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Title	Wavelet based experimental damage calibration using beam-moving load interaction model
Authors	Pakrashi, Vikram;O'Connor, Alan J.;Basu, Biswajit
Publication date	2007
Original Citation	Pakrashi, V., O'Connor, A., Basu, B., 2007. Wavelet Based Experimental Damage Calibration using Beam-Moving Load Interaction Model, In: B.H.V. Topping, (Editor), "Proceedings of the Eleventh International Conference on Civil, Structural and Environmental Engineering Computing", Civil-Comp Press, Stirlingshire, UK, Paper 187, 2007. doi:10.4203/ccp.86.187
Type of publication	Conference item
Link to publisher's version	10.4203/ccp.86.187
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Download date	2026-11-07 03:14:18
Item downloaded from	https://hdl.handle.net/10468/239

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This paper is the original manuscript as submitted to the conference. The final published version is available from http://dx.doi.org/10.4203/ccp.86.187

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Wavelet Based Experimental Damage Calibration using Beam-Moving Load Interaction Model

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Abstract

This paper presents a wavelet analysis based damage calibration of an open crack in a beam traversed by a moving load. The experimental static and dynamic deflected shape data from beam-moving load interactions are obtained using a digital video camera. The data acquired correspond to various extents of damage. The digital images are processed by image processing techniques and analysed using spatial wavelets for damage extent calibration. The proposed calibration technique is applicable to bridge-vehicle interaction data and can be beneficial in situations where the structure can seldom be closed down to obtain structural health monitoring data. The static calibration is simple, fast and efficient if the static deflection or strain data is spatially available by loading a bridge with a static and preselected vehicle of known weight.

Keywords: Wavelet, Image Processing, Structural Health Monitoring, Open Crack, Beam-Vehicle Interaction, Damage Calibration.

1 Introduction

Wavelet based identification of the presence, location and the extent of damage using data from the spatial domain has gained considerable interest in the field of structural health monitoring (Taha et.al [1]). The implementation of such a wavelet based structural health monitoring method is critically dependent on the ability to experimentally identify the local spatial changes in a structure due to the presence of damage. Successful experimental detection of static and dynamic modeshapes and deflected shapes of beams with open cracks and consequent wavelet based identification of damage have been reported by a number of researchers in recent times. Scanning Laser Vibrometer (SLV) device has been used to identify open cracks in beams through wavelet analysis by a number of researchers (Khan et.al [2], Okafor and Dutta [3], Vanlanduit et.al [4]). However, the cost and accessibility of

such sophisticated devices can sometimes be prohibitive. Comparatively less expensive and accessible digital camera based methods in conjunction with image processing techniques have successfully detected damage in beams with open cracks in recent times (Poudel et.al [5], Rucka and Wilde [6], Patsias and Staszewski [7], Pakrashi et.al [8, 9, 10]). Very few of these experimental studies investigate the prediction of the extent of damage (Okafor and Dutta [3], Pakrashi et.al [9]), although the successful identification of the location of damage has been comparatively well dealt with. The presence of damage in a structure usually introduces a local and sharp change in the stress, strain and the displacement fields in the damage region and the change is usually translated as singularities in the derivatives of the modeshapes and the deflected shapes (Bovsunovsky and Matveev [11], Narkis [12], Carneiro and Inman [13]). Since the wavelet transform of a signal can be related to its derivatives based on the number of vanishing moments of the wavelet basis function (Mallat [14]), local maxima of wavelet coefficients are observed at the location of singularities in a signal or in any of its derivatives when a wavelet basis function with an appropriate number of vanishing moments is chosen for the analysis. The degree of singularity can be related to the magnitude of the local maxima thus formed. When spatially varying fields are available from damaged structures, the locations of damage can be related to the locations of the local maxima and the extent of damage can be associated to the magnitudes of the maxima (Gentile and Messina [15]). An important application of such wavelet based damage extent prediction can be related to the structural health monitoring framework of structures which need to be assessed during operation. A typical example is the bridge structure where it can seldom be closed down for experimentation due to practical reasons. A few studies in the time domain have been performed to link the bridge-vehicle interaction process with health monitoring (Majumdar and Manohar [16], Lee et.al [17], Law and Zhu [18]). With the advancement of experimental facilities in the spatial domain, the possibilities of successful application of spatial data acquired from bridge vehicle interaction is deemed important as regards a structural health monitoring framework. Central to such a proposition, is the successful laboratory study of the evolution of damage on a structure with a moving oscillator traversing it.

This paper considers a simply supported phenolic beam traversed by a model two-axle accelerating vehicle. The beam has a crack situated on its underside. The dynamic deflections have been identified through a digital video camera based recording and subsequent image processing. The depth of the crack has been gradually increased and the evolution of the damage has been related to the extent of the local maxima of the wavelet coefficients at the location of damage. A consistent wavelet based damage extent prediction curve has been achieved in the process. Consistent comparison with static deflections due to the presence of the same two-axle vehicle has been performed.

2 Experimental Identification of Deflected Shapes

2.1 Experimental Setup

Experiments were carried out on a 0.925m long simply supported phenolic beam with a model two–axle vehicle traversing it. The axle distance between the two axles of the model vehicle was 0.11m. An open crack was notched at a distance of 0.46m into the lower section of the beam from the left hand side. The cross section of the beam was rectangular and of the dimensions 50mm x 12mm. The vehicle was attached to a string which was coiled around a motor. The acceleration of the vehicle could be controlled by increasing the voltage in the motor and the weight of the vehicle could be adjusted by bolting additional weight on top of it, if needed. Three damage conditions, comprising of crack depth ratios (CDR) equal to 0.167, 0.33 and 0.5 respectively were considered for the beam. The CDR is defined as the ratio of the depth of crack to the depth of the beam cross section. The vehicle started from rest on the beam from the right hand side and left the beam on the left hand side smoothly via an exit platform. Figure 1 shows the general arrangement of the experimental set-up, while Figure 2 provides a representative photograph of the testing. Figures 3 and 4 show the close-up pictures of the motor and the vehicle respectively.

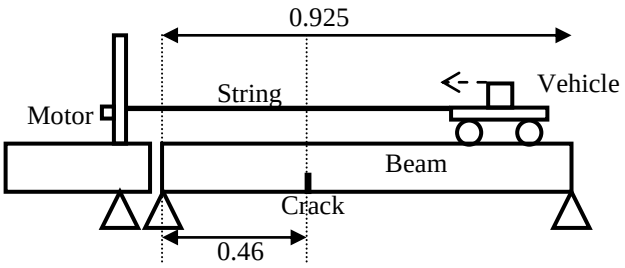


Figure 1. General Experimental Arrangement

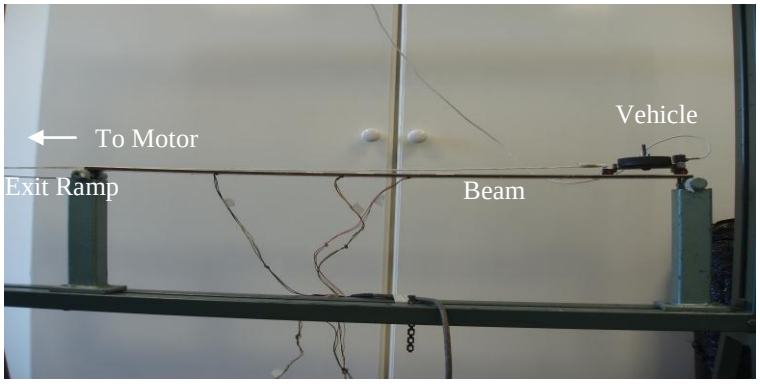


Figure 2. Photograph of Experimental Arrangement

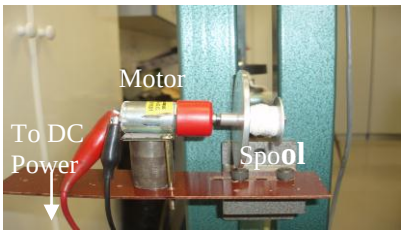


Figure 3. Photograph of the Motor

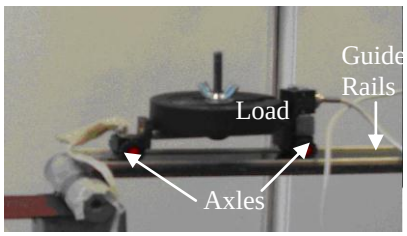


Figure 4. Photograph of the Vehicle

2.2 Identification of Deflected Shapes

The forced vibration of the beam due to the passage of the model two-axle vehicle is recorded in the spatial domain by an Olympus μ 800 digital camera. An appropriate deflected shape, significantly large for the camera to discern is chosen by running the video recording using a commercial software Ulead Video Studio 6 and freezing a single frame. This methodology is similar to that what has been employed by Hartman and Gilchrist [19] to quantify four point bending fatigue in asphalt mix. The frame is converted and saved as a bitmap image of size 240 x 320 pixels and subsequently converted to black and white binary images by thresholding and the edges of the images were found using the Sobel method (Sarfaraz [20]) incorporating the MATLAB 7.0 signal processing toolbox. . It should be noted here that a very high resolution image does not necessarily guarantee low noise in an image. Often the general imperfections of the underside of the beam are accentuated in high resolution images resulting in large file-space, increased computational time and false alarms. The saved image of the deflected shape is essentially a rectangular grid of pixels and the centre of a pixel occupies the integer co-ordinates in the grid so produced. The Sobel method scans a binary image and returns the approximation to the derivative of the two-dimensional data. The edges are returned as the points where the gradient of the image are locally maximum. The lower edge of the beam was detected from the image by the intelligent pattern recognition scheme followed by Pakrashi et.al [8, 10].

3 Methodology

3.1 Continuous Wavelet Transform

The continuous wavelet transform of a function f(x) in a square integrable space can be represented as

$$Wf(b,s) = \int_{-\infty}^{+\infty} f(x) \frac{1}{\sqrt{s}} \psi^*(\frac{x-b}{s}) dx \qquad (1)$$

where s is the scale and b is the translation parameter related to the wavelet family of functions

$$\psi_{b,s}(x) = \frac{1}{\sqrt{s}} \psi(\frac{x-b}{s}) \qquad (2)$$

and the asterisk denotes a complex conjugation. The zero average basis function $\psi(x)$ satisfies

$$\int_{0}^{+\infty} \frac{|\hat{\psi}(\omega)|^2}{\omega} d\omega < +\infty \qquad (3)$$

to ensure the completeness of the wavelet transform and to maintain energy balance. The term $\hat{\psi}(\omega)$ refers to the Fourier transform of $\psi(x)$ and ω denotes the frequency. The identification of a discontinuity in a function or any of its derivatives is linked with the number of vanishing moments of the wavelet basis function chosen for the analysis. For a wavelet with no more than m number of vanishing moments the continuous wavelet transform of a function f(x) can be related to the m^{th} derivative of the signal (Mallat [14]). A deflected shape of a beam with an open crack contains singularities in its derivatives and the wavelet transform of the damaged deflected shape renders a local extremum of the wavelet coefficient at the location of damage consistently at different scales. The measure of the local regularity in the neighbourhood of a point in a function can be related to the local Lipschitz exponent around that point. As per Mallat [14], a function f(x) in the square integrable space is pointwise Lipschitz $\kappa \geq 0$ at a point ν if there exists a K>0 and a polynomial $p_\nu(x)$ of degree $\breve{m}$ such that

$$\forall x \in \square, |f(x) - p_\nu(x)| \leq K|x-\nu|^\kappa \qquad (4)$$

thus providing the degree of singularity in the neighbourhood of the point. If the function f(x) is uniformly Lipschitz over an interval $[\breve{a}, \breve{b}]$, then there exists an $\breve{A} > 0$ such that

$$\forall (b,s) \in [\breve{a}, \breve{b}] \times \square^+, \; |Wf(b,s)| \leq \breve{A} s^{\kappa + \frac{1}{2}} \left(1 + \left|\frac{b-\nu}{s}\right|^\kappa\right) \qquad (5)$$

The magnitude of the wavelet coefficients around a point can be related to the local Lipschitz exponent, and hence to the degree of singularity present at that point indicating the extent of damage present at that point.

3.2 Analysis of Damaged Deflected Shapes

The identified deflected shape is multiplied by a Hanning window of length equal to that of the deflected shape. The windowing is important in suppressing edge effects and helps in better identifying the location of damage through wavelet analysis even in the presence of measurement noise (Gentile and Messina [15]). The windowed deflected shape has been analysed by Coif4 wavelet basis function which possesses eight vanishing moments. Such a choice is justified, since the discontinuity in the signal due to the presence of damage is in the first derivative. The extent of damage is gradually increased as has been described in the previous section and the data acquisition, identification and subsequent wavelet analysis is repeated for each damage condition. An alternative set of analysis is also performed for each damage condition by identifying the damaged deflected shape for a static condition of the vehicle situated symmetrically with respect to the midpoint of the beam for comparison.

4 Experimental Results

The various conditions of damage extent in the experimental beam have been related with the magnitude of the maxima values of the wavelet coefficients situated at the location of damage. A consistent calibration of the extent of damage has been successfully achieved. Figure 5 shows one such calibration for a vehicle load 7.5N and an acceleration of 1.1478 m/s^2. A similar calibration was performed from the static deflected shape of the beam coinciding with the centre of the vehicle with the position of damage. Figure 6 shows the calibration for a vehicle load of 7.5N situated symmetrically about the midpoint of the beam. The calibrations have been achieved at scales 4, 16, 32 and 64 respectively.

The calibration curves are consistent and monotonous with the increase of the damage extent of the open crack. The dynamic and the static predictions of damage extent agree at the various scales. The inconsistency of the single observation for the dynamic calibration of damage extent consisting of a CDR=0.5 at scale 64 most possibly occurs due to the segmented and spurious measurement noise (noted by Pakrashi et.al [10] before) that sometimes accompany an image processing based detection process.

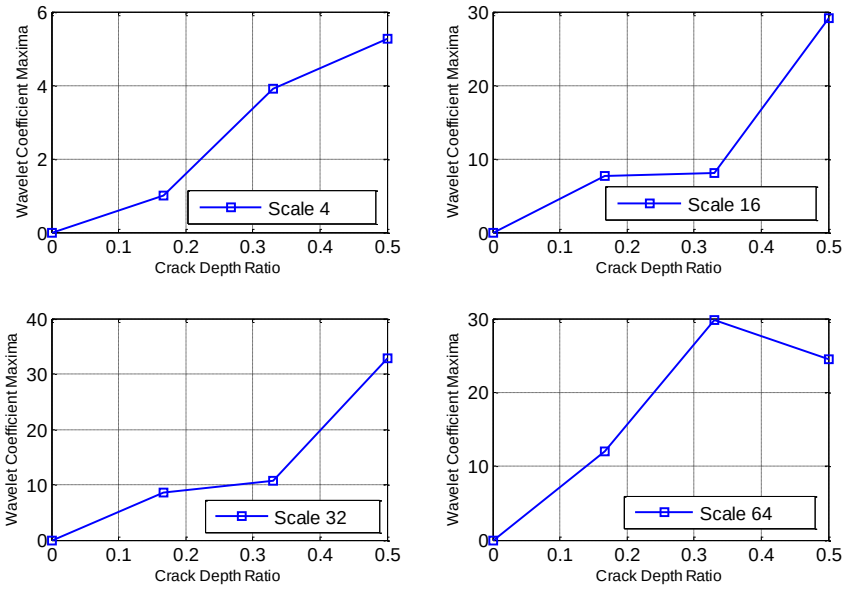


Figure 5. Experimental Calibration of Damage Extent Using Dynamic Deflected Shape.

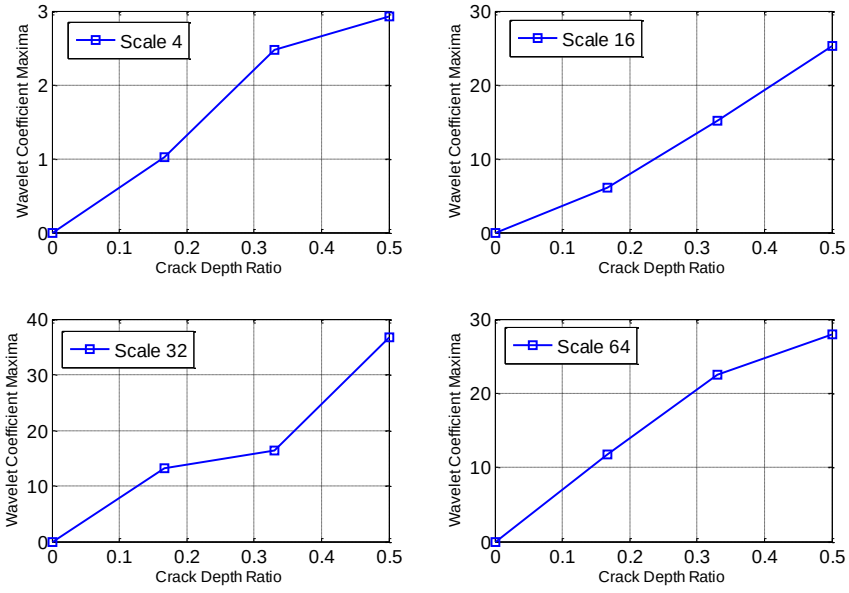


Figure 6. Experimental Calibration of Damage Extent Using Static Deflected Shape.

5 Conclusion

A study of wavelet based prediction curves for the extent of damage using experimental data from the spatial domain has been successfully reported in this paper. The proposed technique for damage calibration has been applied on a simply supported beam with an open crack traversed by a model two axle vehicle for a wide range of crack depth ratios. The calibration on dynamic deflected shapes has been carried out by considering the movement of the vehicle over the beam to be a source of excitation and the dynamic deflected shapes have been identified through an image processing based technique. Calibrations for static deflected conditions have been performed and compared with its dynamic counterpart. For both cases, consistent and comparable monotonous prediction curves have been successfully achieved. The methodology is observed to be important for the health monitoring and assessment of bridge structures in its operating condition through the use of bridge-vehicle interaction data in the spatial domain. The static calibration is particularly useful where the static deflection or strain data can be spatially made available by loading a bridge with a static and preselected vehicle of known weight.

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