

New Approach to Control of Vibrations Generated by Construction in Rock and Soil

Nuevo Enfoque Al Control De Vibraciones Generadas Por Construcción En Suelos Y Roca

Charles H. Dowding

Mickey L. Snider

Professor and Graduate Student

Department of Civil & Environmental Engineering

Northwestern University, Evanston, IL, USA

Abstract

Concern over possible construction vibration-induced cracking has led to a radically new approach to vibration control: Autonomous Crack Measurement (ACM). This paper describes ACM equipment to measure crack response to both long term weather phenomena and transient, construction vibrations with the same sensor. This new approach is useful for control and assessment of vibrations produced by soil interaction (pile driving and vibrating rollers) or rock interaction (blasting). Its inherently digital nature also allows comparative responses to be communicated broadly to interested regulators and public through real-time polling and Internet display. In addition to describing ACM technology, a case history is presented of crack response to weather and construction vibration. Both short (daily) or long term (passage of a front) weather effects are observable, and can be compared to those produced by vibrations. Direct measurement of that which concerns the public – cracks – provides a control mechanism that is based upon the phenomena of concern itself.

Resumen

Preocupación por el agrietamiento de estructuras, posiblemente inducido por actividades de construcción, ha generado una estrategia radicalmente nueva para el control de vibración: Medida Autónoma de Agrietamiento (ACM por sus siglas en inglés). Este artículo describe el equipo utilizado en ACM para medir la respuesta de grietas bajo variaciones de condiciones climáticas de largo plazo y vibraciones de corto plazo producidas por actividades de construcción. Este nuevo método es útil para el control y la evaluación de vibraciones producidas por la interacción del suelo (hinca de pilotes y equipo de compactación) o interacción de la roca (voladuras). Su naturaleza intrínsecamente digital también permite respuestas comparativas que pueden ser transmitidas a entes inspectores y el público interesado a través de Internet en tiempo real. Además de describir la tecnología de ACM, el artículo presenta un caso histórico acerca de la respuesta de agrietamiento a cambios de clima y vibración producida por construcción. Se pueden observar tanto efectos del clima de corto plazo (diariamente) o de largo plazo (el paso de un frente atmosférico) y pueden ser comparados a los efectos producidos por las vibraciones. Medición directa de lo que más concierne al público - las grietas - provee un mecanismo de control que se basa en los fenómenos de preocupación.

1 CONSTRUCTION VIBRATION INDUCED CRACK MONITORING

1.1 Mechanical Construction vs. Blast Induced Vibrations

Most construction related vibrations are generated by mechanical equipment in soil while mine and quarry-induced vibrations are generated by detonating explosives in rock. Thus dominant frequencies tend to be lower for vibrations generated by construction equipment at equivalent small absolute distances. Energies involved in the production of construction vibrations are less than those that produce blast vibrations. Thus distances between source and receiver for equivalent peak ground motions are much shorter for construction. With these substantial differences, one would believe that there should be differences between structural responses to vibrations produced by mechanical construction equipment and those produced by blasting.

Despite these differences, there are few scientific studies of construction generated cracking compared to those related to blasting. As a result most control limits for allowable vibration are based upon blasting experiments. These limits are most likely conservative because of the differences by which the construction vibrations excite adjacent structures. The autonomous crack measurement (ACM) approach presented in this paper can be employed to explore the differences in response by measuring crack response to the vibration regardless whether the source is mechanical or explosive. Thus ACM transcends and integrates disciplines described by the material transmitting the ground motion: rock or soil.

1.2 Correlation of Crack Width with Crack Extension

Autonomous Crack Measurement (ACM) combines two technologies not heretofore integrated: micrometer measurement of crack changes in crack width (shown in Figure 1) and digital seismographic technology. In addition Internet delivery of autonomously obtained data can provide real time display and thereby increase access to graphically displayed data, which should lead to a greater public appreciation of the relative effects of the silent forces affecting crack response. Dowding and Siebert, (2000).

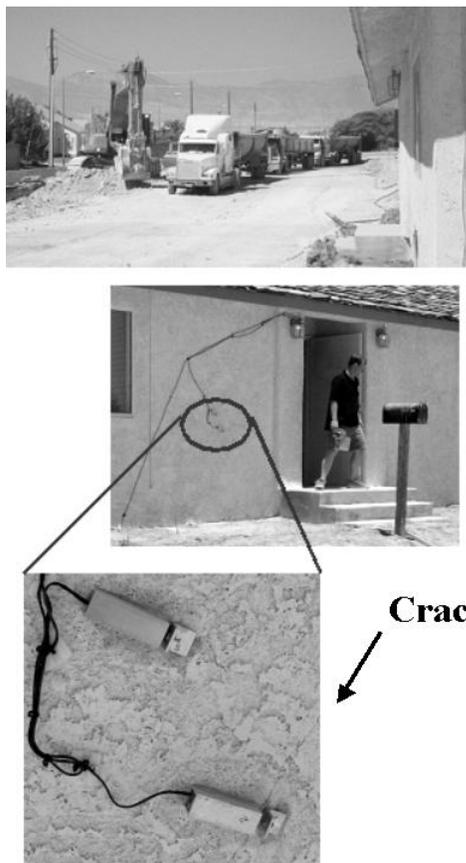


Figure 1. Photographs of construction and External crack sensor. Top: Trackhoe excavation 12 m from the test house. Middle: Location of external crack sensors on south wall. Bottom: Close-up of external crack and sensors on south wall.

Rather than following the standard procedure of measuring only ground motion to compare with results from previous studies, changes in crack width are also measured. This direct measurement is simple to understand and requires no reliance upon previous work by others. Most importantly, the same device, when placed across a crack can be employed to measure changes in crack width from both transient vibratory or long-term environmental effects such as temperature and humidity. Full time histories of vibratorally-induced changes in crack width can be recorded by the same sensor that measures the long-term effects of environmental changes.

Crack width is an index of potential extension of a crack. In other words, the greater the change in crack width, the greater the potential for crack extension. Figure 2 shows the results of special tests Miller, (1989) to determine the change in crack length with the change in the crack mouth opening. The change in crack mouth opening is analogous to the change in crack width. In the test a specimen of cement paste like that shown in the insert to Figure 2 was subjected to increasing

force, F , at the mouth of a crack of length “ a ”. As F was increased, the crack mouth opening, or crack opening displacement (COD), increased, as did the crack length, “ a ”. The main graph portrays the change in COD with the extension of the crack. For instance the crack extends from 40 to 47 mm as $\frac{1}{2}$ COD increased from 15 to 22 x 10⁻⁵ inches = (3.8 to 5.5 micro meters - μm). Hereinafter changes in crack width will be described as crack displacement.

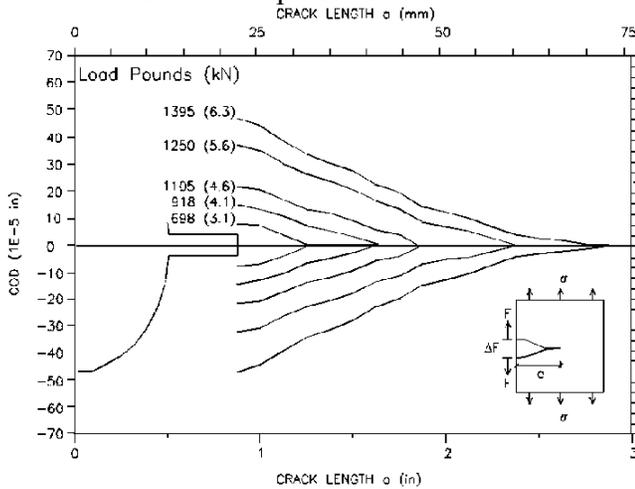


Figure 2. Crack width as index of potential extension of a crack.

Measurements summarized in Figure 2 show the crack extending only when the maximum crack width experienced is surpassed. Thus, if the crack width remains less than its maximum historic value, it will not extend. Crack measurements presented herein show that changes in crack displacement, produced by seasons of the year, advancing weather fronts and sometimes daily temperature changes are large compared to those produced by vibratory excitation. Thus it is unlikely that crack extension would occur as the result of a vibratory event.

1.3 Micrometer Sensors

It is envisioned that a number of types and brands of micrometer displacement sensors will be compatible with ACM system. However, all must meet several requirements. First, they must be small, so they do not interfere with household activity or seem too obtrusive to those who would live with them on their home walls. Since they would be placed predominantly inside a house, they should be as inconspicuous as possible. Second, they must be inexpensive, as price is always an issue. Normally the “best” equipment is the lowest priced equipment. Third, they must have high resolution, which is determined from experience. In a previous study Dowding, (1996), each day the displacement changed cyclically 3

μm (120 μin). To make apparent such small changes over a twenty-four hour period, a resolution thirty times greater than this movement is desirable, which results in a resolution of 0.1 micrometers (4 micro inches). Fourth, they must have an appropriate measuring range. Long term crack displacement may exceed 0.1 mm or 100 micrometers. Since not all cracks behave the same, this range could be extended +/-100% to account for cracks with a larger movement potential. This consideration results in a measuring range of 400 micrometers. If the displacement sensor is placed in the middle of this range it is required to follow movements of no less than +/-200 micrometers.

Sensors that measure long-term response must involve a minimum of drift and thermal hysteresis. In this article, drift is the long-term change in an instrument’s output at a constant measurement, and thermal hysteresis is the change in an instrument’s output with a change in temperature at a constant measurement. To assess these performance measures, different sensors were mounted on an aluminum plate with a known coefficient of thermal expansion (CTE) and their response was recorded over long periods of time under variably cyclic outdoor temperatures. Louis, (2000). Theoretical response was calculated by multiplying the separation of target and sensor and can be compared with the sensor output.

Louis’ comparisons of sensor performance show that the common LVDT (employed in this study) performs as well as and perhaps better than far more expensive eddy current gages. LVDT’s consists of a moveable magnetic core attached to an aluminum bracket mounted on the other side of the crack, which translates parallel to the hollow cylindrical axis of a coil. This relative displacement changes the magnetic field in the coil, which in turn changes the output voltage. As shown in Figure 1, the cylindrical LVDT core is epoxyed in a prismatic mounting bracket that is in turn epoxyed to the wall. Eddy current proximity devices sense the changes in eddy current produced by changes in the distance between the sensor and the target. Two aluminum brackets are epoxyed on either side of the crack, at a distance of 0.25 in (6 mm) apart. One of the brackets supports the sensor and the other serves as the target for the eddy current from the sensor. There is no physical connection between the target and sensor and the initial distance between the two is set to approximately 0.254 mm (10 mils).

If there is concern about sensor performance, a null sensor can be employed. It is mounted on

uncracked material adjacent to the crack sensor of the same model, following the same mounting procedure and temperature exposure. Response of the null sensor will then account for all systematic differences such as temperature hysteresis, drift, and wall material response. When response of the null is subtracted from that of the crack sensor, only the crack response remains. In cases investigated so far, the null response has not been significant to warrant use. For the case history in this paper displacement recorded by null sensor was only ~ 1 % of the daily temperature response of the crack and thus not included in the graphical display.

2 ACM Surveillance of Road Construction in Desert Colluviums

2.1 Setting the Scene: Construction Geometry, Structural Detail, and Soil Profile

Location of the ranch house in Figures 1 & 3 on the right of way of road construction provided the opportunity to test the ACM approach for typical construction activity where soil transmission distances were small. The one-story stucco covered ranch house was located immediately adjacent to the widening and reconstruction of West Ann Road in Las Vegas, Nevada. Backhoe excavation, mechanical trenching and vibratory rolling are expected to produce vibratory crack deformation; however at the time this article was written only the ground motions produced by the trackhoe excavation of a 6 m deep trench shown in Figure 3 had been recorded. Previous attenuation studies indicated that the trackhoe excavation would produce some the largest ground motions.

The 3 x 3.7 m deep trench some 12 m from the test house was excavated through a soil profile of silty clay and sandy clay that was irregularly cemented to form what is locally called “caliche”. Caliche is a calcium-rich cemented soil formed by the evaporation of alluvial groundwater in desert climates. Variability of depth of the cemented layer produced an irregular penetration resistance with depth and location. Three borings to a depth of 6 m (20 ft) were taken in the vicinity of the test house: one was directly in front and the other two were located 150 m (500 ft) to either side. Figure 4 shows the variation of the standard penetration resistance for the three borings.

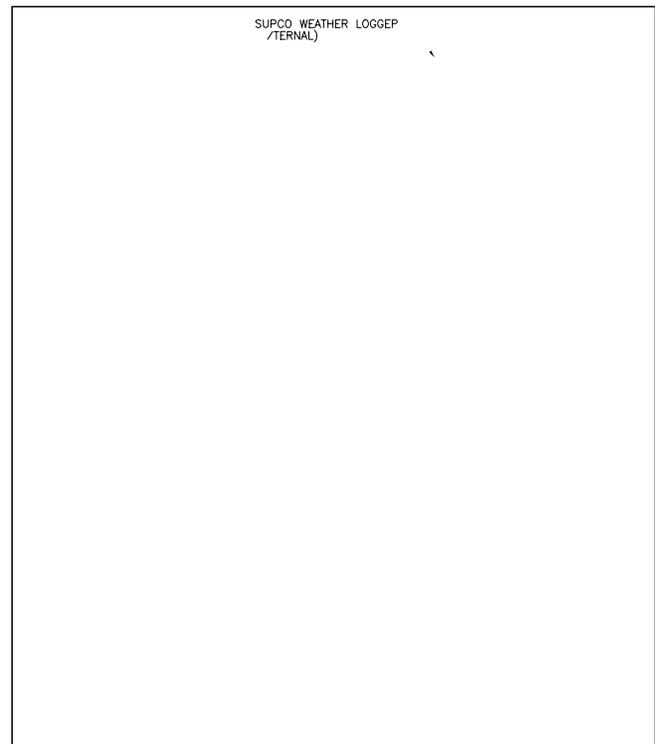


Figure 3. Plan view of Las Vegas test structure and adjacent construction activities

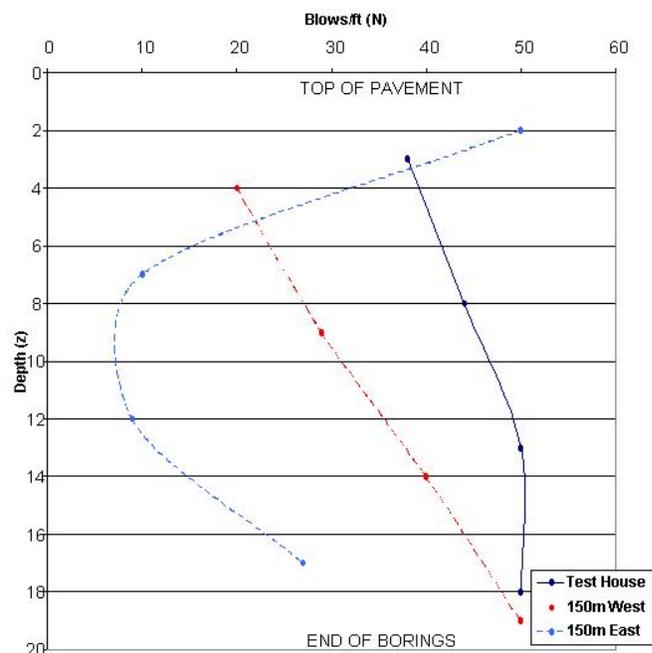


Figure 4. Blow count versus depth showing variation of standard penetration resistance for three borings.

Figure 4 is a plan of the 9 m by 18 m test house. The one-story house is 2.5 m high, floor to ceiling and is built on a slab-on-grade foundation with no crawl-space. The interior walls are constructed of gypsum drywall over a wood-frame and the exterior is covered with a southwestern-style stucco. The house is in generally good condition, with the majority of the cosmetic cracking in the

exterior stucco material. The roof is framed with a modified “W” truss of 2”x4” spaced at 0.76 m (30 in) centers. These trusses and associated ceiling joists are supported mid span by a central 2”x8” beam running the 18 m length of the house.

As would be expected for road construction, intense vibratory excitation was produced only when excavation took place directly in front of the house on 29 August. This excavation produced peak particle velocities between 0.04 and 0.08 inches per second, and maximum crack responses between 0.0 and 1.5 μm (0.0 and 60 $\mu\text{in.}$). Long-term environmental crack responses have been collected between June and November 2002 for this article. During the summer months weather conditions varied daily with out doors temperatures and humidity ranging greatly; 124.5° and 59.6° F and 70.3 to 1.7% respectively. Air conditioning moderated the indoor temperatures and humidity and restricted their range between 85.9° and 72.3° F and 38.1 to 13.9 %.

2.2 Instrumentation

Instrument locations are shown on the plan view in Figure 3. A tri-axial geophone block was installed approximately two feet from the South (construction) face of the structure to measure excitation ground motions in the longitudinal, transverse, and vertical directions. As with previous studies, the longitudinal direction is defined as parallel to the long axis of the structure. Four cracks were instrumented with LVDT micro-inch crack displacement sensors for this study. “Sensor 1” spans a ceiling crack; “Sensor 3” spans a nearby wall crack; and “Sensor 4” is the internal null gage adjacent to “Sensor 3”. Sensor 2, spans an exterior crack (shown in Figure 1) near the front door running vertically up the southern wall, which is the closest, parallel wall to construction along Ann Road. Sensor 5 was originally the external null gage until August 12th, 2002, when it was relocated to a second exterior crack on the west, transverse face of the house.

All of the crack sensors were wired in series with the geophone through a SoMat eDAQ data acquisition system. This eDAQ provides simultaneous triggering of crack sensors to record a three second time history (digitized at 1000 Hz) whenever vibration in any of the three geophone orientations exceeds a predetermined excitation, trigger threshold. In addition the system is programmed to record average crack responses over a period of one second every hour for long-term response. A third trigger type was programmed to account for the continuous vibratory motions expected from the trenching and

vibratory compaction. This third mode provided for recording peak crack displacements and ground motions each second to record continuously the general level of activity.

Hourly temperature and humidity were recorded internally and externally with independent Supco weather loggers. Data from these loggers were manually downloaded and correlated later with the field measured crack data.

2.3 Transient Response

Figure 5 compares time histories of the largest trackhoe induced ground motion (2 mm/s or 0.08 ips in the vertical direction) with internal and external crack sensor response. These motions and responses were generated August 29th during the excavation of the 3.6 m (12 ft) wide trench with an Hitachi 1200 EX Super track-hoe, the centerline of which lies parallel to and approximately 14 m (46 ft) in front of, the house. Displacement time histories of cracks 1, 2, 3, and 5 are shown at top while longitudinal, transverse, and vertical ground velocity time histories are shown at the bottom.

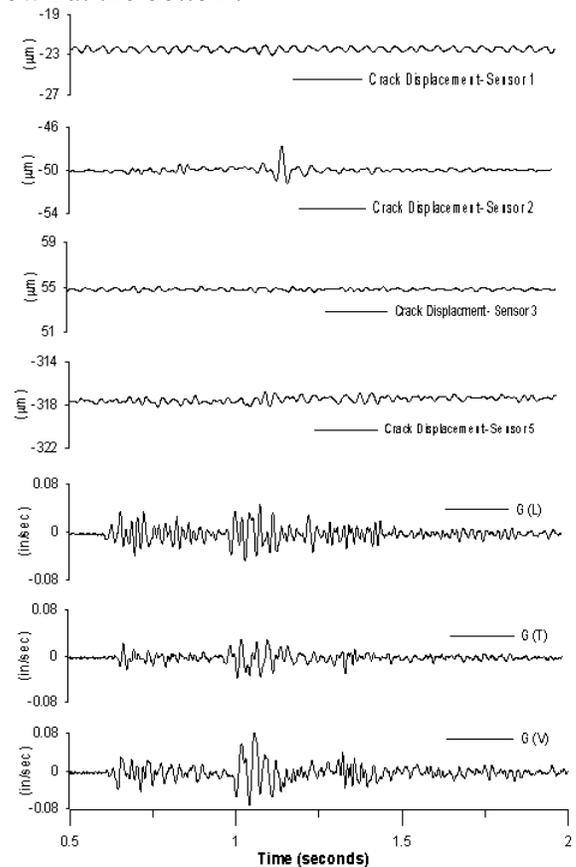


Figure 5. Time histories of crack displacement and ground velocity for trackhoe excavation.

Only Crack 2 on the external south wall experienced a response significantly greater than system noise; 1.8 μm (70 $\mu\text{in.}$) zero-to-peak. Sensor 5 shows a response only slightly greater

than the noise level; 0.6 μm zero-to-peak. Response of cracks 1 and 3 did not rise above the noise level. This electrical noise phenomenon is to be expected when the vibratory response is so low. Typical blast vibrations at this 2 mm/sec level produce crack responses that are 1.3 to 3 times as large as the responses in this case and thus large enough to exceed the noise level McKenna, (2002).

There are many reasons for the low response of the test house. First the excitation frequencies are high with respect to the natural frequency of the structure. As shown by the response spectrum in Figure 6 of the vertical component of the 2 mm/s event shows its dominant frequency to be 25 Hz (the peak in the response curve) with little to no energy in the 10 to 15 Hz range of the natural frequency of single story structures and walls. Second, the motions are very short, 0.1 seconds, with only 1 or 2 significant pulses. Third, the source is so close to the house that the arrival of motions is not uniform and thus entire structure is not excited homogenously.

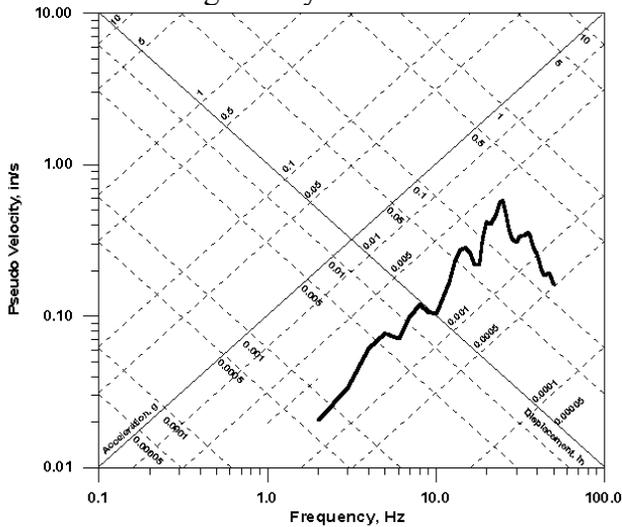


Figure 6. Single degree of freedom response spectra for ground motion induced by trackhoe excavation (7/12/02).

2.4 Long-Term Response to Environmental Effects

Figure 7 displays both long term and vibratory response of crack 2 over some 30 minutes during the early morning of 29 August. During this time of the day the August sun begins to heat the south wall, which in turn distorts the crack. In the course of just 30 minutes the crack width displaces or changes width by just under 25 μm (800 $\mu\text{in.}$). During this time there are a large number of excavation-induced events, each of which is indicated by the vertical spike on the graph. The largest vibratory displacement of crack 2 is ~ 1.5

m (60 $\mu\text{in.}$). Obviously the temperature-induced effects far exceed the vibratory effects.

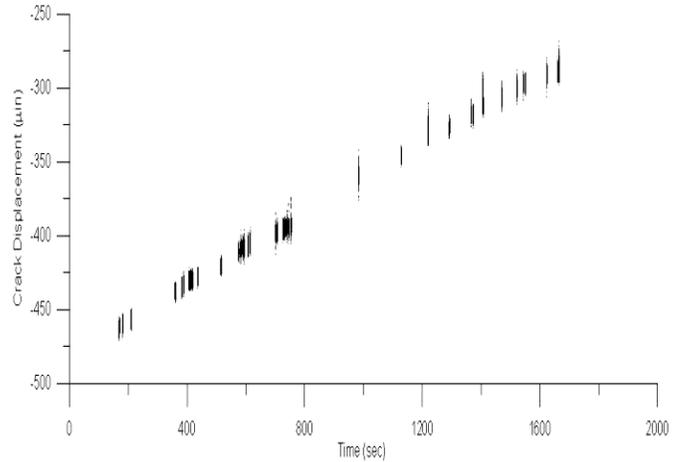


Figure 7. Long-term and vibratory response over 30 minutes on August 29th, 2002 during trackhoe excavation.

A multi-month history of the long-term environmental effects on crack 2 is shown in Figure 8. Here the crack displacement is compared with the change of temperature and humidity. The daily change is clearly visible. On August 29th, the crack displaced some 300 μm (12,000 $\mu\text{in.}$ or 0.012 in) peak to trough. In other words during one day the crack opened and closed some 150 μm from some median position. By reference to the horizontal line this median position (the 24 hour rolling average line) also changes over the course of the observation by some 80 μm (3000 $\mu\text{in.}$) as the result of changing weather fronts. Obviously, the maximum response of 1.8 μm zero to peak of crack 2 to the 2mm/s ground motion is insignificant compared to the silent, environmentally induced response.

Cracks respond most to a combination of humidity and temperature that is a function of framing details, wall covering, insolation, etc. The cause and effect relationships are obvious for this crack. Since it is exterior and faces south is will be highly influenced by sun induced temperature changes, which are large in the desert. Second, changes in humidity affect crack response through shrinkage and swelling of the mortar material as well as the wood to which the stucco is attached just as soil shrinks and swells in response to changes in moisture content. The interior of the house is air conditioned, which reduces the interior temperature and humidity changes and thus crack displacements of interior cracks relative to those outside. For instance on 29 August crack 3 only displaced 28 μm (1150 $\mu\text{in.}$) in response to daily environmental factors.

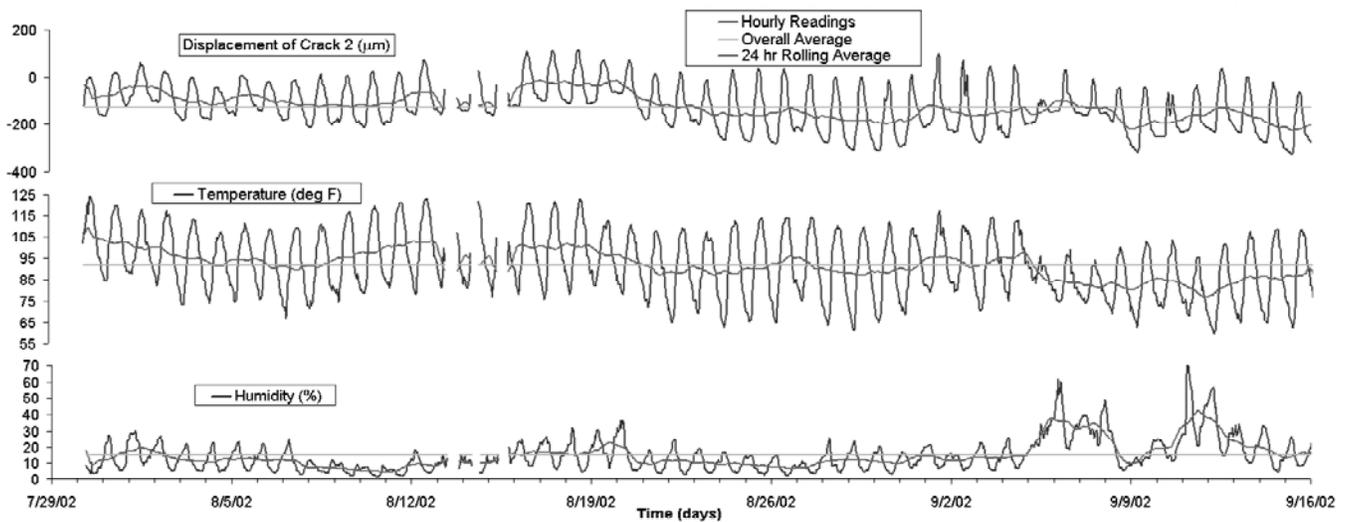


Figure 8. Long term crack displacement, temperature and humidity versus time

3 Web Access to Demonstration of ACM Approach

A web site is maintained by the Infrastructure Technology Institute at Northwestern University to demonstrate the ACM approach and provide background information. This site at <http://www.iti.northwestern.edu/acm> presents both active and archived graphical crack responses as well as papers that describe further details of ACM.

Conclusions

Changes in crack width are related to the potential for crack extension. This observation forms the basis for measuring changes in crack width rather than length.

Micrometer sensors can be deployed with the proper triggering software to measure both vibratory and long-term changes in crack width. Triggering software can be employed to obtain vibratory response from both episodic events such as blasts in rock as well as relatively continuous events such as excavation and vibratory rolling in soil. The ACM approach is not limited to a single family of transducers as evidenced by the reported response of LVDT transducers.

Long term changes in crack width occur slowly without noise or vibration and may be induced by

changes in environmental factors such as changes in temperature and humidity. Even in desert climates changes in humidity affect significantly the response of wood frame structures.

In this case involving close excavation in desert colluvium the long-term weather-induced crack response was two orders of magnitude larger than the vibratory, excavation-induced crack response.

References

- Dowding, C. H. (1996) Construction Vibrations, Prentice Hall Inc., Englewood Cliffs, NJ, 620 pp.
- Dowding, C.H. & Siebert, D (2000) "Control of Construction Vibrations with an Autonomous Crack Comparometer", Explosives and Blasting Technique, R. Holmberg, Ed. , A.A. Balkema, pp 103-110, September 2000.
- Louis, M (2001) "Field Authentication of Autonomous Crack Comparometer," M.S. Thesis, Department of Civil Engineering, Northwestern University, Evanston, IL, USA.
- McKenna, L (2001) "Comparison of Measured Crack Response in Diverse Structures to Dynamic Events and Weather Phenomina," M.S. Thesis, Department of Civil Engineering, Northwestern University, Evanston, IL, USA.
- Miller, R (1989) Analysis of the Fracture Process in Mortar Using Laser Holographic Interferometry, PhD Thesis, Department of Civil Engineering, Northwestern University, Evanston, IL, USA.
- Snider, M (2003) "Autonomous Crack Measurement of Construction Vibrations" M.S. Thesis, Department of Civil Engineering, Northwestern University, Evanston, IL, USA.