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STRUCTURAL HEALTH MONITORING OF BRIDGE USING SMARTPHONE ACCELEROMETER

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ABSTRACT

Accurate and real-time assessment of bridge maintenance is essential for assuring public safety and structure reliability. Structural Health Monitoring (SHM) is a cost-effective, comprehensive inspection and monitoring method for determining the intensity of damage. This study exhibits a method for detecting damage using accelerometer data processing and inspections. External cracks are evaluated by visual inspection, while accelerometer data analysis shows the internal state of a bridge structure. Data from four bridges in Dinajpur district of Bangladesh was acquired using accelerometers under traffic loads. The data is collected using a smartphone and the Arduino Science Journal App. Bridge Deflections are calculated from the acceleration by double-integration method. To reduce errors, the trapezoidal rule is used, which improves accuracy. The study investigates the bridges by monitoring data to determine the severity of damage and degradation. It is feasible to distinguish various structural situations, such as healthy, dangerous, and damaged, by comparing deflections with the AASTHO guideline. From the analysis it is found that the deflection for all the studied bridges are within the AASTHO limit and this is obvious from the visual inspection since there is no visual sagging of the bridge span. However visual inspection also revealed that few bridges required immidiate retrofitting action as there exist severe damage on that bridges. The study would be helpful for Engineers in taking necessary decision of retrofitting, repairing, and maintaining bridges for safe and sustainable construction practices all around the world.

Keywords: *Structural Health Monitoring (SHM), Damage detection, Smartphone Accelerometer, Double integration method, Trapezoidal rule*

1. INTRODUCTION

Civil engineering constructions, particularly bridges are used beyond their design lives expectancy, as well as much beyond their original load capacity. The deterioration or collapse of several bridges such as Morandi bridge in Genoa, Italy, clearly indicates that existing infrastructure requires immediate attention. The significant costs associated with a completely new bridge is not a feasible solution for a deteriorated bridge. Hence the repair of existing structures according to their damage level is more feasible solution in most of the cases (Hoque et al., 2017a,b). This requires the health monitoring of the structures. The need for smart structural health monitoring (SHM) systems is now a growing field. One of the most common goals for bridge monitoring is to obtain the actual state of the bridge so that engineers can take suitable decisions about its future and plan maintenance or replacement especially for existing bridges (Nevas, 2020). Besides for new bridges, SHM can provide quantitative data about structural response to get real-time feedback during construction phases and to confirm design assumptions. One of the basic techniques for assessing the state of functioning bridges is visual inspections, since they are simple to use and provide information directly based on observation (Nevas et al., 2017). However, due to the increasing complexity of modern structural design, this technique alone has numerous flaws. The technique is not suitable if the structure has limited access or if the traffic is unduly disrupted, that its use is time-discrete, and that the result of the visual assessment might be erroneous. The primary purpose of this study is to use the most recent yet handy and cheap advancement in the field of SHM and damage detection. It is universally agreed that, proper monitoring of the health of a structure is able to increase the overall lifespan of a particular structure (Dong et. Al., 2010). So, in overall context, the primary objectives presented in this paper is to measure the deformation of a concrete bridge deck as well as detecting the internal damage of the bridge and hence combine the visual observation with instrumental data analysis.

2. METHODOLOGY

Testing can be a useful method for inspecting and assessing the condition of bridge constructions. Testing procedures are classified as destructive, semi-destructive, or non-destructive testing (NDT) based on their degree of invasiveness [Nassif et al., 2011]. The destructive methods include tests that are often conducted in a laboratory under more or less controlled conditions that may or may not reflect actual field conditions. Furthermore, because it is frequently essential to damage or load the component to failure, these tests are expensive in most cases (Londono, 2006). The non-destructive testing (NDT) methods are a collection of procedures for evaluating the qualities of a material, component, or system without the use of chemicals.

The most common non-destructive evaluation approach used in bridge inspections is visual inspection. One of the objectives of the study is to provide the findings of visual inspection. There are various ways to analyze the health of a bridge (i.e stress-wave methods, deterministic methods, electro-magnetic methods). They may deliver us the condition with quick computation and accurate results, but they have their limitations too, as they are not budget friendly and the related sensors cannot be used in all environmental conditions. On the other hand, Vibration-based damage identification (VBDI) approaches can be employed for a global assessment of the structure's integrity. Vibration based SHM does not have the limitations of the earlier mentioned methods. It is budget friendly and not so delicate but provide highly accurate results (Fritzen, 2005). So, to get budget friendly however accurate results in short time this work is programmed to be carried out in two steps: visual inspection and vibration-based damage identification method. For this project, smartphone sensors were used to detect the current health, faults and defelctions of various bridges.

2.1 Study Areas and Selection of Bridges

The study focused on existing bridges in the Dinajpur District of the Rangpur division. Many bridges have been built in this district, of which some of them are very old. Four bridges have been chosen for the project, two of which are quite old and two of which were newly constructed. The purpose of these bridges is to serve both as national and regional highways. The name and a glimpse of those bridges are shown in figure 1.

(a)Mohonpur Bridge - Beam and arch shaped concrete Bridge

(b)Kakra Bridge: Concrete beam bridge

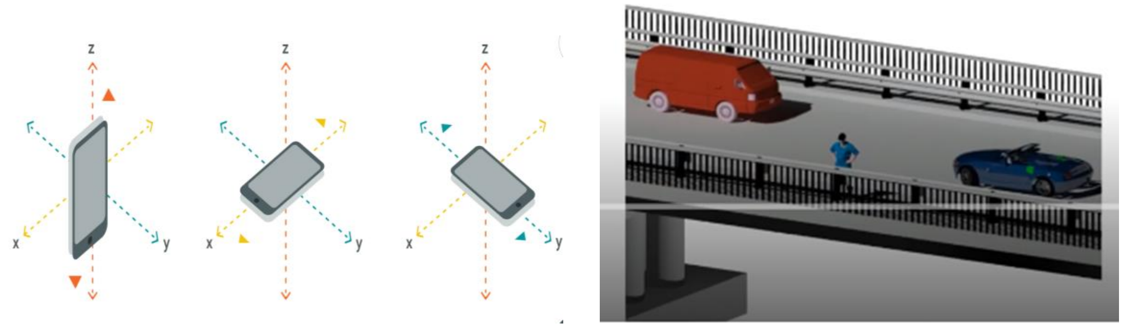
(c) Vushirbandar Bridge: Beam and arch shaped concrete bridge

(d) Kanchan Bridge: Concrete beam bridge

Figure 1: Image of various bridges used for study

2.2 Installation of Device and Data Acquisition

The Arduino Science Journal is a smartphone app that lets anyone conduct scientific experiments by using sensors. All the experiments are free of cost and cover a wide range of topics, including light, sound, motion, and electricity. The software helps students and researchers document and display their findings by allowing them to capture, store, and export data, construct graphs, taking notes, and capturing high-quality images. Small, suspended masses are free to move inside an accelerometer. These masses shift due to the changes in motion, just like our own head flops forward in a car that comes to a quick stop.



(a)

(b)

Figure 2: a) Smart phone 3-axis accelerometer sensor b) Device installation

Modern smartphones, as previously indicated, include gyroscopes, magnetometers, and accelerometers, among other sensors. However, the scope and objectives of this study requires the use of integrated accelerometer only. Several studies have looked into the performance of cell phone sensor and compared the results against commercial accelerometers for small scale prototypes. Strong agreement was seen between two outputs obtained from two types of sensors. (Buyukozturk & Yu, 2003). However, for actual bridges it is still unknown how reliable would be the data obtained using sensors embedded in cell phones for SHM of the infrastructure.

There are some challenges in implementing the smartphones in SHM, such as the pre-processing the data obtained from accelerometer smart sensor, fixing the smart sensor onto the structure, and limited battery charge. Sensors, on the other hand, are portable, pleasant and easy to handle since they are ideally embedded in cell phones; anyone can use them without prior understanding of their physics, and cheaper than GPS receivers and commercial accelerometers, respectively. Mi A3 is the smartphone model used in this study to integrate the smart sensor. Arduino Science Journal App was used to extract acceleration time series (as in figure 5). This free App was developed by mobile tools. This App is proved to be an effective tool for recording acceleration data on smartphones. The App also displays the graphics in real time and saves the data in a csv file for further processing.

3. DATA ANALYSIS AND CALCULATION

Data handling process involves data management, data processing, and data analysis, from collection to transmission and archival to engineering interpretation.

Spectral graphs and displacement and acceleration time histories can be simply modified to gain the appropriate information on the structural system's behavior. Bridge responses during a dynamic event, such as a windstorm, an earthquake, or even normal operational conditions, can be animated for better visualization and interpretation of the results, providing significant insight into bridge behavior (Rainieri, Fabbrocino & Cosenza, 2008).

In Excel, there are two main approaches to execute numerical integration. Those are Tabular Data Integration and VBA Data Integration. Tabular data integration is mostly used for experimental data. It is useful for tracking how some experimental data evolves over time. When it is required to integrate an equation with a huge number of integration points and it is required to produce a single value, VBA is the way to go. It can be configured to perform a user-defined function (UDF). There are two general approximations that are used to estimate the area under the curve.

The trapezoidal rule is a useful technique to calculate the area under the curve by splitting the area into a series of trapezoids. Regardless of the integrand adjustment, this considerably improves the accuracy. The results of these methods will converge as the number of integration points increases. The findings from the field, in this study, are a table of acceleration data from which velocity and location over time will be predicted. The relation between velocity and acceleration are as follows

$$v = \int a \, dt \tag{1}$$

Where v= velocity;
a= acceleration;
t=time;

Using this concept, the velocity at any point is computed by integrating acceleration over time by using trapezoidal approach, as this approach is a good solution for finite amount of data points. After computing velocity, the deflection can then be calculated. Since the deflection or displacement and velocity are connected in general by the equation:

$$s = \int v \, dt \tag{2}$$

Where s= displacement
Same procedure of trapezoidal area under the velocity curve is employed to get the dispalcement data.

4. RESULTS AND DISCUSSION

Since it is not possible to provide the details study of all the four bridges in this paper due to space constraints, hence only the details of Mohonpur bridge are presented and the brief results of other three bridges are provided in short.

4.1 Visual Inspection of Mohonpur Bridge Damage in Pier

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Figure 3: Damage in pier of Mohonpur Bridge

Civil engineering structures are subjected to various degrading environmental situation that can have a major impact on the structures' long-term performance. Chemical action, biochemical action inside the concrete, erosion from the abrasive effects of waves, corrosion of embedded steel, and alkali-aggregate expansion if reactive aggregates are present are all degrading factors in cold and hot weather conditions. This type of degeneration is usually a slow and steady process. Since there are no rapid changes in vibration responses, it is difficult to detect this sort of damage. The damage scenario seen in figure 3 depicts the typical type of damage caused in the bridge. It cannot be said for sure which factors are responsible for this type of failure. The damage pattern that has been found gives a clear indication of where the damage is located

4.2 Visual Inspection of Mohonpur Bridge Damage in Girder Joint

Under repeated vehicle loading, expansion joints will be damaged more. A damaged expansion joint will create considerable dynamic vehicle load effects on the bridge deck near the expansion joint, but will not affect the overall bridge responses, such as deflection and bending moment at the bridge midspan. This type of damage entails even more observable effects. Large spalls have already appeared because of the damage. Figure 4 shows the damage in drop in girder of Mohonpur Bridge.

Figure 4: Damage in Drop-in-girder part of Mohonpur Bridge

4.3 Analysis of Mohonpur Bridge Using Mobile app: Midspan

Figure 5: Midspan raw accelerometer data collection at Mohonpur Bridge

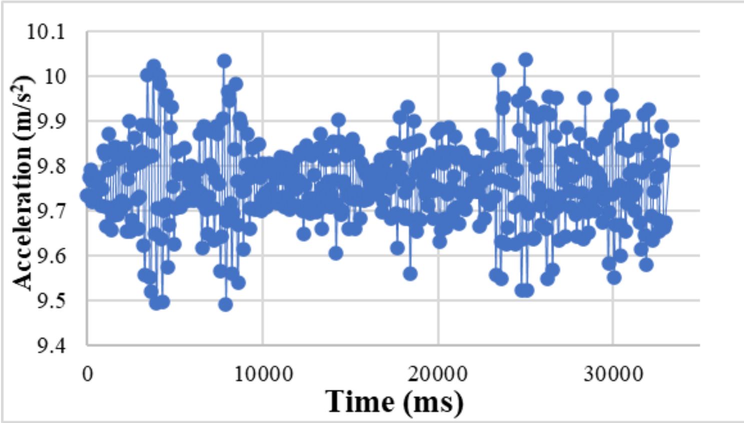


Figure 6: Dynamic response at midspan (Mohonpur Bridge)

Midspan is the point on a flexural member (usually a beam, girder, or spandrel panel) that is equidistant from the two end supports in structural engineering. The smartphone is set at midspan of the bridge. As known, the highest deflection occurs in the midspan. The accelerometer data in the Z-axis as shown in the figure 5 is used to examine the vertical movement of the bridge under significant traffic loads.

Arduino Science Journal application processes the accelerometer data in CSV file which is compatible for analyzing in MS Excel. Figure 6 is developed using the accelerometer data. Figure 6 depicts the dynamic response at the bridge's midspan. The relative time was 25.21 seconds where the greatest upward acceleration was found to be 10.04 m/s^2. Whereas the minimum downward acceleration was found to be 9.49 m/s^2 at the time of 7.949 seconds.

4.4 Velocity Calculation

The acceleration data over time is integrated to achieve the speed. The area under the curve is calculated using the trapezoidal rule, which consists of a series of trapezoids. The integration of these areas provides velocity and real-time action.When the acceleration is 9.8 m/s^2, the accelerometer does not provide actual real time. Hence, the data must be interpolated to obtain the actual time.

Since the acceleration of gravity on the surface of the earth at sea level is 9.8 m/s^2, it is assumed that the object being accelerated is at rest when the acceleration on the Z-axis is 9.8 m/s^2, so its velocity and position are both set “0” at this point . The sample data simulation for few points are shown in Table 1 and Table 2.

Table 1: Data simulation

Time(s)	**accZ(m/s^2)**	**co. time**	**co. accZ**	**velocity(m/s)**	**deflection(mm)**
25.08	9.8	0	0	0	0
25.132	9.96	0.06	0.16	0.005	4.61
25.205	10.04	0.13	0.24	0.019	19.16

The maximum velocity at midspan obtained is 0.019 m/s at the time of 25.205 sec using the trapezoidal method in MS Excel. The deflection is obtained by integrating the velocity curve using the same method. The maximum deflection is found to be 19.16 mm at the time of 25.205 sec using the same method of computing the area under the curve. The maximum downward velocity at midspan is found to be -0.015 m/s using the trapezoidal formula in MS Excel for the highest acceleration of 9.49 m/s^2 at 7.91 sec.

Table 2: Midspan downward maximum velocity (Mohonpur Bridge)

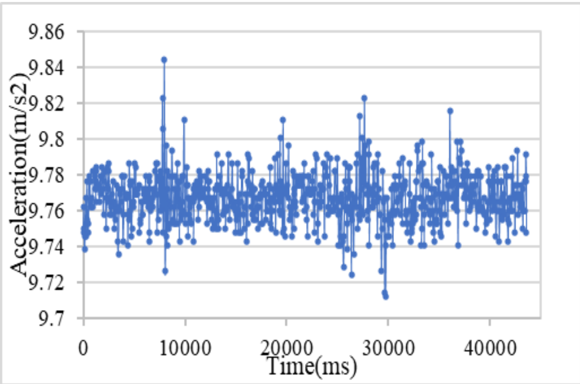
Time(s)	Velocity(m/s)	Deflection(mm)
7.82	0	0
7.84	-0.001	-1.07
7.91	-0.015	-14.73

4.5 Analysis of Mohonpur Bridge: at Various Location

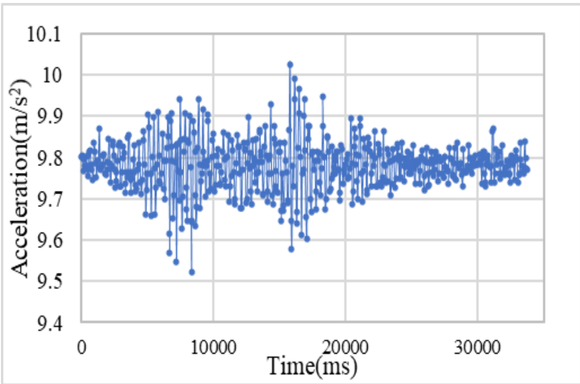
The velocity, deflection attained at various location of Mohonpur bridge found from the analysis are shown in table 3.

Table 3: Maximum upward and downward velocity and deflectiona at various location of Mohonpur Bridge

Location	Upward			Downward		
	Time(s)	Velocity(m/s)	deflection(mm)	Time(s)	Velocity(m/s)	Deflection(mm)
Pier	7.94	0	0	29.60488488	0	0
	7.98	0.0008	2.79	29.65	-0.0007	-0.74
	---	---	---	29.722	-0.005	-5.08
Drop-in-girder	15.70	0	0	8.25	0	0
	15.73	0.001	1.03	8.252	-0.0001	-0.11
	15.79	0.009	9.26	8.326	-0.011	-11.22
Arch cantilever	133.66	0	0	113.64	0	0
	133.68	0.0005	0.52	113.66	-0.0006	-0.6
	133.74	0.008	7.98	113.77	-0.019	-19.36



(a)



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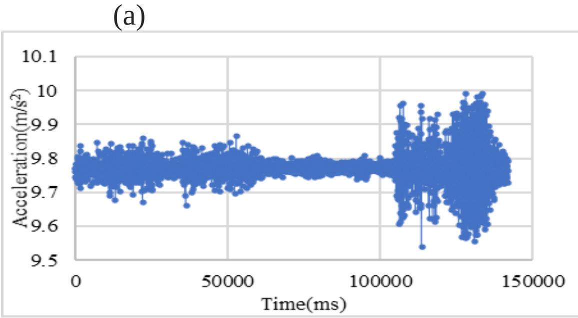

(c)

Figure 7: Dynamic response at (a) pier (b) drop-in girder (c) arch cantilever (Mohonpur Bridge)

Maximum Upward velocity for pier is found to be 0.0008 m/s at the time of 7.98 sec, which yields an upward maximum deflection of 2.79 mm corresponding to an upward maximum acceleration of 9.84 m/s^2. Maximum downward velocity is found to be 0.005 m/s at the time of 29.72 sec, which yields a downward maximum deflection of 5.08 mm corresponding to a downward maximum acceleration of 9.71 m/s^2. Maximum Upward velocity for drop in girder is found to be 0.009 m/s at the time of 15.79 sec, which yields an upward maximum deflection of 9.26 mm corresponding to an upward maximum acceleration of 10.03 m/s^2 Maximum downward velocity is found to be 0.011 m/s at the time of 8.326 sec, which yields a downward maximum deflection of 11.22 mm corresponding to a downward maximum acceleration of 9.52 m/s^2. Maximum Upward velocity for arch cantilever is found to be 0.008 m/s at the time of 133.74 sec, which yields an upward maximum deflection of 7.98 mm corresponding to an upward maximum acceleration of 9.99 m/s^2**.** On the other-hand maximum downward velocity is found to be 0.019 m/s at the time of 113.77 sec, which yields a downward maximum deflection of 19.36 mm corresponding to a downward maximum acceleration of 9.54 m/s^2.

4.6 Results for other three bridges

Table 4 shows the maximum veocity and deflection for other three study bridges. The study was performed for midspan and pier location. From the analysis it is found that the defelction is very low for kakra bridge. On the otherhand for Vushirbandar bridge and for kanchan bridge the deflection at midspan varies from 2-18 mm. However, the deflection at pier location is not that significant and it is quite rationale since the damage in pier for a random traffic load will not take place until the bridge is damaged severely.

Table 4: Maximum upward and downward velocity and deflection at various location of other three bridges

Bridge Name	**Location**	**Upward**			**Downward**		
		Time(s)	**Maximum Velocity(m/s)**	**Maximum deflection(mm)**	**Time(s)**	**Velocity(m/s)**	**Deflection(mm)**
Kakra Bridge	**Midspan**	15.22	0.0005	0.47	16.73	0.0009	0.9
	Pier	At any time	0	0	10.12	0.0006	0.61
Vushirbandar Bridge	**Midspan**	32.5	0.002	2.04	42.8	0.018	17.9
	Pier	17.9	4.1E-7	0.0004	14.31	0.002	2.008
Kanchan Bridge	**Midspan**	24.2	0.01	10.16	24.002	0.01	9.74
	Pier	At any time	0	0	5.2	-0.0008	-0.51

After thorough visual inspection and analysing the data of the bridges found from smartphone sensors that had been discussed on the abovementioned section, risk ranking of these bridges is given below in table 5.

Table 5: Risk ranking of the inspected bridges

Name of Bridge	**Allowable deflection as per AASHTO (L/1000)** (L=span length)	**Problems**	**Health quality**	
			According to smartphone data Analysis	**According to visual Inspection**
Mohonpur Bridge	=L/1000 =0.112ft =34.1376mm>19mm (analyzed value) Status: ok	Deflection is 19mm, fractures are found in significant point	Healthy	Highly risk
Kakra bridge	41mm>0.9mm (analyzed value) Status: ok	Very small deflection, Short embankment, extra span,	Healthy	Healthy

Vushirbandar bridge	35.052mm>17.9mm (analyzed value) Status: ok	Deflection is 17.9 mm, no fracture, railing missing, no sidewalk	Healthy	Public safety concern
Kanchan bridge	42.672mm>10.16mm (analyzed value) Status: ok	Deflection is 10.16mm, no fracture.	Healthy	Healthy

From the table 5 it can be said that two of the bridges (Mohonpur and Vushirbandar bridge) were determined to be at high risk as per visual analysis, while the rest were found to be in good condition. The cantilever component of the Mohonpur bridge has a maximum deflection of 19.4 mm, while the pier of the Kakra bridge has a minimum deflection of zero and it is quite rationale since the damage in pier due to random traffic load will not take place until the bridge is damaged severely. A visible crack was discovered in Mohonpur Bridge, indicating that danger could arise at any time. The maximum permitted deflection at the state of traffic loading will be L/1000, according to the AASHTO LRFD bridge Design specification and it is found to be much higher than the deflection obtained from the analysis. So as per the AASHTO guideline the deflection is within the limit and in that sense the bridges are termed as healthy.

5. CONCLUSIONS

The study reported in this paper has contributed to a better understanding of the possibilities, consequences, and limitations of adopting a data-based approach for structural health monitoring and damage detection in bridges, which is facilitated by a smartphone sensor. This section wraps up the inquiry by summarizing all the findings and offering a smartphone app for calculating a bridge's vertical deflection due to traffic loading. This technique is utilized to accurately estimate the bridges' structural condition. The study shows that the smartphone system can evaluate the impact of all bridge input accelerometers on the bridge's most important location. The expected health is in line with the visual observation for Kanchan and Kakra bridges, however for Mohonpur and Vushirbander bridge the deflection is higher than the other two bridges, though the deflection is still under the AASTHO limit. The visual observations of these two bridges are not satisfactory though, which cannot be measured by deflection only. Those damage are results from other factors too.

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