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MEASUREMENT OF DAMAGE IN MASONRY

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ABSTRACT
Masonry is a fascinating composite material able to withstand significant and sustained environmental loads. Yet, masonry is of such a brittle nature, that its propensity for sudden catastrophic failure frequently results in fatalities amongst the occupants of damaged or collapsing masonry buildings. As an example, the low level of redundancy in churches provides one of the most dangerous combinations to life safety known from environmental loads. Damage and Fracture Mechanics analysis provides a method to estimate the change in stiffness properties for masonry elements as the masonry degrades with strain. The difficulty from a life safety viewpoint, even with this data, is to determine the likelihood of the building's failure from a given design earthquake. The second question is whether sufficient time exists to evacuate the occupants of a building outside the failure shadow, before the collapse occurs. The purpose of the paper is review the use of new sensor technology, specifically accelerometers, for determining the movement of masonry columns subjected to dynamic loads. This paper reports on the early work in the use of these new sensors to determine the accuracy, limits, and appropriate methods of measurement on masonry columns.

KEYWORDS: Accelerometers, masonry damage, vibration measurement, intrinsic properties

INTRODUCTION
Damage to masonry often occurs because of some form of vibration in the adjacent earth block or design or construction error or a combination of these events. This damage can manifest as cosmetic cracking through to complete destruction of the structure, which may result in a significant loss of life [1]. A number of interesting challenges occur in completing a forensic investigation of the causes of damage to buildings. These challenges are in determining the consequences of the damage, estimating the safety of the structure, and establishing the "best" methods to repair the structure.

Heyman defines four stages of a building life in terms of settlement, the five minute failure rule, the generational failure rule, the decay limit rule at about five centuries and implicitly delineates environmental loading failure, defined here as strictly caused by environmental loading between the time of five minute rule and the limit of decay [2]. The five-minute rule or theorem requires that the structure stand for longer than five minutes, once the temporary supports or shoring are removed from the final structural system. The five-minute limit, from a reasonable statistical perspective implies that an environmental load will be highly unlikely to destroy the structure in this short period, so that the failure is due to dead and minor live load only. Heyman uses the example of removal of the timber centering, causing the failure of masonry arch structure. A typical example of timber centering on a bridge is shown on Figure 1 [3].

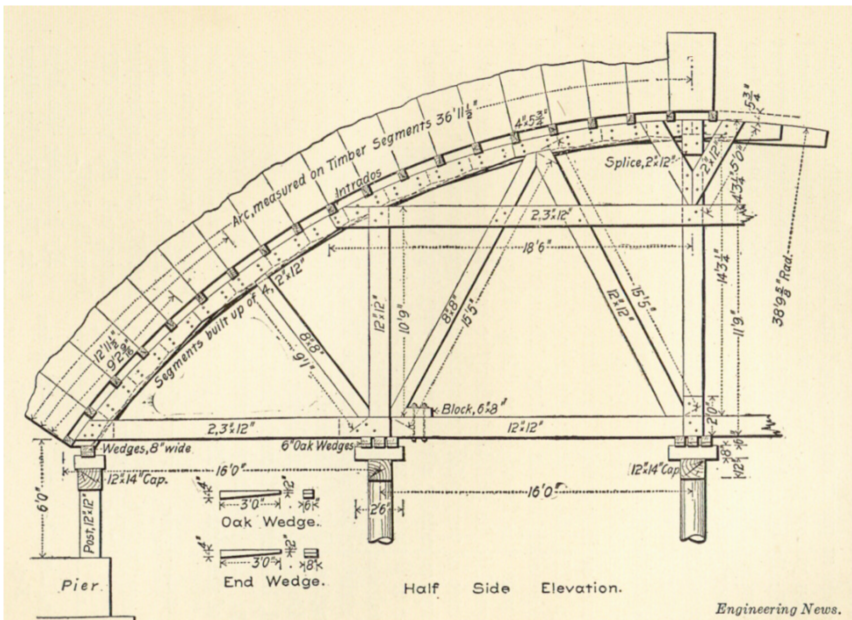

FIG. 17d.—Centering for Stone Arch Bridge of the Chicago, Milwaukee and St. Paul Railway over Rock River at Watertown, Wis. (See Fig. 80i.)

Figure 1: Typical Centering – Sketch in Jacoby and Davis (1930)

The failure of the Pont-y-Prydd bridge caused by the removal of the centering is a classic example of this failure mode [4], as reported on at a previous Canadian Masonry Conference [5]. Figure 1 demonstrates the fundamental concept in building structures, that of supporting the structure until it is in a stable state, able to carry the design loads. The five-minute rule applies the first test to the structural engineer's design. In the case of centering, the timber structure shown in Figure 1 supports the masonry until a complete arch capable of sustaining the compressive loads exists as a single topological entity [6], i.e. it spans from shore to shore. The centering removal transfers the dead weight of the structure to the designed structure. In the case of the Pont-y-Prydd Bridge, one theory about the failure mode is the excessive mass of the haunches caused a significant rise in the centre of the bridge inducing unsustainable tensile stress in the arch. The builder introduced void spaces into the haunches for the third bridge to mitigate the excess mass problem. This reconstructed bridge has stood for several hundred years.

The second explicit rule is the generational rule of twenty to seventy years, where changes in the geometry of the ground block, caused by the building's load, results in the catastrophic failure of the structure. Heyman uses the example of the failure of the towers in Beauvais in 1573, within about 20 years of the construction, to illustrate this rule. This rule relates to long-term settlement or consolidation of the ground inducing differential settlement within the structure leading to failure of structural elements. This failure mode can be exacerbated over time from dynamic loads, as observed in St Mary's Church in Maitland, Australia after the 1989 earthquake. The third explicit Heyman rule relates to the decay of the structure with time, usually measured for masonry in centuries. The slow decay of Scottish Castles in the harsh northern climate and the material decay of soft masonry 1870's drugstore in Tenaha, Texas illustrate this failure mode. The fourth implicit rule is damage to the structure because of environmental loads. In this case, an environmental load describes a load not related to the dead load of the structure, but rather comes from an external source, such as wind, earthquake, traffic vibration or other loads. This load may occur at any time in the building's lifetime.

The purpose of the paper is review the use of new sensor technology, specifically solid-state accelerometers, for determining the movement of masonry columns subjected to dynamic loads from any of the four stages of failure. The new solid-state accelerometers represent a potential whole of life monitoring system for the building, providing continuous monitoring for Heyman's Four Stages of Structural Life, with the main objective of avoiding a sudden catastrophic collapse under extreme environmental loads. This paper is the first to report on the use of this new sensor technology. It presents the initial results for a simple masonry structure and outlines the early development of the test methodology for measurements of building movements.

LITERATURE REVIEW

Newmark and Hall completed extensive investigation into effect of dynamic loads on a range of structures, including nuclear power plants [7]. Nichols provides a review of this work [8]. The key observation from this review is the gradual change in perception as to the upper limit of the maximum design earthquake, from the Richter standard from 1956 [9] to the recent work by Frankel and others [10] on the USA seismic standards.

Figure 2 shows the Fast Fourier transform of a number of the frequently referenced world earthquakes and US earthquake standards. Fast Fourier Transforms (FFT) of two large earthquakes dominates Figure 2. The two major earthquakes shown on Figure 2 have Fast Fourier transform peaks in the range of 1 Hz that exceed the current design standard for the New Madrid fault [10] at this frequency level. The first is the intraplate Nahanni earthquake of 1988 [11], which generated a low frequency pulse with a 1.5 g acceleration wave and the second is the synthetic earthquake developed for Marked Tree, Arkansas by the Lamont Observatory staff [12], with distinctive peaks in the range of 0.8 to 1.2 Hz. These two earthquakes raise the question as to whether evidence exists for earthquake displacements in excess of 0.5 metres, represented by the New Madrid Seismic Zone design standard (Figure 2) in intraplate regions of the world. The Lake Edgar fault in Tasmania, Australia has a measured surface displacements of between 2.5 metres and 5 metres caused by intraplate earthquakes [13, 14], on a fault noted as recently being reactivated, in what is one of the most seismically quiet regions of the world [9]. This height of displacement at the surface suggests existence of historic earthquakes that do not fit within the constant velocity component of the current standard, but that give rise to large low frequency pulses that would be destructive of buildings with a natural response between 0.3 to 2 Hz.

A number of other causes exist that can damage a masonry structure including vibrations from machinery. A significant body of work exists on these types of loads and the likely loading on adjacent structures, from acceptable limits on human vibration, to transport impacts, and geophysical exploration. There is a considerable divergence of opinion as to the level of damage occasioned by the various sources. The current problem with the stated limits is the use of the US Bureau of Mines research [15, 16] for setting limits on all types of vibration. The inherent difference between the blasting and other types of vibration is the duration time of blast when compared to the duration time of vibration from equipment. This new sensor technology provides a quick efficient and economic method to take these types of measurements to mitigate damage to adjacent buildings from construction loads and move away from standards developed in the 1940s and 1970s for safe construction distances and loads.

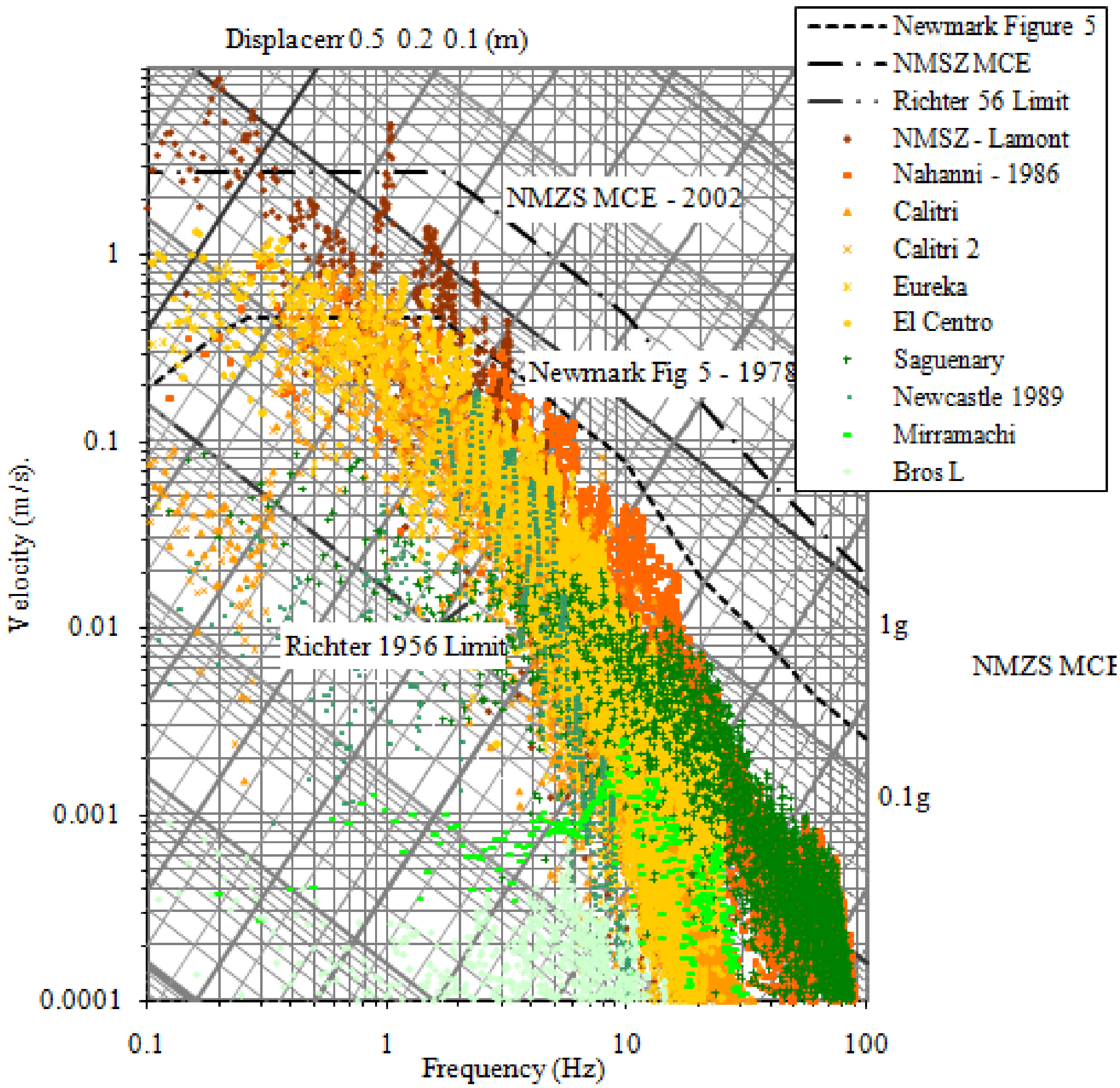

Figure 2: Seismic Standard Evolution 1956 - 2003

The use of the new solid-state accelerometers requires investigation to determine the effective resolution, the methods for analysing the data in real time and quantifying the output into terms of changes in the structural properties of the buildings, particularly the changes to the effective stiffness of the building materials. Guha [17] studied traffic induced vibration in a small masonry building at TAMU using the GP accelerometers. The purpose of this study was to study the lower limits of the instruments output and determine the minimum achievable resolution. This work determined the probable resolution of the instruments is 0.02g for the GP2. The test methods used for this experiment forms the basis for the methodology presented in this paper. The long-term research objective is to determine the movement of masonry columns subjected to dynamic loads, whilst the specific objective for this paper is to present the initial results from testing a single storey simple masonry building subjected to minor dynamic loads.

EXPERIMENTAL METHODOLOGY

The experimental work uses the GP1 and GP2 accelerometers to measure low-level vibration induced with a Ford F150 on the Langford Generator Building. This section outlines the methodology presenting the building details, the loading and the measurement techniques.

The development of the solid-state accelerometer provides a new and affordable technique to monitor accelerations and with some simple calculus to determine approximate velocities and displacements, although this will require correlation using a displacement measurement system to avoid integration induced errors. The SENRS GP2 is a modified *3-axis MEMS* accelerometer. The specific characteristics of the GP2 are:

- Accelerometer sensitivity — 800mv/g
- Accelerometer resolution — .001 g, testing suggests a actual limit of ± 0.020g
- Sampling Rate — 400 samples / sec - per axis
- Maximum Reading — programmable to 10g
- Output — USB cable side mounted

The test building is a single storey generator building at Texas A & M University (Figure 3). The building has damage of the masonry columns caused by steel corrosion. This damage does not interfere with the results, as the research interest is time and damage parameter independent.

Figure 3: Test Building – Langford Architectural Complex (9.1 x 2.2 x 3.1 m)

Permanent mounting points have been provided at five locations on the building, labelled A to E on Figure 3. Accelerometer GP 2 was mounted at Point C with the Y-axis vertical, the X-axis in plane and the Z-axis out of plane. Data was recorded using the Standard SENSR program that records, time, integer time steps, accelerations in the local instruments X, Y and Z directions, the resolved vector maximum for the acceleration and the temperature using a Pentium 4 Dell Portable. The signal analysis was completed using SIGVIEW 1.98. The building has two roller doors on the southern side, with solid masonry walls (203 mm) and a reinforced concrete roof (100 mm thick). Figure 4 shows the south-western column adjacent to the left-hand roller door, with GP2 in place on the wall at mounting point C.

Figure 4: Building One – Mounting point C – GP2 Installed on White Oak Block

The column damage predates the experiments resulting from steel corrosion not related to the experiments. The corrosion does not affect the conclusions reached from the study. The mounting points are 1.475 m above the adjacent RC pathway. White oak mounting blocks 140 x 114 x 19 mm attach the accelerometers to the permanent mounting positions. The assumption is the white oak blocks do not affect the results. This assumption will require further study, but it is considered reasonable for this early work.

The loading pattern developed for the study evolved from the early experiments. The first earlier experiments had the purpose of determining the sensitivity of the accelerometers and establishing the best methods to log and analyse the results. The conclusion from these results was a lower resolution limit of approximately 0.015 – 0.02g based on a quiescent period of study on a four storey Reinforced Concrete building. The loading function for the current experiments uses a step kerb of approximately 130 – 150 mm to generate a pulse load in the reinforced concrete pathway. The point load comes from a Ford F150, with a mass of 2120 kg passing over the kerb at a slow speed. Figure 5 shows the kerb setup adjacent to Mounting Point C. The kerb is centred approximately one metre from the wall to allow for truck clearance issues.

Figure 5: Test Building – Measurement at Mounting Point C – 150 mm Kerb Point

EXPERIMENTAL RESULTS

The experiments were completed on 28 November 2008 using Mounting Point C on the Langford Architectural Complex Generator building. The experiment occurred between 03:00PM to 04:00PM. The recording time for each experiment was about six to seven seconds, with the load point in the middle of the recorded period. No recording occurred on the F150. Figure 6 shows the local axis Z time signal for the accelerometer for the experiment, which is the out of place direction for the Generator Building. The load application point for the truck is at about 2.6 seconds.

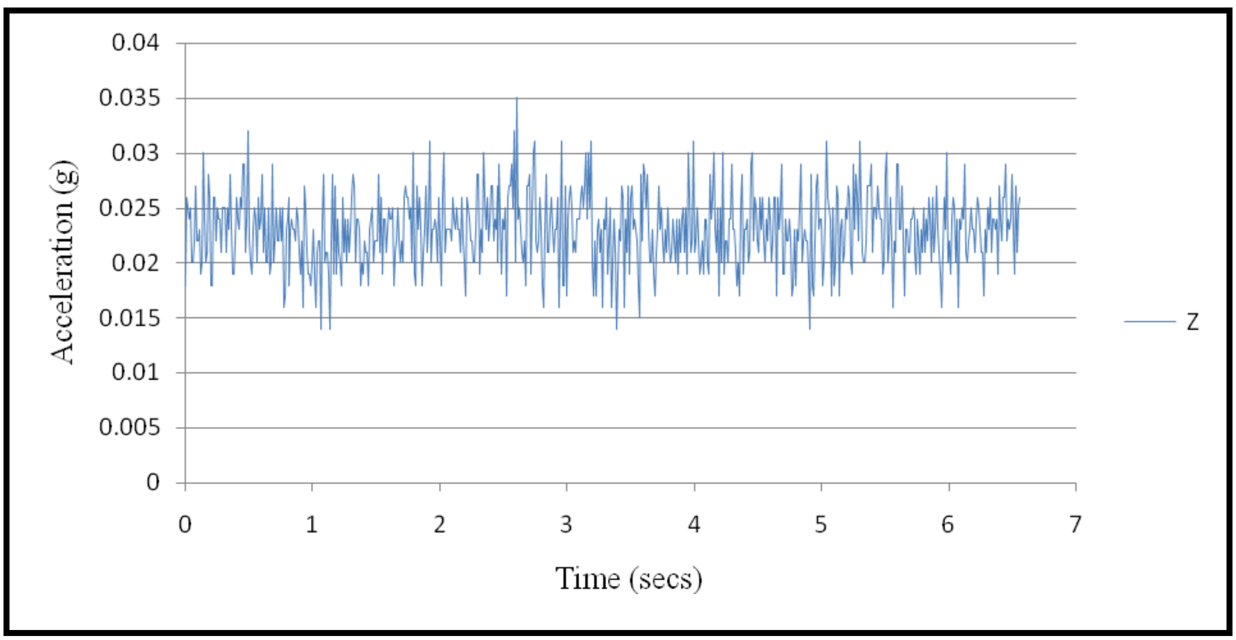

Figure 6: Building One – Out of plane - Acceleration on Wall – Loading F150 Ford

Figure 7 shows a Fast Fourier Transform of the Signal in Figure 6. The FFT analysis was undertaken using SIGVIEW 1.98. The visible maximum peak is at about 5 Hertz.

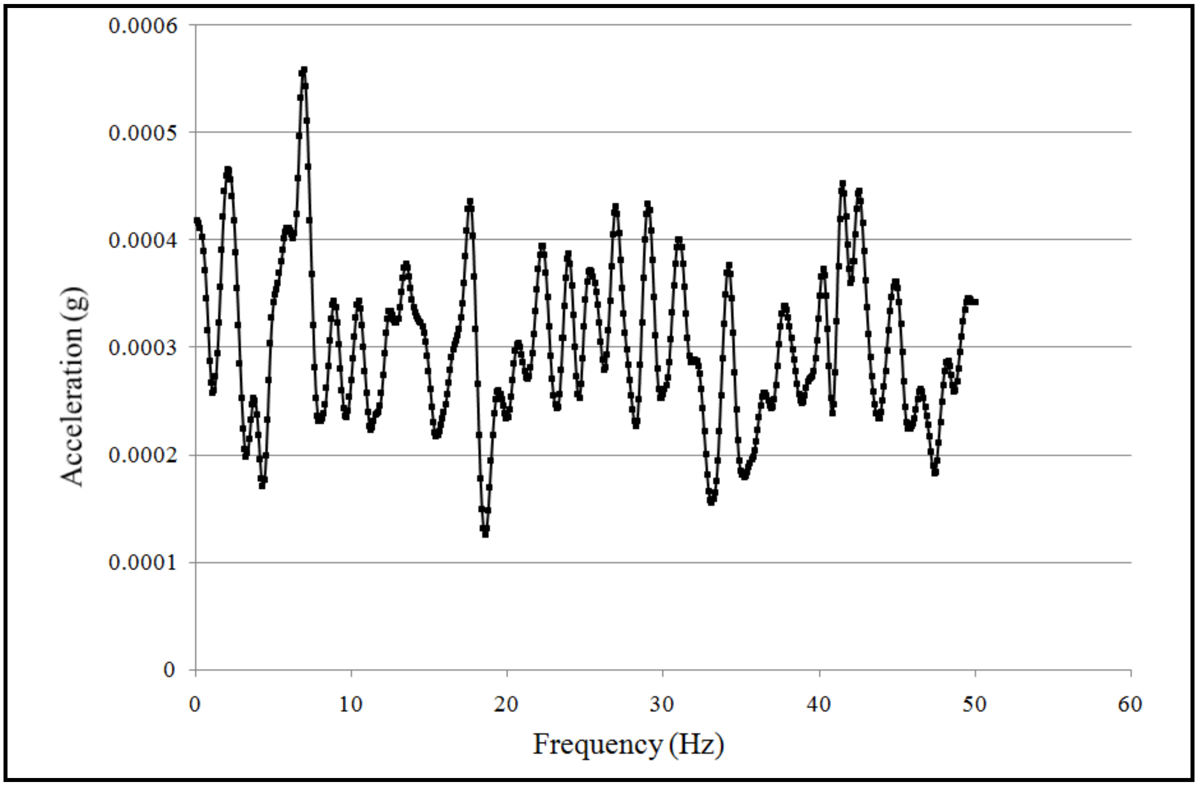

Figure 7: Building One – Out of plane – FFT of Acceleration Z

Figure 7 shows a peak sway at about 5 Hertz. This result is consistent with other observations on the building. Figure 7 shows a number of interesting features that influence the analysis:

- A constant acceleration exists in the results caused by the earth's gravitational field. This problem arises as it is not possible to align the local axes of the instrument with the world's gravitational field so that two of the three axes have a base zero gravity. This feature requires translation of the results to create a two axis system that is normal to the gravitational acceleration
- The resolution of the instrument is evident in the signal, as this loading period corresponded with no discernable wind, a very seismically quiet area and no traffic loading other than the F150 at 2.5 seconds. The Generator building sits in a wind-shielded area.
- The spike in loading at 2.5 seconds resulting from the F150 mounting the kerb is evident.
- The small results shows the very high damping one expects on masonry buildings with a induced loaded from a vehicle moving at very low speeds over a small step.

DISCUSSION

The long-term objective of these experiments is to develop a monitoring system that can determine the evolution of damage in masonry with increased strain levels [18-22]. An experimental program to monitor accelerations, velocities and displacements, with the view to determine loss of strength and stiffness has started on three buildings at Texas A&M University. This paper presents the results of the study on the masonry building. The study buildings comprise a four-storey reinforced concrete building, a small adobe and timber hut and the generator building. In themselves, the buildings have no great historic value, but the buildings are located in areas of low environmental loading typically for days at a time. So for example, the generator building is only used in these experiments because the building can be used for the experiments at times when no other discernable live load is occurring in the immediate area of the building and permanent mounting points can be placed on the building. This point is not true for most buildings at TAMU. The building suffers from spalling due to corrosion of the internal reinforcement in some of the vertical column. This spalling occurred before the experiments and is not considered likely to affect the conclusions reached in this study [23, 24]. The experimental data shows that an acceleration of about 0.035 g's or 0.034 ± 0.015 m/s^2, approximately one metre from the wall could be detected by the accelerometer. The results show the problem of non-alignment of the local axes with the world system, leaving a non-zero residual value for two nominally normal zero-g axes. It is a significant computational and statistical exercise given the movement of the accelerometer in three directions and with three rotations to resolve this issue. This type of system will require measurement of the absolute displacements to the ground block at regular time intervals [25]. The final problem is establishing a system that provides a real time method of determining the load function, measuring the load function with time and relating this to the acceleration data. The current system requires manual data entry and analysis. This is also a significant exercise, but one that would benefit from a simple structural application, such as an elevator shaft.

CONCLUSIONS

This paper outlines a simple experiment using new solid-state *3-axis MEMS* accelerometer to measure the accelerations from traffic-induced vibration loading on a single-storey masonry building. The results showed a measured out of plan sway at five hertz, was measurable with a result of 0.035 ± 0.02g's. The results show the new accelerometers can detect small vibrations in the buildings, but the difficulty is in analysis and investigation of the results. The logical place to integrate these instruments into the building is in the elevator shaft that has a clear view from the roof to the basement levels of buildings.

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