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A New Damage Indicator for Drive-by Monitoring using Instantaneous Curvature

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Abstract: Drive-by monitoring has enhanced the possibilities for bridge damage detection, with the potential to deliver a bridge rating in the time it takes an instrumented vehicle to pass overhead. This paper outlines the importance of Instantaneous Curvature (IC) as an indicator of local damage. For the IC calculation, bridge deflections are measured from the vehicle before and after the occurrence of damage, so that a comparison between the two situations can be made. Differences in curvature are clearly visible in numerical simulations, especially at the damage location. A Finite Element model of a simply supported bridge subject to a crossing vehicle is modelled dynamically. In this paper, the Curvature Ratio (CR) is proposed as the damage indicator, defined as the ratio of IC in the current bridge to IC in the corresponding healthy bridge. Road profile and random noise in the simulated measurements are considered to represent realistic conditions. Simulations in MATLAB demonstrate that CR is an effective indicator in most of the analysis cases.

Keywords: Drive-by, Monitoring, Structural Health Monitoring, SHM, Bridge, Damage Detection, Instantaneous Curvature, Curvature Ratio.

1. Introduction

Instrumentation is an increasingly popular approach to bridge damage detection. However, sensor installation can be costly and inefficient for short-span and medium-span bridges [1]. Moreover, traffic disruption and congestion may result [2] especially in heavily trafficked routes. This form of Structural Health Monitoring is called 'direct' monitoring as all the sensors are installed on the bridge [3]. Direct monitoring has been proven to be a satisfactory technique: continuous readings of the bridge response can be extracted but most direct monitoring systems require a constant power supply.

These concerns have resulted in a new method of bridge monitoring called 'indirect' monitoring. In this method, the required instrumentation is not directly installed on the bridge. Instead, the response is measured on a vehicle travelling over the bridge as proposed by Yang et al. [4]. In this case, the vehicle is both exciter and receiver. Indirect monitoring avoids issues as traffic disruption derived from direct monitoring [5].

Most of the vibration-based bridge damage detection approaches are based on four bridge dynamic properties: natural frequencies [6], mode shapes [7], damping ratios [8] and deflection curvatures [9]. Curvatures are particularly interesting for local damage monitoring and, as the vehicle in the indirect system has to pass over the whole length of the bridge, there is the potential to monitor all parts of the bridge [10]. In this case, local damage can be inferred from measured curvatures. However, few efforts have been made to quantify damage using this method [10].

In this paper, Instantaneous Curvature (IC) proposed in [11] is analysed for developing a new damage indicator. A Half-Car vehicle passing over a simply supported beam is modelled using Finite Element (FE) method. Measurement noise and road profile are included in the model to make the system more realistic. Simple and multiple damage cases are introduced in the bridge using the method described by Sinha [12] and compared to the simple loss of stiffness approach to simulating local damage. Curvature Ratio (CR) is introduced for damage evaluation, which is demonstrated to be a really accurate tool for the quantification of change in curvature for drive-by monitoring.

2. Vehicle-Bridge Interaction Model

The Vehicle-Bridge Interaction (VBI) model includes a 4 degree of freedom (DOF) Half-Car. Body bounce translation (y_s), body pitch rotation (θ) and the two axle vertical translations $(y_{u,1}$ and $y_{u,2})$ are the parameters related to the DOFs – see Fig. 1.

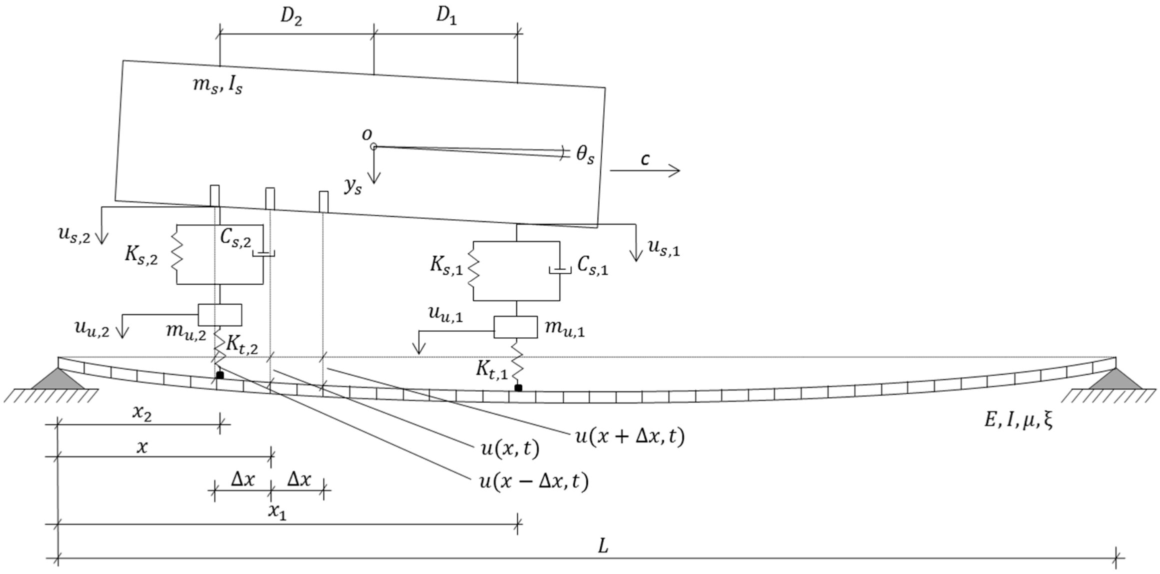


Figure 1. Vehicle-Bridge interaction using a Half-Car, adapted from [13]

Vehicle and bridge properties are presented in Tables 1 and 2. A constant velocity of 90 km/h is assumed to represent highway conditions. A 10 m approach road is also introduced before the vehicle reaches to the bridge.

Table 1. Vehicle properties.

Half-Car property	Notation	Value
Weight of the sprung mass	m_s	8 t
Unsprung mass axle 1	m_{u1}	600 kg
Unsprung mass axle 2	m_{u2}	600 kg
Length of the vehicle	L_v	8.75 m
Axle spacing	A_s	6 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	$C_{s,1}$	10^3 Ns/m
Damper 2 damping	$C_{s,2}$	2×10^3 Ns/m
Centre of gravity distance form axle 1	D_1	4.5 m
Centre of gravity distance from axle 2	D_2	1.5 m
Height of the vehicle	h	2.53 m
Constant velocity	c	90 km/h (25 m/s)

Table 2. The bridge properties.

Bridge Property	Notation	Value
Number of elements	N	200
Frequency	f_s	1000 Hz
Length	L	20 m
Width	w	15 m
Height	h	1 m
Young's modulus	E	3.5×10^{10} N/m^2
2nd moment of area	J	1.26 m^4
Mass per unit length	μ	37500 kg/m
Damping	ξ	3%
First natural frequency	f_1	4.26 Hz
Length of the approach	L_{app}	10 m

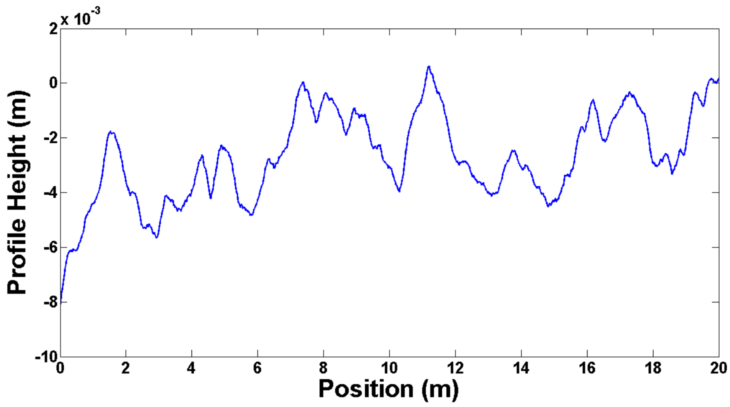


Figure 2. Bridge road profile

Drive-by monitoring is influenced by road profile and several techniques for reduction have been developed [1]. A class A road roughness is randomly generated, representing a 'good' quality road profile as would be typical of a well maintained highway (Fig. 2). White noise is also introduced in the simulation. The noisy signal, u_{noise} , is generated using Eq. 1 in every sensor:

$$u_{noise}(x,t) = u(x,t) + E_P \times N_{noise} \times 10^{-5} \tag{1}$$

where E_P is the noise level (0 for 0% noise and 1 for 100% noise) and N_{noise} is a normally distributed vector with zero mean and unit standard deviation. The 10^{-5} value represents the 10 microns as maximum deviation.

2.1 Damage detection using IC

By definition, curvature is the ratio of bending moment to stiffness (equal to product of elastic modulus and 2nd moment of area). Therefore, a sharp local increase in curvature will occur where there is a sharp reduction in stiffness, as would occur due to a 'bridge bashing' incident from a vehicle passing underneath.

Three deflection measurements are necessary for the numerical estimation of instantaneous curvature, defined as the 2nd derivative of bridge deflection with respect to distance. These measurements have to be at different locations but at one instant in time. A constant distance $\Delta x = 1.0\ \mathrm{m}$ is considered in this paper for the IC calculation procedure. IC is defined using central difference approximation as follows:

$$IC(x,t) = \frac{u(x-\Delta x,t) - 2u(x,t) + u(x+\Delta x,t)}{\Delta x^2} \tag{2}$$

where x is the position of the bridge and t is time.

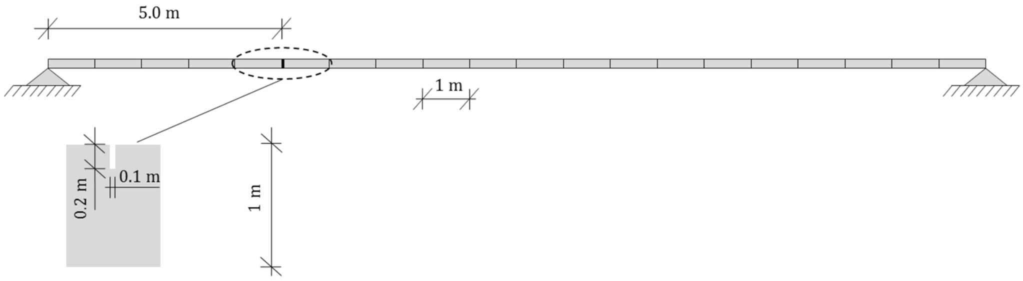
3. Results and discussion

Two different models of damage for two different damage cases are analysed in this paper. These are a simple loss of stiffness in one element over 0.1 m (Fig. 3a and b) and Sinha's model of damage which assumes a gradual reduction of stiffness in the vicinity of the point of damage. The simple loss of stiffness considers only a loss of stiffness in the damaged area. On the contrary, Sinha's model considers that the influence of damage spreads to the neighbouring locations [12]. In that approach, the stiffness close to the crack $EI_e(\xi)$ is defined as:

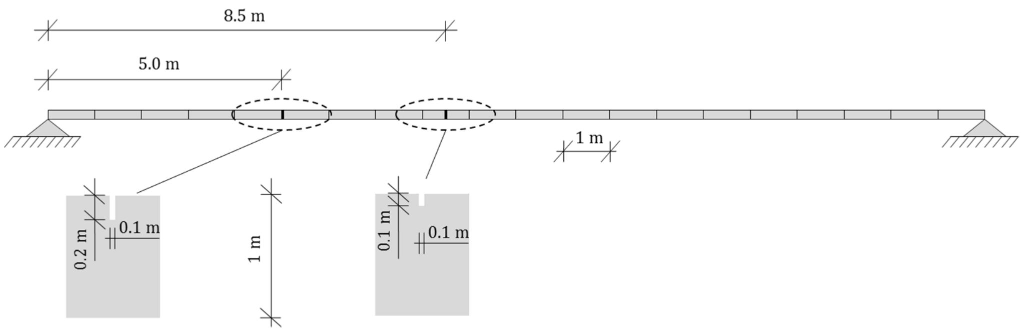
$$EI_e(\xi) = \begin{Bmatrix} EI_0 - E(I_0 - I_{cj})\frac{(\xi-\xi_{j1})}{(\xi_j-\xi_{j1})} & if \quad \xi_{j1} \le \xi \le \xi_j \\ EI_0 - E(I_0 - I_{cj})\frac{(\xi_{j2}-\xi)}{(\xi_{j2}-\xi_j)} & if \quad \xi_j \le \xi \le \xi_{j2} \end{Bmatrix} \tag{3}$$

where ξ_{j1} is the start of the damage influence, ξ_{j2} is its end and ξ_j is where the crack is located. Using Eq. 3, a triangular shape reduction of stiffness is obtained, as can be seen in Fig. 3c and 3d.

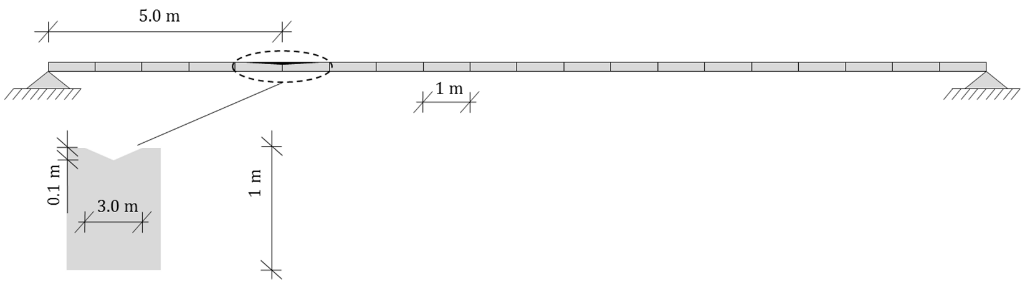
Deflection measurements are taken from the vehicle at a distance $x = 1.0\ \mathrm{m}$ from the second axle, where the curvature calculation is done. The absolute deflection of the bridge is assumed to be measured disregarding vehicle motion effect. The deflections at two more sensor locations are also measured at a constant distance of $\Delta x = 1.0\ \mathrm{m}$ before and after the first sensor. Fig. 4 shows IC in a noise free environment. Figs. 4a and 4b represent IC in the case that damage is modelled as a loss of stiffness. IC is slightly changed at the damage locations, $x_1 = 5\ \mathrm{m}$ in Fig. 4a and $x_1 = 5\ \mathrm{m}$ and $x_2 = 8.5\ \mathrm{m}$ in Fig. 4b. As the stiffness of the bridge is influenced in a longer length in Sinha's damage model, in the IC is more changed in Figs.4c and 4d.



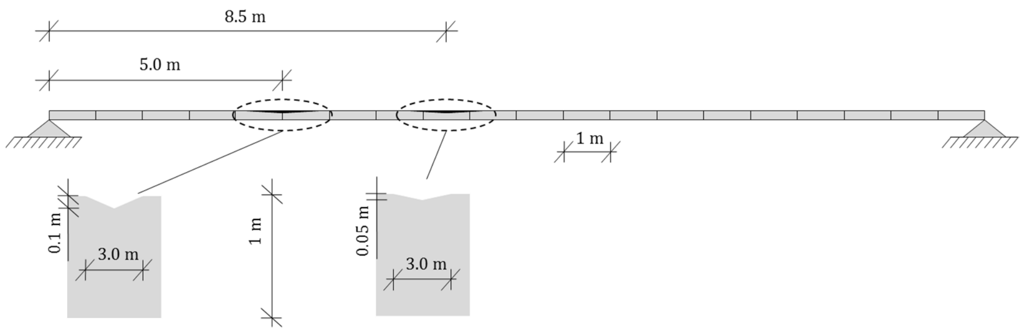
a) Single damage as simple loss of stiffness



b) Multiple damages as simple losses of stiffness

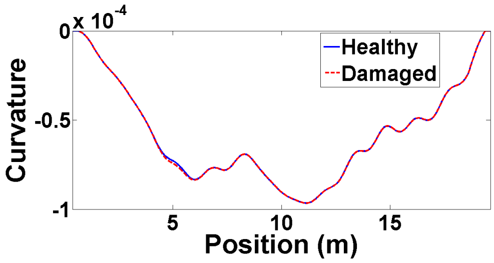


c) Single damage using Sinha's model

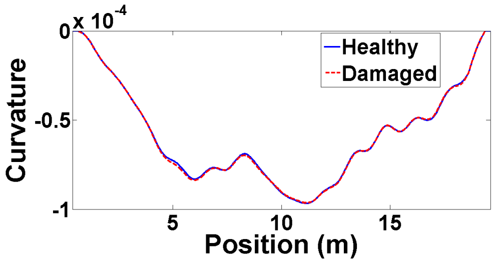


d) Multiple damages using Sinha's model

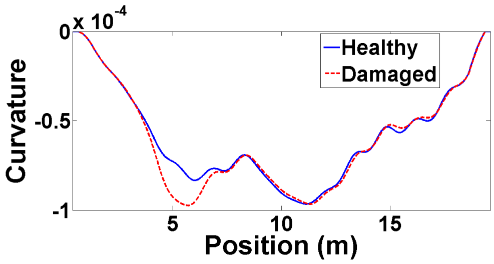
Figure 3. Damage cases.



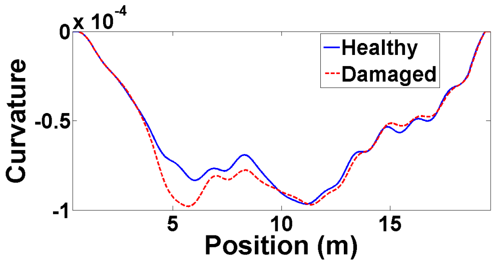
(a) Single damage, simple loss of stiffness



(b) Multiple damages, simple loss of stiffness



(c) Single damage, Sinha's model



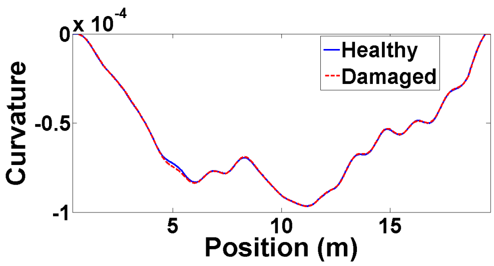
(d) Multiple damages, Sinha's model

Figure 4. IC damage cases with no noise

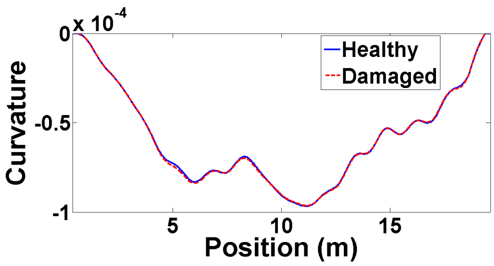
In order to investigate the efficiency of the method in a noisy environment, 0.1% noise is added to the measurements. A moving average filter [14] is used as:

$$z[i] = \frac{1}{N} \sum_{j=-(N-1)/2}^{(N-1)/2} y[i+j] \qquad (4)$$

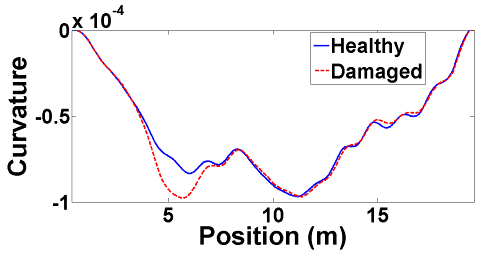
where $y[i+j]$ is the input signal, $z[i]$ is the filtered signal and N is the number of points used in the moving average. $N = 31$ is used for curvature filtering. Fig. 5 represents the filtered IC in the different damage scenarios in presence of noise. The results show that the method can still identify the damage with an acceptable accuracy.



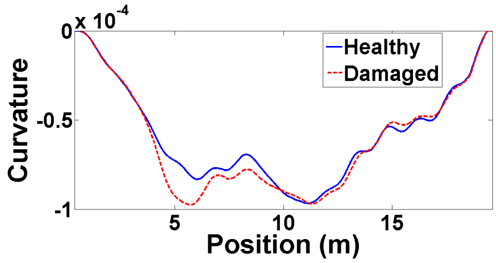
(a) Single damage, simple loss of stiffness



(b) Multiple Damages, Simple Loss of Stiffness



(c) Single damage, Sinha's model



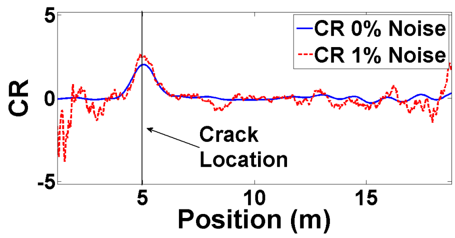
(d) Multiple damages, Sinha's model

Figure 5. IC damage cases with 0.1% noise

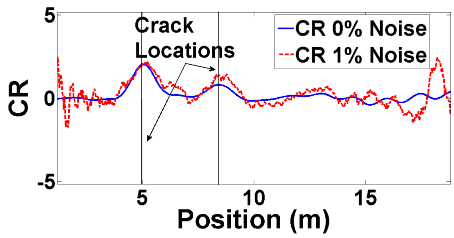
An IC-based damage indicator is proposed. The change in the curvatures at the damage location is clear in Figs 4-5. Curvature Ratio (CR) in Fig. 6 is implemented as damage indicator, which is defined in Eq. 5.

$$CR(x) = \left(1 - \frac{IC_{healthy}}{IC_{damaged}}\right) \times 100\ (\%) \qquad (5)$$

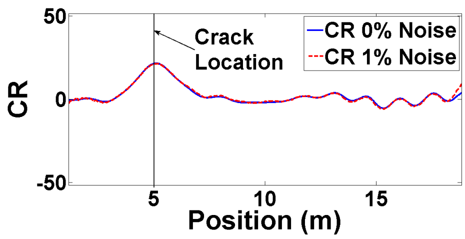
CR is a great tool for damage quantification, considering that with curvature damage can be accurately located. CR at every damage situation is calculated in Fig.6.



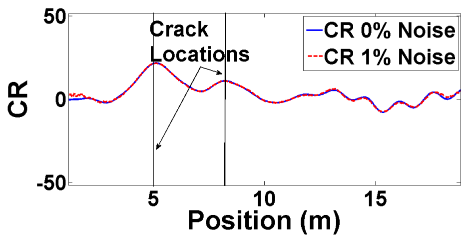
(a) Single damage, simple loss of stiffness



(b) Multiple Damages, Simple Loss of Stiffness



(c) Single damage, Sinha's model



(d) Multiple damages, Sinha's model

Figure 6. CR for damage quantification

The loss of stiffness of the bridge is directly quantified using the CR in Fig. 6 for Sinha's model of damage. On the other hand, CR does not work for damage quantification in the simple loss of stiffness model. CR value in loss of stiffness model is lower than the true damage. This is caused by the short length of the simulated loss of stiffness. Real damage maximum cannot be reached in lengths lower than $0.5\ \mathrm{m}$ and only part of the loss of stiffness is measured. In both damage models, noise influence is greater in the extremes, where lower curvatures are measured. Noise can cause only little variations of stiffness in the prediction at damage location for Sinha's model. However, a higher noise influence is expected when attempting to quantify damage in loss of stiffness model. Extra deflection caused by loss of stiffness damage is lower, mixing results from healthy . IC is also greater at the crack due to this reason, making the curvature being sharper at that time.

4. Conclusions

Curvature Ratio (CR) is proposed as a damage indicator. Two different damage models of a crack on a bridge are analysed, considering single and multiple damage situations. CR is demonstrated to provide an accurate indication of damage for the Sinha's damage model. On the other hand, only a rough indication can be obtained using loss of stiffness model due to a very short length of damage for the crack. Noise is introduced, but it is concluded that there is practically no influence if the damage introduced is able to cause a remarkable difference between healthy and damage situations. On the other hand, little damage will cause little deflections differences and it both healthy and damage outputs can be mixed. More analysis is required for reducing the effect of noise in measurements.

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