Autonomous Crack Measurement for Comparison of Vibratory Compaction Excitation and Climatological Effects

Pierre Abeel, Cathy Aimone-Martin, Charles Dowding

7th European Workshop on Structural Health Monitoring
July 8-11, 2014. La Cité, Nantes, France

AUTONOMOUS CRACK MEASUREMENT FOR COMPARISON OF VIBRATORY COMPACTION EXCITATION AND CLIMATOLOGICAL EFFECTS

Pierre Abeel[1], Cathy Aimone-Martin[2], and Charles Dowding[3]

[1] *Subsea 7, 17220 Katy Freeway, Houston, Texas, USA*
[2] *Aimone-Martin Associates, 1005 Bullock Ave, Socorro, New Mexico, USA*
[3] *Department of Civil & Environmental Engineering, Northwestern University*

c-dowding@northwestern.edu

ABSTRACT

Establishment of the fragility of historic structures near rights of way often produces costly delays in construction. Autonomous Crack Measurement (ACM) of micro meter response of cracks can be employed to assess the potential for adjacent construction activities to cause cosmetic cracking in both historic and non-historic structures. ACM measurement of micro meter crack width changes caused by long term climatological and vibratory roller compaction adjacent to an adobe (native mud brick) structure is employed to illustrate the use of micro meter changes in crack width as a tool for structural health monitoring.

It was found that long term or weather-induced crack responses are much larger than those induced by high frequency vibratory compaction, even at US and above European regulatory limits. At more typical levels the potential for formation of cosmetic cracks in newer adobe structures are negligible. Thus for this class of adobe structures, normal regulatory guidance is sufficient for construction or operation of transportation facilities.

KEYWORDS: micrometer crack response, weather, construction vibration, cosmetic

INTRODUCTION

The paper begins with a description of the use of changes in crack width as an index of the potential for crack extension or structural health monitoring. Description of the adobe structure and its excitation by vibratory rollers, producing ground motions of some 12 mm/s then follows. Performance of several micro meter displacement or proximity sensors used with the Autonomous Crack Measurement (ACM) system is then compared. Crack response produced by the vibratory rollers is then compared to that produced by climatological effects and conclusions are then made.

1 CHANGE IN DISTANCE ACROSS A CRACK IS AN INDEX OF POSSIBLE CRACK DEVELOPMENT OR STRUCTURAL HEALTH

Susceptibility of structures to cosmetic cracking from blasting and construction vibrations can be determined with localized measurement of micrometer changes in crack width. Change in crack width is an index for the potential for crack extension or development or structural health and is measured through the Autonomous Crack Measurement [ACM] system (Dowding, 2008). The logic of ACM system is similar to splitting wood with a wedge. Hammering the wedge into the wood increases the width of the crack, extends the crack, and eventually splits the wood. Thus comparing changes in crack width (or distance between sensor and target- i.e. displacement) provides a comparison of the potential

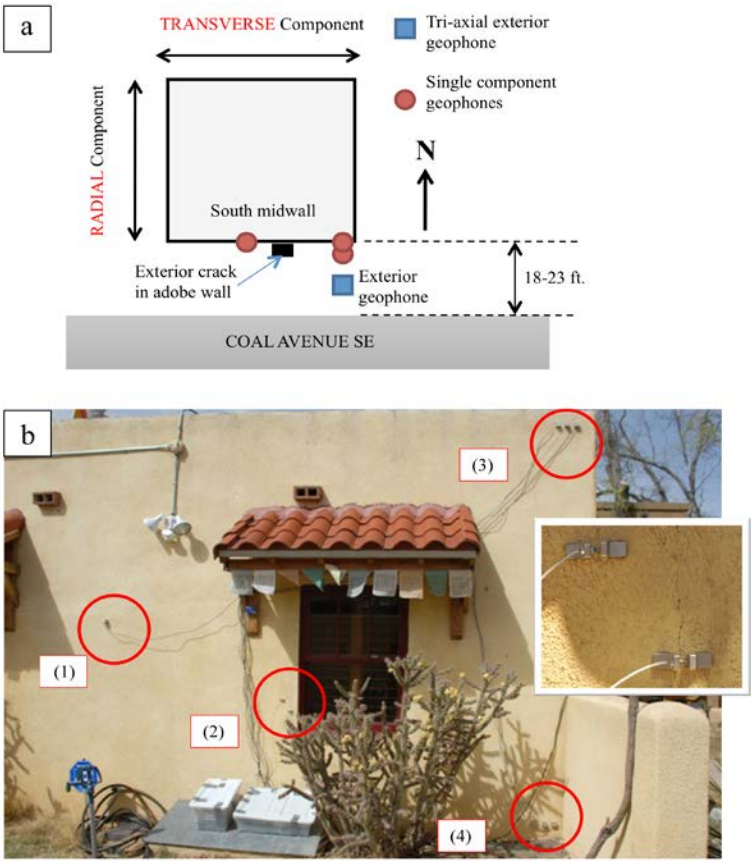

Figure 1: (a) Instrumentation on south wall of the adobe house and vibratory compaction 5.5-7.0 m (18-23 ft) to the south. (b) locations of (1) midwall, (3) upper (4) bottom velocity transducers, and (2) crack sensors.

for crack extension (or in this case crack appearance). This analogy is similar to the observation in fracture mechanics that increasing crack mouth opening increases crack length.

Just as splitting wood requires the "V" from the wedge to be progressively widened by the wedge, crack width must increase beyond its previous maximum for the crack to extend. It is unlikely that measurement of crack width in a structure under observation would begin at the previous maximum width. Thus the question then becomes, "what outside effects produce the largest change in crack width (or in this case displacement across a weakness)?" Those changes are the most likely to extend cracks (or in this case initiate a crack). It also stands to reason that cyclic response at widths smaller than the maximum will not extend the crack.

Two types of crack response are recorded, long-term and dynamic, in order to compare long term, climatological response to the short term dynamic, or construction vibration response. Herein after changes in crack width will be called crack response. The ACM system allows the same micro meter displacement sensor to measure both long and short term response.

- Long-term response is obtained by measuring crack response once every hour. These single points are averages of 1000 samples obtained at 1000 samples per second (sps)
- Dynamic response is obtained by measuring crack response, ground and structural velocity, and air overpressure at 1000 sps for 3 seconds when triggered during dynamic events, with a 0.5 second pre-trigger.

2 EXAMPLE STUDY OF ADOBE HOUSE CRACK RESPONSE DEMONSTRATES USE OF ACM SYSTEM

Response to vibratory roller excitation of a crack in the 80 year old adobe (mud and straw brick) house in Albuquerque, NM shown in Figure 1 will be used to describe use of the ACM system. The vertical crack in the exterior stucco wall beside the window is shown in the insert. While response was monitored only from April 7 to 18, 2011, it is sufficient to compare construction-induced dynamic crack responses with those induced by changes in temperature and humidity. Normally cracks should be monitored for at least six months to observe the results of seasonal effects (Dowding, 2008)

Figure 1 also shows instrumentation at the structure. Velocity transducers were placed in the upper corner (S2), lower corner (S1) to measure horizontal motions in the radial (R, north) and tangential (T, east) and vertical (V). Another horizontal sensor was mounted at the center of the south wall (mid-wall, MW) to measure motions in the R direction (perpendicular to the wall). A LARCOR multi-component seismographs were used to record data from velocity transducers as well as excitation motions from a tri-axial geophone buried in the ground near the southeast structure corner 6.7 m (22 ft) from the road. Stucco crack responses to construction activities and variations in climate conditions (temperature and humidity) were measured with two (crack and null) Kaman eddy-current mico-meter displacement sensors, which were interrogated with a SOMAT field computer. LARCOR and SOMAT units were simultaneously triggered by the ground motion geophones. Temperature and relative humidity were recorded using a SUPCO data logger.

3 ACM SYSTEMS CAN EMPLOY A VARIETY OF MICROMETER DISPLACEMENT SENSORS

Kaman, eddy current micro-meter displacement sensors employed in this example are one of three types that have been employed in ACM systems. The others are LVDTs and string potentiometers, and are compared to scale in Figure 2. Operating parameters of the Kaman gages include: displacement monitoring range of 0.5 mm (0.02 in) , output voltage range ± 5 volts, resolution of 0.1 micro-meter (4 micro-inch), and frequency response of 10,000 Hertz (Hz). Attributes of micro meter displacement sensors employed in this work have varied. Among other attributes of importance are noise, sensitivity, range, need for power supply, and cost. Eddy current sensors cost some $1500 US while the LVDT and potentiometer cost some $150 US. Potentiometers do not require a power supply and thus are the most likely candidate for wireless sensors.

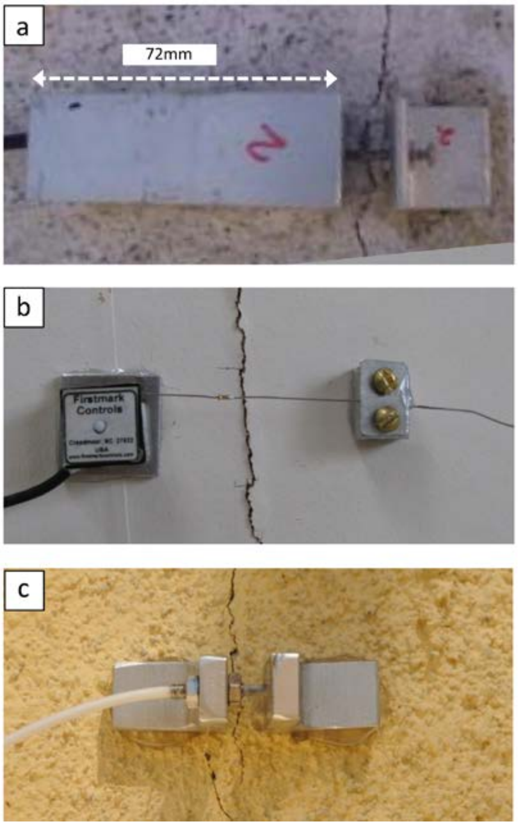

Figure 2. (a) LVDT, (b) string potentiometer, (c) eddy current displacement sensors employed with ACM systems as shown to scale as affixed across various cracked surfaces.

Ozer (2005) compared the dynamic response of the three types of sensors through a laboratory dynamic test. This study revealed the following comparisons for the eddy current, LVDT and potentiometer: when operated with similar ranges and resolutions: zero to peak noise is; 0.15, 0.2, 2.0 μm respectively with comparable amplitudes. E ddy current sensors served as the basis of comparison. In the field, noise levels can rise without proper grounding. For instance LVDT noise in the field has been observed to rise to 0.3 to 1 μm as wiring distance increases from 10 to 30m (Koegle, 2012). This noise occurs at 60 Hz in the US, and can be filtered because structural response frequencies are less than 30 Hz.

Null sensors measure response of the sensor itself and wall materials to climatological effects (temperature and humidity). Null responses are subtracted from the crack responses to zero out (or "null") sensor responses. It has been found (Dowding 2008) that null sensor response is so small compared to crack response, it need not be considered.

4 COMPARISON OF CONSTRUCTION AND CLIMATOLOGICAL CRACK RESPONSE

Ground and structure motions were recorded during roller compaction of the road adjacent to the house on April 18, 2011. Peak vibratory roller excitation ground motions and their dominant frequency measured at the house are compared in Figure 3 to safe vibratory (blasting) controls adopted by US regulatory agencies (Siskind, at al 1980) to prevent even cosmetic, hair-sized cracking. The highest amplitude was 0.48 in/s (12 mm/s) with a frequency of 32 Hz falls below the guidelines, although it exceeds European standards. The single story super structure with a fundamental frequency estimated to be ~ 10 Hz did not respond to the high frequency excitations as S1 and S2 T motions were 3 and 6.6 mm/s (0.11 and 0.26 ips) compared to the 12 mm/s (0.48 ips) motions.

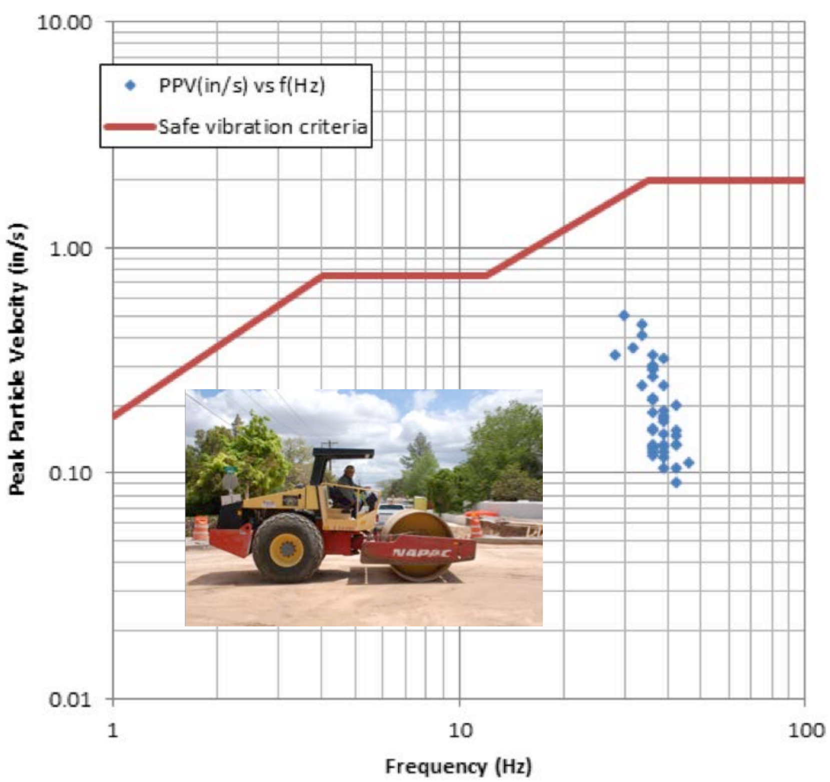

Figure 3. Peak particle velocity vs. frequency produced by vibratory rollers compared to control limits for the threshold of cosmetic cracking in the United States (Siskind et al, 1980). 1 in/s = 25.4 mm/s

Of the 54 passes of vibratory rollers, 4 typical events were studied in depth. Table 1 compares crack response and the ground vibrations for these 4 events. These events present the clearest dynamic response all around, as well as the largest crack displacements. They account for the use of two different machines, as evidenced by the change in excitation frequency. Table 1 also presents calculated dynamic strains, both in- and out- of-plane, induced in the structure by the vibratory compaction. Strains are compared to the micro meter crack response as well as the differential or relative wall displacement and the ground vibration velocities. The highest strain levels 14 μ m (595 μ in) were induced by the highest vibratory compaction excitation, 12 mm/s (0.48 in/s) on April 18th (event #1). Both in shear and bending strains were calculated from relative displacements (Abeel, 2012) and compare well with previous observation and analysis of other vibratory roller excitation (Snider, 2004).

Table 1. Comparison of peak excitation ground velocity, maximum differential wall displacements (calculated from integrated velocity time histories), measured crack opening and calculated strains (in plane shear and bending) as well as out of plane bending strains. 1 in. = 25.4 mm, 1 in/s = 25.4mm/s.

Event #	Shear (μstrains)		In-plane tensile (μstrains)		Bending (μstrains)	Maximum crack opening	Maximum differential wall displacement, S2-S1 (10^{-3}in)		Maximum ground velocity (in/s) (zero-to-peak)		
	South wall	East wall	South wall	East wall	South wall	(μinches) (peak to peak)	Radial (NS)	Transverse (EW)	[T]	[R]	[V]
1	33.72	28.87	14.93	11.79	13.95	595.5	2.934	2.512	0.11	0.48	0.14
2	27.88	26.00	12.34	10.62	11.53	108.6	2.425	2.262	0.12	0.13	0.08
3	6.68	2.83	2.96	1.16	2.76	103.6	0.581	0.246	0.024	0.116	0.055
4	3.78	7.25	1.68	2.96	1.57	255.7	0.329	0.631	0.040	0.085	0.070

The magnitude of induced strains in structure components ultimately determines the likelihood of cosmetic cracking. Global or whole structure shear strains leading to in-plane tensile wall strains and mid-wall bending strains arise from corner distortions and wall flexure. They are computed for the largest external ground motion excitation and compared with failure strain levels required to cause cosmetic cracking in wall covering materials. For example in-plane shear and tensile strains can be calculated by dividing the relative (top minus bottom) in-plane displacement, δ_{max}, by the height of the wall. Velocity time histories measured at structure corner locations S1 (lower corner) and S2 (upper corner) are integrated to obtain displacement time histories. The difference between the time histories are computed and the largest time-correlated difference, δ_{max}, between corner responses (S2 minus S1) is found. Computation of out of plane bending strains requires more space than available to explain but is based upon the same use of the proper relative wall displacements (Dowding, 1996).

Failure strains of construction materials under dynamic loading have been long studied. The range of failure strains in the gypsum core of drywall is 300 to 500 micro-strains (Dowding, 1996) while for plaster it can be as low as 200 micro-strains. The maximum observed in-plane tensile strain of some 15 micro-strains in the south wall during vibration is well within the safe limits to prevent cracking.

Seven seconds of radial excitation and response motions are compared in Figure 4. The net crack response is placed at the bottom of the figure. Crack response (bottom) matches most closely in time the difference between the midwall and the average of the top and bottom response (second from the top). In other words the crack responded to the response of the wall, whose fundamental or natural frequency (15 to 25 Hz) more closely matches the excitation frequency of 30 to 40 Hz.

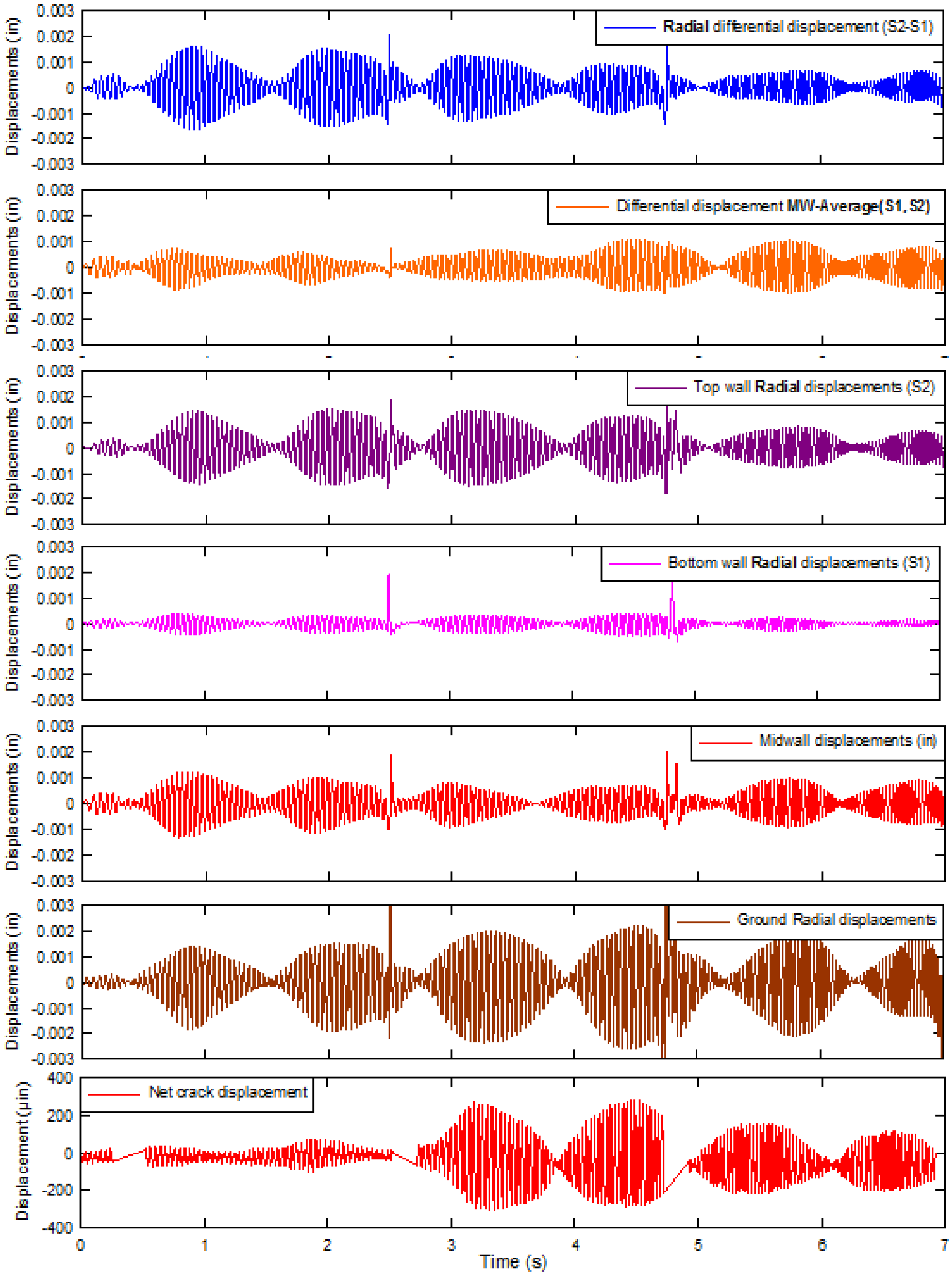

Figure 4. Comparison of displacement response from integration of velocity responses (middle 4 graphs), differential wall displacements (top two graphs) and the crack sensor (bottom). 1 in. = 25.4 mm

The time history of the vibratory crack response motions is compared to five days of climatological crack response in Figure 5. Compared are the daily variation of the temperature (top), humidity (middle) and crack response (bottom). The crack is heavily affected by the temperature of the south facing wall. Seven seconds of vibratory response from Figure 4 are shown at the bottom of the figure. Vibratory crack response ~15 μ m (600 μ in) is small when compared to that induced by the weather ~ 124 μ m (5000 μ in) as shown by the arrow defined insert of the vibratory response in the long term crack response. This almost 10 fold difference is typical of the comparison of vibratory and climatological responses as described by Dowding (2008).

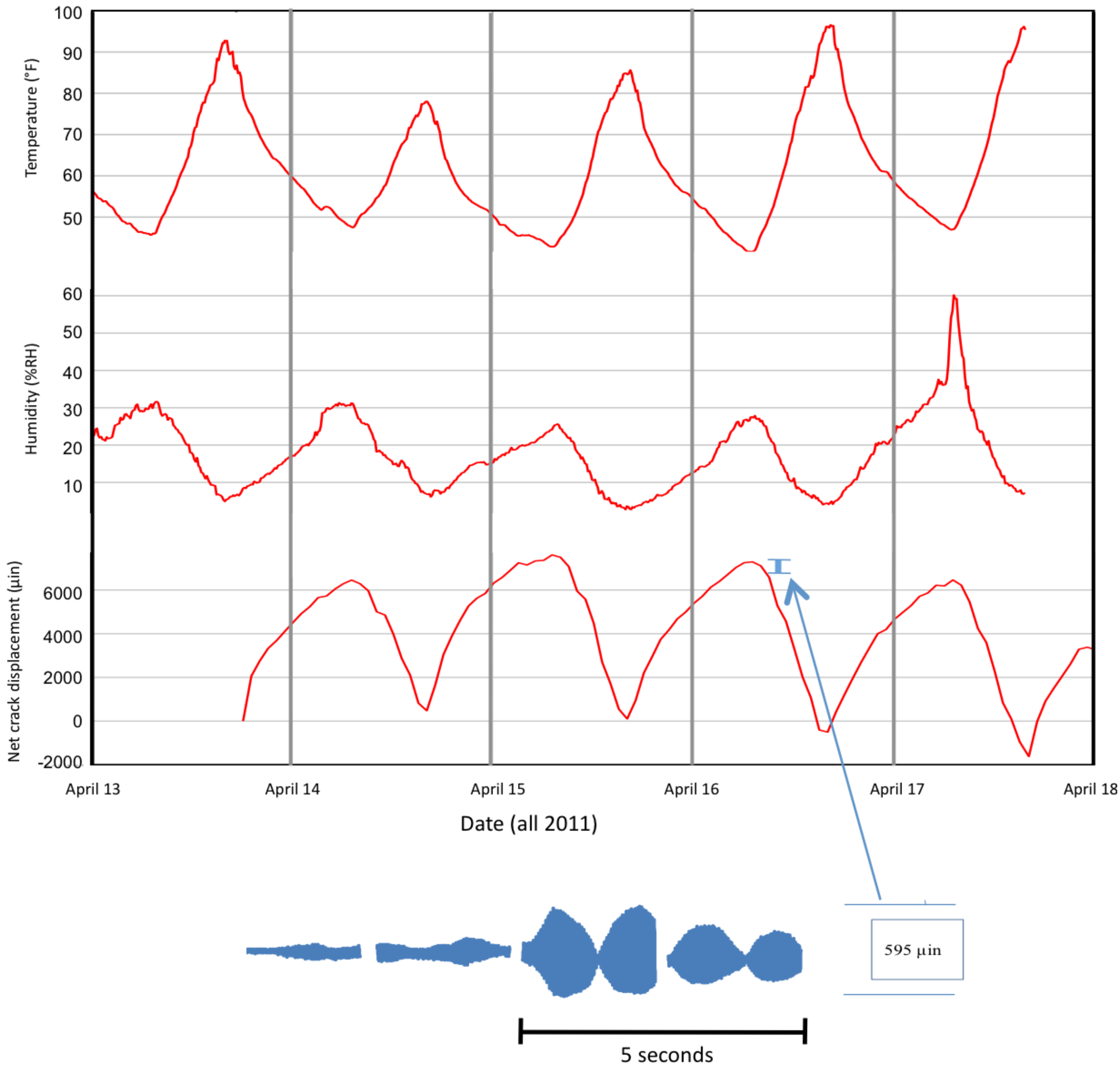

Figure 5. Comparison of long term temperature, humidity, and net crack displacement over 6 days (top 3 graphs), with dynamic crack displacement (inserted in long term crack response in the bottom long term graph) shows greater influence of long term climatological effects. 1 in. = 24.4 mm & °F – 32 = 5/9 °C.

CONCLUSIONS

Observation of structural and crack response over a period of a week during which vibratory rollers compacted an adjacent road showed that the influence of temperature and humidity is some 10 times greater than vibratory excitation. This low crack response occurred despite ground motions that exceed European standards. Strains computed from measured structural and wall response strains are some 20 times lower than expected failure strains.

This and other studies show that large weather-induced effects contribute the most to crack response. Thus they are the most likely to produce cosmetic cracking in structures.

REFERENCES

[1] Abeel, P.A. (2012) *Building and Crack Response to Blasting Construction Vibrations and Weather Effects,* MS Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL[1].

[2] Dowding, C.H (1996) Construction Vibrations, Prentice Hall. Saddle River, NJ. 405 pgs. Now available through Amazon.com.

[3] Dowding, C.H (2008) Micrometer Crack Response to Vibration and Weather, International Society Explosive Engineers, Cleveland OH. 400 pgs.

[4] Koegel, T. (2011). Comparative Field Qualification of ACM and ACSM Systems at Sycamore, IL. ITI Internal Report, Northwestern University, Evanston, IL[1].

[5] Ozer, H. (2005), *Wireless Sensor Networks for Crack Displacement Measurement*, MS Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, Illinois[1].

[6] Siskind, D. E., Stagg, M. S., Kopp, J. W., & Dowding, C. H. (1980). RI8507 - Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting. U. S. Bureau of Mines.

[7] Snider, M. L. (2003). *Crack Response to Weather Effects, Blasting, and Construction Vibrations,* MS Thesis, Department of Civil & Environmental Engineering, : Northwestern University,Evanston, IL[1].

[1] These theses and reports as well and others supporting the book, Micrometer Crack Response to Vibration and Weather, as well as raw data sets of climatological and vibratory crack response are available at http://www.iti.northwestern.edu/acm/.