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The Use of Multichannel Random Decrement for Monitoring of Concrete Bridge Girders

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ABSTRACT: The Random Decrement (RD) technique is a time domain procedure, where the structural response of service loads is transferred into a random function. Structure Health Monitoring (SHM) is a process implementing damage identification of structures that is a requirement for majority of important civil engineering applications, especially for essential infrastructures such as bridges, offshore structures and nuclear reactors. Recently, damage monitoring is performed using non-destructive testing techniques not only using visual investigation as in the past for continuous assessment, to identify the structures integrity. In this investigation, a theoretical and experimental investigation is conducted to detect the existence of damage and its location to monitor the integrity of reinforced concrete beam using embedded of Fiber Bragg Grating (FBG) array sensor. Damage detection is evaluated through changes of dynamic parameters of the bridge girders. The technique is sensitive to damage existence of the structure and is classified as a non-destructive technique. Random decrement is a fast converging technique,that converts random response to equivalent free decay of the structure where the dynamic parameters were determined. Locating the damage using multichannel random decrement by the use of FBG array sensor has several advantages of wavelength multiplexing of high capacity, small size, very low noise and high sensitivity. The experimental results showed that using the random decrement technique to detect damage existence and multichannel random decrement to determine the exact damage location in reinforced concrete elements.

1 INTRODUCTION

Health monitoring of infrastructures is one of the challenging concerns nowadays in civil engineering, bridges are one of the transportation infrastructures that are aging and there is a rapid growing of traffic needs to continuous improving and maintaining high level of service to public. It has been reported that the US Federal Highway Agency stated in 2005 that 166,000 bridges are being deficient including 15% of the number as a structural deficient. According to Ministry of Transportation (MTO) in Ontario, Canada; an assessment range is proposed to ensure bridge safety, and to identify members in need of maintenance/replacement. The bridge inspections are supplied into a Ministry database, known as the Bridge Management System (BMS), which is a measure of the bridge's overall structural condition where this range is (0 to 100) and it is called bridge condition index (BCI). The bridge is considered as a structurally deficient if there is a need of rehabilitation or replacement for a major element that has serious deterioration at BCI value is about (60-70). Bridge is deemed critical when it doesn't have redundant protections and is at risk of collapse, BCI less than 60, so that the bridge requires monitoring systems in order to ensure the bridge integrity. Therefore, the status of infrastructure should be monitored to prevent probable catastrophic or sudden failure. SHM is a process, which investigates the current status of structures by measurement to detect the damage that means a degradation of the structure performance that is basically due to changes in material properties, boundary conditions or system connectivity. SHM includes a long term dynamic response measurement using different array of sensors, capturing sensitive features to damage and analyzing of these features to determine the current status of the structure (Sohn et al., 2003). The main categories of SHM are non-destructive testing techniques such as pattern recognition, and dynamic properties changes for damage detection. Furthermore, visual inspection that is requires a detailed inspection for each local member; it is not feasible for big scale structures. The idea of using dynamic properties changes is related to the physical changes in structures as the damage causes changes in parameters of the structure such as mass, damping, stiffness and flexibility of a structure. These detectable changes are determined using a non-destructive RD technique. The focus of this study is on the use of RD technique to detect the dynamic parameters for reinforced concrete members, and to explore the possibility of identifying the existence of damage and its location. The main advantage of RD technique is to determine the structure free vibration response from stationary response measurement without knowledge of excitation forces. RD signature can be estimated as the average of the time segments of the response. This averaging is for the noise reduction and discrimination of the random part of the response. The application of multi-channel random decrement method is shown to have significant results in the damage detection of highway steel bridges using dynamic response.

Several SHM methods have been proposed based on changes in natural frequencies, mode shapes or stiffness. It has shown that natural frequencies and mode shapes are much less sensitive to local structural damage (Chen et al., 1995) and the change in natural frequencies was observed when the level of damage is severe (Carden and Fanning, 2004). An approach is proposed for reinforced concrete beams to detect the damage and to locate its area using local stiffness as a damage indicator based on the change of the derivatives of the mode shape [6]. In New Mexico a highway bridge was detected for damage from both ambient and forced vibration using local flexibility concepts (Doebling and Farrar 1996). For identification of damage location, four methods of normalizing the mass matrices and flexibility matrix were used. All the methods had approximately the same results; however, the modes from ambient vibration data were the same to the modes obtained from forced vibration data for flexibility based damage detection. The evaluation of the damping has been found to be most promising value for damage and condition detection, there are five methods to determine the damping; half power bandwidth, RD technique, logarithmic decrement, curve fitting and stochastic subspace identification.it has been shown that RD technique seems to be more reliable all over these methods (Wenzel, H. 2008).

Finally, the damage identification process is described with four main procedures; the first one is to know the existence of the damage and what is the kind of damage in the structure, second to locate this damage followed by the identifying the severity of the damage on the structure integrity and finally estimate the structure remain life. The focus in this paper in the two steps, detection of damage existence and locating the damage in a reinforced concrete beams. The damage could be introduced as a change into the structure state, changes of the dynamic parameters of the structure is a significant indicator of the damage where RD technique used to determine the dynamic parameters for different states for the structure. RD is showed to have a potential to damage detect and using multi-channel RD the damage could be located accurately.

2 MULTICHANNEL RANDOM DECREMENT

2.1 Theoretical investigation

The random decrement function X_{Ri} (τ) can be estimated as the average of the response time segments x_i (ti + τ),

$$X_{Ri}(\tau) = \frac{1}{N}\sum_{i=1}^{N} xi(ti+\tau) \tag{1}$$

where; the estimate of the RD function X_{Ri} (τ) is a function of time variable $\tau = t - t_i$, which represents the time past the triggering time t_i, N is the number of triggering points. RD is an averaging process of time history segments of random responses in a time domain that exceed certain triggering condition. The advantage of the averaging is the noise reduction and discrimination of the random part of the response. Figure 1 presents the procedure where a measured response is averaged using a certain triggering level resulting a RD signature that is equivalent to the structure free decay response in order to identify the structure dynamic parameters. Random decrement functions that were based on multi-channel measurements are showed by Ibrahim (Ibrahim, 1977). This was important development in the technique as it enabled estimation of modal parameters from RD functions.

$$RD_L = \frac{1}{N}\sum_{i=1}^{N}\left\{X_L(t_{isL}+\tau)X_L = X_S\right\} \tag{2}$$

$$RD_{NL} = \frac{1}{N}\sum_{i=1}^{N}\left\{X_{NL}(t_{iNL}+\tau)t_{iNL} = t_{isL}\right\} \tag{3}$$

where; RD_L is the random decrement at leading channel, X_L is the triggering conditions of the leading channel, t_{isL} is the time corresponding to the triggering conditions, and RD_{NL} is the random decrement for the non-leading channels. As shown in Figure 2, RD signature is determined at each channel along the girder span, the response averaging is using the triggering level of the leading point are used to extract the excited mode shapes of the girder. MCRD extends the approach by applying it at multiple points on the structure at the same time. In order to locate the damage MCRD is used by extracting the RD response at simultaneous points across the beam, specify a leading point and it's triggering level then get the RD responses for these points, finally using these RD values this shape indicate the normalized mode shape for the beam where it could be utilized to indicate the damage existence and location.

In the current study, a proposed approach using MCRD is implemented in identifying system for bridge monitoring in order to locate the damage within the bridge girders where the sensors are simultaneously distributed conducting a network from different data channels that connects the data extracted from the channels along the cross girder and data within the main girders of the bridge, this identifying system approach is based on RD technique using multi-channels that determines precisely the dynamic properties of the bridge indicating the damage existence and location.

2.2 Experimental investigation

Two simply supported reinforced concrete beams B1 and B2 were tested having a cross sectional dimension (200 mm x 350 mm) and 3000 mm span length, using reinforcement top two bars ϕ10, two bars ϕ15 bottom reinforcement and stirrups ϕ10 @ 400 mm. Compressive strength of the concrete is (47 MPa) and Canadian steel bars conforming CSA Grade 400 reinforcing are used. Beam (B1) was induced to a damage at 850 mm from one end of the beam; the damage is presented as a gap in the concrete mould using a foam cube with dimensions (50x50x50 mm) during the concrete casting and a cut of one of the bottom reinforcement bar using an electrical saw tooth cutter as shown in Figure 3. The beams were loaded using concentrated three point load setup illustrated in Figure 4. The concentrated load was applied directly at the midpoint of the beam. The beams were excited randomly at different positions along the beam length using an 0.5 Kg impact hammer type Kistler 9728A with sensitivity of 1.05mV/LbF, the response was captured at multiple channels by FBG arrays and also using 10 g accelerometers type Kistler (8704B500), two crack gauges and the data acquisition system is compact (DAQ-NI-9184) with four channels was used. The FBG arrays were manufactured at Ryerson University fiber optic laboratory with an effective gauge length of 10 mm and were inscribed at different wavelengths as shown in Table 1 where the sensors wavelength before, after packaging and splicing is presented. FBG arrays were embedded at the two tested beams, the arrangement of the sensors is shown in Figure 5, and it was arranged simultaneously in order to capture the random response that is used to detect the damage location applying multi-channel RD technique. Two FBG arrays A-1, A-2 were embedded in B1 where the damage was induced and one array A-3 was embedded in B2. FBG wavelength shifts is measured using a sensor interrogation system (Ibsen, model: I-MON E-USB2.0 DAQ system) that is connected to the FBG optical circulator. The circulator box has three port devices that allows light to propagate, was used in the experiment. A broadband light source was connected to the first circulator port and the FBG sensing array was connected to the second port, and the reflected wavelengths from the FBG sensors could be measured where its connection to the third port 3.

3 RESULTS

For both beams, the wavelength of the FBG arrays and the vertical acceleration was measured with sampling rate of 1000 Hz, by the accelerometer at different places within the beam span at different applied load, RD signature are calculated. In order to detect the damage existence using RD technique once the responses are captured, the numerical RD signature is estimated using triggering level equals to the standard deviation of the response. Figure 6 and Figure7 present the extracted RD signature of beams B1 and B2 at point 1; respectively. Integration is conducted using a time increment of 0.001 sec and the number of segments used to construct the RD is 400 time segment. For the two beams, the results of the natural frequency and damping ratio are given in Table 2 and Table 3 for B1 and B2; respectively. These results are showed to be for different beam loading, natural frequency value is decreased by 6.59% of its intact value for B1; where for the second beam B2 it is decreased by 8.33% of its intact value indicating the damage existence. Also, the damping ratio increased as the damage level is increased where the damping ratio of B1 started at 0.86% for the intact beam to 5.93% for the failed beam that means the increase reaches to 6.89 times the original ratio, B2 started at 0.78% for the intact beam to 3.43% for the failed beam that means an increase reached to 4.39 times the original ratio. These changes are indicating degree and severity of damage. A significant result is achieved in order to locate the damage using MCRD, the approach precisely locate the damage by extracting the mode shapes of the beams before and after inducing the damage. A MATLAB code used to apply MCRD using point 2 as shown in Figure 8 as a leading channel then determine the times corresponding in the response at the other non-leading channels then get the RD responses for these points, finally using these RD values this shape indicate the normalized mode shape thus, it is precisely locating the damage where it indicates the presence of the damage at approximate the same location at which the beam was induced to the damage.

4 CONCLUSIONS

RD technique is a promising approach for RC girders monitoring of bridge integrity over time during its operation time, it is output measurement identification for the structure dynamic properties without the knowledge of the excitation force magnitude. An experimental study was performed on two RC beams to investigate the feasibility of using RD technique to identify the damage existence, and using MCRD to locate the damage. The results obtained indicated that using this technique is efficient for identification of the structure dynamic properties by detecting the damage in RC beams and the use of MCRD is essential to locate the damage. The change in the dynamic damping ratio for RC beam is more sensitive to extent of damage. The RD technique is simple, efficient and a fast approach for damage existence and location identification for bridge monitoring.

5 REFERENCES

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Table 1. FBG Array Wavelength

Array	Sensors No.	Wavelength	Wavelength after packaging	Wavelength after splicing	Wavelength after casting
A-1	01-1	1555.70	1555.56	1555.36	1555.34
	01-2	1554.54	1553.53	1553.00	1552.90
	01-3	1540.65	1538.07	1537.98	1537.50
	01-4	1545.38	1545.12	1544.99	1548.60
A-2	02-1	1550.17	1548.64	1548.85	1548.50
	02-2	1545.71	1544.79	1543.96	1543.54
	02-3	1550.72	1549.00	1530.97	1530.92
A-3	03-1	1540.76	1537.57	1537.37	1533.26
	03-2	1550.38	1549.99	1549.90	1549.12
	03-3	1532.93	1531.49	1530.00	1530.00
	03-4	1555.15	1554.42	1553.60	1553.45

Table 2. Mode 1, Natural Frequency and Damping Ratio for B1 at Different Applied Loads

Applied Load	Natural frequency (Hz)	Damping ratio (%)	Increase in Damping ratio (%)
Intact	65.93	0.86	1.00
Cracking	64.62	1.12	1.30
Yield	62.5	2.34	2.72
Ultimate	61.85	5.93	6.89

Table 3. Mode 1, Natural Frequency and Damping Ratio for B2 at Different Applied Loads

Applied Load	Natural frequency (Hz)	Damping ratio (%)	Increase in Damping ratio (%)
Intact	62.50	0.78	1.00
Cracking	60.00	0.84	1.07
Yield	58.82	3.16	4.05
Ultimate	57.69	3.43	4.39

Table 4. Comparison of Natural Frequency and Damping Ratio for the beam before and after inducing damage

Applied Load	Natural frequency (Hz)	Damping ratio (%)	Increase in Damping ratio (%)
Before damage	64.62	1.12	1.30
After damage	62.5	1.89	2.19

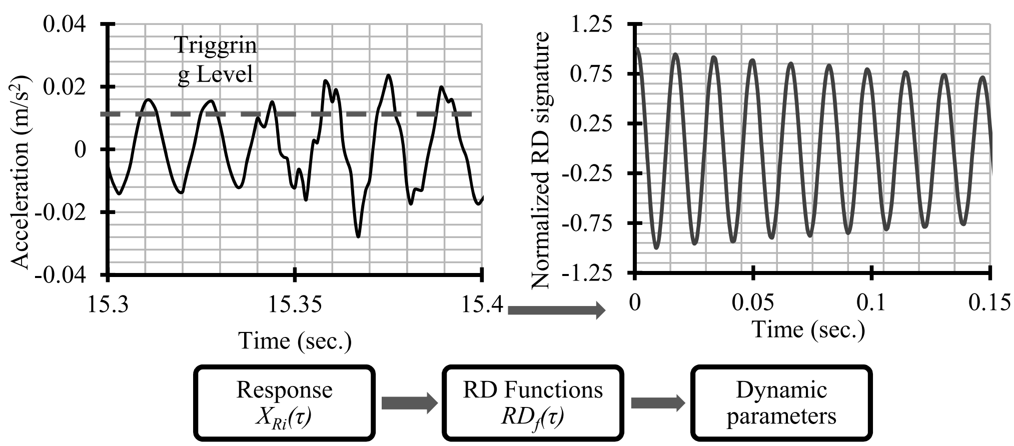

Figure 1. Random decrement analysis.

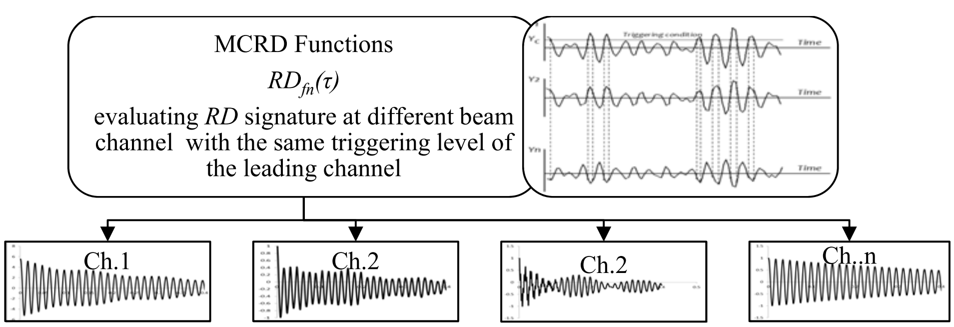

Figure 2. Multichannel random decrement analysis.

a) Embedded foam cube and the FBG sensors   b) Cut into the reinforcement bar
Figure 3. An overview of beam B1 setup.

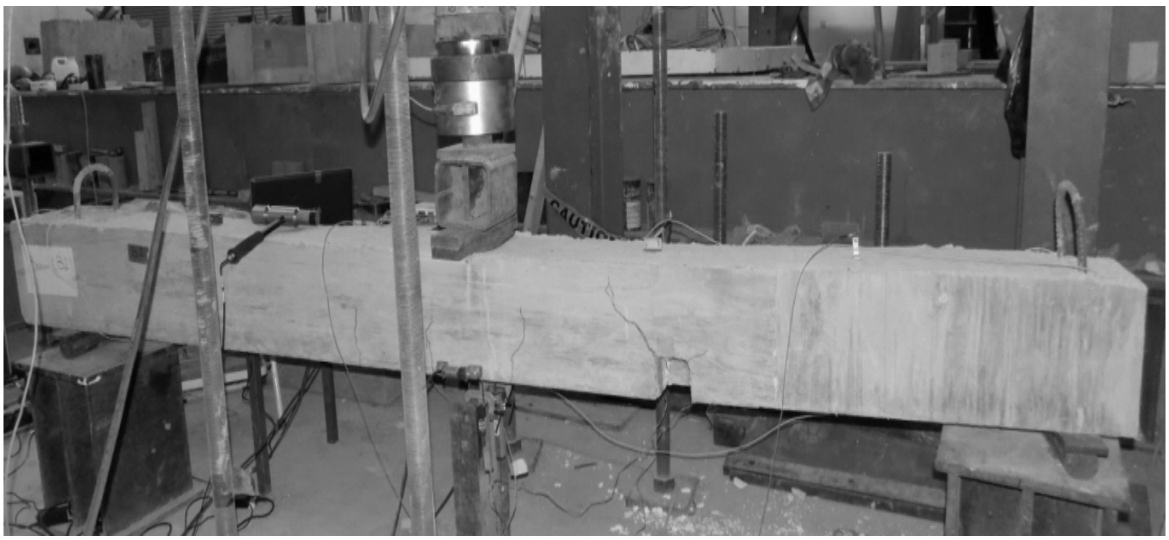

Figure 4. Overview of the beam setup.

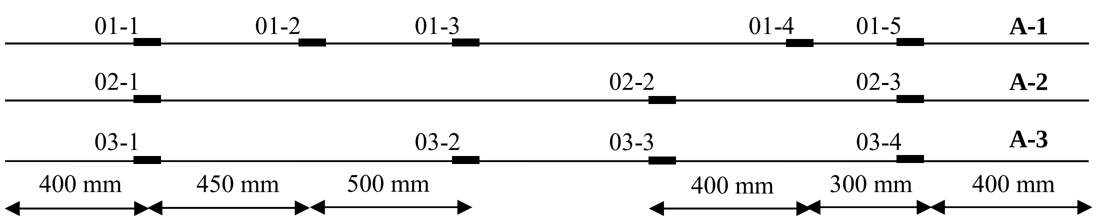

Figure 5. Schematic view of the arrangement of the embedded FBG sensors.

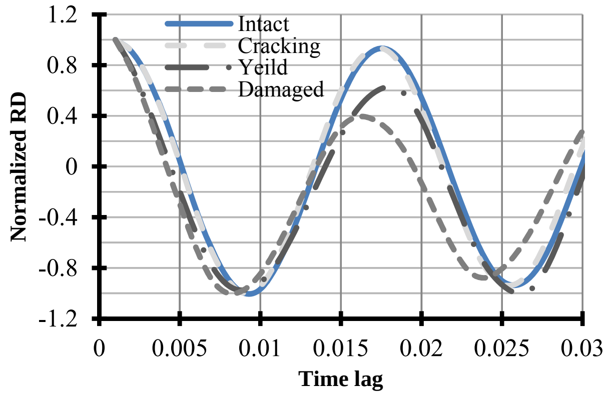

Figure 6. Normalized random decrement signatures for B1 under different applied loads.

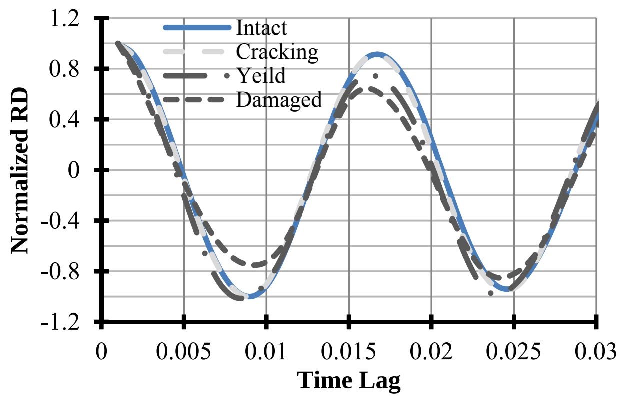

Figure 7. Normalized random decrement signatures for B2 under different applied loads.

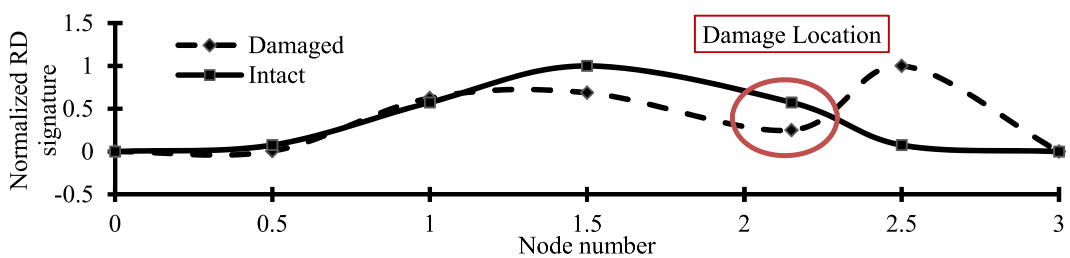

Figure 8. Shape of mode 1 as extracted by multichannel random decrement.