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Monitoring the Condition of a Bridge using a Traffic Speed Deflectometer Vehicle Travelling at Highway Speed

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ABSTRACT

The Traffic Speed Deflectometer (TSD) is a vehicle incorporating a set of laser Doppler vibrometers on a straight beam to measure the relative velocity between the beam and the pavement surface. This paper describes a numerical study to see if a TSD could be used to detect damage in a bridge. From this measured velocity it is possible to obtain the curvature of the bridge, from whose analysis, it will be demonstrate that information on damage can be extracted.

In this paper a Finite Element model is used to simulate the vehicle crossing a single span bridge, for which deflections and curvatures are calculated. From these numerical simulations, it is possible to predict the change in the curvature signal when the bridge is damaged. The method looks promising and it suggests that this drive-by approach is more sensitive to damage than sensors installed on the bridge itself.

Key words: Bridge, TSD, Doppler Laser, vibrometer, dynamics, deflection, curvature, damage, SHM, Instantaneous Curvature, IC.

INTRODUCTION

Many efforts have been put in recent years to develop monitoring methodologies in order to enhance and complement the health inspections of a wide range of engineering infrastructures, bridges among them. Most of these approaches are based on structural vibration data, so that conclusions about damage existence can be inferred from the measurable changes in the dynamic properties of the bridge (natural frequencies, mode shapes, etc.). However, the main drawback of all these methods is the necessity of a high number of sensors directly installed on the bridge.

Bridge monitoring traditionally relies on visual inspections. While this is arguably still the best means of confirming structural condition, there are issues with the objectivity of inspectors. There have been considerable efforts in recent years to develop systems of sensors to complement or replace the information obtained by the inspector. Some authors [1] have suggested that visual inspection alone may not be adequate for bridge health monitoring. In countries like Japan, which is prone to natural disasters, it is recommended that monitoring of engineering infrastructure should be conducted continuously [2].

A popular SHM approach is the use of structural vibration data for damage assessment. The principle is that if damage occurs in a structure, its physical properties change, (e.g. local loss of stiffness) which cause measurable changes in the bridge's dynamic properties. Based on which dynamic properties or damage features are considered, such damage identification methods can be categorized as [3]: (i) natural frequency-based; (ii) mode shape-based; (iii) modal curvature-based or (iv) other approaches based on modal parameters. Methods based on curvature are particularly promising but require a great number of sensors on the bridge if damage is to be detectable at all points.

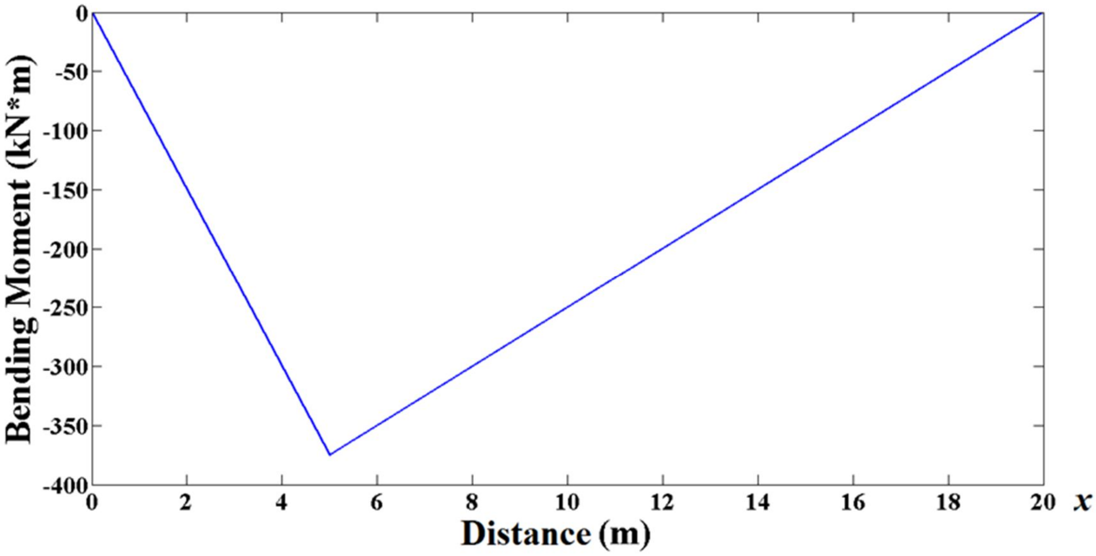
In that sense, 'drive-by' monitoring has risen in importance as an alternative to the sensor network based solutions, given its capability to derive the dynamic properties of bridge structures from the dynamic response of a passing vehicle. The idea of drive-by monitoring, in which the dynamic properties of bridge structures are inferred from the dynamic response of a passing vehicle, is proposed by Yang et al. [4, 5]. While the vehicle may be expensive, this approach is low cost as it can be applied throughout the fleet without the need to install any sensors on the bridges themselves. It involves a vehicle instrumented with sensors through which dynamic properties of the bridge are extracted. Through interaction between the bridge and vehicle, the moving vehicle can be considered as both exciter and receiver. The feasibility of this method in practice was experimentally confirmed by Lin and Yang [6] by passing an instrumented vehicle over a highway bridge in Taiwan.

Falling Weight Deflectometers are traditionally used to measure pavement stiffness, but the vehicle is stationary and there are concerns about safety and traffic disruption. As a result, the Traffic Speed Deflectometer (TSD) has been developed as an alternative means of measuring pavement stiffness using a vehicle travelling at full highway speed. OBrien & Keenahan [7] were the first to propose the idea of using a TSD for bridge monitoring. While the concept has yet to be proven, this paper will demonstrate that there is considerable potential, provided measurements of sufficient accuracy can be obtained [8]. However, the number of measurements is affected by the time the vehicle is on the bridge, making it harder to develop an indicator that is sensitive to damage. A TSD uses a set of laser vibrometers to accurately measure the derivative of the distance between the vehicle and the road surface profile [9, 10]. In the case of the TSD travelling over a bridge, this distance will include a combination of vehicle movements, road surface profile and bridge vibrations. The latter information, when separated from the other components, has the potential to be sensitive to damage in the bridge.

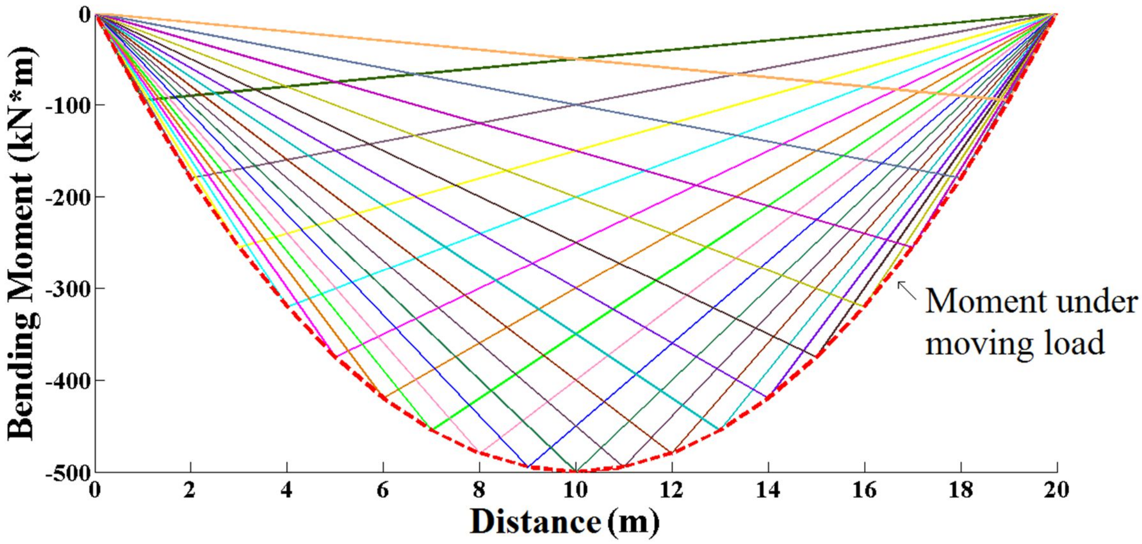
STATIC RESPONSE TO PASSING LOAD

The simplest case is considered first: the static response to a point force crossing a beam (Figure 1(a)). The bending moment diagram due to a point force at a fixed point is illustrated in Figure 1(b) and the bending moment diagrams due to a moving point force (various values of x) are illustrated in Figure 1(c). In a TSD, the sensors constitute moving references so a sensor located at the force would always sense data corresponding to the maximum bending moment. This corresponds to the peaks of the bending moment diagrams of Figure 1(c). This peak bending moment varies smoothly from the start to the finish.

(a) Force at a fixed point, *x*, on the beam with *P=100kN*.



(b) Bending moment diagram due to force at a fixed point, *x*



(c) Bending moment diagrams due to moving load

Figure 1. Bending moment response to point force on a beam

Curvature, the second derivative of deflection, is given by *M/EI*, where *M* is moment and *EI* is stiffness, product of modulus of elasticity, *E*, and second moment of area, *I*. Hence, for a beam of constant stiffness, curvature varies smoothly and in proportion to the peak moments illustrated in Figure 1(c). Hence, if there is a local loss of stiffness, as would occur if a beam were damaged, there will be a sharp local increase in curvature. An example is illustrated in Figure 2, where stiffness has been reduced by 20% locally at quarter-span and mid-span.

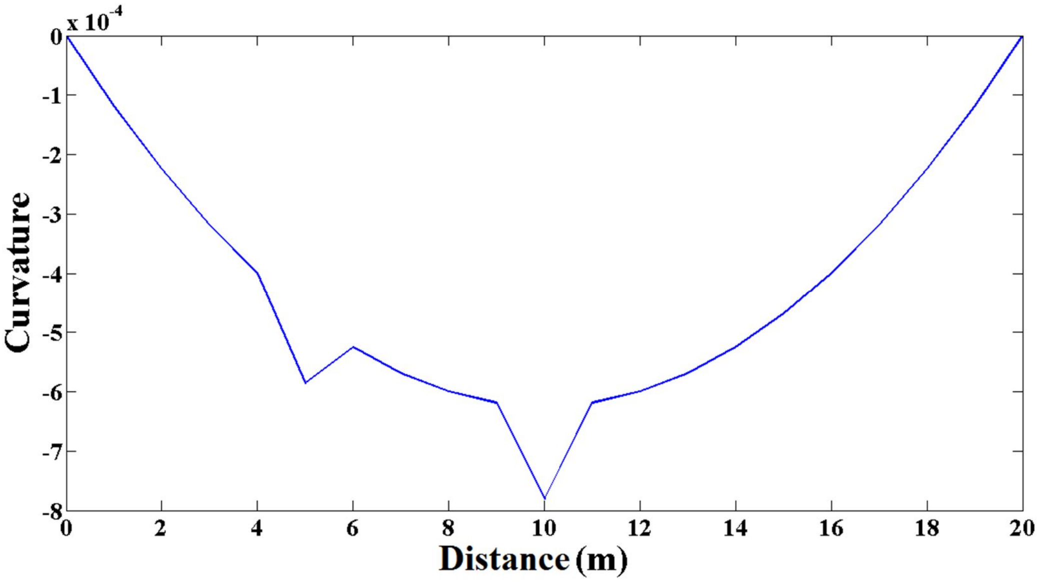


Figure 2. Curvature, calculated numerically from deflections at adjacent points, under a moving point force in a beam with 20% local stiffness reductions at quarter- and mid-span

VEHICLE BRIDGE INTERACTION MODEL

A vehicle/bridge dynamic interaction model has been developed in MATLAB. The half-car (HC) vehicle model of Figure 3 has been developed using the vehicle properties listed in Table 1. The HC model has 4 degrees of freedom (DOFs): sprung mass bounce translation, pitch rotation and the two unsprung mass (axle hop) translations. Some of the Traffic Speed Deflectometer (TSD) characteristics have been taken into account in the model, in view of its potential as a drive-by monitoring vehicle [8]. A high velocity is chosen to represent highway conditions.

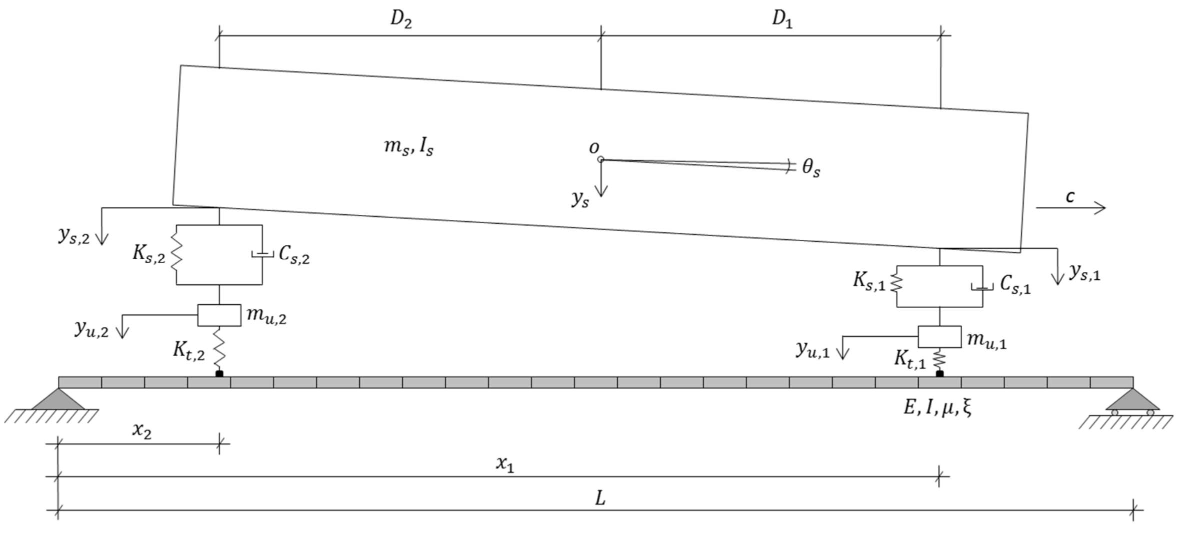


Figure 3. Half-car model, adapted from [11]. (Notation given in Table 1)

Table 1. Geometrical and mechanical properties of the modelled HC vehicle

Property and notation	Notation	Value
Weight of the sprung mass	m_s	18 t
Unsprung mass axle 1	m_{u1}	1000 kg
Unsprung mass axle 2	m_{u2}	1000 kg
Length of the vehicle	L_v	11.25 m
Tyre 1 stiffness	$K_{t,1}$	1.75×10^6 N/m
Tyre 2 stiffness	$K_{t,2}$	3.5×10^6 N/m
Damper 1 stiffness	$K_{s,1}$	4×10^5 N/m
Damper 2 stiffness	$K_{s,2}$	10^6 N/m
Damper 1 damping	$C_{s,1}$	10^5 Ns/m
Damper 2 damping	$C_{s,2}$	2×10^5 Ns/m
Distance of centre of gravity from axle 1	D_1	3.8 m
Distance of centre of gravity from axle 2	D_2	3.8 m
2nd moment of area	h	3.76 m
Velocity	c	80 km/h (22.22 m/s)

The bridge is modelled as a beam with 1-dimensional finite elements. Contact is imposed at each time step between the axles and the relevant points on the bridge. A smooth road surface profile has been used for this example. It is acknowledge that this removes the influence of road profile thereby greatly improving the prospects of damage detection. The healthy bridge has the properties listed in Table 2.

Table 2. Geometrical and mechanical properties of the modelled bridge

Bridge Property	Value
Number of elements	20
Frequency	1000 Hz
Length	20 m
Young's modulus	35×10^6 kN/m^2
2nd moment of area	1.26 m^4
Mass per unit length	37500 kg/m
Damping	3%
First natural frequency	4.26 Hz
Length of the approach	100 m

RESULTS AND DISCUSSION

Damage is represented in this example as a 20% loss of stiffness over a 2m length, 7.5 m from the left support of the 20 m long bridge as shown in Figure 4. It can be seen in Figure 5 that (assuming that vehicle motion can be removed) there is a clear difference in the absolute bridge displacements under the axles between the healthy and damaged cases. It is not apparent from this figure where the damage is located. Furthermore, the quantity of the damage is difficult to estimate, as the influence of damage propagates through the entire beam and damage near the centre causes more displacement than damage near the supports. Due to this influence, damage location and the maximum increase in deflection do not correspond in the figures. For the first axle in particular, there is little difference in the displacements at the damage location. It is only when the first axle is near three quarter-span and the second axle reaches the damage location that the difference between the signals becomes large. Both axles interact and it causes the change of curvature at the first stage in Figure 5a due to the entrance of the second axle and the second stage in Figure 5b when the first axle leaves the bridge.

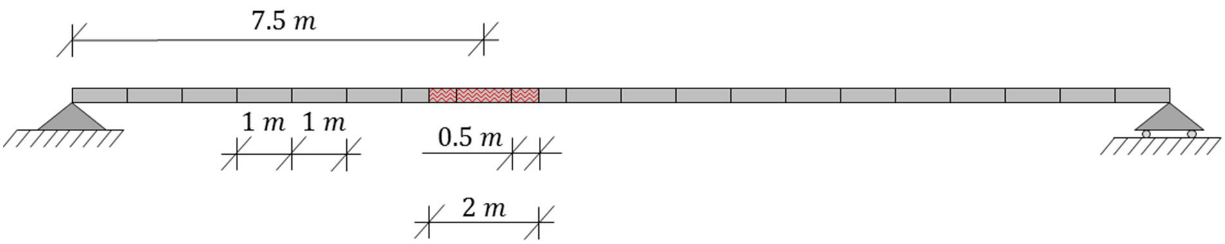


Figure 4. Bridge displacements at axle location, a) first axle, b) second axle.

Fortunately, while translation under the moving reference is not a good indicator of local damage location, curvature is much better. This is illustrated in Figure 6 which shows the Instantaneous Curvatures (ICs), i.e., the 2nd derivatives with respect to distance (calculated at fixed points in time) of the calculated displacements under or near the moving load. These derivatives are calculated numerically, assuming three laser measuring devices at 1 m intervals that record simultaneously.

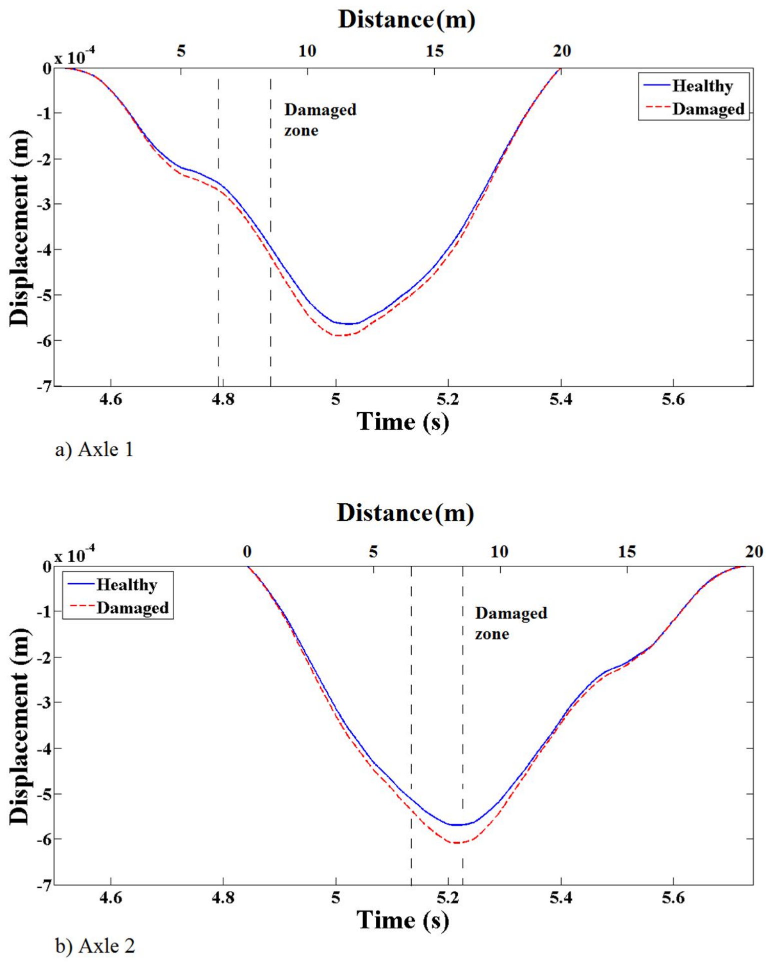


Figure 5. Bridge displacements at axle location, a) first axle, b) second axle.

The damage can be easily detected by IC in Figure 6, since the change in the curvature matches exactly with the damaged location in the bridge. Hence, this approach is able not only to identify damage in the bridge, but also to accurately localize it. Furthermore, just by calculating the difference between the healthy and the damaged bridge ICs, it is easy to check that the maximum relative error is 23% for the first axle’s curve and 26% for the second one; in both cases around 8 m from the left support of the 20 m long bridge. As 1/0.8=1.25, this constitutes a fairly good prediction of the induced 20% loss of stiffness, as specified above. Hence, quantification of damage magnitude is also possible when using IC as a damage indicator. Finally, focusing on the healthy and damaged curvatures at any point outside of the damaged region, it is shown in Figure 6 they match almost perfectly for the rest of the length of the bridge. In Figure 4, on the other hand, this does not happen, especially from the instant when the second axle arrives to the bridge, due to some dynamic effects.

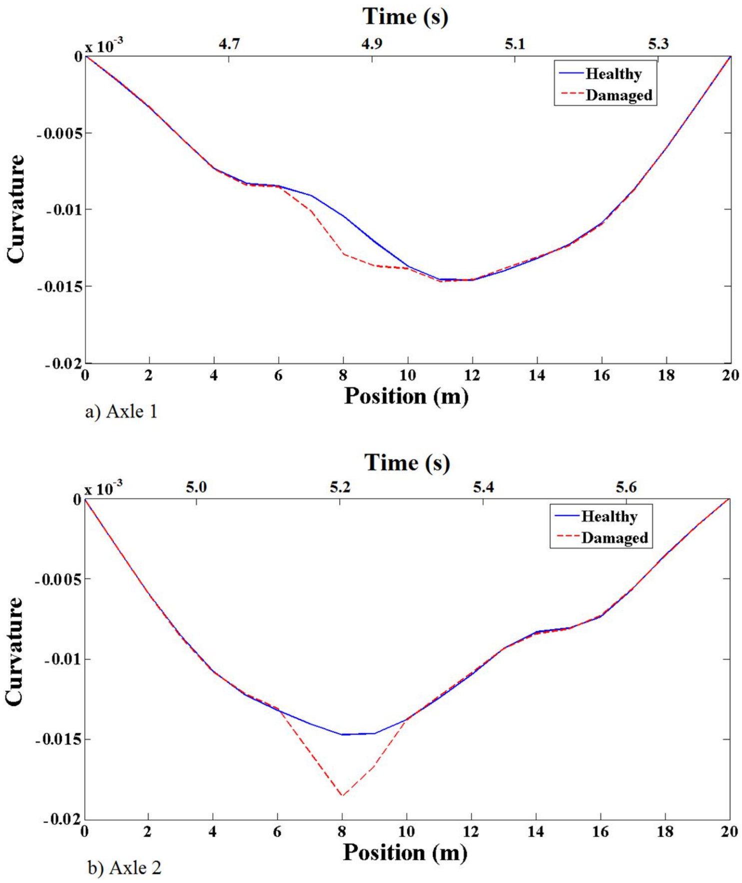


Figure 6. Instantaneous curvatures at axle location, a) measured at first axle, b) measured at second axle.

It is important to note that IC is not the 2nd derivative of the curves shown in Figure 5. These are moving reference translations so successive points represent different points in both space and time. IC is, by definition, the 2nd derivative with respect to distance at a *fixed* point in time. Figure 7 shows the 2nd derivatives of the curves in Figure 5 which can be seen to be quite different from the curves of Figure 6. While there are clear differences between the healthy and damaged cases in Figure 7, some of these differences are the result of bridge vibration under the moving axles.

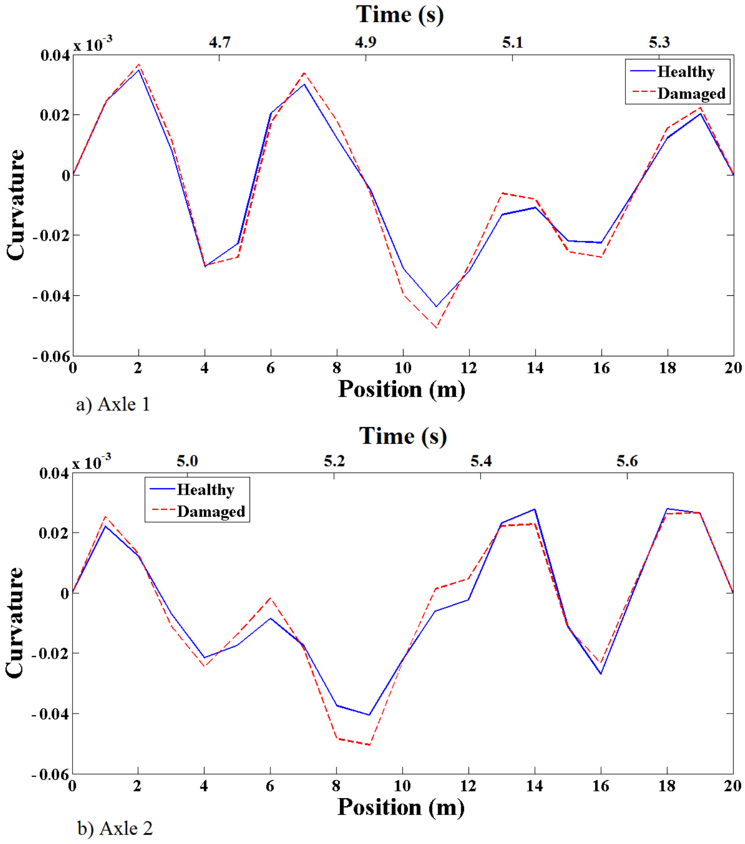


Figure 7. Second derivatives of moving reference translation: a) measured at first axle, b) measured at second axle, as they are influenced by the time.

CONCLUSIONS

IC is a promising parameter for use as a damage indicator. The differences between healthy and damaged curves are clearly greater around the damage location when using curvatures rather than deflections. Of course measuring curvature is considerably more difficult than measuring translation. As a second derivation, it is much more sensitive to measurement noise. However, the TSD already measures the curvature of the deflection 'trough' under the heavy weight for pavement stiffness assessment purposes. Further, curvature is independent of the road profile. In addition, as demonstrated with the example studied in this work, curvature enables damage identification at three levels: damage identification, location and quantification, which was not possible when using deflection measurements to estimate damage. Furthermore, healthy and damaged bridge curves suffer small or negligible differences from each other in non-damaged locations, which means that this approach can also lead to a reduction in the number of false warnings in the damage prediction procedure.

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