive to the drivers. Quick and convenient installation of the sensors without interrupting the traffic and damaging the bridge are some of the benefits of BWIM (Jacob and Feypell-de La Beaumelle, 2010). The system's capability to precisely recognise the number of axles and distance between them is crucial to guarantee a reliable weight estimation. Identification of closely-spaced axles including tandem and tridem axles is also a key factor to ensure accurate classification of the passing vehicles. Furthermore, real-time traffic characterisation on a bridge is beneficial for asset managers and bridge owners as it provides statistical data about the configurations of the passing vehicles.

Nothing-On-Road (NOR) technique offers tactically located sensors underneath the deck or girders of a bridge to obtain the information about the axles' configuration (OBrien and Žnidarič, 2001). NOR generally implements sensors placed at quarter and three-quarter-spans to measure the bending strains (Kalin et al., 2006; Žnidaric et al., 2002; Žnidarič et al., 2005). As the lateral location of the vehicles greatly impact the results, the strain gauges are normally positioned under the wheel path. Once the vehicle travels over the bridge and the axle arrives to the location of the gauge, a sharp peak is generated in the signal. Bridges with secondary structural elements as in the orthotropic bridges or short span bridges are best choices for NOR (Kalin et al., 2006). Long bridges might mask the peaks created by the axles and exhibit only the combined contribution of the closely-spaced axles. Recently, a NOR system based on data captured by the advanced fibre optical sensors (FOS) has been introduced (Lydon et al., 2015). As a contactless method, a roadside camera has also been proposed to identify axles (Ojio et al., 2015).

The NOR algorithm is on the basis of detecting distinct peaks in the strain signal, as each peak corresponds to a single axle or a group of axles in the closely-spaced axle configuration. To increase the efficiency of the process, band-pass filtering has been applied (Kalin et al., 2006). Wavelet transforms have also been adopted to recognise the pattern of the signals for axle detection purposes (Chatterjee et al., 2006; Lechner et al., 2010; Yu et al., 2015).

In NOR strategy, the sensors are often installed either underneath the girders or the deck. However, since the girders are the major load-carrying components of the bridge, their response indicates the global behaviour of the bridge to all the axle loadings; making it troublesome to identify the number of the axles. Instead, shear strains have been used in several BWIM algorithms to take the local responses of the bridge into account (Bao et al., 2015; Helmi et al., 2015; Lydon et al., 2015; O'Brien et al., 2012; Salem).

In this study, field testing over a cable-stayed bridge has been performed considering light and heavy vehicles with tandem and tridem axles. The main objective is to identify which strain response and in which structural member can reliably identify the presence of all axles including the closely-spaced axles regardless of traffic direction, speed and lateral location of the vehicle on bridge.

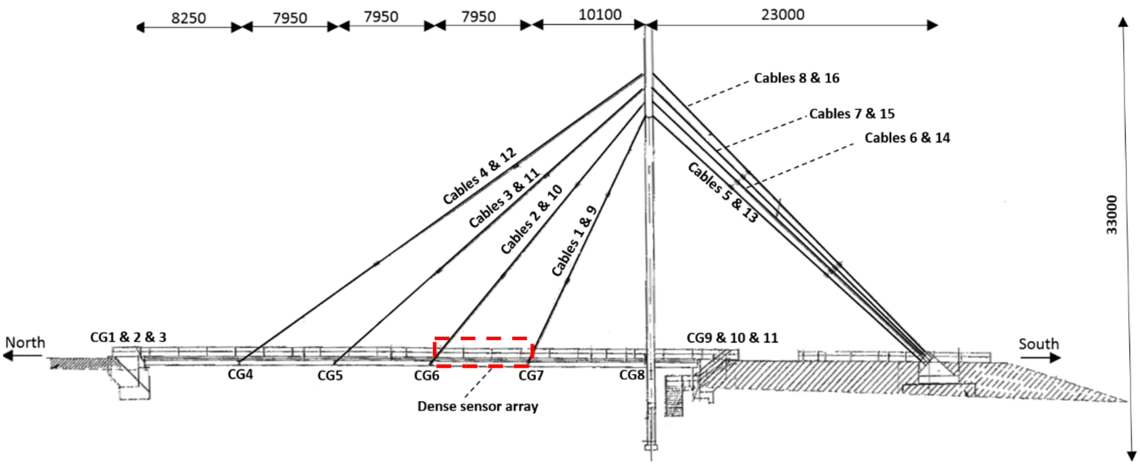
2 Experimental Set-up and Procedure

A cable-stayed bridge over the Great Western Highway in the state of New South Wales in Australia has been instrumented to investigate the axle detection schemes. This bridge provides a connection between the two Western Sydney University campuses over the Great Western highway and carries a traffic lane and a sidewalk. Figure 1 shows an illustration of the bridge where the field testing was carried.

Figure 1. A cable-stayed bridge over the Great Western Highway in the state of New South Wales in Australia.

The cable-stayed bridge has a single A-shaped steel tower with a composite steel-concrete deck. The bridge is composed of 16 stay cables with semi-fan arrangement, see Figure 2 (a). The bridge span and the tower height are 46 m and 33 m, respectively. The deck has a thickness of 0.16 m and a width of 6.3 m and it is supported by four I-beam steel girders. These girders are internally attached by a set of equally-spaced diaphragms.

(a)



(b)

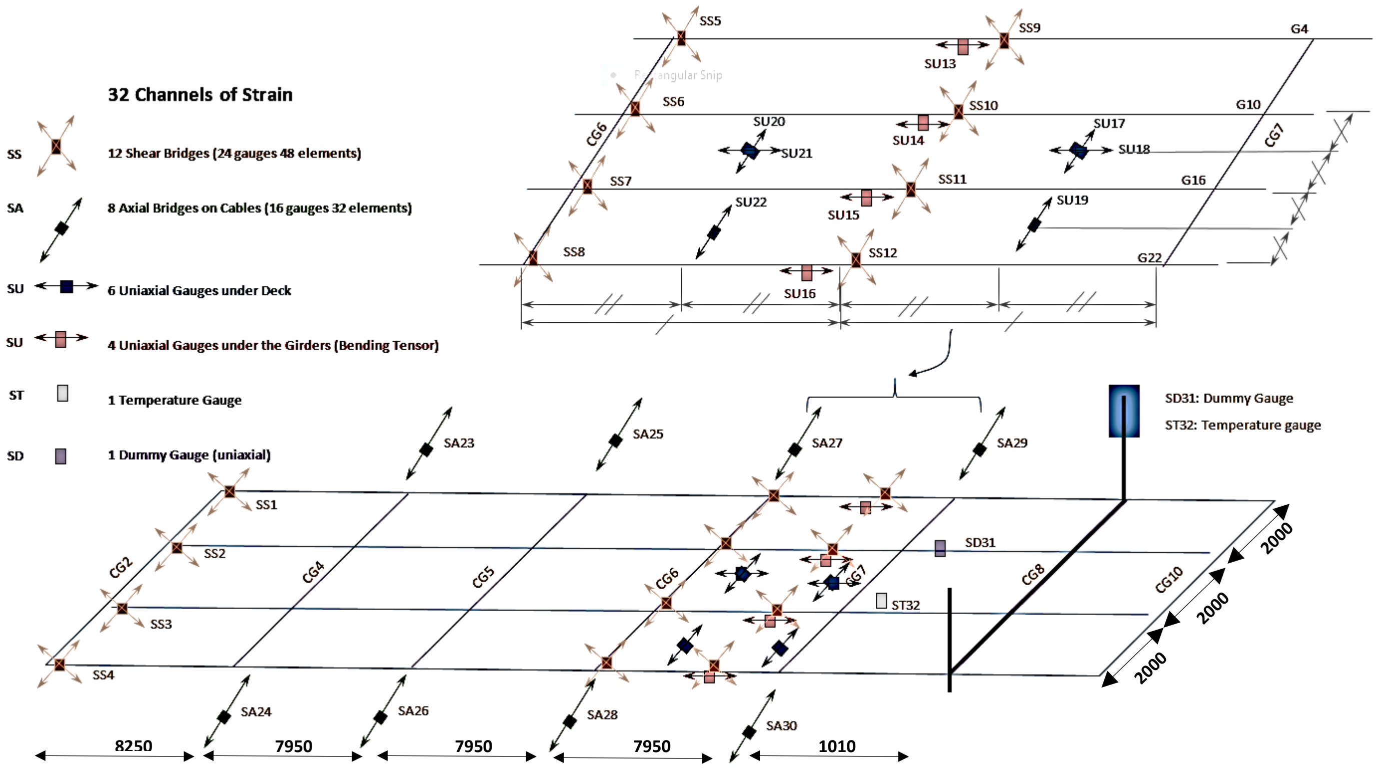


Figure 2. Illustration of (a) the elevation view of the bridge, (b) the deck plan and dense array of strain gauges installed between CG6 and CG7.

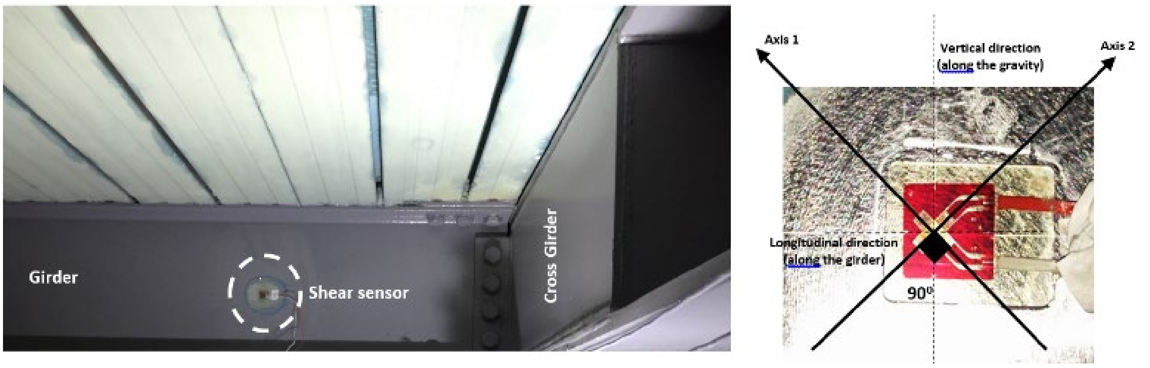
The bridge has been instrumented with an array of strain gauge sensors. The location of the sensors has been elaborated in Figure 2 (b) and (c) where most of the sensors are located in between CG6 and CG7 as indicated in Figure 2 (a). The instrumentation array comprises of the following sensor placements,

- All 8 cables have been instrumented with uniaxial strain gauges as denoted by SA_i (i=23 to 30) in Figure 2 (b).
- Uniaxial strain gauges SU_i (i=17 to 22) have been mounted under the deck in either longitudinal or transverse directions between diaphragms CG6 and CG7. The longitudinal distance between SU19 and SU22 is almost 4 m which is appropriate for

calculation of speed. As reported in (Kalin et al., 2006), the distance between speed determination sensors should be around 4 m, although it can be as low as 2m.

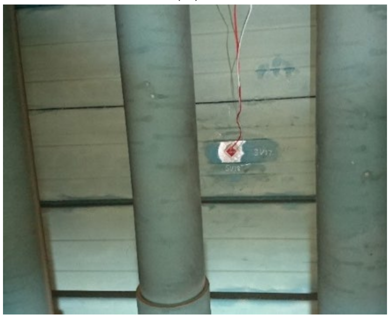
- Strain gauges SU_i (i=13 to 16) has been installed under the flange of the longitudinal girders at middle of the span between CG6 and CG7 to measure bending strains. These strain gauges are also located close to mid-span of the bridge, where large deflections are expected.
- Shear rosettes have been mounted at three different longitudinal locations along the bridge; north end of the span near diaphragm CG2, (north end-span of the entire bridge), bridge mid-span close to diaphragm CG6 (this is also located at the north end of the span between CG6 and CG7), mid-span close to diaphragm CG6, and half-way between diaphragms CG6 and CG7. Figure 3 illustrates the sensor placements on different structural members in the bridge.

(a)



(b)

(c)



(d)

Figure 3. Sensor placements, (a) shear strain gauge on the web of the girder and magnified view of the shear sensor, (b) uniaxial strain gauge in the cable, (c) uniaxial gauges in

longitudinal and transverse directions under the deck, (d) uniaxial gauge under the flange of the girder.

An HBM Quantum-X data acquisition system has been adopted for signal conditioning and data logging. The Quantum system provides an integrated and reliable device to log high quality data with 24 bit resolution with bandwidth capability of 0 to 3 kHz. The response signals of the bridge were collected at 600 Hz while various controlled test vehicles were traveling over the bridge.

Field testing has been performed using vehicles with tandem and tridem-axle configurations. In the first case study a but with a gross weight of 13 tonnes which comprises of two axle groups including one individual axle at front and one tandem-axle at rear has been considered. In the second case study, a more complicated vehicle with a gross weight of 25 tonnes which comprises of three axle groups including one axle at front, one tandem-axle at middle and one tridem-axle at rear has been tested. Figure 4 (a) and (b), respectively, illustrate the tested vehicles in the first and the second case study.

The vehicles have been driven at various speeds from north to south and south to north. In order to investigate the effect of lateral location of the vehicle on the accuracy of the results, three different lateral locations on the bridge was also considered. In order to properly determine the location of the vehicles, two lines were marked on the pavement as shown in Figure 5 (a). Figure 5 (b) depicts the different routes for the vehicles travelling north to south. For the direction of north to south, in route 1: the truck travelled on centre line; in route 2: right tyres were on Axis II; and in route 3: left tyres were on Axis I. For the direction of south to north, in route 1: the truck travelled on centre line; in route 2: right tyres were on Axis I; and in route 3: left tyres were on Axis II.

(a) (b)

Figure 4. Illustration of the testing vehicles, (a) a tandem-axle vehicle, (b) a tridem-axle vehicle.

(a) (b)

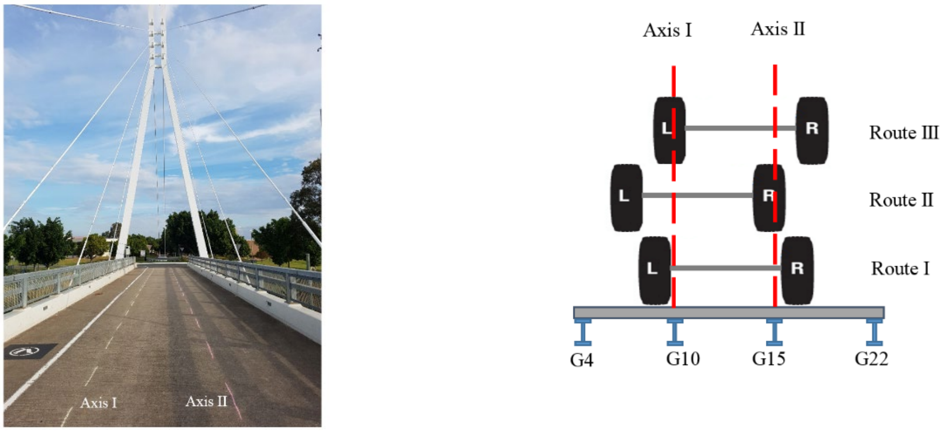


Figure 5. Illustration of, (a) the lines (Axis I and Axis II) on the pavement, (b) lateral location of the vehicle on different routes.

3 Results and Discussions

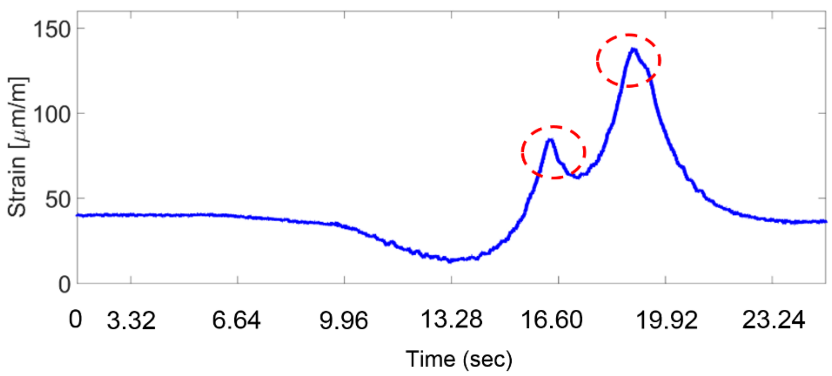
The objective of this section is to investigate which sensor response can reliably identify all the axles including the closely-spaced axles regardless of the lateral location of the vehicle on the bridge, speed and travel direction.

3.1 Case Study I: A tandem-axle vehicle

3.1.1 Bending Strain Response at Girders

The bending strain response captured from sensor SU14 (see Figure 2 (c)) was illustrated while the bus is traveling from north to south (Figure 6 (a)) and from south to north (Figure 6 (b)). This sensor is located under the flange of G10 between the diaphragms CG6 and CG7. From Figure 6 (a) and (b), it can be clearly observed that the structure behaves in a statically indeterminate manner which is expected for a cable-stayed bridge. Two distinct peaks are observed in the bending strain which are due to presence of two axle groups, one axle in front of the bus and one tandem axle at the rear of the bus. As demonstrated, no information regarding the presence of tandem axles can be acquired from the bending strain response. The same conclusion was obtained from all the other case studies while the bus was traveling with different speeds and at different lateral locations on the bridge.

(a)



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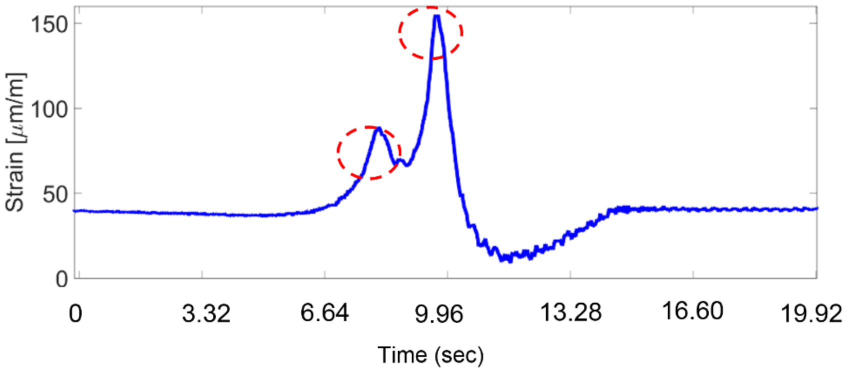


Figure 6. Bending strain response under G10 captured from sensor SU14 while the bus was travelling, (a) north to south, (b) south to north.

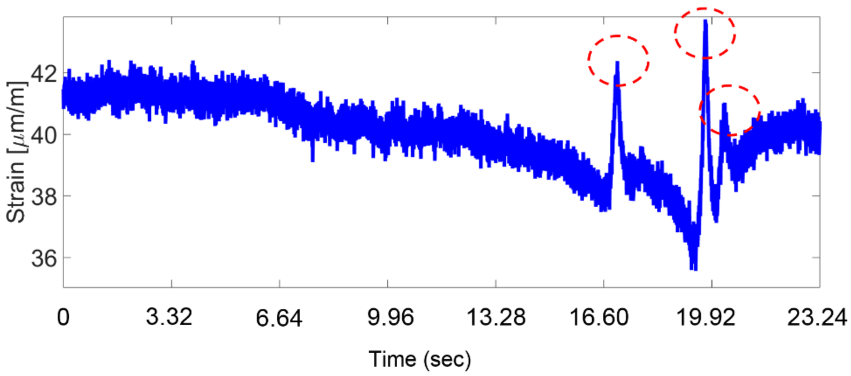
3.1.2 Longitudinal and Lateral Strains of the Deck

The collected strain response from sensors SU17 and SU18 was studied to see whether the bending response under the deck in longitudinal direction (SU18) and lateral direction (SU17) are able to provide any information regarding individual axle load on the bridge. These two sensors are collocated under the orthotropic deck between diaphragms CG6 and CG7.

It was observed that the bending response under the deck in longitudinal direction can pinpoint the presence of all three axles including the closely-spaced axles when the bus is traveling from the north to south (Figure 7 (a)) whereas it can only identify the two axle groups while the bus is travelling from the south to north (Figure 7 (b)). In contrast, the bending response in transverse direction fails to identify the closely-spaced axles no matter what the travelling direction is (Figure 78 (a) and (b)). Further investigation was carried out using collected responses from all the other case studies including variable speeds, traffic directions, and lateral locations of the vehicles. It was realised that in all the cases, the transverse strain under the deck fails to identify the three axles, however, the longitudinal strain under the deck is able to detect all the three axles when the bus is passing over the sensor only. It indicates that the wheel position must be aligned with the lateral position of the sensor. From this investigation, it was concluded that the longitudinal strain under the deck has potential to identify the presence of individual axles provided the location of the wheel is very close to the lateral location of the sensor on the bridge.

It should be noted that the noise in Figure 7 are of very high frequencies. The noise could be caused by the rough contact between the wheels and the pavement. The high frequency vibrations induced by the vehicle's engine can also be transferred to the bridge. If the level of load-induced strains is virtually the same as the level of noise, identification of the closely-spaced axles, especially at high speeds, can be difficult.

(a)



(b)

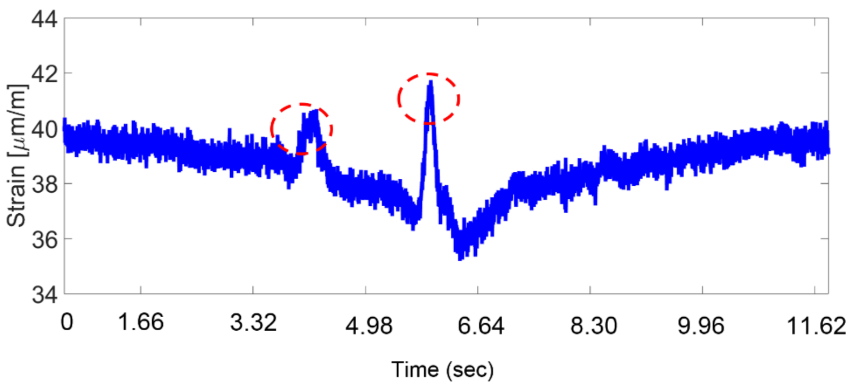
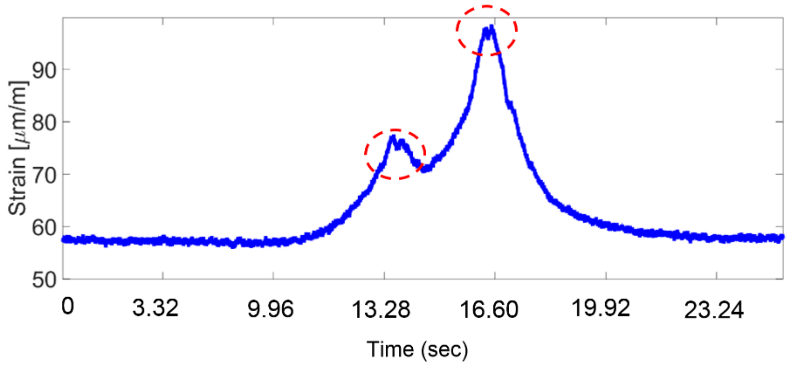


Figure 7. Longitudinal strain response under the deck captured from sensor SU18 while the bus was travelling, (a) north to south, (b) south to north.

(a)



(b)

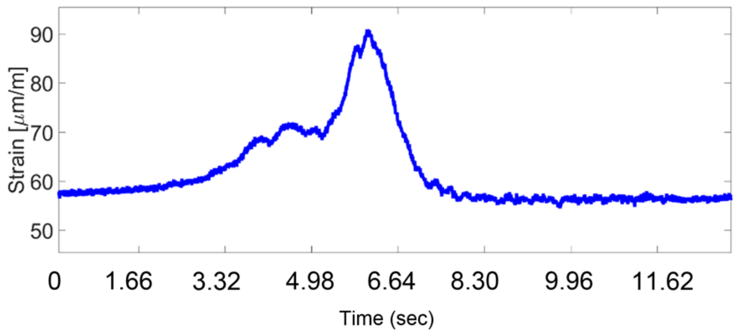
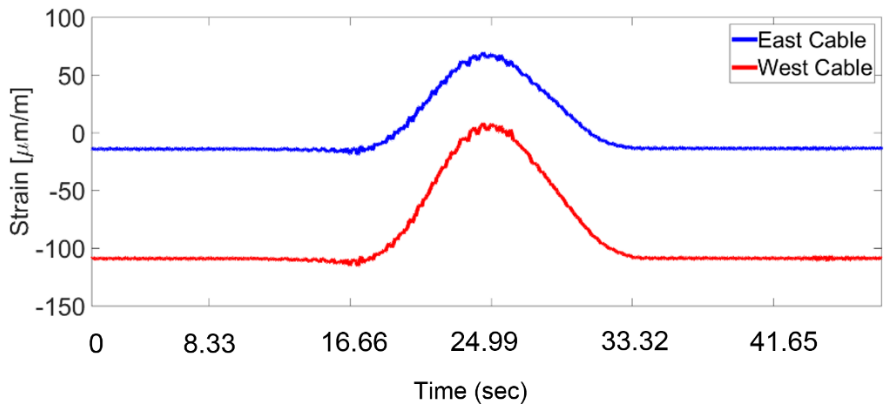


Figure 8. Lateral strain response of the deck captured from sensor SU17 while the bus was travelling, (a) north to south, (b) south to north.

3.1.3 Axial Strain Response in Cables

The axial strain response in the cables collected from sensors SA29 and SA30 were investigated to see the effectiveness of cables responses in identifying the axles. These two sensors are, respectively, located in the eastern and western side of the bridge and are connected to diaphragm CG7 as depicted in Figure 2. Neither of these two cables could provide any information about the number of axles (see Figure 8 (a) and (b)), no matter what the travel direction is. It is due to the fact that the cable response pictures the global behaviour of the bridge. It should be noted that the sensors on the other cables also present the same behaviour.

(a)



(b)

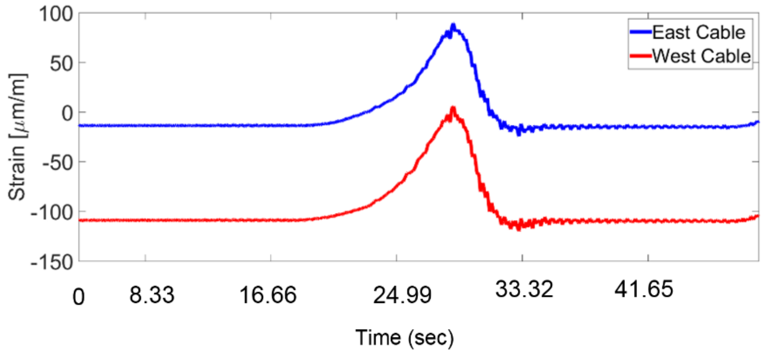
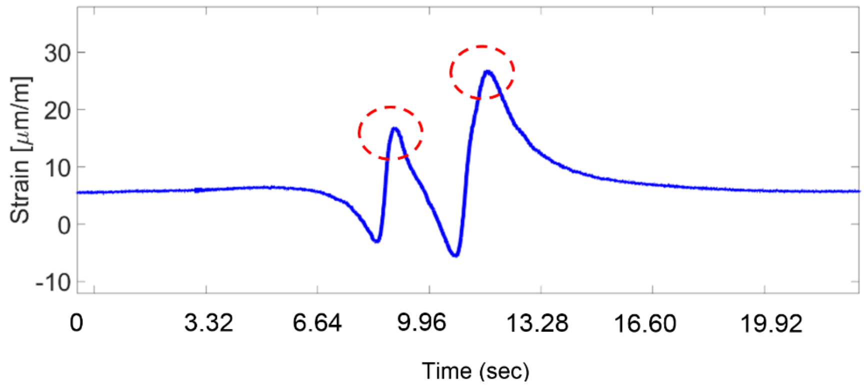


Figure 9. Axial strain response in the cable captured from sensors SA29 (blue line) and SA30 (red line) while the bus was travelling, (a) north to south, (b) south to north.

3.1.4 Shear Strain Response of the Girders

The shear strain response collected from sensor SS6 was investigated for the purpose of axle detection. This sensor is located at G10 at a distance of 400 mm from the diaphragm CG6 to avoid the localised stress concentration as seen in Figure 3 (a). The sensor is mounted at the middle of the web, where the shear strain is expected to be maximum. It was realised that in all the cases, only two axle groups can be identified and the shear response at this location fails to identify the presence of three axles on the bridge. Figure 10 (a) and (b), respectively, illustrate the shear strain response obtained from SS6 while the vehicle is traveling at both directions.

(a)



(b)

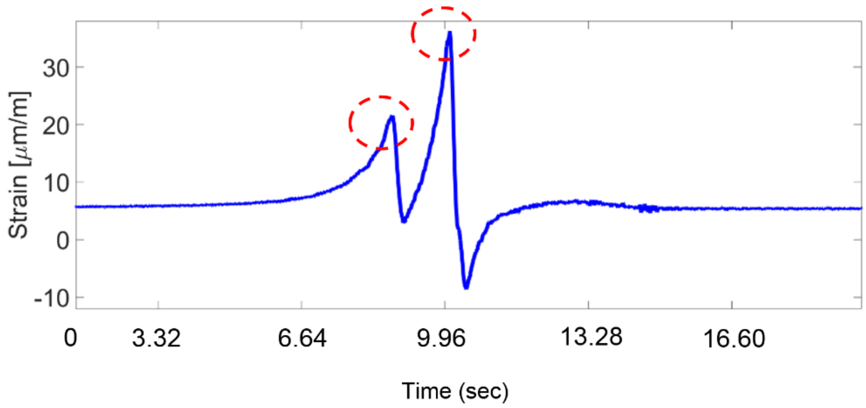
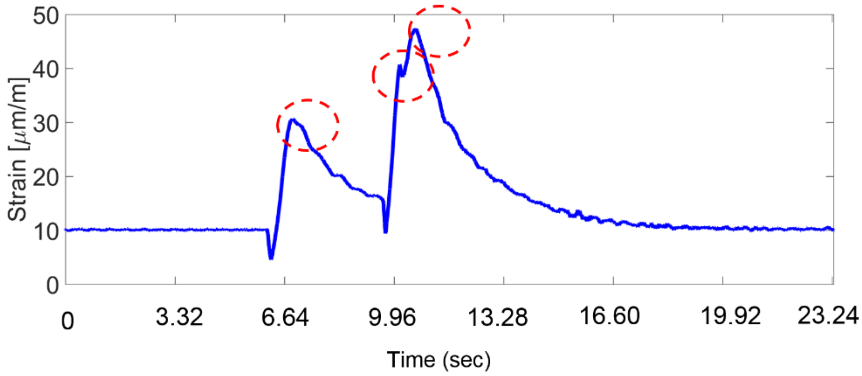


Figure 10. Shear strain response captured from sensor SS6 while the bus was travelling, (a) north to south, (b) south to north.

3.1.5 Shear Strain Response at North End of the Span

Based on the concept of influence line for shear action at support location, it is expected to observe a noticeable discontinuity as a result of each axle entry to/exit from the bridge. To investigate this, the shear response from the sensor SS2 was studied. This sensor is located at the middle of the web of the G10 at a distance of 400 mm from the diaphragm CG2 as seen in Figure 2. In two different scenarios while the bus was travelling from north to south or from south to north, the response was investigated and the results are, respectively, presented in Figure 11 (a) and (b). From this figure, there exists three discontinuities in the shear strain signal which indicates the number of vehicle's axles. The time interval between the second and the third discontinuities is much less compared to the time interval between the first and the second discontinuities. It coincides with our expectation that the second and the third axles form a tandem axle configuration in the rear of the bus. From this figure, it can be implied that shear response from SS2 can reliably identify all individual axles regardless of traffic direction. This conclusion was obtained from all the other case studies while the lateral location of the bus is varying on the bridge.

(a)



(b)

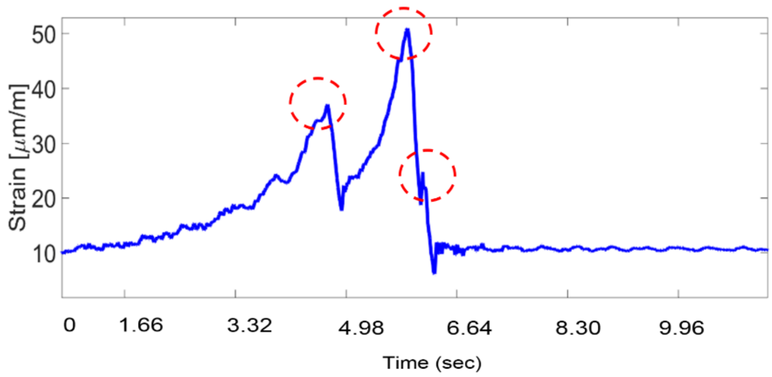


Figure 11. Shear strain signal captured at sensor SS2 while the bus was travelling, (a) north to south, (b) south to north.

It looks like that the method of using shear rosettes at the beginning of the bridge is independent of the bridge length and it can be applied to all kinds of bridges. However, this is still an open question and needs to be further investigated.

3.2 Case Study II: A tridem-axle vehicle

In order to further validate the previous observations, a more complicated field test was arranged in which a 6-axle truck was driven over the bridge. The results from this investigation are presented in Figure 12 to Figure 18.

Same as before, the bending strain response from sensor SU14 could only identify the number of axle groups and not each individual axle, see Figure 12 (a) and (b).

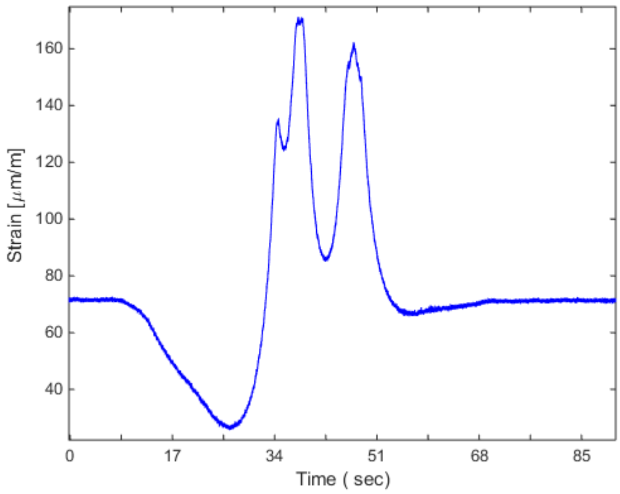
Unlike the previous case, the bending strain at deck in longitudinal direction obtained from sensor SU18 could identify the presence of all the axles regardless of the traffic direction (see Figure 13 (a) and (b)); whereas in the first case study the results were dependent on the traffic direction. This is due to the fact that in the second case study a much heavier vehicle has been adopted and as a consequence, the level of response is high, even when the sensor is not located under the wheel path. Although, the performance of SU18 in identification of all of the axles in the second case study is very promising but in general it is suffering from some drawbacks. First, the signal is quite noisy and identification of each individual peak might not be straight forward and more importantly, in order to detect the closely-space axles, either the vehicle should be very heavy or the location of the load must be very close to the sensor location.

Consistent with the first case study, successful identification of all axles were not obtained from the transverse bending strain response from the deck as illustrated in Figure 14 (a) and (b).

No indication of axles was obtained from the cable response, same as before, (see Figure 15 (a) and (b)). Shear response obtained from sensor SS6 could only identify the number of axle groups and fail to identify each individual axle, see Figure 16 (a) and (b).

Successful identification of all of the axles can be obtained from the shear response at sensor SS2 as illustrated in Figure 17 (a) and (b). Figure 18 also demonstrates the fact that these results are independent of the lateral position of the sensor.

(a)



(b)

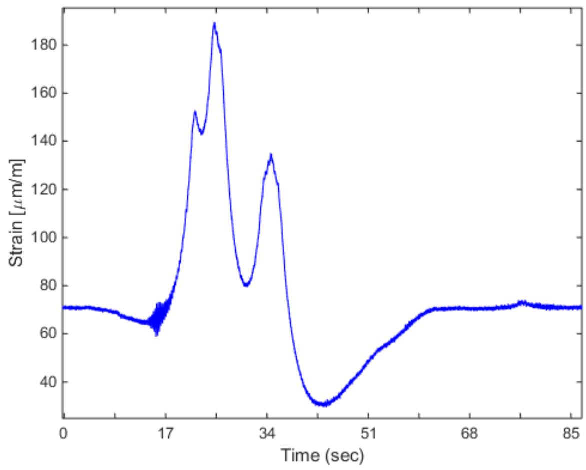
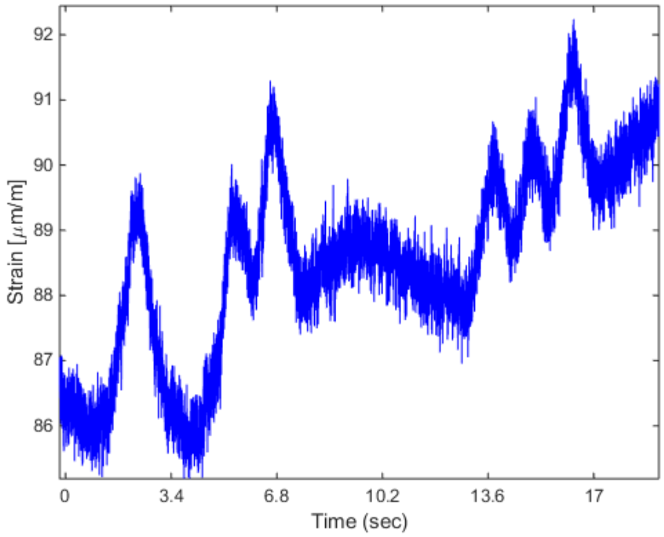


Figure 12. Bending strain response captured from sensor SU14 while the truck was travelling, (a) north to south, (b) south to north.

(a)



(b)

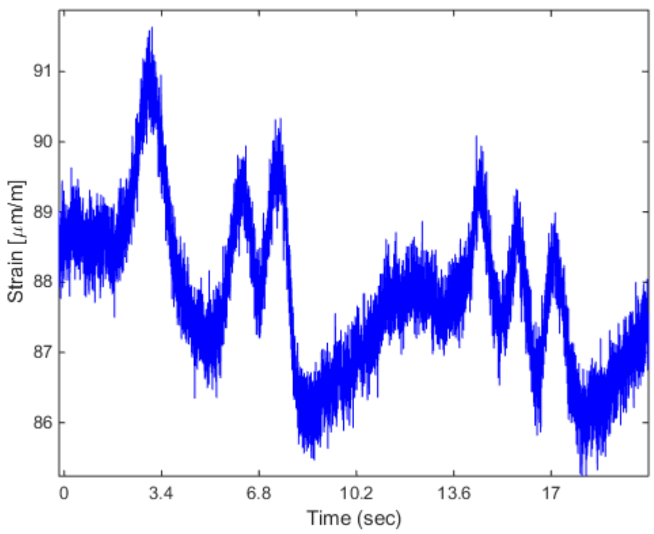
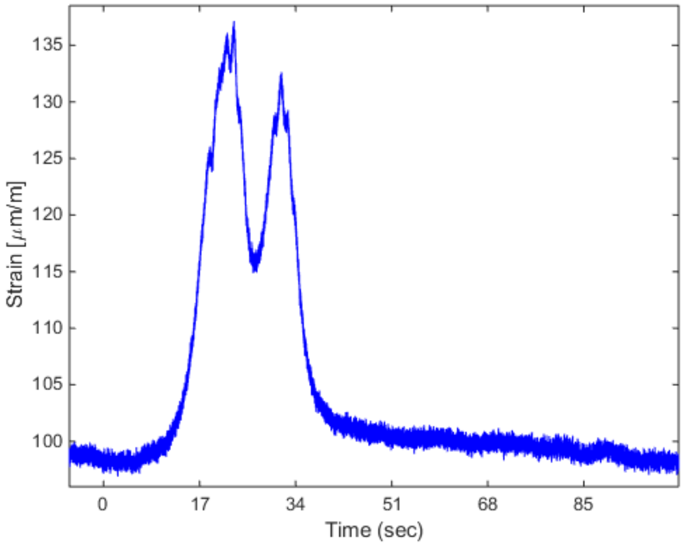


Figure 13. Longitudinal strain response under the deck captured from sensor SU18 while the truck was travelling, (a) north to south (b) south to north.

(a)



(b)

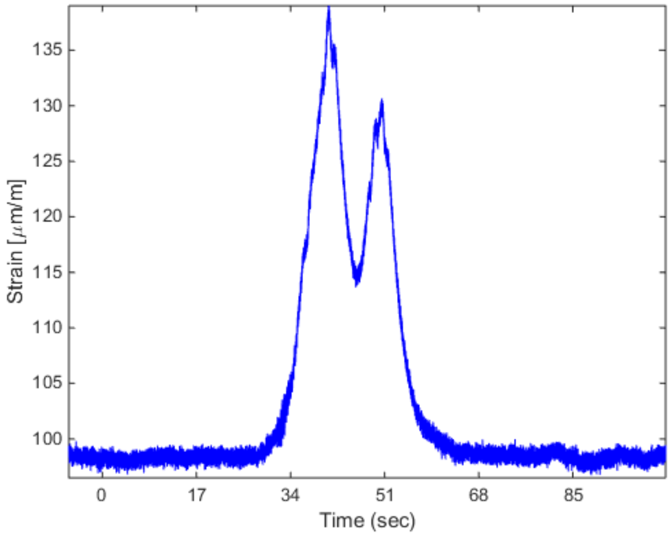
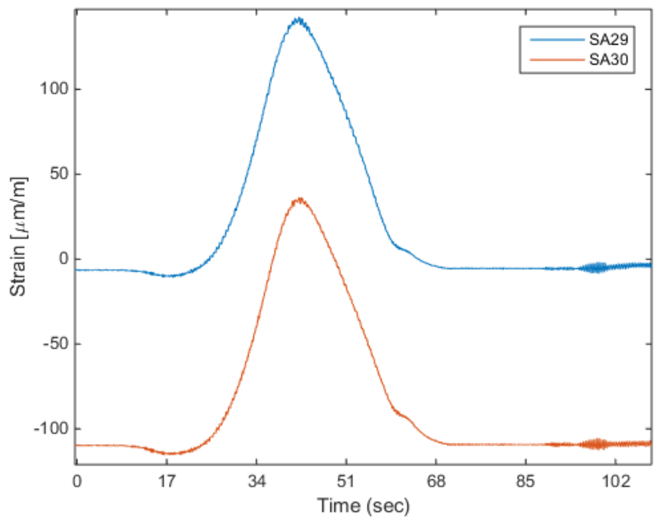


Figure 14. Transverse bending strain response under the deck captured from sensor SU17 while the truck was travelling, (a) north to south, (b) south to north.

(a)



(b)

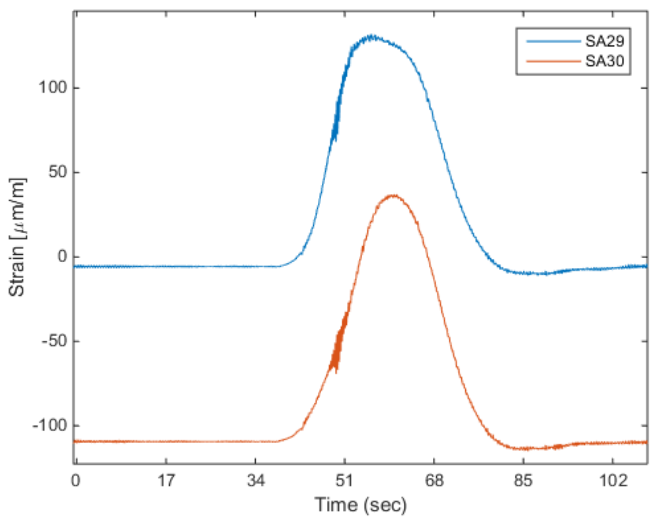
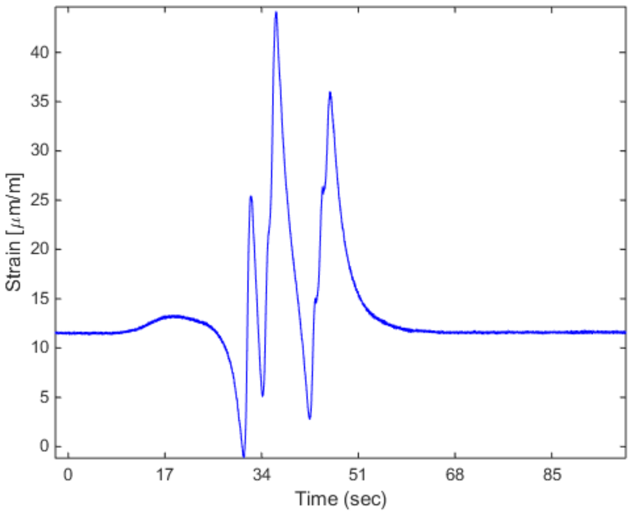


Figure 15. Axial strain response in the cable captured from sensors SA29 (blue line) and SA30 (red line) while the truck was travelling, (a) north to south, (b) south to north.

(a)



(b)

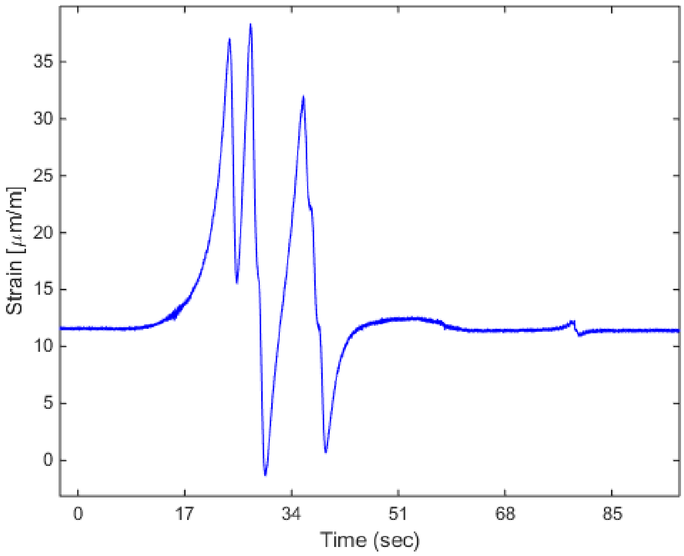
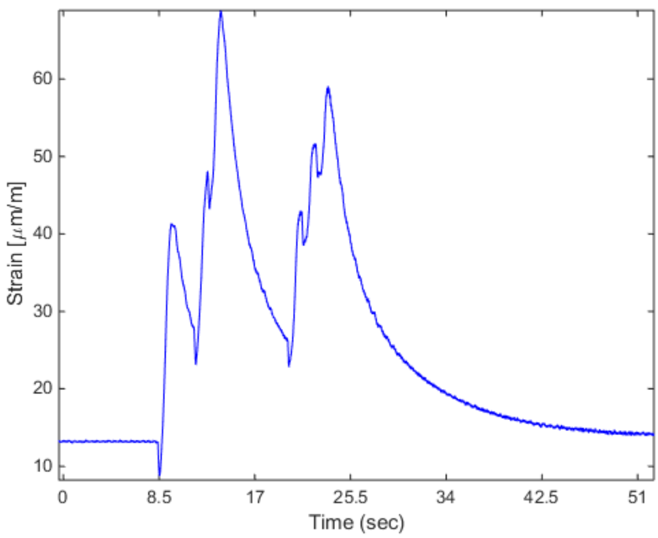


Figure 16. Shear strain response captured from sensor SS6 while the truck was travelling, (a) north to south, (b) south to north.

(a)



(b)

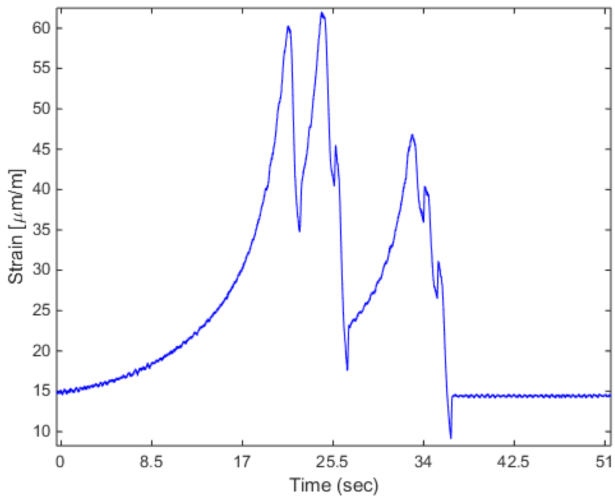


Figure 17. Shear strain signal captured at the north end from sensor SS2 while the truck was travelling, (a) north to south, (b) south to north.

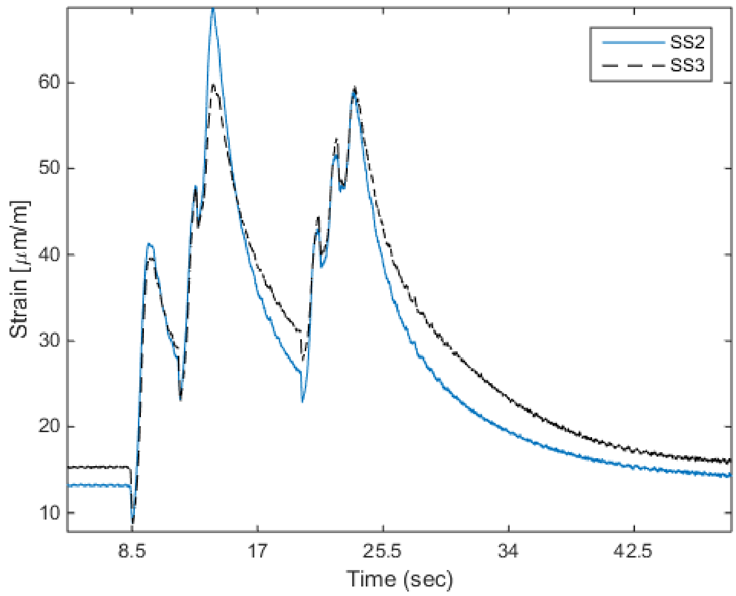


Figure 18. Shear strain signal captured at the north end using SS2 and SS3 while the truck was travelling north to south.

4 Multiple vehicle testing

For further validation of the method, it is critical to investigate the effect of multiple vehicles passing on the bridge at the same time on the identification results. In order to do this, a separate test was conducted in which the bus was followed by a light vehicle. Figure 19 (a) illustrates the test and Figure 19 (b) shows the response from sensor SS2. As seen, the shear response at the end of bridge can successfully identify all the axles corresponding to two different vehicles passing over the bridge.

(a)

(b)

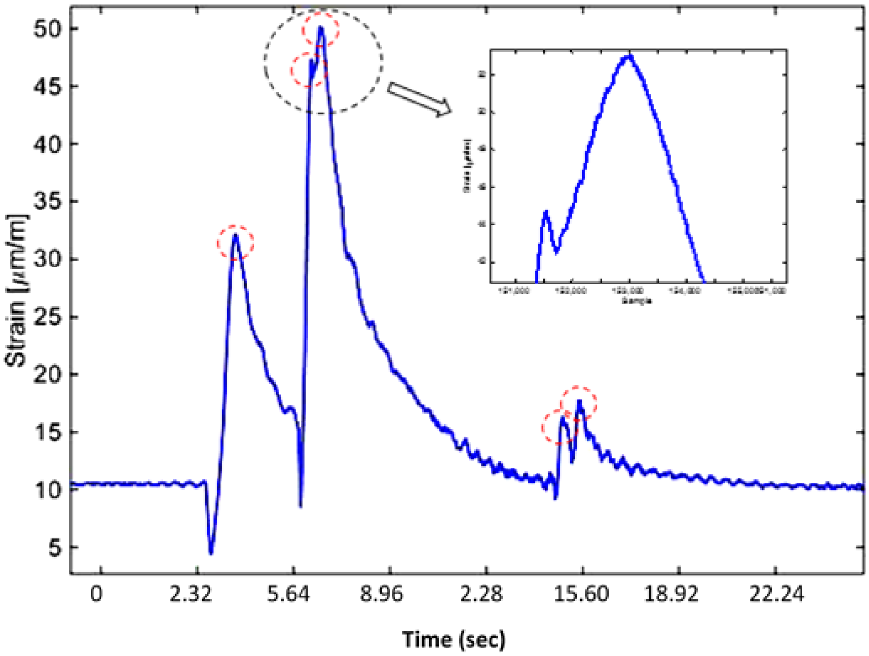


Figure 19. (a) A bus followed by a light vehicle simultaneously passing over the bridge, (b) shear strain signal captured at the north end while the bus followed by a light vehicle were crossing over the bridge [Kalhori et al., 2017].

5 Automation of Axle Detection

Wavelet analysis was adopted to automatically identify the closely-spaced axles. For a discrete signal *F(t)*, the continuous wavelet transform (CWT) can be expressed as the convolution of *F(t)* and a scaled normalised mother wavelet function as

$$C_{\psi}^{F}(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}F(t)\psi^{*}\left[\frac{(t-b)}{a}\right]dt \tag{1}$$

where a is the scale parameter, b is the space parameter (translation), ψ is the mother wavelet and * denotes the complex conjugate.

The CWT is basically a convolution of the input data sequence and a set of functions generated by the mother wavelet (Makki Alamdari, 2015). The CWT decomposes a signal at different time and frequency scales, such that each scale may emphasise different signal characteristics. Wavelet coefficients represent how closely correlated the wavelet is with a section of the signal. The larger the absolute value of the coefficient, the greater the similarity. Due to its multi-resolution properties, the wavelet transform acts as a microscope with the ability to analyse the details of a signal, enabling temporal localisation of signal features e.g. discontinuities. This property is adopted in the present study to identify the number and the locations of discontinuities observed as a result of each individual axle load in the shear response measured at the north end of the bridge.

In this study, Haar mather wavelet with scale value ranging from 1 to 256 was adopted for CWT. For a closely-space axle presented earlier in Figure 11 (b), while the bus is traveling from south to north, the normalised wavelet coefficients were obtained and presented in Figure 20. From this figure, the presence of three axles including one at front and two closely-spaced at rear of the bus is obtained. Successful identification of the number of axles can be obtained from all of the scale values within the range of 1 to 256. However, the result presented in Figure 20 is only illustrating the normalised wavelet coefficients at scale 64.

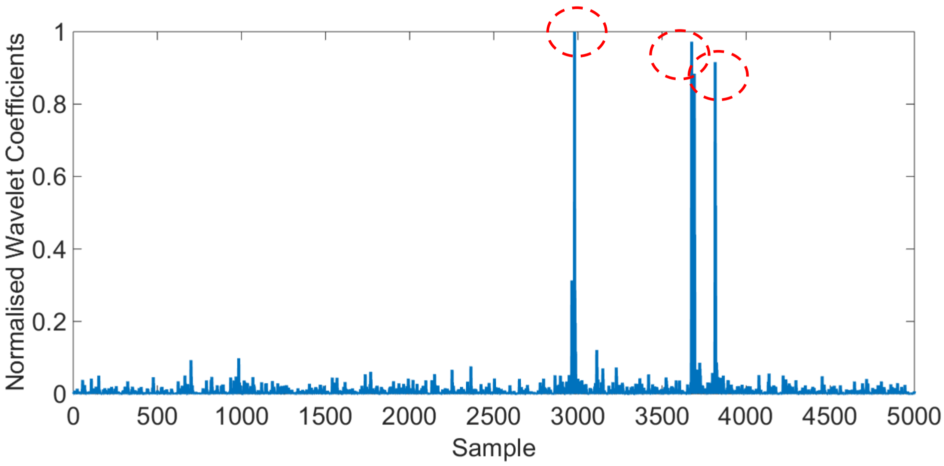


Figure 20. The normalised wavelet coefficients of the shear response captured at sensor SS2 presented earlier in Figure 10 (b).

6 Conclusion

This paper presented the results of axle detection in a cable-stayed bridge. The research purpose was to investigate which type of strain response and in which structural members is capable of providing reliable identification of axles, particularly for the closely-spaced axle configuration. The major structural subsystems of the bridge including cables, deck and girders were instrumented with strain gauges to measure strain responses. Numerous tests comprising of vehicles with different gross weights and axle configurations were driven over the bridge with different speeds, various lateral locations and at different traffic directions. It was realised that the axial strain response of the cables fail to identify the axles. The bending response of the girders were successful to identify the number of axles when the axles were not closely spaced. The longitudinal response of the deck could detect all the axles including the closely-spaced axles while the vehicle was passing over the sensor, whereas the transvers response of the deck failed to identify the axles. The results from our investigations illustrated that only the shear response of the girders at the end of the bridge can reliably identify all the axles including the closely-spaced axles regardless of vehicle seed, traffic direction and lateral position of the vehicle on the bridge. The process of axles detection was then automated utilising the wavelet analysis.

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