



Title	Damage detection and calibration from beam–moving oscillator interaction employing surface roughness
Authors(s)	Jaksic, Vesna, O'Connor, Alan, Pakrashi, Vikram
Publication date	2014-08-18
Publication information	Jaksic, Vesna, Alan O'Connor, and Vikram Pakrashi. "Damage Detection and Calibration from Beam–Moving Oscillator Interaction Employing Surface Roughness," August 18, 2014. https://doi.org/10.1016/j.jsv.2014.04.009 .
Item record/more information	http://hdl.handle.net/10197/10404
Publisher's statement	This is the author's version of a work that was accepted for publication in Journal of Sound and Vibration. Changes resulting from the publishing process, such as peer review, editing, corrections structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Journal of Sound and Vibration (333, 17, (2014)) https://doi.org/10.1016/j.jsv.2014.04.009
Publisher's version (DOI)	10.1016/j.jsv.2014.04.009

Downloaded 2026-05-01 23:33:46

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

1 **Damage Detection and Calibration from Beam-Moving**
2 **Oscillator Interaction Employing Surface Roughness**

3 **V. Jaksic¹, A. O' Connor² and V. Pakrashi¹**

4 **¹Dynamical Systems and Risk Laboratory, Department of Civil and Environmental**
5 **Engineering, University College Cork, Ireland**

6 **²Department of Civil, Structural and Environmental Engineering, Trinity College**
7 **Dublin, Ireland**

8 **Corresponding Author:** Dr. Vikram Pakrashi, Lecturer in Structural Engineering,
9 Department of Civil and Environmental Engineering, University College Cork, Ireland.

10 Phone: +353(0)214903862 Email: V.Pakrashi@ucc.ie Fax: +353(0)214276648

11

12 **Abstract**

13 The possibility of employing bridge deck surface roughness for Structural Health
14 Monitoring (SHM) under operational conditions is proposed in this paper. A bilinear
15 breathing crack in a damaged Euler Bernoulli beam traversed by a moving oscillator is
16 considered in this regard. The Road Surface Roughness (RSR) of the beam is classified
17 as per ISO 8606:1995(E). The interaction of the moving oscillator with surface roughness
18 is exploited to define simple, consistent, easy to implement and robust statistical
19 descriptors to detect and calibrate the existence, the location and the extent of damage.
20 The effects of vehicle speed and variable RSR profiles for such detection are investigated
21 and preferable conditions for detection are identified. The proposed method is also

1 suitable for experimental analysis where a theoretical model is not available or is not
2 credibly ascertained.

3 Keywords: Structural Health Monitoring (SHM), Euler – Bernoulli Beam, Breathing
4 Crack, Road Surface Roughness, Bridge-Vehicle Interaction.

5 **Authors:**

6 Vesna Jaksic, Doctoral Researcher, Department of Civil and Environmental Engineering,
7 University College Cork, Ireland. V.Jaksic@umail.ucc.ie

8 Dr. Alan O’Connor, Associate Professor in Structural and Environmental Engineering,
9 School of Engineering, Trinity College Dublin, Ireland. alan.oconnor@tcd.ie

10

11 **1. Introduction**

12 Structural Health Monitoring (SHM) can be a practical tool for remote monitoring of in-
13 service structures aiming to improve the prediction of safety level and system
14 performance while reducing maintenance costs. SHM is also critical for the prioritization
15 of the time and nature of investment in a structure or a network of structures [1-3]. Non-
16 destructive structural damage detection as an essential part of SHM is becoming an
17 important aspect of integrity assessment for aging, inaccessible or extreme-event affected
18 structures. Generally, damages or alterations to a structure tend to change its dynamic
19 characteristics. Often, such damages are local and significant changes are not reflected in
20 the global dynamic response. Consequently, methodologies are developed to capture the
21 local change through some marker to estimate the presence, the location, and the severity
22 of damage. In this regard damage detection employing bridge-vehicle interaction is of
23 considerable interest since the structure can be kept in operation throughout the process.

1 The problem of bridge-vehicle interaction is well understood [4-6] and there exists a
2 number of numerical methods [7-9] for damage detection. This provides a motivation to
3 employ bridge-vehicle interaction for monitoring damage evolution. Local damages like
4 cracks pose a particular challenge in this respect since the changes are local. The local
5 changes may be attributed to a sharply changing function corresponding to locally
6 appearing high frequency components. With rapidly improving experimental capabilities,
7 the measurement options have also increased to a very significant extent and the
8 implementation of novel methodologies have become more feasible than ever before.

9 Vibration based techniques for crack detection have been widely employed since they
10 offer fast and inexpensive means for crack identification [10]. Narkis [11] has proposed a
11 method for calculation of natural frequencies of a cracked simply supported beam where
12 the crack is simulated by an equivalent rotational spring. This method was applied to
13 identify crack location from frequency measurements. Recently, there have been works
14 involving bridge-vehicle interaction to detect damage. Law and Zhu [12] have
15 investigated the dynamic behavior of damaged reinforced concrete bridges under moving
16 loads using a model of a simply supported beam with open and breathing cracks. The
17 phase space of the damaged beam response was distorted in comparison with an
18 undamaged phase space. Majumdar and Manohar [13] have proposed time domain
19 damage descriptors to reflect the changes in bridge behavior due to damage represented
20 by local reduction in stiffness. Lee et al. [14] have experimentally investigated the
21 possible application of bridge-vehicle interaction data for identifying the loss of bending
22 rigidity by continuously monitoring the operational modal parameters. Bilello et al. [15]
23 have observed dynamic response of the small-scale bridge model and compared findings

1 with the continuous Euler–Bernoulli beam theory. Bilello and Bergman [16] have
2 considered, theoretically and experimentally, the response of a damaged Euler–Bernoulli
3 beam traversed by a moving mass, where the damage was modeled through rotational
4 springs. An increase in structural damage sensitivity under the effect of a moving load
5 was observed in this case. Pakrashi et al. [17] have performed experimental investigation
6 of simply supported beam traversed by a moving load and subjected to different levels of
7 damage. The wavelet transformed phase spaces for damaged and undamaged cases
8 differed distinctly at high scales but were often masked due to the presence of noise
9 within the signal. The masking effect has also been observed from a different context by
10 Gentile and Messina [7]. Bu et al. [18] have proposed a damage assessment approach
11 from the dynamic response of a passing vehicle through a damage index and have
12 considered effects of different vehicle models, vehicle speed, vehicle and bridge mass
13 and stiffness ratios, sampling frequency, road surface roughness, measurement noise, and
14 model error. The road surface roughness was observed to affect the bridge-vehicle system
15 similar to a random noise excitation. The maximum dynamic responses were related to
16 the worst surface roughness. Abdel-Rohman and Al-Duaij [19] have recognized the
17 importance of unevenness in the bridge deck on the dynamic response of single span
18 bridges due to moving loads. They have assumed unevenness to be a sinusoidal wave
19 shape function and found that it has a significant effect on the acceleration response. Da
20 Silva [20] has proposed a methodology to evaluate the dynamical effects, displacement
21 and stress on highway bridge decks due to vehicles crossing rough pavement surfaces
22 defined by a probabilistic model. It was concluded that the effects due to interaction of
23 the vehicles with an irregular pavement surface could be more important than those

1 produced by the load mobility alone. Also, dynamical effects increase drastically with the
2 decrease of pavement surface quality. A lower quality pavement surface was one with an
3 amplitude of irregularity larger than 1.4 cm. Wu and Law [21] have proposed a stochastic
4 vehicle axle load identification algorithm and studied the effect of different road surface
5 profiles on algorithm accuracy. They demonstrated that the Gaussian assumption of the
6 road surface roughness can be helpful.

7 Although there are many interesting numerical and statistical markers and methods
8 available for damage detection [9, 22-24], surface roughness has always been treated for
9 parameter studies, improved analysis or for establishing the bounds of efficiency of an
10 algorithm. This paper directly uses surface roughness as a main aid to detect damage by
11 focusing only at the high frequency components. Jaksic et al. [25] have investigated the
12 basis of using surface roughness where a white noise excitation response of a single
13 degree of freedom bilinear oscillator was investigated. The white noise represented a
14 broadband excitation, qualitatively similar to the interaction with surface roughness, the
15 bilinearity attempted to capture a breathing crack. The stiffness of one of the springs was
16 theoretically degraded at different levels. It was observed that there are markers [26], i.e.
17 first and second order cumulants of the response of this system in this case, which behave
18 consistently with this change. The conclusions of this work provided an impetus to carry
19 out a damaged-beam vehicle interaction based damage detection study from multiple
20 point observations in the time domain using the interaction with realistic surface
21 roughness, which is presented here. The damage has been modeled as a localized
22 breathing crack and surface roughness has been defined by ISO 8606:1995 [27]. The
23 responses of the first mode of undamaged and damaged beam are observed [9, 28] since

1 they are easy to detect and are a good approximation of the actual displacement.
2 Cumulant based statistical markers are established for damage detection utilising these
3 responses, using a new detection method. The markers are investigated against key
4 variables like the location and the extent of the crack, vehicle velocity and type of surface
5 roughness in order to obtain preferable conditions of detection. The proposed method is
6 well-suited for output-only operational conditions of bridges and can contribute to the
7 SHM of bridge structures to a significant extent.

8

9 **2. Theory**

10 The schematic of the problem considered is presented in Figure 1 where the damaged
11 bridge-vehicle interaction system is represented as a simply supported Euler-Bernoulli
12 beam with a breathing crack traversed by a single degree of freedom oscillator. The beam
13 represents the bridge and the oscillator represents the vehicle. The vehicle is assumed to
14 be moving on the surface without losing contact with it. The length of the beam is L (m)
15 and the crack is at a distance x_c (m) from the left support. The beam has a constant cross-
16 sectional area A (m²) and a second moment of area I (m⁴). The material properties of the
17 beam are the Young's modulus E (N/m²) and the mass density ρ (kg/m³). The crack is
18 modeled as a rotational spring [11] when the crack is open.

19 **2.1 Equations of motion of a simply supported beam with breathing crack**

20 The governing equation of motion of cracked beam with mass per unit length $m=\rho A$
21 (kg/m) and structural damping of the material c , subject to the weight of the moving load
22 P (N) are coupled through continuity and jump conditions at crack location as:

$$1 \quad EI \frac{\partial^4 y_i(x, t)}{\partial x^4} + c \frac{\partial y_i(x, t)}{\partial t} + \rho A \frac{\partial^2 y_i(x, t)}{\partial t^2} = P \delta(x - vt); \quad i = 1, 2 \quad (1)$$

2 where EI is flexural rigidity (Nm^2); t is the time coordinate with the origin at the instant
3 of the force arriving upon the beam (s); x is the length coordinate with the origin at the
4 simply supported end of each beam (m); $y_i(x, t)$ is the transverse deflection of the i^{th} beam
5 segment at the point x and time t , measured from the static equilibrium position
6 corresponding to when the beam is loaded under its own weight; δ is the Dirac Delta
7 function [25]; and vt is the position of the vehicle moving with constant speed v from
8 left support (m). The external force P is defined as in [19]:

$$9 \quad P = \{m_v g + K[z - y_i(vt, t) - r(vt)]\}; \quad i = 1, 2 \quad (2)$$

10 where m_v is the mass of the vehicle (kg); g is acceleration due to gravity (9.81 m/s^2); K is
11 the stiffness of the vehicle's tires and springs (N/m); z is the vertical displacement of the
12 vehicle with respect to its static equilibrium position (m); and r is the surface roughness
13 (m). The effects of structural damping are often small [26] and under such circumstances
14 equation (1) can be rewritten as:

$$15 \quad EI \frac{\partial^4 y_i(x, t)}{\partial x^4} + \rho A \frac{\partial^2 y_i(x, t)}{\partial t^2} = \{m_v g + K[z - y_i(vt, t) - r(vt)]\} \delta(x - vt);$$

$$16 \quad i = 1, 2 \quad (3)$$

17 with the condition:

$$18 \quad K[z - y_i(vt, t) - r(vt)] \geq 0 \quad (4)$$

1 The solution of the eigenvalue problem related to this system provides the natural
 2 frequencies and mode shapes. The open and the closed crack states are considered to
 3 obtain two sets of natural frequencies and mode shapes for a breathing crack formulation.

4 **2.2 The open crack eigenvalue problem**

5 When the crack is open, the system is considered to consist of two beams connected by a
 6 rotational spring, where each continuous segment of the beam can be described by the
 7 Bernoulli-Euler partial differential equation of motion (3). The eigenvalue problem can
 8 then be solved through the method of separation of variables:

$$9 \quad y_i(x, t) = \sum_{j=1}^n \phi_j^i(x) q_j(t); \quad i = 1, 2 \quad (5)$$

10 where ϕ_j^i is the orthogonal mode shape of the i^{th} beam for the j^{th} mode shape and q_j is the
 11 time dependent amplitude. By separating temporal and spatial variables, the following
 12 differential equation system is obtained:

$$13 \quad \phi_j^{i''''}(x) - \frac{\omega_j^2 \rho A}{EI} \phi_j^i(x) = 0; \quad i = 1, 2; j = 1 \text{ to } n \quad (6)$$

$$14 \quad \ddot{q}_j(t) + \omega_j^2 q_j(t) = 0; \quad j = 1 \text{ to } n \quad (7)$$

15 where ω_j is natural frequency of the beam and the superscripted primes denote
 16 differentiation with respect to the spatial coordinate. For free vibrations of the beam,
 17 there is no external excitation and consequently there are no displacements or moments at
 18 the supports. The corresponding boundary conditions are:

$$19 \quad x = 0 \Rightarrow \phi_j^i(0) = 0; \quad \phi_j^{i''}(0) = 0; \quad i = 1, 2; j = 1 \text{ to } n \quad (8)$$

1 Boundary conditions at the crack location x_c must satisfy continuity of displacement,
 2 bending moment and shear, leading to:

$$3 \quad \phi_j^1(x = x_c) = \phi_j^2(x = L - x_c) \quad (9)$$

$$4 \quad \phi_j^{1''}(x = x_c) = \phi_j^{2''}(x = L - x_c) \quad (10)$$

$$5 \quad \phi_j^{1'''}(x = x_c) = -\phi_j^{2'''}(x = L - x_c) \quad (11)$$

6 The slope between the two beam segments can be related to the moment at this section
 7 as:

$$12 \quad \phi_j^{1''}(x_c) + \frac{K_T}{EI} [\phi_j^{2'}(x = L - x_c) + \phi_j^{1'}(x = x_c)] = 0 \quad (12)$$

8 where K_T is the equivalent rotational spring stiffness as defined by Sundermeyer and
 9 Weaver [29] and expressed as a polynomial function of Crack Depth Ratio (CDR). The
 10 solution of the spatial differential equation (6) satisfying all eight boundary conditions is
 11 thus:

$$13 \quad 0 < \bar{x} < x_c \rightarrow \phi = A(\sin a\bar{x} + \alpha \sinh a\bar{x}) \quad (13)$$

$$16 \quad x_c < \bar{x} < L \rightarrow \phi = A \left(\frac{\sin(ax_c) \sin(a(L - \bar{x}))}{\sin(a(L - x_c))} + \alpha \frac{\sinh(ax_c) \sinh(a(L - \bar{x}))}{\sinh(a(L - x_c))} \right) \quad (14)$$

14 where

$$17 \quad a^4 = \frac{\omega_j^2 \rho A}{EI} \quad (15)$$

$$18 \quad \alpha = \frac{\cos ax_c + \frac{\sin ax_c}{\tan a(L - x_c)}}{\cosh ax_c + \frac{\sinh ax_c}{\tanh a(L - x_c)}} \quad (16)$$

15 with the constant A chosen so that the mode shapes are normalized as:

$$1 \quad \int_0^{x_c} (\phi_j(\bar{x}))^2 d\bar{x} + \int_{x_c}^L (\phi_j(\bar{x}))^2 d\bar{x} = 1 \quad (17)$$

2 where the spatial coordinate \bar{x} is considered from the left hand support and ϕ is the
 3 generalised representation of any mode shape as $\{\phi_j^1, \phi_j^2\}$ for any mode, arbitrarily
 4 represented as the j^{th} mode here.

5 The natural frequencies of the beam with the open crack can also be calculated replacing
 6 boundary conditions in an assumed solution of mode shape equation (6):

$$7 \quad \phi(x) = A_1 \cos ax + A_2 \sin ax + A_3 \cosh ax + A_4 \sinh ax \quad (18)$$

8 and setting its determinant to zero, or by using equations (15) and (16) [29]. A
 9 comparison of natural frequency results using the approach of Sundermeyer and Weaver
 10 [29] was carried out against the approach of Narkis [11] and the results were found to be
 11 in agreement.

12 **2.3 The closed crack eigenvalue problem**

13 When the crack closes, the beam is treated as one continuous Euler-Bernoulli beam and
 14 the first mode shape equation is:

$$17 \quad 0 < x < L \rightarrow \phi(x) = \sqrt{\frac{2}{L}} \sin(ax) \quad (19)$$

15 Since the displacement at the supports equals zero, the equation (18) is satisfied when \sin
 16 $(aL)=0$. Therefore the natural frequencies of the beam when the crack is closed are:

$$18 \quad \omega_j = j^2 \pi^2 \sqrt{\frac{EI}{mL^4}}; \quad j = 1, 2, 3, \dots \quad (20)$$

1

2 **2.4 Equation of motion of vehicle**

3 The equation of motion of the vehicle, modeled as a single degree of freedom oscillator
4 can be represented as:

$$5 \quad m_v \ddot{z} + c_v \dot{z} + K[z - r(vt) - y_i(vt, t)] = 0, \quad i = 1, 2 \quad (21)$$

6 where c_v is the vehicle damping coefficient.

7 **2.5 Surface roughness**

8 The moving vehicle loads are time dependent, because the position of wheel loads
9 changes with time (t) and the suspension of the vehicle oscillates (z) due to irregularities
10 of the Road Surface Roughness (RSR) [21]. The randomness of the RSR can be
11 represented through a periodic modulated random process [20, 21, 30, 31]. In the ISO
12 8606:1995(E) [27] specifications, RSR is related to the vehicle's speed by a formula
13 linking velocity and displacement power spectral density (PSD), where the general form
14 of displacement PSD of RSR in (m^3/cycles) is:

$$18 \quad S_d(f) = S_d(f_0) \left(\frac{f}{f_0} \right)^{-\alpha} \quad (22)$$

15 where $f_0 = 1/2\pi$ (cycles/m) is the discontinuity frequency; f is the spatial frequency
16 (cycles/m); $S_d(f_0)$ is roughness coefficient (m^3/cycles); α is an exponent of PSD. In this
17 paper, since this roughness classification is based on constant vehicle speed PSD, $\alpha = 2$.

19 The RSR function $r(\hat{x})$ in its discrete form [21, 30, 31]:

$$20 \quad r(\hat{x}) = \sum_{k=1}^N \sqrt{4S_d(f_0) \left(\frac{2\pi k}{L_c f_0} \right)^{-2} \frac{2\pi}{L_c} \cos \left(\frac{2\pi k f_0}{L_c} + \theta_k \right)} \quad (23)$$

1 where \hat{x} is the discrete representation of the spatial coordinate.
2 Here L_c is twice the length of the bridge; N is number of data points of successive
3 ordinates of the surface profile; and θ_k is a set of independent random phase angles
4 uniformly distributed between 0 and 2π .
5 The road classification according to ISO 8606:1995(E) is based on the value of $S_d(f_0)$ and
6 in this paper five classes of road surface roughness representing different qualities of the
7 road surface have been observed, defined as A-E [18] from the best to the worst
8 respectively, as shown in Table 1.

9 **2.6 Damaged Beam – Moving Oscillator Interaction Including Surface Roughness**

10 The bridge vehicle interaction can be defined by a system of second order differential
11 equations coupling the equations of motion of the beam (1) and of the vehicle (21). For
12 the first mode shape, equations (1) and (21) can be written in matrix form as:

$$\begin{aligned}
15 \quad & \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \times \begin{Bmatrix} \dot{q}_1 \\ \dot{z} \end{Bmatrix} + \begin{bmatrix} 2\xi_1\omega_1 & 0 \\ 0 & 2\xi_v\omega_v \end{bmatrix} \times \begin{Bmatrix} \dot{q}_1 \\ \dot{z} \end{Bmatrix} \\
16 \quad & + \begin{bmatrix} \omega_1^2 + \frac{K}{\rho A} \phi_1(vt)\phi_1(vt) & -\frac{K}{\rho A} \phi_1(vt) \\ -\omega_v^2 \phi_1(vt) & \omega_v^2 \end{bmatrix} \times \begin{Bmatrix} q_1 \\ z \end{Bmatrix} \\
17 \quad & = \begin{Bmatrix} \frac{m_v g}{\rho A} \phi_1(vt) - \frac{K}{\rho A} r(vt)\phi_1(vt) \\ \omega_v^2 r(vt) \end{Bmatrix} \quad (24)
\end{aligned}$$

13 where the natural frequency of the vehicle is $\omega_v^2 = \frac{K}{m_v}$; and ξ_j and ξ_v are the damping
14 ratios of the j^{th} mode of the bridge and that of the vehicle respectively.

1 The displacements and the velocities of the beam and the vehicle are obtained by solving
2 the system of second order differential equations (24) using a 4/5th order Runge-Kutta
3 method available in Matlab [32].

4

5 **3. Damage Detection through Surface Roughness**

6 The dynamic response of the beam due to beam-moving oscillator interaction is utilized
7 to detect and calibrate the location and the extent of damage. The data used for the bridge
8 model are, $L = 15\text{m}$; $\xi_1 = 2\%$; $E = 200\text{e}9\text{N/m}^2$ and $\rho = 7900\text{kg/m}^3$. The static deflection
9 of the beam is 0.005m . The depth (h) of the beam is 1.5 times the width (b) of the beam.
10 Other geometric descriptors like I , A and other values are computed based on this
11 assumption. For the simulations, the selected values are $I = 0.0021\text{m}^4$ and $A = 0.1287\text{m}^2$.
12 The data used for vehicle are $m_v = 3000\text{kg}$ and $K = 3.65\text{e}6\text{N/m}$ [33]. Responses of the
13 beam and the vehicle corresponding to changes in x_c at mid-span, quarter-span, and close
14 to the support; CDR from small (0.1) to large (0.45) with 0.05 increment; V_v from slow
15 to fast within a range of 10 to 150 km/h with 10 km/h increment and RSR from very good
16 to very poor were considered.

17 The proposed detection scheme in this paper is illustrated in Figure 2 through an example.
18 The general schematic of the methodology is presented in Figure 3. The beam is first
19 divided into a number of equal segments. In this regard different numbers of segments
20 have been tested. A beam with a minimum of 20 (0.75m) or more reasonably, 100 (0.15m)
21 segments were observed to be adequate for analysis and discussion of the proposed
22 technique based on comprehensive numerical experiments. Figure 2a shows 20 segments.
23 The first mode shape of the beam closed and open crack conditions are computed next. In

1 Figure 2b the crack is located at mid-span ($x_c = 0.5L$). The first mode shape differs very
2 little from the undamaged shape from the global point of view. Locally, there exists a
3 discontinuity in the slope of damaged mode shape at the location of damage. The extent
4 of this change of slope, though difficult to detect, is indicative of the extent of damage,
5 since small cracks have little effect on natural frequencies and mode shapes of beams.
6 Only crack ratios larger than 0.5 result in moderate frequency and large mode shape
7 changes [34]. This ratio range is not useful as structure failure will probably occur before
8 such damage extents are reached. The difference between the damaged and the
9 undamaged mode shapes is found (Figure 2c) along with their ordinate values at the
10 middle of each segment. The mode shape difference function ($\Delta\Phi$) has a local maximum
11 and discontinuous slope at the indicated single damage location, although the same will
12 appear in the case of multiple cracks [28]. In the case where cracks are very close to each
13 other, there could be an overlap as these cracks influence each other structurally. In
14 practice, the mode shape difference in the spatial domain may be hard to detect. However,
15 an initial benchmarked estimate of the undamaged mode shape and natural frequency
16 should be carried out even under such circumstances. The bridge response (displacement
17 is chosen in this case) obtained by solving equation (24) is multiplied with the mode
18 shape difference function ordinate at the middle of each segment ($\Delta\Phi_m$) (Figure 2d). The
19 multiplication, $\Delta\Phi_m q(t)$, is not implicit but explicit as in reality the bridge responses are
20 not too difficult to measure using small sensors placed in multiple locations along the
21 structure. The location and the extent of damage is then computed by choosing an
22 appropriate descriptor on the values of $\Delta\Phi_m q(t)$ at multiple locations. The involvement of
23 surface roughness ensures that the high frequency components take part in forming the

1 descriptor features apart from the slow moving, vehicular weight driven response. This
2 participation cannot be described without the consideration of surface roughness or by
3 representing the vehicle as a moving point load. Noise is cancelled out by considering the
4 passage of many vehicles and the consideration of normalisation. The undamaged mode
5 shape response can be found by considering the estimated values, as mentioned in the
6 previous section. It is observed that the location near the damage is affected in this
7 differenced time domain response (Figure 2d). Figure 3 indicates the steps to reach the
8 multi-point observation signal $\Delta\Phi_m q(t)$, for which an appropriate descriptor of damage is
9 to be chosen. As discussed, the level of participation for each of these elements in the
10 schematic depends on the available information, degree of experimentation and modeling
11 complexity. The location of the damage(s) could be indicated by using wavelet analysis
12 as shown in many papers [9, 35-37]. The presence of multiple damages will be
13 accumulated and represented as a single equivalent damage when considering such an
14 approach if they are too close spatially, correctly indicating that in effect such close
15 damages behave like a single damage of a modified extent. Time-frequency techniques,
16 like wavelet analysis [7, 9] can detect singularities in a signal or sharp local changes in
17 the signal. However, they may require significant computational time for deployment
18 consequently, there remains the interest in developing simple and consistent descriptors
19 from the output so that computation time is minimized when deployed in real time as in
20 SHM system Network.

21

1 **4. Choice of Damage Detection and Calibration Markers**

2 Statistical descriptors on $\Delta\Phi_{mq}(t)$ for each segment of the observed beam and for each
3 combination of variables; x_c , CDR, V_v and RSR were investigated for monotonicity and
4 consistency. The statistical measures considered included mean (μ), standard deviation
5 (σ), skewness (λ), and kurtosis (κ). The choice of mean and standard deviation stemmed
6 out of the recent study [25]. In a separate study [23], the skewness and kurtosis were
7 observed to be markers for beam with an open crack vibrating under white noise and
8 consequently these two parameters were also chosen owing to the similarity of the
9 present problem. The parameters are computed as follows:

$$10 \quad \mu = \frac{1}{m} \sum_{i=1}^m x_i \quad (25)$$

$$11 \quad \sigma = \sqrt{\frac{1}{m} \sum_{i=1}^m (x_i - \mu)^2} \quad (26)$$

$$13 \quad \lambda = \frac{\frac{1}{m} \sum_{i=1}^m (x_i - \mu)^3}{\left(\sqrt{\frac{1}{m} \sum_{i=1}^m (x_i - \mu)^2} \right)^3} \quad (27)$$

12

$$14 \quad \kappa = \frac{\frac{1}{m} \sum_{i=1}^m (x_i - \mu)^4}{\left(\frac{1}{m} \sum_{i=1}^m (x_i - \mu)^2 \right)^2} \quad (28)$$

1 Additionally, the applicability of a simple R/S analysis based Hurst exponent (H) was
2 also investigated [38] in these studies since this measure has been applied before for
3 predicting events [39, 40] or sudden stiffness changes [41].

4 Figure 4 shows an example of mean (4a), standard deviation (4b), kurtosis (4c), skewness
5 (4d) and Hurst exponent (4e) measures of $\Delta\Phi_{mq}(t)$ calculated for each beam segment
6 where crack location is at 0.1L (1.5m) from the left support; 0.25L (3.75m) from the left
7 support and at 0.5L (7.5m) respectively, the vehicle speed is 80km/h, CDR is 0.45 and
8 RSR is class C. It is found that the obtained mean (Figure 4a) and standard deviation
9 (Figure 4b) functions are similar in shape and clearly show the discontinuous slope at the
10 damage location, as per the mode shape difference functions. This finding is consistent
11 with [25] where it has been proven that first and second order cumulants of bilinear and
12 linear system responses are consistent and monotonic descriptors of the system
13 characteristics and are sensitive to sudden changes in stiffness, which can be associated
14 with the sudden failure of a part of a structure. Due to the similarity of the shapes of
15 damage calibration curves related to mean and standard deviation, a Coefficient of
16 Variation (CoV) based marker will not be efficient. This marker was investigated in this
17 study and was confirmed not to be consistent. Following the method proposed by
18 Cacciola et.al [23] for beam vibrating under white noise, kurtosis (Figure 4c) and
19 skewness (Figure 4d) measures were tested but they appear to be insensitive to crack
20 presence for practical ranges of values. Only for the crack located at mid-span, in the
21 proximity of the crack, does the skewness function suddenly change sign, but this change
22 does not have a consistent monotonic trend in case of change of any observed variables.
23 The relative insensitivity of skewness and kurtosis for this detection scheme comes from

1 the scaling of data of these measures for time domain responses of different segments
2 multiplied by the ordinate of the mode shape difference estimate at the centre of each
3 segment. Hurst exponent (Figure 4e) is also found to be insensitive to presence of the
4 crack. Therefore μ and σ are chosen as markers for further calibration analysis.

5

6 **5. Results**

7 Figure 5 represents an example of mean and standard deviation functions for the case
8 where the crack is located at quarter-span, RSR is type C, the vehicle is moving with a
9 speed 80km/h and CDR increases from 0.1 to 0.45. From this and the similar figures
10 obtained by varying x_c , RSR type and V_v , a number of observations are noted. The
11 markers μ and σ show slope discontinuity at the damage location. The values of statistical
12 parameters relative to each other increase with increasing CDR and the slope
13 discontinuity of μ and σ at the crack location become more obvious when CDR increases.
14 These indicate that the location of crack can be identified by the chosen markers and that
15 consistent calibration is possible. Values of μ and σ at crack locations for all
16 combinations of x_c , RSR type, CDR, and V_v were investigated. More than 1800 cases
17 were observed in order to establish the calibrations of μ and σ at crack locations and
18 variable dependence of the calibrations. Only the essential findings are presented here. In
19 general, the relation between μ and σ and CDR for different V_v increases exponentially.
20 These curves can be separated into four groups depending on V_v : very low speed
21 (10km/h); low speed (20-60km/h); medium speed (70-100km/h) and high speed (110-
22 150km/h), for which variation of μ and σ is very high, high, medium, and low,
23 respectively. This grouping becomes more obvious for higher CDR when RSR is type D

1 and E, while for the RSR type A and B there is very little difference between statistical
2 parameters even for a higher values of CDR. The exception is very low V_V for which
3 statistical parameters are observed to be much higher than for other V_V for all cases of
4 RSR. RSR type C and $V_V = 80\text{km/h}$ are found to be optimal for calibration purposes.
5 Figures 6 a) and b) show the relation of μ and σ , respectively with changes in CDR for
6 different positions of the crack along the beam. In general, calibrations are monotonic (μ
7 and σ increase with CDR) but there is no obvious relation between the curves
8 representing different crack locations. This leads to a conclusion that it is not necessarily
9 true that the edge crack has the smallest statistical parameters. Therefore, plotting μ and σ
10 at crack location as a function of crack distance from the left support of the beam for
11 different CDR is more appropriate. This is shown Figures 6 c) and d). It is observed that
12 the values of statistical parameters increase as the position of the crack moves from the
13 support towards the quarter-span ($x_c = 0.25L$), where it reaches the maximum, and then
14 decrease from quarter-span to $0.4L$, to the minimum, before increasing again at mid-span.
15 It is also shown here that more intense cracks are always more responsive in terms of
16 their markers. Since the location of the crack will be identified beforehand, as presented
17 in Figure 5, the calibration of the damage extent can always be projected to specific
18 curves.
19 The relationship between the statistical parameters and CDR in relation to RSR types for
20 three different V_V (50; 100 and 150km/h representing low, medium and high vehicle
21 speed respectively) are shown in Figure 7. From this figure, it is observed that the
22 statistical descriptors are larger for lower V_V . This becomes more obvious as CDR
23 increases. For RSR type D and E, the variations of μ and σ are more obvious even for

1 lower vehicle speed, while for type A, B and C it is almost the same for the higher speeds
2 of the vehicle. Therefore the consistency of calibration is dependent on the speed and
3 road type. This is more pronounced when the damage extent is higher. Better roads give
4 consistent but less sensitive results, while worse roads are less consistent in value but
5 give more sensitive results. Therefore, for calibration purposes it is recommended to use
6 RSR type C as an optimum.

7 Figure 8 shows the results of calibration of standard deviation as a function of vehicle
8 speed variation (low, medium, and high) observed for the position of damage close to the
9 support, at quarter-span and mid-span of the beam. The calibration functions are shown
10 for small, medium, and high CDR. The dotted grey lines represents a 6th degree
11 polynomial fit (which for the coefficients with 95% confidence bounds give the goodness
12 of fit measure of R^2 as 0.9735 and 0.9865, for the worst and the best fit function
13 respectively) which incorporates very low vehicle speeds. A speed of 10km/h shows
14 much higher values of statistical descriptor when compared with other speeds. When the
15 10km/h value is excluded from the analysis, linear polynomial equations are obtained and
16 represented with the solid line. Corresponding straight line equations coefficients with 95%
17 confidence bounds are shown in Table 2. A straight line fit is found to be satisfactory as
18 the goodness the fit (R^2) is close to one in all cases. Therefore, by knowing the vehicle
19 speed it is possible to determine the CDR using the proposed calibration procedure, but it
20 is hard to determine the location of the crack for low CDR.

21 Figure 9 shows a generic fit of damage calibration curve using the detection measures, i.e
22 the calibration of standard deviation in the function of CDR for three different vehicle
23 speeds (40; 80 and 130km/h representing low, medium and high vehicle speed

1 respectively), analysed separately for three different positions of the crack. The best fit is
2 represented by power law equations. The relevant coefficients and indicators of goodness
3 of the fit are given in Table 3. A comprehensive numerical study based on the damage
4 extent calibration using the proposed markers are provided as additional material along
5 with this paper and is made available online. The markers are calibrated against CDR and
6 the speed of the traversing vehicle.

7

8 **6. Conclusions**

9 This paper directly uses bridge deck surface roughness for damage detection in
10 bridges through consideration of bridge-vehicle interaction effects. A new methodology
11 is presented in this regard. Statistical descriptors are computed on a modified time
12 domain response measure for consistent detection of the location and calibration of
13 damage extent. It is shown that mean and standard deviation are consistent and
14 monotonic descriptors of the system characteristics sensitive to crack presence. The first
15 and second order cumulants of response can be efficiently used as damage detection
16 markers, where discontinuity in the slope of the mean and standard deviation curves give
17 the position of damage, with the jump size related to the extent of damage. The proposed
18 methodology eliminates the need for complex analysis and can accommodate
19 experimental observations and real time implementation easily. The fact that the
20 proposed method is well-suited for output-only operational conditions has disadvantages
21 and advantages. The disadvantage is that numerous sensors for monitoring structure
22 operational conditions are needed, while the advantage is that the online monitoring of
23 the structure is possible just by analysis of its response which can contribute to the SHM

1 of bridge structures to a significant extent. The consistency of calibration depends on the
2 vehicle speed and road type. This is more pronounced in the case of higher damage.
3 Damage calibration on better roads is less uncertain and gives consistent but less
4 sensitive results. Worse roads are less consistent in calibration values but give more
5 sensitive results. The study is particularly useful for continuous online bridge health
6 monitoring since the data necessary for analysis can be obtained from the operating
7 condition of the bridge and the structure does not therefore need be closed down.

8

9 **Acknowledgements**

10 The authors wish to thank the Irish Research Council (IRC) for providing grant to support
11 this research.

12

13

References

1. O'Connor, A. and Eichinger, E. M., 2007, "Site-Specific Traffic Load Modelling for Bridge Assessment", ICE Journal of Bridge Engineering., 160 (4), pp.185-194.
2. O'Connor, A. and Enevoldsen, I., 2009, "Probability-Based Assessment of Highway Bridges According to the New Danish Guideline", Structure & Infrastructure Engineering: Maintenance, Management, Life-Cycl, 5 (2), pp.157-168.
3. O'Brien, E., Znidaric, A., Brady, K., Gonzalez, A. and O'Connor, A., 2005, "Procedures for the Assessment of Highway Structures", ICE Transport Journal, 158 (TR1), pp.17-25.
4. Delgado, R. M. and dos Santos, R. C. S. M., 1997, "Modelling of a Railway Bridge-Vehicle Interaction on High Speed Tracks", Computers and Structures, 63 (3), pp.511-523
5. Pesterev, A. V. and Bergman, L. A., 1997, "Vibration of Elastic Continuum Carrying Accelerating Oscillator", ASCE Journal of Engineering Mechanics, 123 (8), pp.886-889.

6. Song, M.-K., Noh, H.-C. and Choi, C.-K., 2003, “A New Three-Dimensional Finite Element Analysis Model of High-Speed Train–Bridge Interactions”, *Engineering Structures*, 25 (13), pp.1611-1626.
7. Gentile, A. and Messina, A., 2003, “On the Continuous Wavelet Transforms Applied to Discrete Vibrational Data for Detecting Open Cracks in Damaged Beams”, *International Journal of Solids and Structures*, 40 (2), pp.295–315.
8. Patsias, S. and Staszewski, W. J., 2002, “Damage Detection Using Optical Measurements and Wavelets”, *Structural Health Monitoring*, 1 (1), pp.5-22.
9. Pakrashi, V., Basu, B. and Connor, A. O., 2009, “A Statistical Measure for Wavelet Based Singularity Detection”, *Journal of Vibration and Acoustics*, 131 (4), pp.041015 (6 pages)
10. Doebling, S. W., Farrar, C. R., Prime, M. B. and Shevitz, D. W., 1996, “Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics: A Literature Review”, Report No LA-13070-MS, Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36,
11. Narkis, Y., 1994, “Identification of Crack Location in Vibrating Simply Supported Beams”, *Journal of sound and Vibrations*, 172 (4), pp.Pages 549-558

12. Law, S. S. and Zhu, X. Q., 2004, "Dynamic Behaviour of Damaged Concrete Bridge Structures under Moving Vehicular Loads", *Engineering Structures*, 26 (9), pp.1279–1293.
13. Majumder, L. and Manohar, C. S., 2003, "A Time Domain Approach for Damage Detection in Beam Structures Using Vibration Data with a Moving Oscillator as an Excitation Source. ", *Journal of Sound and Vibration*, 268 pp. 699–716.
14. Lee, J. W., Kim, J. D., Yun, C. B., Yi, J. H. and Shim, J. M., 2002, "Health Monitoring Method for Bridges under Ordinary Traffic Loadings", *Journal of Sound and Vibration*, 257 (2), pp.247–264.
15. Bilello, C., Bergman, A. L. and Kuchma, D., 2004, "Experimental Investigation of a Small-Scale Bridge Model under a Moving Mass", *ASCE Journal of Structural Engineering*, 130 (5), pp.799–804.
16. Bilello, C. and Bergman, L. A., 2004, "Vibration of Damaged Beams under a Moving Mass: Theory and Experimental Validation", *Journal of Sound and Vibration*, 274 (3-5), pp.567–582.
17. Pakrashi, V., O'Connor, A. and Basu, B., 2010, "A Bridge–Vehicle Interaction Based Experimental Investigation of Damage Evolution", *Structural Health Monitoring*, 9 (4), pp.285 - 296.

18. Bu, J. Q., Law, S. S. and Zhu, X. Q., 2006, "Innovative Bridge Condition Assessment from Dynamic Response of a Passing Vehicle", *ASCE Journal of Engineering Mechanics*, 132 (12), pp.1372–1379.
19. Abdel-Rohman, M. and Al-Duaij, J., 1996, "Dynamic Response of Hinged-Hinged Single Span Bridges with Uneven Deck", *Computers & Structures*, 59 (2), pp.291-299.
20. da Silva, J. G. S., 2004, "Dynamical Performance of Highway Bridge Decks with Irregular Pavement Surface", *Computers & Structures*, 82 (11-12), pp.871-881
21. Wu, S. Q. and Law, S. S., 2011, "Vehicle Axle Load Identification on Bridge Deck with Irregular Road Surface Profile", *Engineering Structures*, 33 (2), pp.591-601
22. Sohn, H., Farrar, C. R., Hunter, N. F. and Worden, K., 2001, "Structural Health Monitoring Using Statistical Pattern Recognition Techniques", *ASME Journal of Dynamic Systems, Measurement and Control* 123 (4), pp.706-717.
23. Cacciola, P., Impollonia, N. and Muscolino, G., 2003, "Crack Detection and Location in a Damaged Beam Vibrating under White Noise", *Computers and Structures*, 81 pp.1773–1782.
24. Hadjileontiadis, L. J., Douka, E. and Trochidis, A., 2005, "Crack Detection in Beams Using Kurtosis", *Computers & Structures*, 83 (12–13), pp.909-919.

25. Jaksic, V., Pakrashi, V. and O'Connor, A., 2011, "Employing Surface Roughness for Bridge-Vehicle Interaction Based Damage Detection", ASME 2011 International Mechanical Engineering Congress and Exposition (IMECE 2011) Denver, Colorado, USA,
26. Jaksic, V. and Pakrashi, V., 2013, "Robust Skewness-Kurtosis Descriptor for Damping Calibration from Frequency Response", Journal of Aerospace Engineering, 26 (4), pp. 887–893.
27. ISO 8606:1995(E). Mechanical vibration - road surface profiles-reporting of measured data.
28. Poudel, U. P., Fu, G. and Ye, J., 2005, "Structural Damage Detection Using Digital Video Imaging Technique and Wavelet Transformation", Journal of Sound and Vibration, 286 (4-5), pp.869–895.
29. Sundermeyer, J. N. and Weaver, R. L., 1994, "On Crack Identification and Characterization in a Beam by Non-Linear Vibration Analysis", Journal of Sound and Vibration, 183 (5), pp.857-871.
30. Henchi, K., Fafard, M., Talbot, M. and Dhatt, G., 1998, "An Efficient Algorithm for Dynamic Analysis of Bridges under Moving Vehicles Using a Coupled Modal and Physical Components Approach", Journal of Sound and Vibration, 212 (4), pp.663-683

31. Law, S. S. and Zhu, X. Q., 2005, "Bridge Dynamic Responses Due to Road Surface Roughness and Braking of Vehicle", *Journal of Sound and Vibration*, 282 (3-5), pp.805-830
32. 2004. The MathWorks, Inc., Natick, Massachusetts.
33. Law, S. S., Bub, J. Q., Zhua, X. Q. and Chana, S. L., 2004, "Vehicle Axle Loads Identification Using Finite Element Method", *Engineering Structures*, 26 (8), pp.1143-1153
34. Shen, M.-H. H. and Pierre, C., 1990, "Natural Modes of Bernoulli-Euler Beams with Symmetric Cracks", *Journal of Sound and Vibration* 138 (1), pp.115-134.
35. Chang, C.-C. and Chen, L.-W., 2003, "Vibration Damage Detection of a Timoshenko Beam by Spatial Wavelet Based Approach ", *Applied Acoustics*, 64 (12), pp.1217-1240
36. Okafor, A. C. and Dutta, A., 2000, "Structural Damage Detection in Beams by Wavelet Transforms", *Smart Materials and Structures*, 9 (6), pp.906–917.
37. Loutridis, S., Doukab, E. and Trochidis, A., 2004, "Crack Identification in Double-Cracked Beams Using Wavelet Analysis ", *Journal of Sound and Vibration*, 277 (4-5), pp.1025-1039

38. Qian, B. and Rasheed, K., 2004, “Hurst Exponent and Financial Market Predictability”, IASTED conference on Financial Engineering and Applications (FEA 2004), Cambridge, Massachusetts, USA, pp. 203 – 209.
39. Morales, R., Di Matteo, T., Gramatica, R. and Aste, T., 2012, “Dynamical Generalized Hurst Exponent as a Tool to Monitor Unstable Periods in Financial Time Series”, *Physica A: Statistical Mechanics and its Applications*, 391 (11), pp.3180-3189.
40. Vela-Martínez, L., Jáuregui-Correa, J. C. and Álvarez-Ramírez, J., 2009, “Characterization of Machining Chattering Dynamics: An R/S Scaling Analysis Approach”, *International Journal of Machine Tools and Manufacture*, 49 (11), pp.832-842.
41. Pakrashi, V., Kelly, J., Harkin, J. and Farrell, A., 2013, “Hurst Exponent Footprints from Activities on a Large Structural System”, *Physica A: Statistical Mechanics and its Applications*, 392 (8), pp.1803-1817.

List of Tables

Table 1. The road surface classes (ISO 8606:1995(E)) and corresponding value of roughness coefficient $S_d(f_0)$.

Table 2. Calibration function for Standard deviation and vehicle speed.

Table 3. Calibration function for Standard deviation and CDR.

Table 1

Road class	A Very good	B Good	C Average	D Poor	E Very poor
Roughness coefficient $S_d(f_0)$ (m ³ /cycle) × 10 ⁻⁶	6	16	64	256	1024

Table 2

General form of fit is linear polynomial equation $\sigma = a \times V_V + b$

X_c CDR	0.1L	0.25L	0.5L
0.10	a = -1.209e-007 b = 2.567e-006 SSE: 2.209e-013 R ² = 0.9378	a = -2.224e-007 b = 4.795e-006 SSE: 9.34e-013 R ² = 0.9234	a = -1.062e-007 b = 2.233e-006 SSE: 1.747e-013 R ² = 0.9362
0.25	a = -7.436e-007 b = 1.553e-005 SSE: 7.513e-012 R ² = 0.9436	a = -1.368e-006 b = 2.842e-005 SSE: 2.514e-011 R ² = 0.9443	a = -6.743e-007 b = 1.418e-005 SSE: 5.505e-012 R ² = 0.9495
0.40	a = -2.199e-006 b = 4.401e-005 SSE: 5.689e-011 R ² = 0.9508	a = -3.823e-006 b = 7.512e-005 SSE: 2.346e-010 R ² = 0.9341	a = -2.321e-006 b = 4.624e-005 SSE: 8.783e-011 R ² = 0.9331

Table 3

General form of fit is power equation $\sigma = a \times CDR^b + c$

$V_V \backslash X_c$	0.1L	0.25L	0.5L
low	a = 0.0001925 b = 1.997 c = -4.744e-007 SSE: 2.266e-012 R ² = 0.9981	a = 0.0002747 b = 1.916 c = 4.194e-007 SSE: 2.816e-012 R ² = 0.999	a = 0.0002072 b = 2.022 c = -1.595e-006 SSE: 1.211e-011 R ² = 0.9912
medium	a = 0.0001756 b = 1.986 c = -7.936e-007 SSE: 2.648e-012 R ² = 0.9974	a = 0.0002629 b = 1.935 c = 6.323e-007 SSE: 2.954e-012 R ² = 0.9988	a = 0.0002058 b = 2.091 c = -1.478e-006 SSE: 1.109e-011 R ² = 0.991
high	a = 8.9e-005 b = 1.899 c = -6.129e-007 SSE: 8.243e-013 R ² = 0.9973	a = 0.0001353 b = 1.88 c = -7.43e-008 SSE: 8.575e-014 R ² = 0.9999	a = 0.0001084 b = 2.053 c = -8.127e-007 SSE: 2.524e-012 R ² = 0.993

List of Figures

Figure 1. Simply supported beam with breathing crack modeled as two beams connected by torsional spring.

Figure 2. Concept employed: a) Simply supported beam, with damage located at the mid-span, divided into equal segments; b) First mode shape of damaged and undamaged beam; c) Difference in mode shapes of undamaged and damaged beam; d) Difference in mode shape of damaged and undamaged beam at mid location of each segment multiplied with beam response (displacement).

Figure 3. Schematic Diagram of Methodology

Figure 4. Statistic measures observed: a) Mean (μ); and b) Standard Deviation (STD); Figure shows statistics for crack located at mid-span ($X_c = 0.5L$); Speed of the vehicle ($V_v = 80\text{km/h}$); Crack Depth Ratio (CDR = 0.45); and Type C Road Surface Roughness (RSR) defined as per ISO 8606:1995(E).

Figure 5. Effects of different Crack Depth Ratio (CDR) on: a) Mean (μ) and b) Standard Deviation (STD); for crack located at quarter-span ($X_c = 0.25L$); Speed of the vehicle ($V_v = 80\text{km/h}$); and Type C Road Surface Roughness (RSR) defined as per ISO 8606:1995(E).

Figure 6. a) Mean (μ) and; b) Standard Deviation (STD) variation in function of Crack Depth Ratio (CDR) for different position of crack location (X_c) and; c) Mean; and d) STD in function of X_c for different CDR; while speed of vehicle is constant and type of road is class C as per ISO 8606:1995(E).

Figure 7. Mean (μ) and Standard Deviation (STD) variation in function of Crack Depth Ratio (CDR) for different Road Type defined as per ISO 8606:1995(E) analyzed for three different Vehicle speed (V_v): Low, Medium and High.

Figure 8. Calibration of Standard Deviation (STD) variation in function Vehicle speed (V_v): Low, Medium and High; for three different positions of the damage: a) Edge; b) Quarter-span and c) Mid-span.

Figure 9. Calibration of Standard Deviation (STD) variation in function Crack Depth Ratio (CDR); for Low, Medium and High Vehicle Speed (V_v) and three different positions of the damage: a) Edge; b) Quarter-span and c) Mid-span.

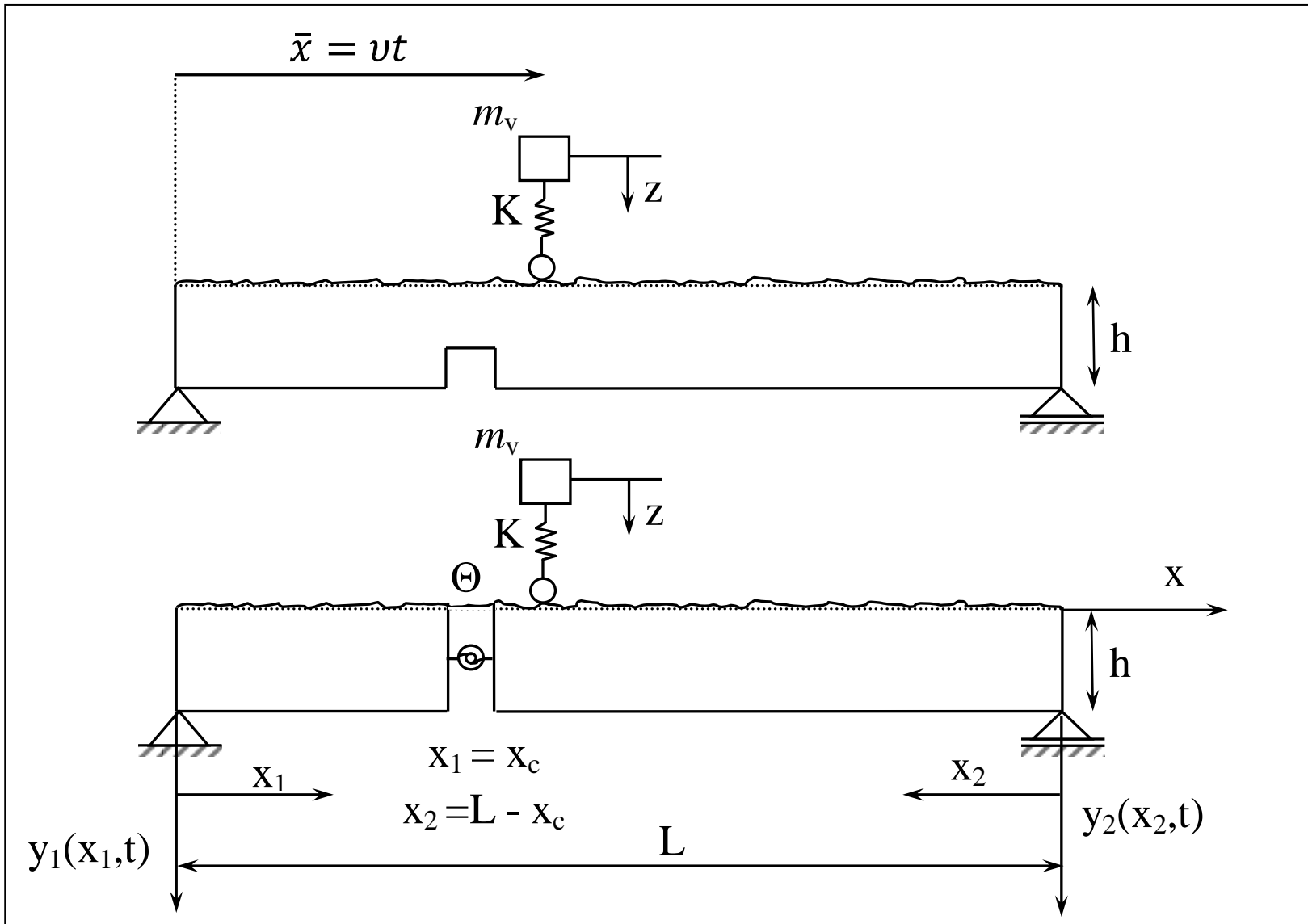


Figure 1.

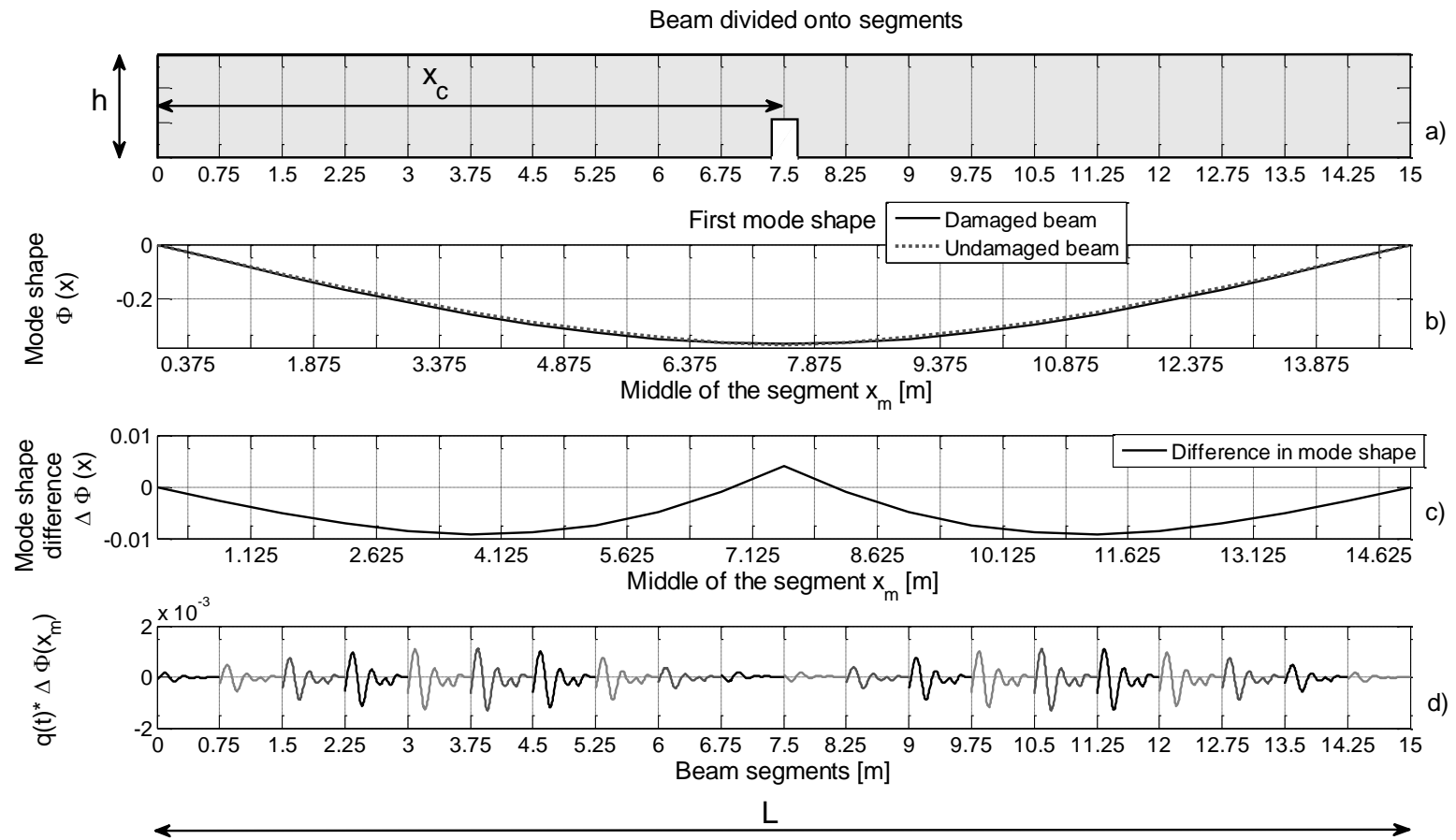


Figure 2.

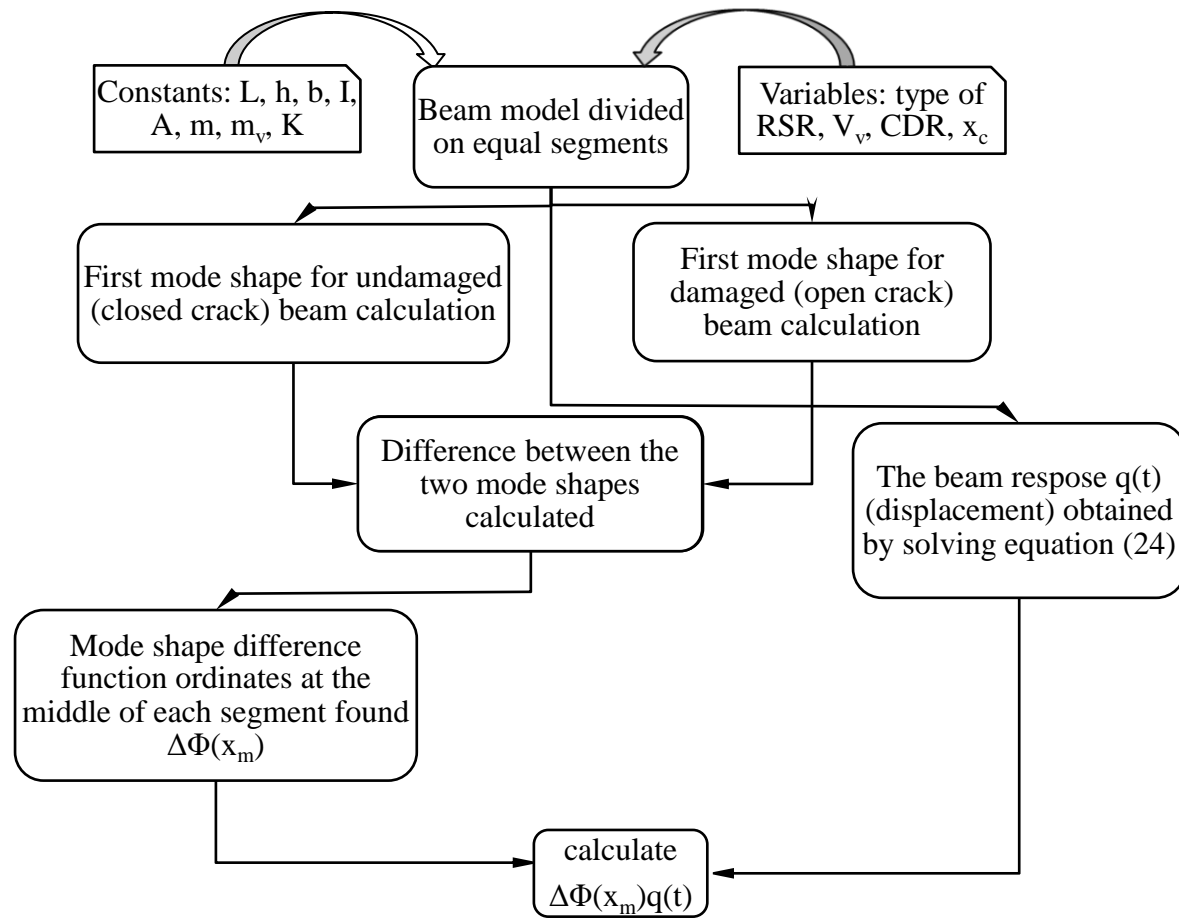


Figure 3.

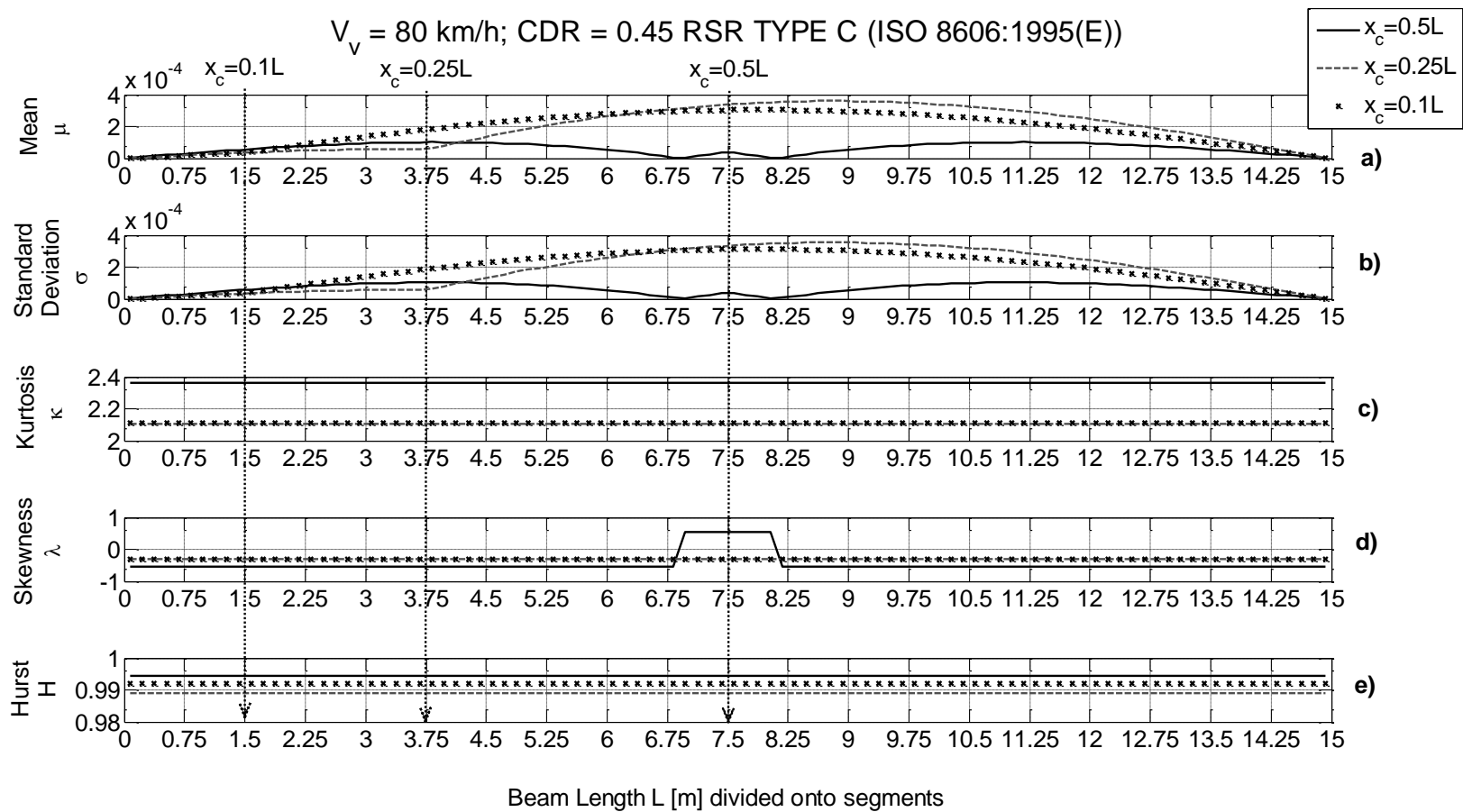


Figure 4.

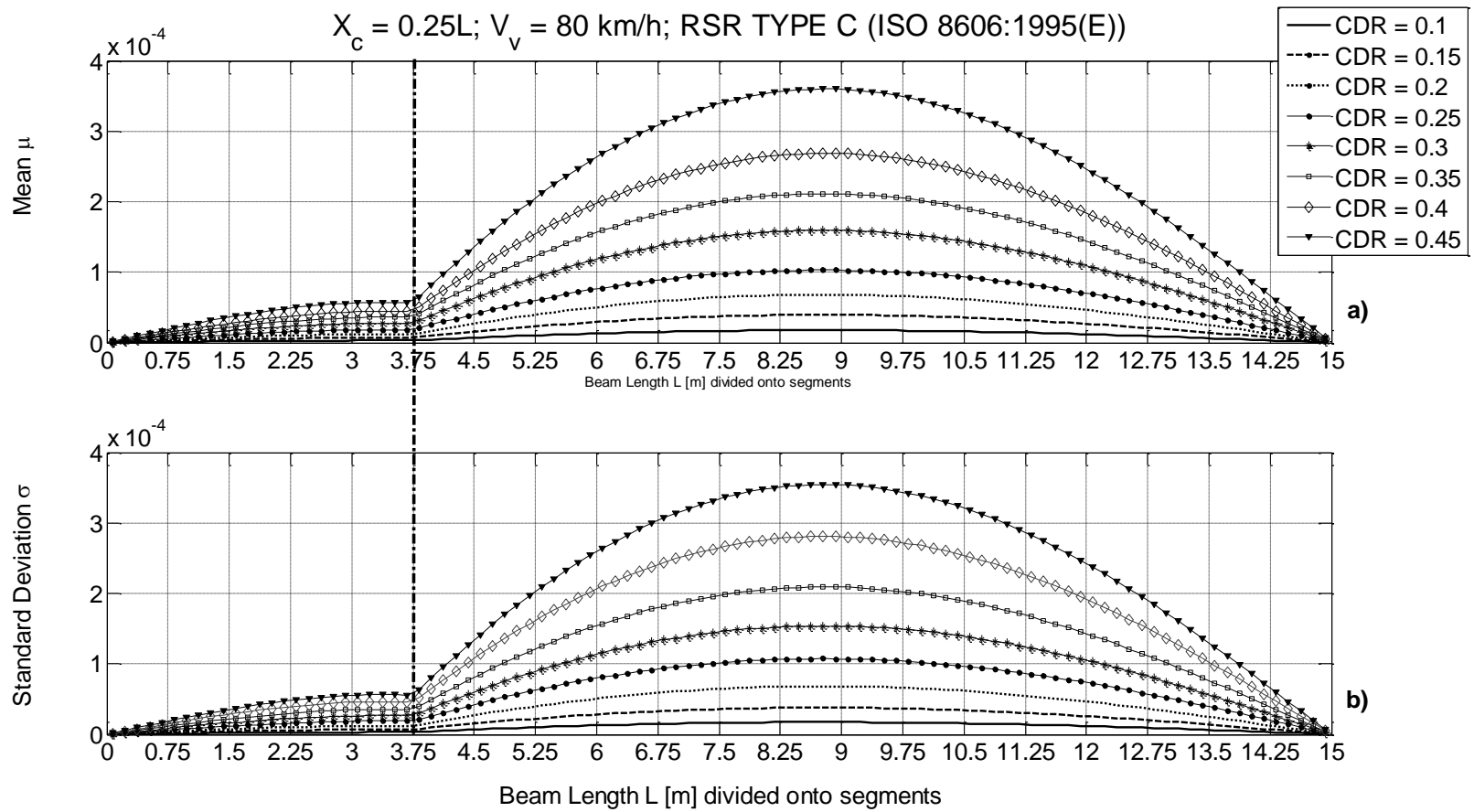


Figure 5.

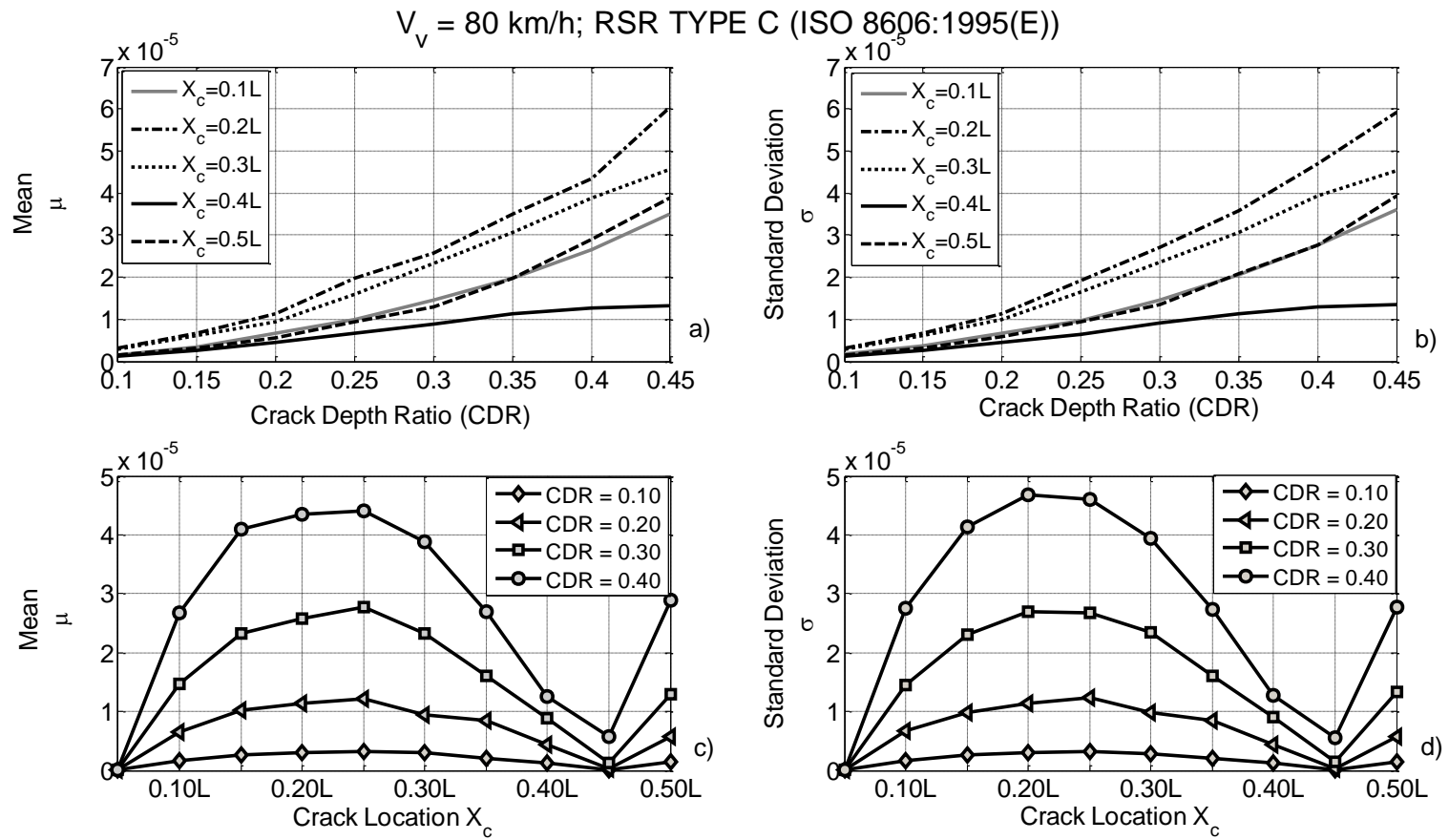


Figure 6.

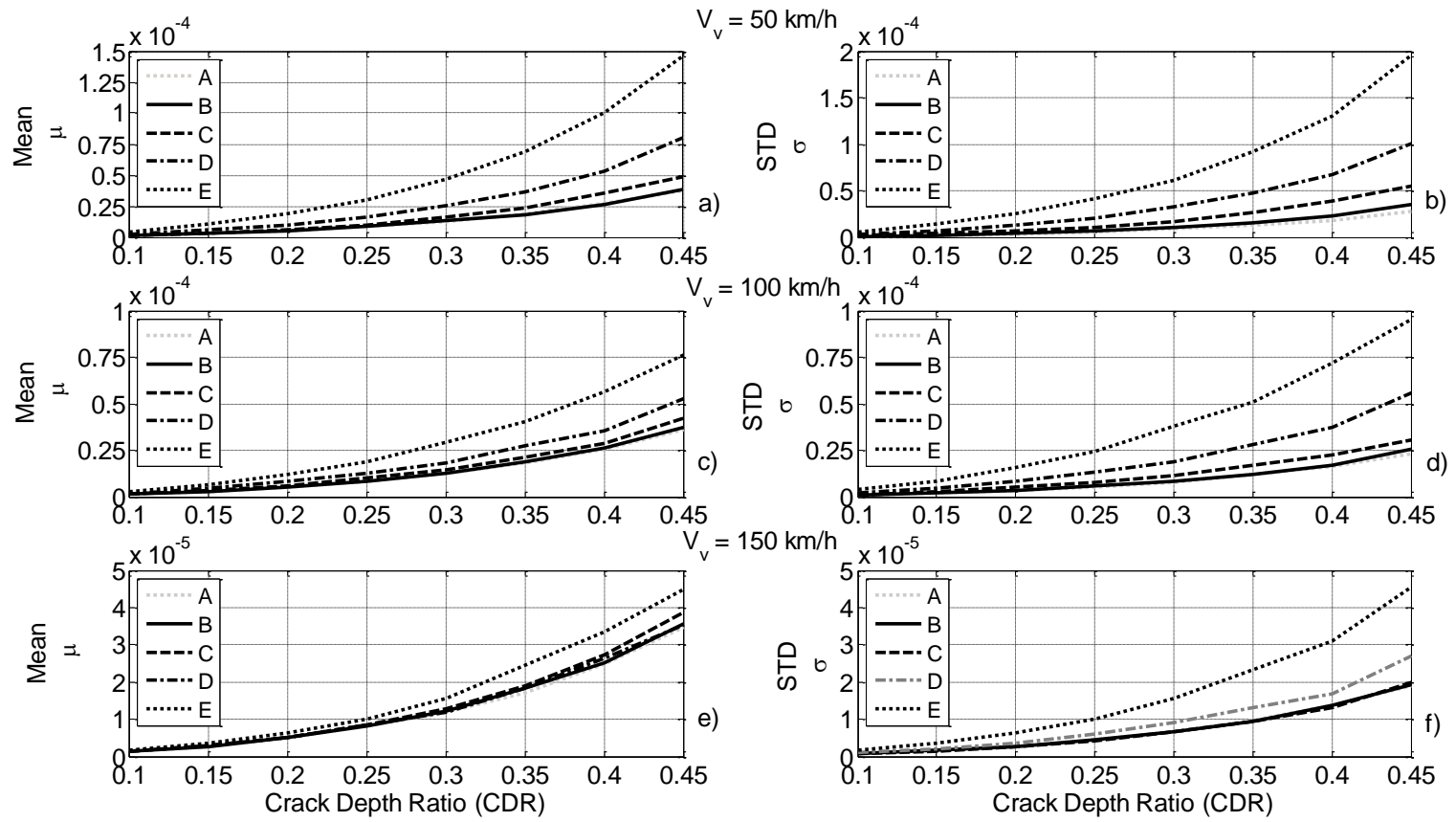


Figure 7.

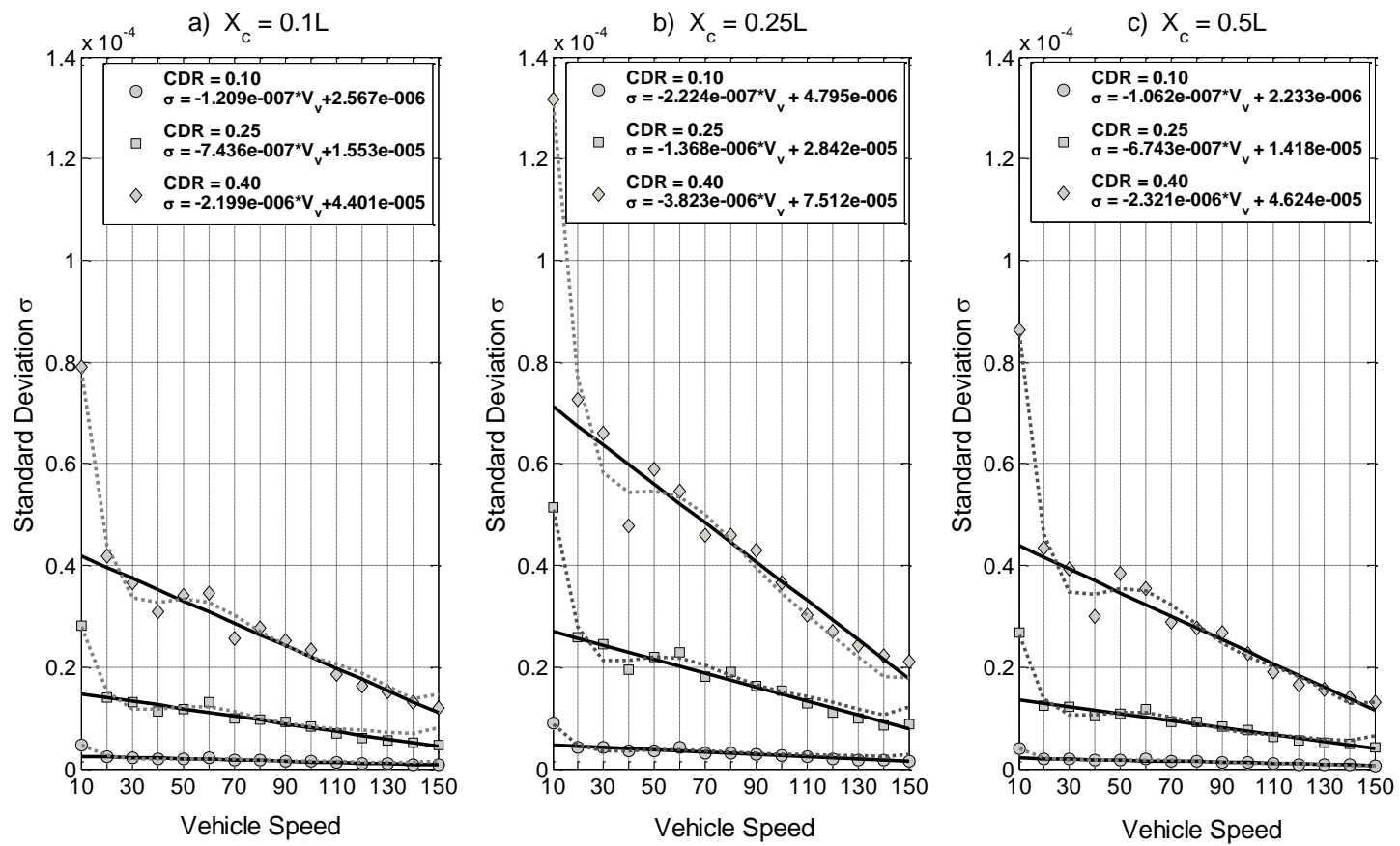


Figure 8.

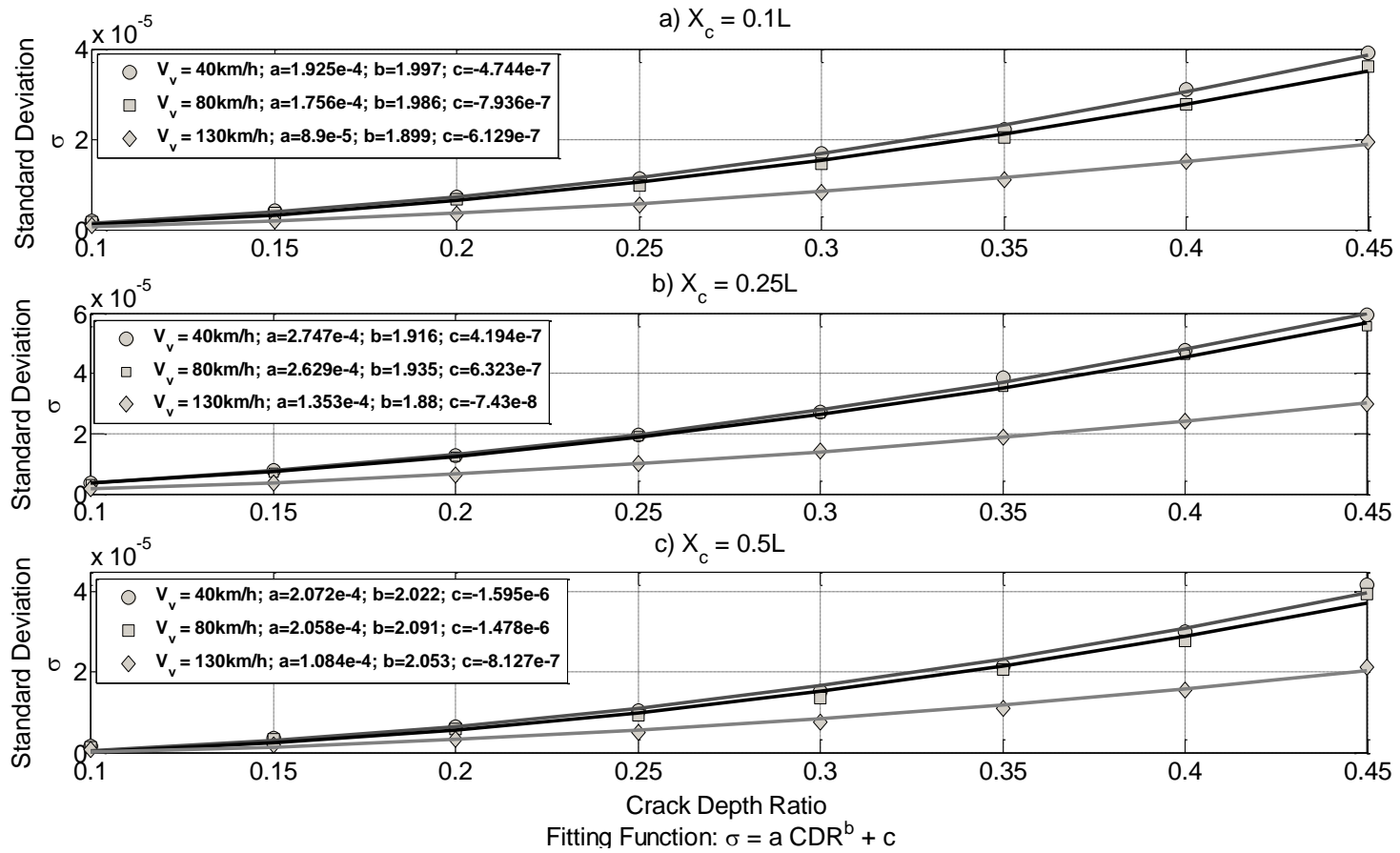


Figure 9.