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RESIDUAL DRIFT ESTIMATION USING A SINGLE ROTATION MEASURMENT FOR SEISMIC HEALTH MONITORING OF CONCRETE COLUMNS

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ABSTRACT

Structural health monitoring (SHM) is emerging as an important field in reducing the seismic hazard to civil structures. A critical feature that indicates seismic damage is the residual drift ratio. Although drift is difficult and expensive to measure directly in the field, it can be estimated from direct rotation measurements. Rotation measurements can be made using inexpensive MEMS accelerometers. The fact that these sensors can be inexpensive and convenient to install is vital to the widespread deployment of SHM sensors. Previous work has demonstrated that this rotation algorithm is capable of estimating the residual drift ratio of a simple fixed-free column that simulates a bridge pier; however, overestimation and inaccuracy remain a problem. Using results from previous concrete column tests, drift estimation can be improved significantly, thus allowing for more accurate damage assessments and application to more complicated structural systems. This approach is applied to an example experimental column shaking test, where the results indicate significant improvement in the drift estimate. Future steps include generalizing this framework for damage diagnosis to columns in moment resisting frames, allowing for monitoring of many diverse structures.

Introduction

The field of structural health monitoring (SHM) for civil engineering applications is emerging as an effective method of reducing the seismic hazard of buildings and infrastructure. SHM systems can support the response to earthquakes in the following ways. Immediately following a large earthquake, information obtained from the SHM system can be rapidly transmitted to decision-makers in order to assist in the deployment of emergency response crews and to determine whether critical structures (e.g. bridges, hospitals) can remain operational. This rapid compilation of structural health information may significantly reduce the seismic hazard due to aftershocks. Later, SHM systems can augment traditional site inspections in order to help make the appropriate repair or occupancy decision.

In order for an SHM system to have widespread deployment, it needs to be robust and inexpensive. Robustness is achieved by selecting a damage metric that is well correlated with seismic damage. One common metric for seismic damage to civil structures is the residual drift ratio. Large residual drifts are indicative of structural damage; furthermore the residual drift

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itself weakens the structure through the P-Δ effect (Pahn et al. 2007). Identification of permanent drift is one of the first steps in preliminary postearthquake building inspection (FEMA-352), and residual story drift can be used to determine the damage state of frame structures (FEMA-356). Unfortunately, typical methods of directly measuring drift are expensive and suffer from several disadvantages. Use of global positioning systems is expensive and is limited by the need for a direct line of sight to the satellite (Celebi 1998). Laser interferometry methods are limited in only being able to measure relative displacement. However, permanent displacement can be estimated from direct rotation measurements on the structure, which can be made using MEMS accelerometers. Use of MEMS accelerometers allows the development of inexpensive and easy to install sensors, which is critical for widespread deployment of an SHM system. Recent research has demonstrated that wireless sensor networks are a viable and more cost-effective method of SHM than equivalent wired networks (Straser and Kiremidjian 1998, Lynch et al. 2004). The low data transmission and computation costs of the rotation algorithm make it particularly suited for use in wireless health monitoring.

The process for damage diagnosis using direct rotation measurements is termed the rotation algorithm. Previous research has demonstrated that for simple structural systems, the rotation algorithm is capable of estimating residual drift with sufficient accuracy to effectively diagnose damage (Cheung and Kiremidjian 2009). However, difficulties with the accuracy of the drift estimate remain. The accuracy of the drift estimate depends in large part on the structural model for the plastic deformation of the column. Because only one or at best several point rotation measurements along the column length are available, a number of assumptions are necessary, which are prone to error. In order to improve the accuracy of the drift estimate, data from laboratory experiments can be used to update the models for predicting the plastic deformation of the column.

This paper presents an updated rotation algorithm for single columns that uses the results from experimental concrete column tests in order to increase the accuracy of the residual drift estimate. First, the theoretical basis for predicting residual drift using rotation measurements is presented. One possible implementation of the rotation algorithm is briefly summarized for clarity. Finally, these approaches are implemented for an example application of structural health monitoring of a concrete column under seismic loading using experimental data collected from several tests at the University of California Berkeley and the University of Nevada Reno.

Residual Drift Prediction for Columns Using Rotation Measurements

The rotation algorithm is based on the principle that plastic hinging (which causes residual drift) after an earthquake will also cause corresponding residual rotations in structural members, and that given knowledge of the rotations, the residual drift can be reliably estimated. Recent research has demonstrated that residual deformations can be directly linked to economic losses (Ruiz-Garcia and Miranda 2005, Ramirez 2009). If the complete rotation profile across the length of the column were known, it would be possible to calculate the drift directly. However, due to sensor deployment limitations, the residual drift must be estimated using one or more rotation measurements taken at single points on the column. This can be done using Paulay and Priestley’s method for determining plastic hinge length.

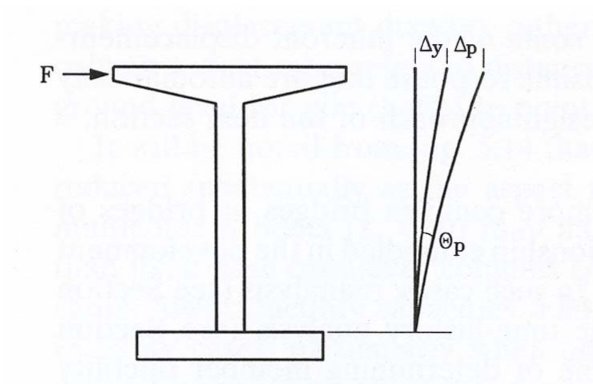

Figure 1. Displacement profile for a single bridge column (reprinted from Priestley et al.1996)

Fig. 1 shows a typical displacement profile for a bridge column subjected to a lateral load. The following equation relates plastic displacement Δ_p to the plastic rotation θ_p (Paulay and Priestley 1992):

$$\Delta_p = \theta_p \left(l - 0.5 l_p\right) \quad (1)$$

where l is the length of the column and l_p is the plastic hinge length. It is assumed that the plastic rotation is concentrated at midheight of the plastic hinge region (equivalently, the plastic rotation is distributed evenly across the hinge region), and that no plastic rotation occurs outside of the hinge region. The plastic hinge length l_p can be estimated by the following equation (Paulay and Priestley, 1992):

$$l_p = 0.08l + 0.22 d_b f_y \quad (2)$$

where d_b is the nominal rebar diameter and f_y is the rebar yield stress in MPa. In the ideal scenario, θ_p can be measured using deployed sensors and l_p is estimated using Eq. 2. Eq. 1 can directly calculate the residual drift. Although this model may not be completely accurate due to non-ideal behavior, it provides a framework to begin developing a rotation algorithm for residual drift estimation.

Rotation Algorithm Summary

One possible implementation of the rotation algorithm is summarized here. The first step is to calibrate the sensors by taking initial rotation measurements at each sensor node. The set of initial measurements is denoted as the vector $\boldsymbol{\theta_0}$. This is done in order to account for initial biases in the sensor orientation. Future rotation measurements will be based off of this initial measurement.

Performing damage diagnosis consists of three steps: (1) rotation measurement, (2) residual drift estimation, and (3) damage classification. The damage diagnosis may be scheduled to take place at regular intervals, or in the case of seismic health monitoring, immediately after a strong motion is detected.

Rotation Measurement

During the rotation measurement step, rotation measurements are taken at each sensor node on the structure. The set of rotation measurements is denoted as the vector $\boldsymbol{\theta}$. In order to account for the initial rotation bias described earlier, the initial rotations must be subtracted from the current measurement in order to determine the change in rotation since the sensors were initially installed on the structure. For the sake of notational simplicity, this bias correction will be assumed and the measurements $\boldsymbol{\theta}$ will refer to the corrected measurements. The actual process of measuring rotation using MEMS accelerometers is now described in greater detail.

Use of MEMS accelerometers to measure rotation is common in many engineering applications and a full description of the procedure is available in several datasheets and application notes (Analog Devices 2007, Tuck 2007). For rotation measurement purposes, the most important characteristic of MEMS accelerometers is that they are capable of measuring DC (zero frequency) accelerations and consequently the accelerometer measures the force of gravity acting on the sensor. This makes it possible to calculate the rotation of the sensor relative to the direction of gravity by measuring the magnitude of acceleration along each axis of the sensor. Fig. 2 shows an accelerometer with its y-axis initially aligned parallel to the direction of gravity and one which has rotated about its z-axis relative to the direction of gravity by an angle θ.

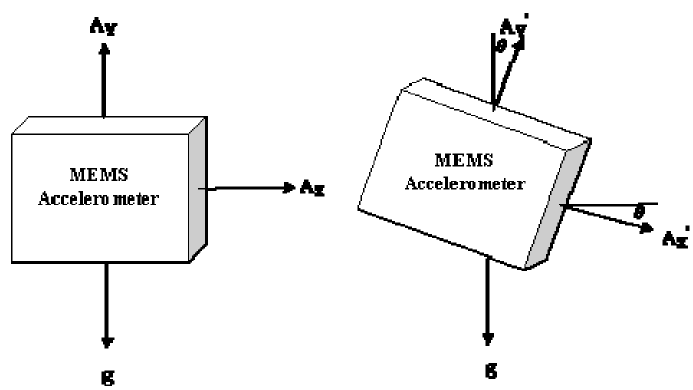

Figure 2. Alignment of accelerometer to measure rotation about one axis

Initially, the acceleration measured in the x-axis A_x will be zero and the measurement along the y-axis A_y will be 1g. As the sensor rotates about its z-axis, the current acceleration measurements A_x' and A_y' can be related to the angle of rotation θ by the following trigonometric equation:

$$\theta = \arctan\left(\frac{A_x'}{A_y'}\right) \tag{1}$$

Displacement Estimation

Once the rotation measurements have been recorded, they can be used to estimate the residual drift following the strong motion. This can be done using Eq. 1 and 2 as described earlier. Using Eq. 1 and 2, only one sensor measurement is necessary in order to accurately estimate the residual drift for a single column. However, as will be shown, non-ideal behavior can cause this estimate to overpredict the residual drift in a column.

Damage State Classification

Following the displacement estimation, the next step is to classify the damage state of the structure. The primary strength of the rotation algorithm for SHM is that robust relationships between residual drift and damage have been developed from the field of performance based earthquake engineering (PBEE) in the form of performance thresholds (Ghobarah 2001). The goal of performance thresholds in PBEE is to establish objectives for structural design. However, thresholds can also be used as damage state classifiers in SHM. Typical performance thresholds are displacement based (Moehle 1996), and although maximum transient interstory drift ratio is one of the more common parameters (Moehle 2004), relationships between residual drift and damage have also been developed. Table 1 presents an example of a damage table for residual drift, summarizing FEMA 356 Table C1-2. The table defines three damage states and sets residual drift thresholds for each state. For SHM purposes, the drift estimates obtained from the rotation algorithm can be compared with the table to classify the damage state of the structure.

Table 1. Classification of damage states based on permanent drift from FEMA 356

	Structural Performance Level for Permanent Interstory Drift		
Structural System	Collapse Prevention	Life Safety	Immediate Occupancy
Concrete Frames	4%	1%	negligible
Steel Moment Frames	5%	1%	negligible
Steel Braced Frames	2%	0.50%	negligible

Application to Experimental Data

The rotation algorithm using improved drift estimation was validated by applying the techniques described above to experimental data collected from several single bridge column seismic loading tests. Data from a set of column tests conducted at the University of California, Berkeley was used to develop the improved structural models for estimating residual drift. These models were then validated using the data collected from a single column test at the University of Nevada, Reno, which was instrumented with MEMS accelerometers capable of implementing the rotation algorithm for SHM. Although the design of the columns from the University of California, Berkeley test is slightly different than the column used for the University of Nevada, Reno test, it is shown that the improvements are still able to increase the accuracy of the residual drift estimate significantly.

Description of Experiments and Instrumentation

More comprehensive descriptions of the experiments can be found in the available literature; for the University of California, Berkeley tests see (Hachem et al. 2003) and for the University of Nevada, Reno test see (Choi et al. 2007). However, for clarity, the experiments are briefly summarized.

University of California Berkeley, PEER Column Tests

The University of California, Berkeley tests involved four separate but identical circular reinforced concrete columns; however, only the two tests (designated A1 and B1) which were loaded unidirectionally are considered for this analysis. Column A1 was subjected to the 1994 Northridge Earthquake Olive View record; column B1 was subjected to the 1985 Chile Earthquake Llolleo record. Each column was fixed to a seismic mass and subjected to multiple shake tests at design (PGA approximately 0.5g) and maximum (PGA approximately 0.9g) ground motion magnitudes and damage observed was cumulative. The columns were designed according to Caltrans specifications in effect during the 1990's. Fig. 3 shows the column dimensions and reinforcement.

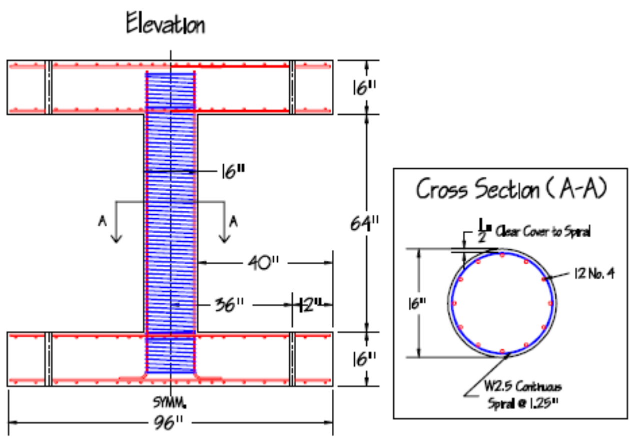

Figure 3. Column dimensions and reinforcement details (reprinted from Hachem et al. 2003)

For brevity, only the instrumentation relevant to this analysis is described here. The columns were instrumented with displacement transducers along the length of the column. The locations of the displacement transducers on the column are shown in Fig. 4. The displacement transducers are used to determine the residual displacement profile of the column after each shaking test. This information is then used to validate the residual drift estimation step described earlier.

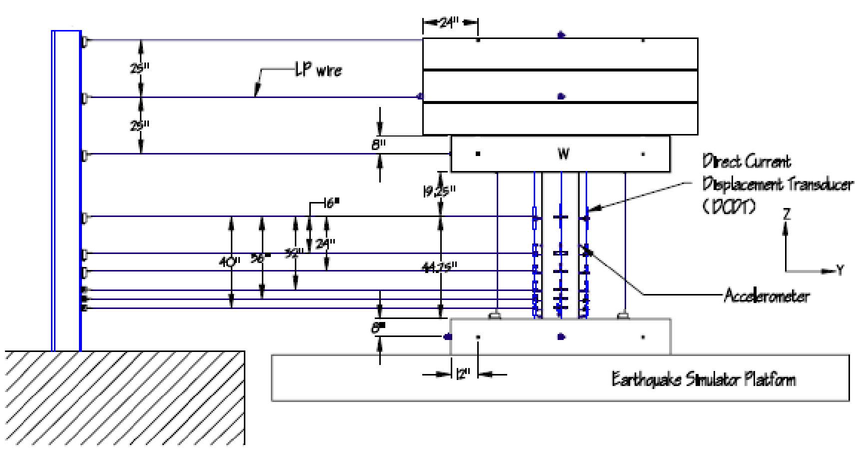

Figure 4. Instrumentation for Berkeley columns (reprinted from Hachem et al. 2003)

Fig. 5 shows the residual column displacement profile for columns A1 and B1 after each shaking test. The plastic hinge length l_p was found to be between 12 and 14 inches (Hachem et al. 2003), which is consistent with the displacement plots. Although direct rotation measurements were not taken along the column, the rotation of the column can be calculated from the displacement measurements and used for algorithm validation.

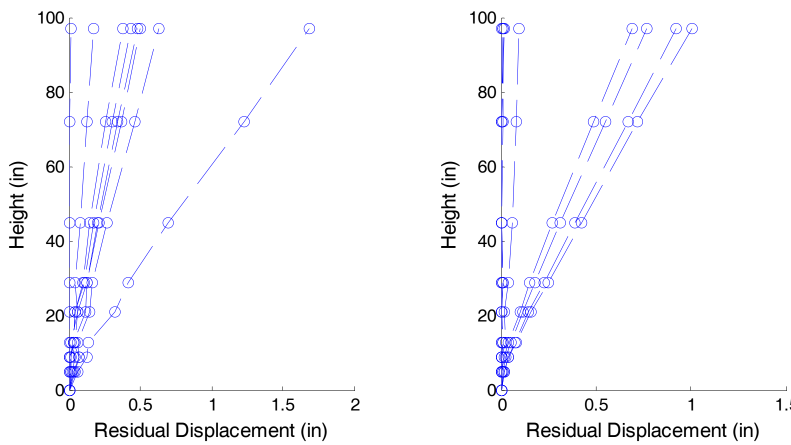

Figure 5. Column residual displacement profiles for (a) column A1 and (b) column B1

University of Nevada, Reno NEES Column Test

The University of Nevada, Reno test column was also a circular reinforced concrete column which was designed based on the 2004 Caltrans seismic design code. The column was subjected to increasing magnitudes of the 1994 Northridge Earthquake Rinaldi record and again damage was cumulative. The column was loaded with a seismic mass mounted on a separate apparatus and attached with a pin connection. Fig. 6 shows the column dimensions and detailing as well as the test setup. The length of the plastic hinge was found to be 18 inches (Phan et al. 2005).

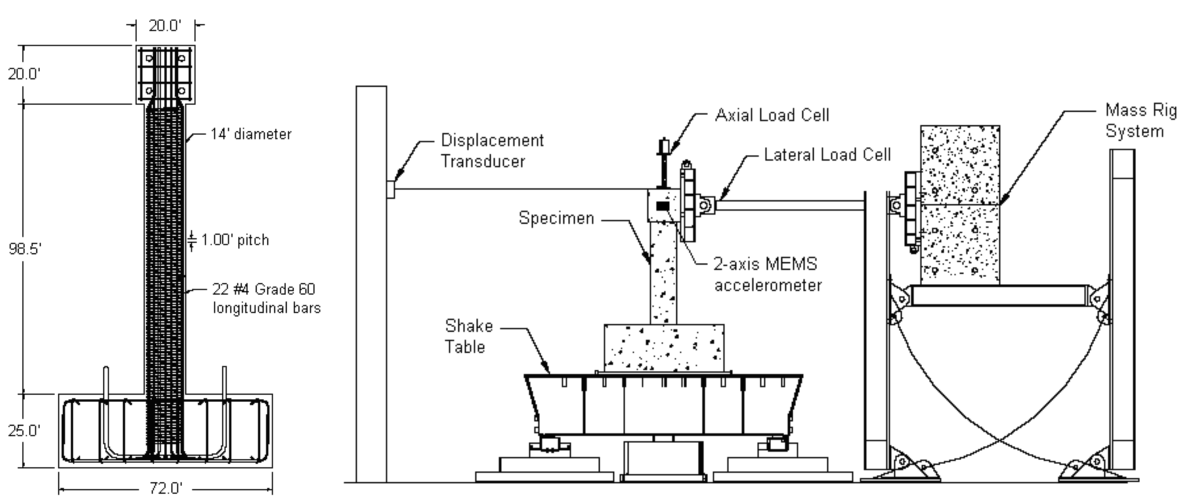

Figure 6. Column dimensions and detailing and test setup

Again only the instrumentation relevant to the analysis in this paper is discussed. The column was instrumented with a displacement transducer at the top of the column, which is shown in Fig. 6. In addition, a sensing unit equipped with a 2-axis MEMS accelerometer was installed at the top of the column. The accelerometer was used to estimate column residual drift using the rotation algorithm which can then be validated using the actual drift measured by the transducer. A comparison of the two column experiments is shown in Table 2.

Table 2. Comparison of University of California, Berkeley and University of Nevada, Reno columns

	Height	Diameter	Design Code
A1, B1	64 in	16 in	1990's Caltrans
ETN	98.5 in	14 in	2004 Caltrans

Rotation Algorithm Results and Discussion

For both sets of data, the rotation algorithm was validated by comparing the actual drift measured at the top of the column with the predicted drift estimated according to the procedure described previously. Fig. 7 shows the results for the University of California, Berkeley column tests and Fig. 8 shows the results for the University of Nevada, Reno test. For drift estimation, the plastic hinge length was estimated using Eq. 2.

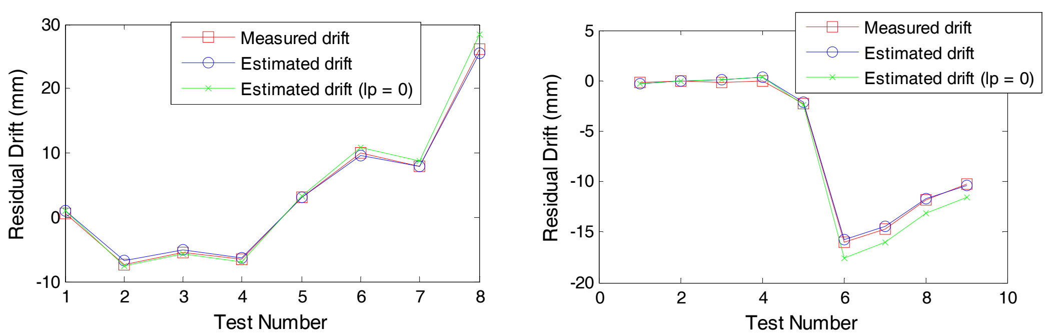

Figure 7. Comparison of measured and estimated residual drift for (a) column A1 and (b) column B1

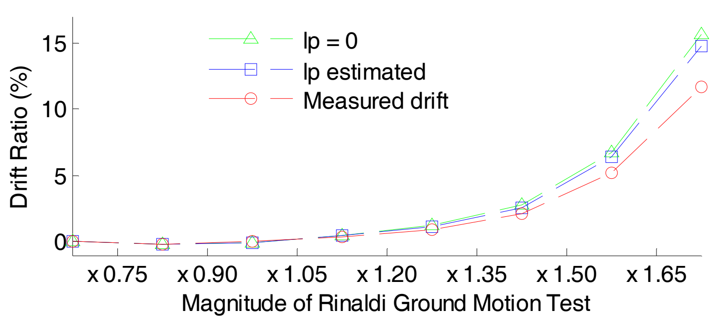

Figure 8. Comparison of measured and estimated residual drift for the ETN column test

The results demonstrate the importance of accounting for the length of the plastic hinge region when calculating the residual drift. In particular, for column B1 in Fig. 7, accounting for the hinge length increases the accuracy of drift estimation significantly. However, for the ETN column in Fig. 8, the rotation algorithm still overpredicts the residual drift, even when the plastic hinge is taken into account. Several differences in the column detailing may account for the differences in the results from the two sets of data. The ETN column was significantly taller than columns A1 and B1, and therefore the effect of the plastic hinge is less significant compared to other sources of error. Also, the ETN column was designed according to more recent seismic design codes, and may therefore form plastic hinges that are not modeled accurately by the Paulay and Priestley model.

Conclusion

Because the rotation algorithm error is primarily governed by the drift estimation step, it is important to develop better methods of estimating residual drift. This paper presents a method of estimating residual drift for columns instrumented with a single rotation sensor, which is based on Paulay and Priestley's plastic hinge model. The method is validated using two sets of experimental column shaking test data as an example health monitoring application. The algorithm is shown to be capable of detecting and quantifying damage, despite inaccuracy in drift estimation for one of the columns.

The methodology has been developed for single concrete bridge columns that fail in bending. Future work in this area involves extending the methodology to more complicated structures (e.g. moment resisting frames) and different materials (e.g. steel). This necessarily involves more complex plastic hinging models that explain the error observed in the University of Nevada, Reno column drift estimation. In addition, further development of the algorithm should include testing and validation of the algorithm embedded on a wireless sensing unit.

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