

Identification of Damage in Steel Beams Using Frequency Response Changes

Paul Archbold and Liu Shidong

Athlone Institute of Technology, Dublin Road, Athlone, Co. Westmeath, Ireland

Abstract: The issue of structural condition monitoring is becoming increasingly important as the Ireland's and the world's civil engineering infrastructure ages. An efficient monitoring process is essential as part of a modern infrastructure management system. Automated monitoring processes offer advantages over traditional, subjective techniques including repeatability, reliability and flexibility. They also offer potential for incorporation into remote monitoring systems. This paper presents a technique developed by the authors for detecting damage in steel laboratory scale beams by identification of changes in the natural frequencies of the first four vertical modes of vibration of the beams. This method was successfully employed to both locate and quantify a range of actual damage scenarios. Using twelve damage scenarios, this method successfully detected the damage location 92% of the time, while detecting the magnitude of the damage with a 75% success rate.

Key words: damage detection, vibration response, steel beams, structural monitoring, FE modelling, natural frequency

INTRODUCTION

Given Ireland's vastly expanded bridge stock in recent times and the on-going change in emphasis from bridge construction to bridge management, establishment of robust bridge monitoring procedures is becoming increasingly important. Many structural condition monitoring techniques based on vibration response data have been widely employed in various fields in the past. More recently these have begun to receive attention from the civil engineering community.

The basic premise of vibration based condition monitoring is quite straightforward: any damage in a structure would have an impact on its dynamic behaviour - each damage scenario having a unique influence. Based on this theory, measured dynamic response changes could indicate the location and extent of the damage which caused these changes. A number of approaches have been developed (with varying degrees of success) to identify damage based on the specific dynamic response characteristic which is being analysed. Typically these involve interrogation of the changes in either the natural frequencies or mode shapes, but also include higher order effects such as mode shape curvature, for example. As the natural frequency is probably the easiest dynamic characteristic to measure, the approach developed here will focus on changes in this property.

One of the first methods that claimed to be able to detect damage in an elastic structure by using natural frequency changes was introduced by Cawley and Adams in 1979. Palacz and Krawczuk discussed this approach which is named Cawley-Adams Criterion in detail (Palacz, M. and M. Krawczuk, 2002). They proposed a method of predicting the site of damage based on changes in the natural frequencies. The principle of this method is that the change in stiffness is independent of frequency and the ratio of frequency in two modes is therefore only a function of the damage location. This method was refined to provide a Damage Location Assurance Criterion, which was used to detect damage in laboratory specimens, although problems were identified when the damage levels were low. Other authors have reported other frequency-based methods (Chaudhari, T.D. and S.K. Maiti, 2000; Lee, J., 2008; Dilella, M., 2011). The success of these methods when applied to physical structures was mixed.

This paper presents an overview of the successful development of an algorithm for detecting damage in steel laboratory beams through comparison of changes in natural frequencies of the first 4 modes of vibration. The algorithm consists of developing and calibrating a finite element model of the undamaged specimen, then generating a matrix of natural frequencies for each selected mode shape for a range of combinations of damage location and damage severity from 'damaged' FE models. Comparison of measured simulated natural frequencies can then be used to both locate and quantify the damage.

Experimental Programme:

The primary experimental activities reported herein are dynamic tests on intact and damaged steel beam sections. The proposed damage detection approach will be applied to these structures as well to validate its accuracy and effectiveness. This section describes the experimental test procedures operated on the steel beam, its FE model construction and the FE model's verification process based on the measured vibration response results.

Laboratory scale steel beams were employed in this project. Figure 1 shows both a photograph and a diagrammatic representation of one of these steel beams. All dimensions are given in mm. These square hollow section steel beams have a length of 1m. Their cross section is a square box with a side length of 0.05m; the steel side thickness is 0.003m which leaves the side length of inner-hollow square 0.044m long. The dynamic performance of each of these beams was assessed in an intact state and in damaged states. The damage in this study consisted of sawn notches of varying depths at different locations along the length of the beam.

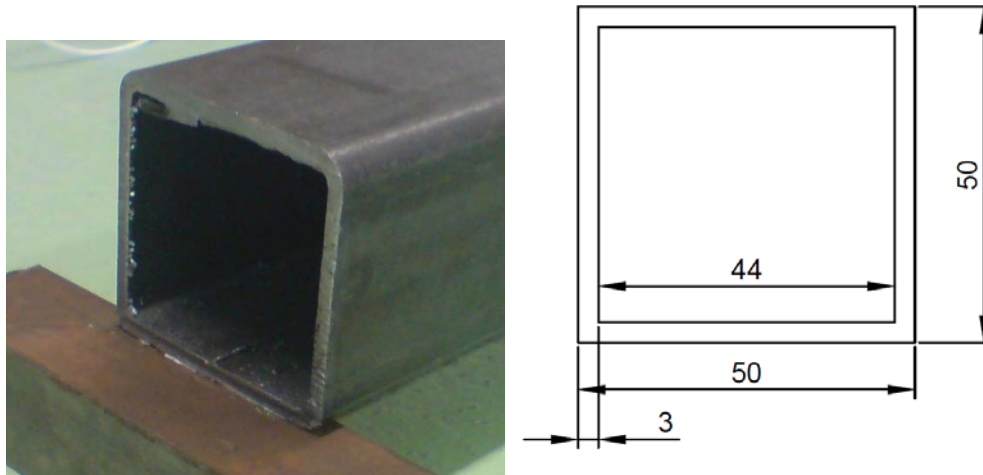


Fig. 1: Steel Beam Specimen.

Dynamic Testing:

Figure 2 shows the setup of dynamic test on undamaged steel beam. 2 no. accelerometers were mounted at mid-span and 2 no. at $\frac{1}{4}$ -span, the beam was directly supported by 2 no. bricks on a concrete floor slab. The sample rate was 5000 readings/second. Figure 3.11 shows the actual steel beam test specimen.

Dynamic Test Procedure:

Excitation was provided through hammer blows to the structure near mid-span. Each test consisted of 3 no. hammer blows at 2 second intervals and the test was repeated three times, giving 9 sets of free vibration response data from the four accelerometer locations. Each test was repeated several times and the dynamic responses of first four modes were recorded.

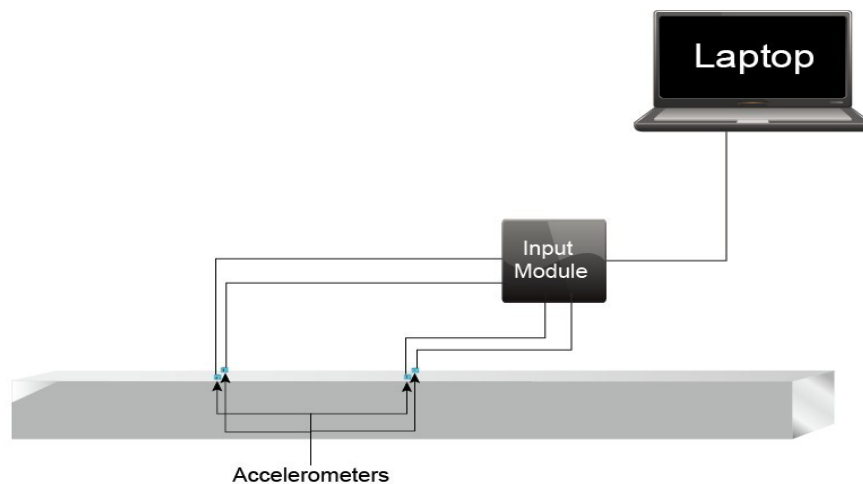


Fig. 2: Steel Beam Test Set-up.

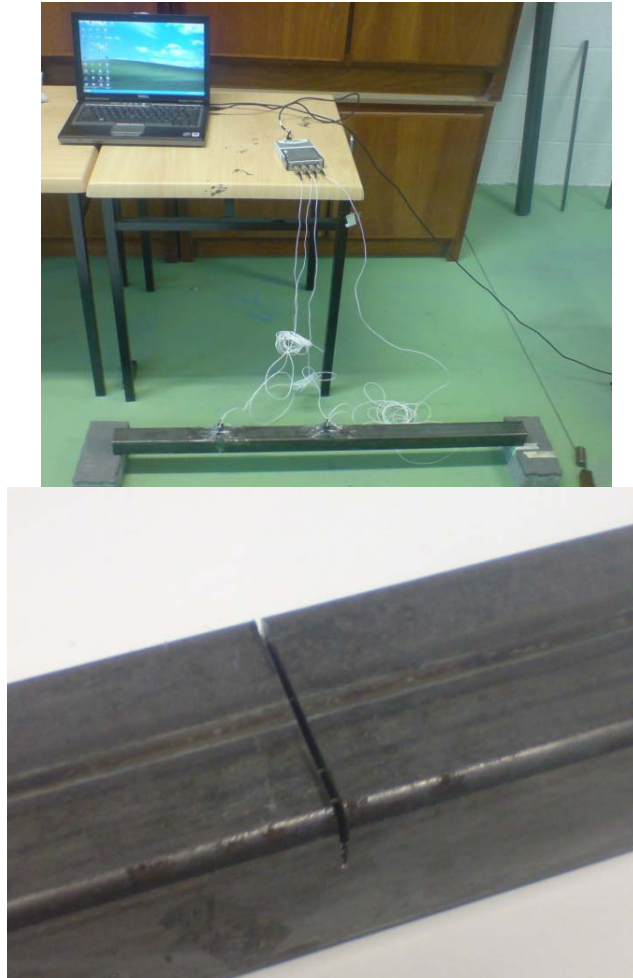


Fig. 3: Steel Beam Test and Detail of Induced Cut to Represent Crack.

Finite Element Model Development:

A finite element model was generated in ANSYS using three-dimensional elastic beam elements. The structure was discretised into 100 elements, as shown in Figure 4. The model was calibrated and updated through comparison of predicted and measured natural frequencies. The updating parameters were the Modulus of Elasticity and the density of the steel. Further static tests were undertaken to verify the actual values of these parameters. The model was successfully updated and showed close agreement with the measured responses as shown in Table 1.

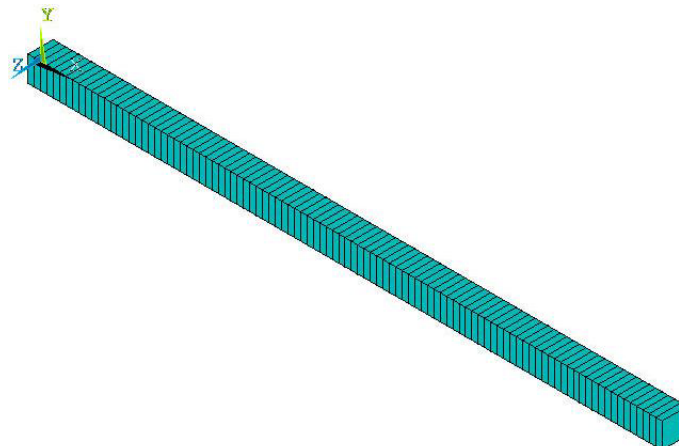


Fig. 4: FE Model of Steel Beams.

Table 1: Measured and Updated Predicted Natural Frequencies.

Mode No.	Measured Natural Frequency [Hz]		Predicted Natural Frequency [Hz]		Error [%]	
	Beam 1	Beam 2	Beam 1	Beam 2	Beam 1	Beam 2
1	130.6	138	139.51	139.42	6.82%	1.03%
2	612	521.4	555.02	554.69	9.28%	6.38%
3	1270	1339	1238	1237	2.52%	7.62%
4	2013	2054	2174	2172	7.99%	5.74%

Damage Simulation:

In order to simulate damage in the beam, various damage scenarios were envisaged. The most practical case to model was that of a crack in the beam. Several methods for numerical simulation of beam cracks are reported in the literature. Some of those considered herein include:

1. Reduced stiffness method (single element)
2. Reduced stiffness method (multiple element) (Chaudhari, T.D. and S.K. Maiti, 2000)
3. Rotational spring method (Sinha, J.K., 2001)

To determine the most applicable method among these three for this project, each method has been tested and the results were compared. Following this analysis, it was decided to employ the single element reduced stiffness method as there was minimal difference in accuracy with the other methods, yet this technique was far quicker and more straightforward to employ.

Damage Identification Algorithm:

Firstly, a reference matrix of damaged model dynamic behaviour was created. This reference matrix contains the dynamic behaviour of damaged models with 81 no. different damage scenarios. The depth ratio of the cracks, λ , varies from 10% to 90% which means the damage extents are from 10% of the beam height to 90%. And the various damage extents were numerically applied at locations along the FE beam model from 0.1m from left hand side (LHS) to 0.9m from LHS using single element reduced stiffness method to create the 81 damage scenarios.

Natural frequencies of the first four vertical modes were recorded. Some literature indicated that the dynamic behaviour of first three modes is enough to identify the damage (Nandwana, B.P. and S.K. Maiti, 1996; Chaudhari, T.D. and S.K. Maiti, 2000), while some employed first four to improve the accuracy of the results (Sinha, J.K., 2001; Yang, X.F., 2000). Theoretically, the more modes involved, the better results will be obtained. But too many modes considered will increase the complexity of the damage detection process. Due to other researchers' experience, the author decides to employ the natural frequencies of first four vertical modes.

The reference matrix consists of four sub matrices, each of which contains 81 no. theoretical natural frequencies of one mode p . Which is represented as $\delta_{\omega_p(s,\lambda)}$, where s is damage location, λ stands for crack's depth ratio. Therefore, this reference matrix demonstrates the natural frequency changes, δ_{ω} , of first four modes caused by a large range of different damage scenarios.

Subsequently a reference matrix consists of the natural theoretical frequency changes in percentage, $\delta_{\omega_p(s,\lambda)}$, caused by 81 no. damage scenarios was created. This reference matrix of natural frequency changes in % is entirely based on the reference matrix of natural frequency of damaged model. Each value is calculated based on its corresponding data.

$$\delta_{\omega_p(s,\lambda)} = \frac{F_p - F_p(s,\lambda)}{F_p} \times 100\% \quad (1)$$

Where $\delta_{\omega_p(s,\lambda)}$ is the theoretical natural frequency changes for mode p caused by damage with a depth ratio of λ , location s . F_p is the undamaged natural frequency for mode p . $F_p(s,\lambda)$ is the theoretical damaged natural frequency for mode p , caused by damage with a depth ratio of λ , location s . This matrix shows how much each damage scenario would theoretically change the natural frequency through four modes.

Suppose there is a measured natural frequency, G_p , of first four modes of a damaged model. The actual damage scenario needs to be detected based on this set of natural frequency. The difference between measured natural frequencies and undamaged natural frequencies, δ_{ϕ_p} , will be calculated as

$$\delta_{\phi_p} = \frac{F_p - G_p}{F_p} \times 100\% \quad (2)$$

Where δ_{ϕ_p} is the actual natural frequency change for mode p caused by unknown damage. F_p is the undamaged natural frequency for mode p . G_p is the actual natural frequency for mode p .

At this stage the actual natural frequency changes of damaged structure, δ_{φ_p} , and a reference matrix contains theoretical natural frequency changes, $\delta_{\omega_p(s,\lambda)}$, caused by a large range of damage scenarios are obtained. The next step is to compare each of the measured natural frequency changes to all values of its corresponding sub matrix of natural frequency changes. For unknown damage to be detected, the actual natural frequency changes δ_{φ_p} caused by the unknown damage can be measured. These will be compared against the $\delta_{\omega_p(s,\lambda)}$ data in natural frequency changes reference matrix. Theoretically, the same or the closest comparison data in the matrix will indicate the scenario or the most likely scenario of the unknown damage since they have a similar impact on the dynamic behaviour of the structure.

In order to determine the closest match between the actual damage scenario and the simulated conditions, the author calculated the differences between each measured natural frequency changes and all data of its corresponding natural frequency changes sub matrix, $\phi_p(s, \lambda)$, as following:

$$\phi_p(s, \lambda) = \frac{\delta_{\omega_p(s,\lambda)} - \delta_{\varphi_p}}{\delta_{\omega_p(s,\lambda)}} \times 100\% \quad (3)$$

Where $\phi_p(s, \lambda)$ is the difference between the theoretical natural frequency changes for mode p caused by damage with a depth ratio of λ , location s and the actual natural frequency changes for mode p caused by unknown damage.

These natural frequency changes differences, $\phi_p(s, \lambda)$, can generate a new matrix with four sub matrices. The data of each damage scenario combination will be added up through these four sub matrices, the damage identification table will be developed by the sum of these values, $\eta(s, \lambda)$. The lowest value in this table indicates the scenario combination of unknown damage.

$$\eta(s, \lambda) = \sum_{p=1}^4 \phi_p(s, \lambda) \quad (4)$$

Example A:

A damage scenario located at 0.4m from LHS, with a depth ratio of 40% was induced in the FE steel beam model. The natural frequencies of first 4 no. vertical modes of the damaged model and their δ_{φ_p} values are presented in Table 2.

Table 2: Actual Natural Frequency and δ_{φ} value.

	Mode 1	Mode 2	Mode 3	Mode 4
Actual Natural Frequency (Hz)	136.43	551.03	1230	2141.2
δ_{φ} values (%)	2.20772704	0.718893013	0.646204	1.5087397

Then this set of natural frequency changes were compared against all the data in reference matrix of natural frequency changes respectively to generate a new matrix called natural frequency changes comparison matrix. This matrix consists of $\phi_p(s, \lambda)$ values. Each value in this matrix was calculated based its corresponding data in natural frequency changes matrix using Equation 3.

A damage scenario identification table consisting of $\eta(s, \lambda)$ value was thus generated. (Table 3). The smallest entries represent the likely damage scenario. In this case, the unknown damage was identified as a crack at 0.4m or 0.6m from LHS with a depth ratio of 40%.

Table 3: Damage Scenario Identification Table of Example A.

Depth Ratio Location (m From LHS)	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0
0.1	400.0	286.1	224.4	710.3	1483.4	2734.6	4880.5	8171.9	12352.7	15929.3
0.2	400.0	240.5	465.9	956.3	1834.9	3245.6	5225.6	7789.9	10590.2	13144.4
0.3	400.0	299.4	334.6	562.7	1089.6	2066.4	3488.0	5373.5	7507.8	9949.0
0.4	400.0	301.8	0.0	437.6	1085.6	2043.2	3413.0	5191.2	7127.5	9096.3
0.5	400.0	303.2	413.1	840.9	1464.7	2371.0	3633.0	5208.1	6770.9	8823.1
0.6	400.0	301.8	0.0	437.6	1085.6	2043.2	3413.0	5191.2	7127.5	9096.3
0.7	400.0	299.4	334.6	562.7	1089.6	2066.4	3488.0	5373.5	7507.8	9949.0
0.8	400.0	240.5	465.9	956.3	1834.9	3245.6	5225.6	7789.9	10590.2	13144.4
0.9	400.0	286.1	224.4	710.3	1483.4	2734.6	4880.5	8171.9	12352.7	15929.3
1	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0

Practical Damage Scenarios:

A saw cut in the steel beam was created to represent the single open crack as shown in Figure 3. The steel beam was cut by an electric saw at the location of the damage. The depth of the saw cut is the same as damage extent. Four damage scenarios were created consisting of 25% and 50% cuts at mid-span (i.e. 0.5m from LHS) and 20% and 40% cuts at $\frac{1}{4}$ span (i.e. 0.25m from LHS). Each damage scenario was then tested three times, generating a total of twelve data sets of frequency responses.

Results:

Figure 5 and Figure 6 show the comparison between actual and predicted damage extents and locations respectively. This method accurately predicts both the extent and the location of the damage in most cases, particularly where a tolerance of 5% is allowed. This method compares well with others reported in the literature, particularly as many of those reported have also only been tested against theoretical damage scenarios, whereas this works for actual damage conditions.

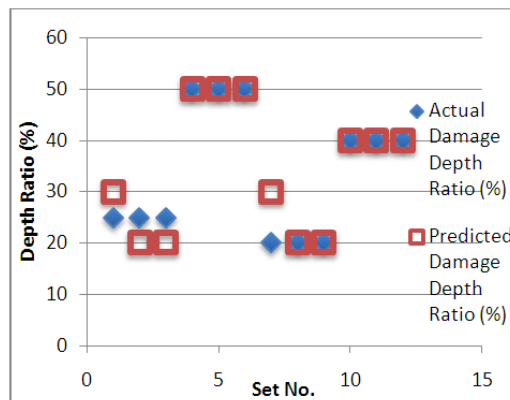


Fig. 5: Comparison Figure between Actual and Predicted Damage Depth Ratios.

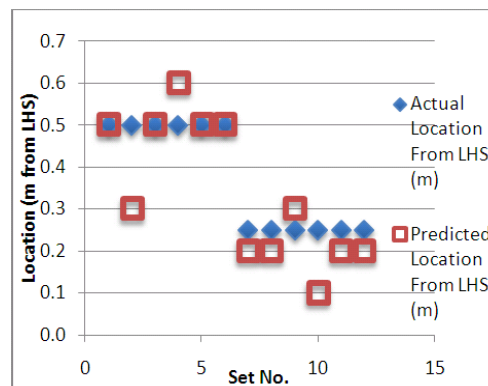


Fig. 6: Comparison Figure between Actual and Predicted Damage Locations.

Among those who have validated other methods through comparison with physical measurements, Sinha *et al.* (2001) also used natural frequency changes to identify crack location and size. Their results show that the crack location estimation is more accurate (error < 5%) compared to the crack depth (error < 30%). The error of crack size identification was considerably high although the accuracy of damage location identification was satisfactory.

In this paper, the actual damage detection results can be expressed in many ways. If the damage extent and location identification needs to be described separately, this approach identified the damage extents correctly with a rate of 91.67%, and the damage locations were detected correctly 75% of the time. If a tolerance of 5% is applied to analyse the results, all damage depth ratios were identified correctly, and 10 no. out of 12 no. damage locations were successfully indicated. The author also carried out a combined result analysis of damage extent and location detection. 66.67% of the total damages were discovered to be identified successfully. With a tolerance of 5%, the number goes up to 83.33%. This approach compares very favourably to similar approaches reported in the literature.

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