Bridge Damage Detection using the Inverse Dynamics Optimization Algorithm

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ABSTRACT
The current methods to identify the bridge damage depend on time-consuming visual inspection and/or based on the data collected from a sensor based monitoring, which make the assessment process very expensive. In this paper, the bridge damage is identified using the data collected from an ordinary strain transducer. In order to demonstrate the new method, 3-D finite element models followed by the Inverse Dynamics Optimization Algorithm are performed. The inverse algorithm utilized to calculate the weight of the force that pass on the bridge. Any change in the bridge stiffness by damage will influence the force history which calculated by the inverse algorithm. The proposed method divided into two stages: in the first one, two finite element models are used to simulate the bridge displacement due to quarter car model one representing the healthy bridge and the other for the damage one. In the second stage, the inverse dynamics optimization algorithm used to identify the damage locations.

Keywords: Bridge Damage Detection, Inverse Dynamics, MFI, Vehicle-Bridge Interaction, Bridge Damage Location, Drive-by Bridge Monitoring

INTRODUCTION
In the United States, there are almost 611,000 bridges in operation, but roughly one-third of them are rated as structurally deficient or functionally obsolete [1].To ensure the National Bridge Inventory (NBI) remains safe for use and to reduce the number of bridges accidents, bridge damage detection studies are necessary. While the causes of deterioration in bridges can be tied to a diverse set of sources and factors, the dominant cause of long-term deterioration can be attributed to heavy vehicles (i.e., trucks). To understand the trucks influence on the bridge health, vehicle-induced bridge behavior must be studied. Furthermore, understanding the vehicle-Bridge Interaction (VBI) can potentially lead to the control of truck vibrations so that truck-induced bridge deterioration can be minimized.

To date, there is a lot of research explored the modeling of VBI; most of them used finite element programs to imitate the bridge model using 1-D or 2-D elements [2-6]. Comparatively, less research utilized the 3-D elements to mimic the VBI.

The basic idea of damage detection techniques is that the dynamic characteristics are functions of the physical properties of the structure. Therefore, any change in these properties caused by damage results in the change of structures response. To detect the damage, the change in dynamic characteristics must be monitored such as eigenfrequencies, modal damping ratios, mode shapes, stiffness and mass matrices[7]. Elhattab, Uddin and OBrien [8, 9] have used the change in the bridge displacement as damage index for the bridge, and the results showed to be promising. However, the authors found that the approach is sensitive to the truck transverse location on the bridge, where the change in road roughness masks the change in the bridge displacement. In this paper, the Inverse Dynamic Optimization algorithm will be utilized to detect the bridge damage location. The Inverse Dynamics algorithm is providing an inverse solution for structure equation of motion, where the input is the structure response, and the output is the force history. The algorithm works to estimate the moving force that causes the system to best match the known or measured response. The algorithm solution can be achieved using three areas of mathematics; the least squares minimization with regularization known as Tikhonov regularization [10-12], dynamic programming that gives an efficient solution to the least squares parameter and finally the L-curve technique [13]to calculate the optimal regularization parameter.

NUMERICAL VEHICLE-BRIDGE INTERACTION MODEL

In this paper, LS-Dyna finite element program utilized to imitate the bridge models as a simple beam using 3-D solid elements, each element has eight nodes with total 24 degrees of freedom or three degrees of freedom per node (vertical and the two horizontal displacements). The vehicle represented by spring vehicle models – quarter car - as have been used by many researchers.

INVERSE DYNAMICS OPTIMIZATION ALGORITHM

Firstly, solving the discretized equation of motion, shown in Equation 1.

$$[M_g]\{a\} + [C_g]\{v\} + [K_g]\{u\} = [L]\{g(t)\} \qquad \textbf{(Eq.1)}$$

Where

$[L] =$ The $[\mathrm{n_{dof}}.\,\mathrm{n_{force}}]$ a time-varying location matrix.

{a}, {v}, and {u}= are the acceleration's, velocities and displacements of the degrees of freedom, respectively.

The [L] matrix assigns the forces of the vector g (t) $[\mathrm{n_{force}} * 1]$ to the degrees of freedom and can be defined –for solid element- using the solid element shape functions Equation 2:

$$N_i = \frac{(1 + xx_i)(1 + yy_i)(1 + zz_i)}{8} \qquad \textbf{(Eq.2)}$$

Where

$x_i, y_i, z_i = \pm\frac{2}{a}, \pm\frac{2}{b}, \pm\frac{2}{c}$

$x, y, z =$ the load coordinates according to the origin. $i = 1,2, \dots, 8$.

a, b, c = the solid element dimensions as shown in Figure 1.

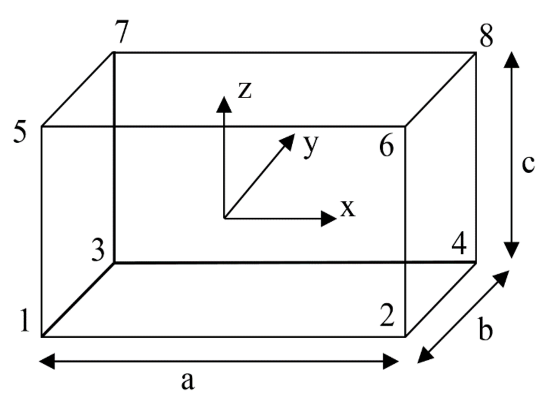

Figure 1: Sloid element dimension and numbering.

When the vehicle load moved to any position on the bridge as shown in Figure 2, the location vector can be defined as illustrated in Equation 3.

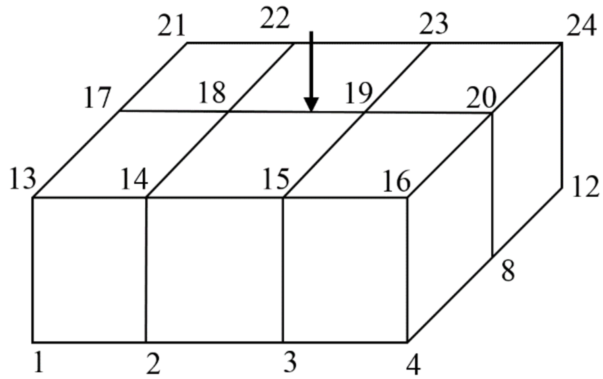

Figure 2: Vehicle load on the bridge at t=x/v sec.

$$\mathbf{L} = \begin{Bmatrix} \mathbf{u1} \\ \mathbf{v1} \\ \mathbf{z1} \\ \vdots \\ \mathbf{z2} \\ \vdots \\ \vdots \\ \mathbf{z18} \\ \vdots \\ \mathbf{z19} \\ \vdots \\ \vdots \\ \vdots \\ \mathbf{zN} \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \vdots \\ \mathbf{N1} \\ \vdots \\ \vdots \\ \mathbf{N7} \\ \mathbf{0} \\ \mathbf{N8} \\ \mathbf{0} \\ \vdots \\ \vdots \\ \mathbf{0} \end{Bmatrix}_{\mathbf{n\,dof*n\,force}} \qquad \textbf{(Eq.3)}$$

The remaining steps to calculate the force history using and the full system K,M matrices or by applying the eigenvectors reduction technique can be found in [2, 4].

DAMAGE DETECTION

The proposed method to detect the damage location depends on monitoring the change in the force history due to the same force in two different situations; Moving force cross over the healthy bridge and the damaged bridge, which calculated by the inverse algorithm. Firstly, extracting the K, M matrices or the eigenvector for the healthy bridge model from an eigenvalue analysis. Secondly, the displacement history will be extracted from the VBI simulation considering the healthy bridge, and using the moving force identification algorithm (MFI) the force history can be identified. The third stage exactly like the second one otherwise, the damaged bridge will be considered during the VBI simulation, and the displacement response from the damaged bridge will be used to calculate the moving force history. The same moving force will be utilized during the two VBI simulation, and the significant different between the two output- force history will refer to the damage location.

To reveal the damage location, large number of measurements are needed to be collected, and this process is difficult to achieve in the field. The new approach developed utlizing a fewer number of measurements. Three displacement measurements are used at (1/4, 1/2 and 3/4) of the bridge span as shown in Figure 3. These measurements are used to give excellent estimation about the displacements at the nearest two nodes to the load position. Each measurement is responsible for estimating the displacement at a particular area.

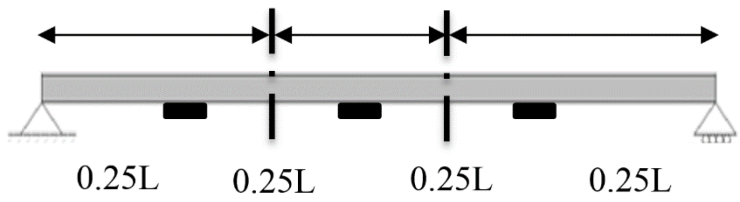

Figure 3: Sensors positions.

The estimation process done using the static formula in equations (4, 5 and 6). Figure 4 shows that the displacement (y_1 and y_2) can be estimated using the displacement at mid-span (y_0) assuming constant EI for the health and damage beam.

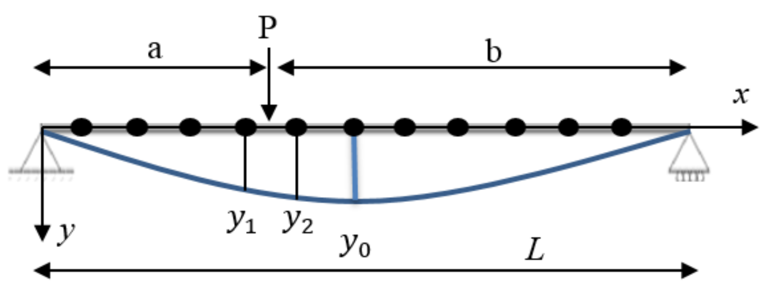

Figure 4: Deflection of a simply supported beam.

$$P = \begin{cases} \dfrac{6y_0LEI}{bx_0(L^2 - x_0{}^2 - b^2)}, & 0 < x_0 < a \\ \dfrac{6y_0LEI}{a(L - x_0)(2Lx_0 - x_0^2 - a^2)}, & a < x_0 < L \end{cases} \tag{Eq.4}$$

$$y_1 = \frac{Pbx_1}{6LEI}\left(L^2 - x_1{}^2 - b^2\right) for\ 0 < x_1 < a \tag{Eq.5}$$

$$y_2 = \frac{Pa}{6LEI}(L - x_2)(2Lx_2 - x_2^2 - a^2) for\ a < x_2 < L \tag{Eq.6}$$

The Moving Force Identification (MFI) algorithm which developed by [2] depends on defining [Q] matrix which is a [*mz . 2ndof + nforce*] to relate the measurements to the DOF. The [Q]matrix will change every time steps according to the load position of the beam as shown in Figure 5.

Where:
m_z = the number of measurements (in this case two).
ndof = the number of degree of freedom.
nforce = the number of the moving force on the beam.

$$Q(i) = \begin{bmatrix} zeros(1, n1 - 1), 1, zeros(1,2ndof + nforce - n1) \\ zeros(1, n2 - 1), 1, zeros(1,2ndof + nforce - n2) \end{bmatrix} \tag{Eq.7}$$

Where:
n1 = the degree of freedom at the first measurement location.
n2 = the degree of freedom at the second measurements location.
i= time step.

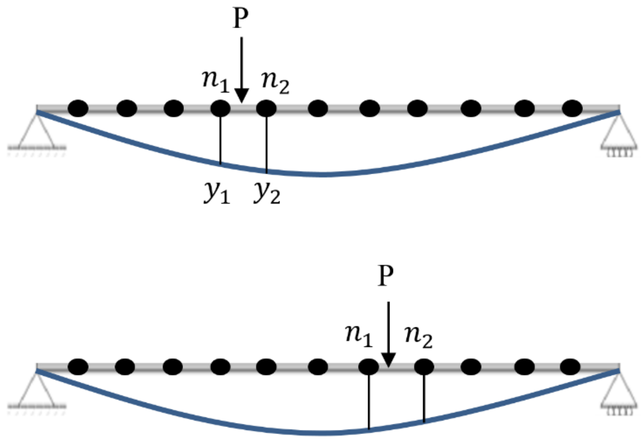

Figure 5: Measurements change according to the load position.

NUMERICAL RESULTS AND DISCUSSION

A simply supported beam model was generated using the following specification: span=10 m, width=1.0 m and thickness = 0.5 m, with young modulus E= 2E10 kg/m2, passion ratio = 0.2 and the mass density = 2500 kg/m3. The model is divided into 40 solid elements as shown in Figure 6. A moving load p = 60 KN is considered with the speed = 10 m/s, 20 m/s. For the healthy beam, a constant EI is assumed for all elements, while the damaged beam is modeled by reducing EI of some specific elements at different locations by different reduction percentage (10%, 20%, and 30%).

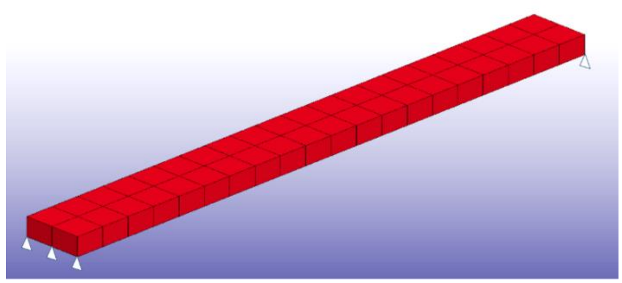

Figure 6: Simply supported 3-D solid elements beam.

To measure the sensitivity for detecting the damage location, three damage locations are created with (10%) damage percentage at three different location in separated cases as shown in Figure 7. Using three displacement measurements at three different positions (0.25L, 0.50L, and 0.75L) as an input to estimate the displacement at the nearest two degrees of freedom to the load position. The calculated force history utilizing the measurements from the healthy and the damaged beams showed in Figure 8.

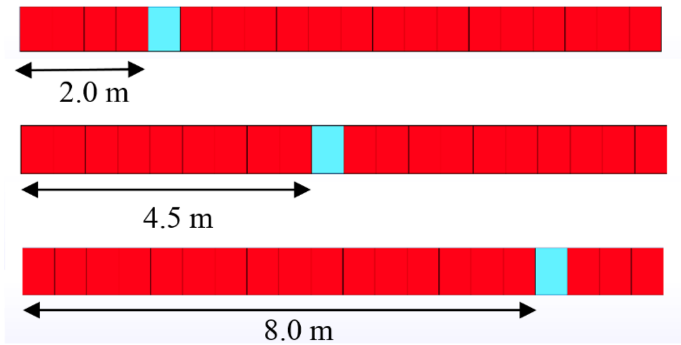

Figure 7: Three different damage locations.

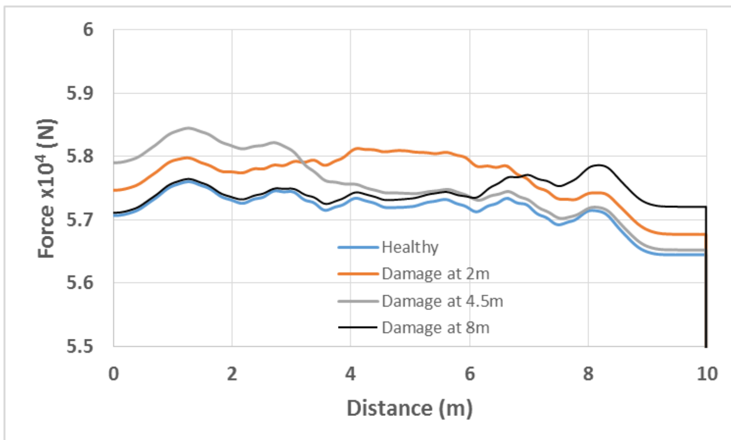

Figure 8: Force history for healthy and damaged beams.

The different between the force history in case of the healthy beam and the damage one is shown in Figure 9. The figure illustrates that the algorithm detects the damage location with high accuracy at all locations

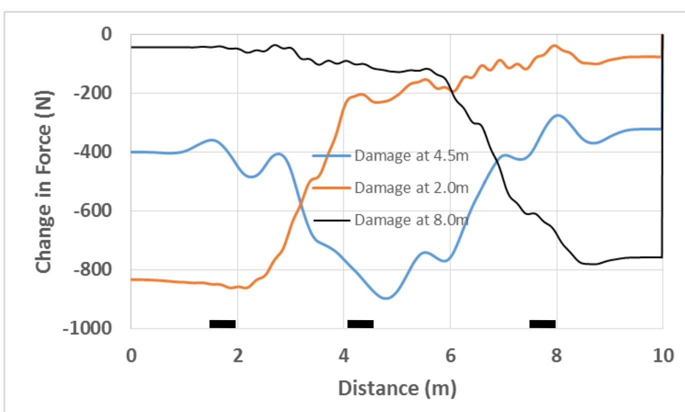

Figure 9: Damage locations.

One damage location

The damage was created at 4.50 m from the left support with three different damage levels (10%, 20%, and 30%), using (10 m/sec) force speed. Figure 12-a shows the sensitivity of the method to detect the damage location and Figure 12-b indicates that in high-speed force, the method gives low accuracy in detecting the damage location, but the results still consider excellent.

Two damage location

To measure the sensitivity of the alogorithm in detecting more than one damage location, two damage locations are created at 2.0 m and 7.50 m from the left support as shown in Figure 10.

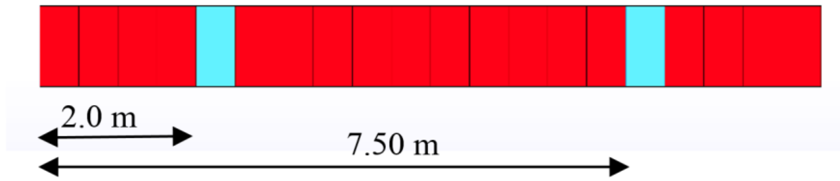

Figure 10: Two different damage locations.

The problem was resolved using three different damage levels (10%, 20%, and 30%) and considering (10 m/sec) force speed. The damage detection results are shown in Figure 13-a. The case of 10% damage was analyzed with different force speeds (10 m/s and 20 m/s). The result in Figure 13-b indicates that the method detects the first location with high accuracy but the second location with a good accuracy. In high-speed force, the method gives very good damage detection estimation.

Three damage location.

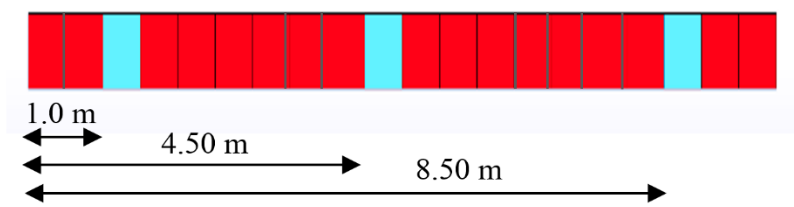

Figure 11: Three different damage locations.

Three damage location are generated at 1.0, 4.5 and 8.5 m from the left support as shown in Figure 11. Three different damage levels (10%, 20%, and 30%) with (10 m/sec) force speed. The damage detection results are shown in Figure 14-a. The case of 10% damage was anatomized with different force speed (10 m/s and 20 m/s) as shown in Figure 14-b.

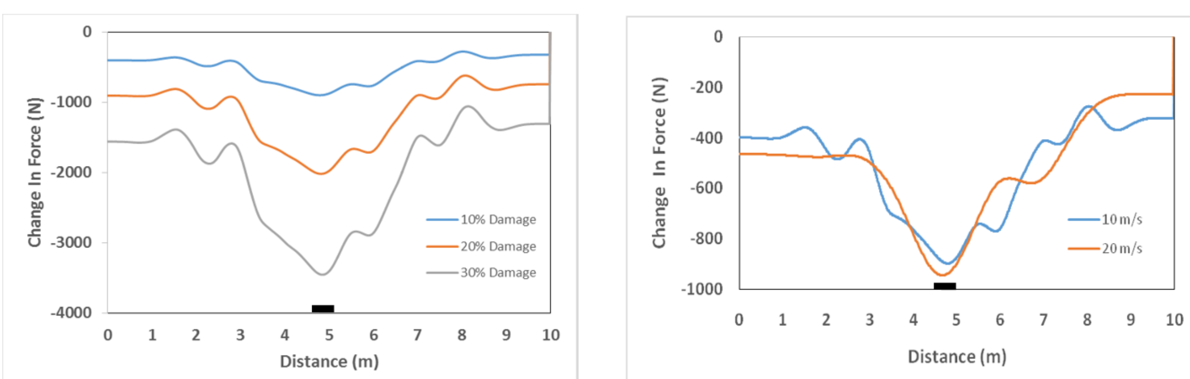

Figure 12: (a) one damage location at mid-span. (b) Damage at mid-span with different speeds.

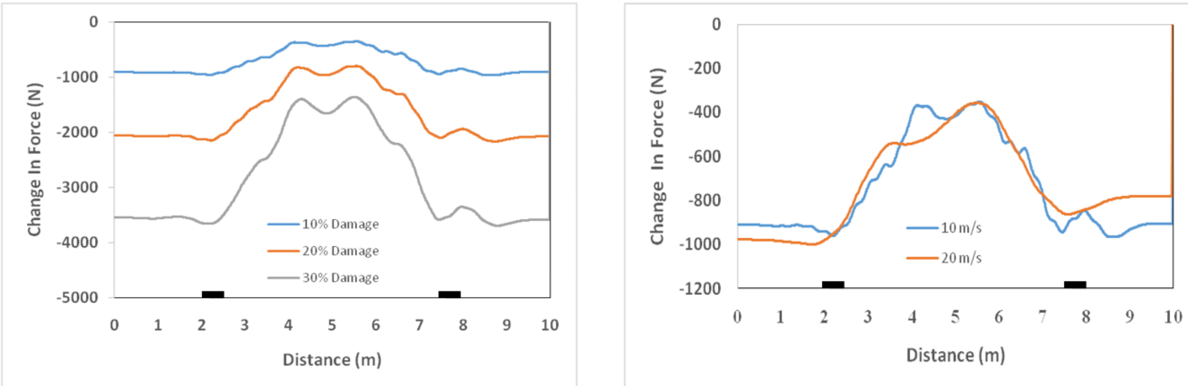

Figure 13: (a) Two damage location bet. (2-2.5) m and (7.5-8) m. (b) Damage with different speeds.

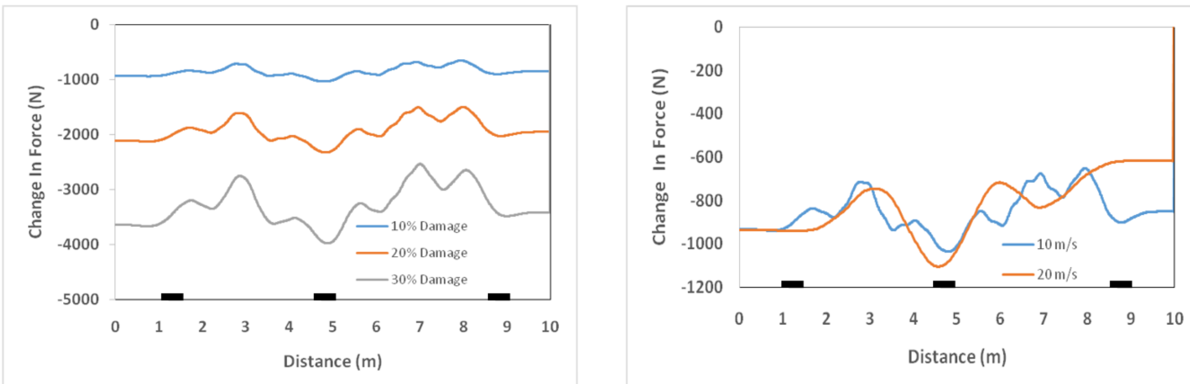

Figure 14: (a) Three damage location bet. (1-1.5) m, (4.5-5) m, and (8.5-9) m (b) Damage with different speeds.

The result shows that the approach detects all locations with a good accuracy. For the high-speed force, the method gives a acceptable damage detection for the second location and unclear location for the other two locations.

Three damage location very closed.

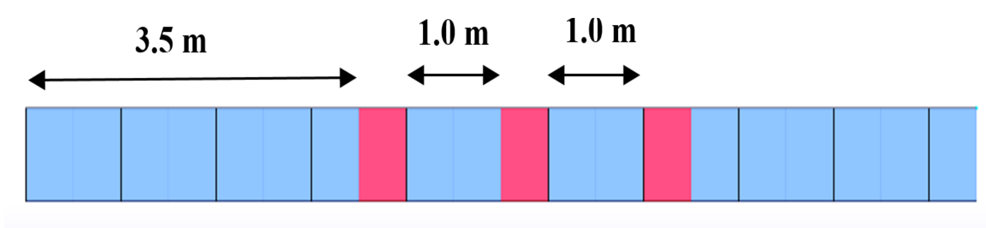

Figure 15: Three much-closed damage locations.

To measure the sensitivity of this method to detect a much-closed damage locations, three-damage locations are created with (1.0 m) spacing as shown in Figure 15. The result in Figure 16 demonstrates that it is not clear that there are three damage locations and the curve needs more spacing between the damage location to come up and down at another location.

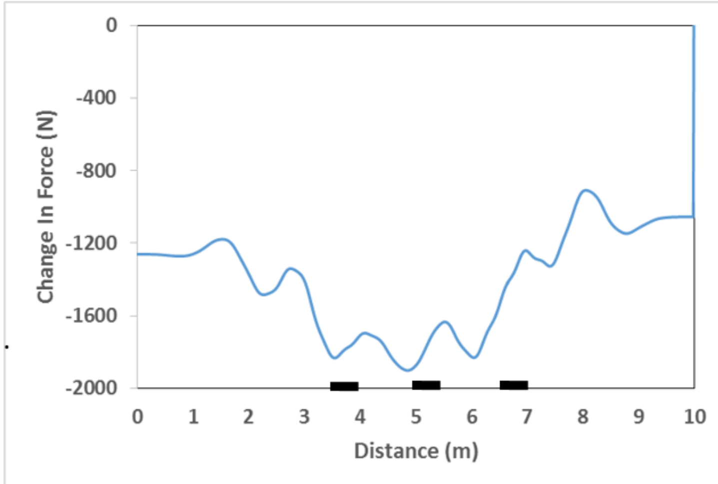

Figure 16. Three closed damage locations.

CONCLUSION

The Inverse Dynamics Optimization Algorithm can be used to detect the damage locations in bridges with high accuracy. The method gives good results to detect one, two and three damage locations. It shows high sensitive accuracy in detecting the damage for lower speed, and clear damage location for high one. Also, it can detect the very close damage locations but not as well as detect the far locations.

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