MICRO-METER MEASUREMENT OF CRACKS TO COMPARE BLAST AND ENVIRONMENTAL EFFECTS.

Charles H Dowding,
Professor of Civil & Environmental Engineering, Northwestern University
Micheal Louis
Staff Engineer, Reinforced Earth Co. Atlanta, GA

ABSTRACT: Concern over construction vibration-induced cracking has led to development of a new approach to vibration monitoring called autonomous crack measurement (ACM) and illustrated in Figure 1. This paper describes the concept as well as sensor performance in the first test house fitted an ACM system. Response of three cracks in this concrete masonry unit (CMU) house was measured as part of the system verification. ACM employs a single sensor that measures both weather-induced micrometer changes in crack width and those produced by habitation and ground motion-induced vibration. This comparison is displayed in real time via the Internet without human interaction. Graphic display through the Internet provides a new pathway for communication with the public. Such visual comparison of changes in crack width provides a simple alternative to the present system of comparison of measured and allowable vibration time histories. Measurements reported herein show that weather-induced response of cracks is greater than that caused by presently allowable construction-induced vibration.

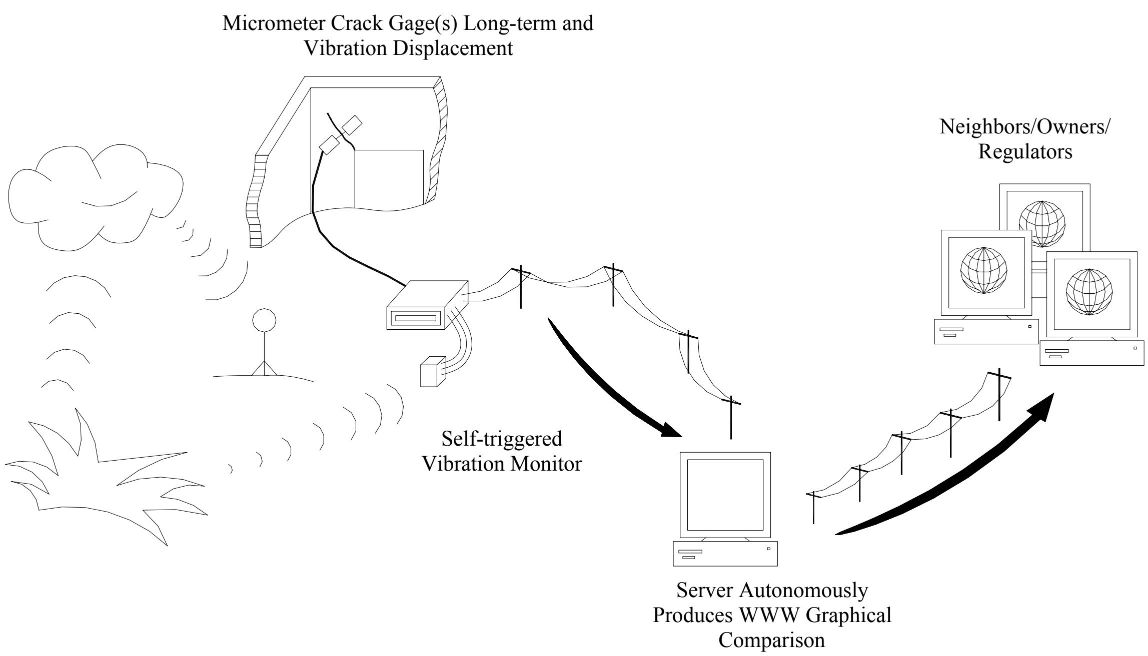

Figure 1 AUTONOMOUS CRACK MEASUREMENT
Automatically produces graphical comparisons of vibratorally and environmentally-induced crack displacement, which are accessible to interested parties via the Internet.

ADVANTAGES OF ACM TECHNOLOGY AND MARKET POTENTIAL

Autonomous Crack Measurement (ACM) illustrated in Figure 1 (Siebert, 2000 and Djowding and Siebert 2000) combines three technologies not heretofore integrated: micrometer measurement of crack response, digital seismographic technology and Internet communication for autonomous. Autonomous operation and Internet delivery increases public access to data, which should lead to a greater public appreciation of the relative effects of the forces affecting crack response.

Dual purpose sensors directly measure crack response, the issue of concern to the public. Rather than measure only ground motion, which in turn is correlated with the results from previous studies, crack behavior is also measured directly. This direct measurement is simple to understand and requires no reliance upon previous work by others or understanding of the physics of ground motion. Most importantly, the same device, when placed across a crack can be employed to measure changes in crack width that result 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 effect of environmental changes.

A number of these systems have been deployed. The Infrastructure Technology Institute at Northwestern University (ITI) has deployed 4 systems in two stages of ACM operability. Vibration monitoring instrument OEM's are have either built or are considering building systems for manual downloading of data. Systems with manual downloading have been employed in an Office of Surface Mining study of atypical structures. In the near term, the number of deployed instruments should increase by 50% each year for the next five years or so.

MICROMETER CHANGES IN CRACK WIDTH

As shown in Figure 2, the sensors measure changes in crack width rather than total crack width. Monitored cracks change width during various events that are described in greater detail throughout this paper. From this point on, this change in crack width will be referred to as displacement

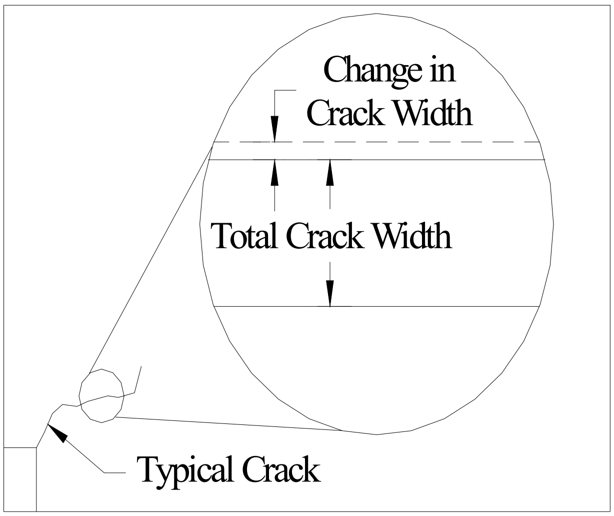

Figure 2 Definition of the change in crack width hearafter called crack displacement.

Micrometer crack displacements can be measured with a variety of proximity sensors. These sensors are able to respond statically as well as dynamically. Thus the same sensors are able to measure micrometer displacements produced by both long-term changes in temperature and humidity as well as dynamic, construction-induced vibration excitation. So far a specific model of eddy current sensors and a wide range of LVDT's have been found acceptable for use (Louis, 2000).

Micrometer Displacement Sensor Requirements

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 may 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 micrometers (0.000120 inches). 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. Total displacement of cracks during the heating season may reach several 1/10's of a mm (100 micrometers). Since not all cracks behave the same, the range should be extended +/-200 micrometers or a measuring range of 400 micrometers. If the displacement sensor is installed at the middle of this range it will be able to follow movements of +/-200 micrometers.

Null Sensor Compensation of Drift and Hysteresis

In the field, drift and thermal hysteresis are compensated through the use of a null displacement sensor attached to an un-cracked section of wall next to the crack displacement sensor. The null sensor and its' mounting should be identical to the displacement sensor over the crack except that it is not placed over a crack, but as close as possible. All geometry should be the same on both sensors. If the temperature increases, continuous material on which null sensors are mounted expands, and the sensor will separate from its target. On the other hand for a sensor spanning a crack undergoing an increase in temperature, material on either side will expand toward each other and the sensor will approach its target. This opposite movement of the null sensor should be subtracted to obtain the actual crack movement. Furthermore, any other response of the null should be subtracted from the crack sensor's, as the null's crack response should be zero. The advantage of the null sensor is that the temperature does not need to be recorded to correct for effects, such as the mounting bracket material around the crack, electrical drift or thermal hysteresis.

TEST HOUSE DESCRIPTION WITH SENSORS LOCATIONS

House Description

The Test House shown in Figure 3 backs up to a limestone aggregate quarry near Milwaukee Wisconsin. Blasting occurs some 600 meters (2000 feet) away and during the period of study produced ground motions with peak particle velocities of 0.04 to 0.13 inches per second (ips) with dominant frequencies of 10 to 40 Hz. The side yard of the one-story house slopes down to allow the basement to open out to a backyard one story below the front yard as shown in the insert. The adjacent garage is attached only at the roof.

Figure 3 Test House Front and Rear Views

The exterior stone covers the exterior CMU walls, which are in turn faced in the interior with gypsum drywall. Interior walls are constructed with 2 x 4 wooden studs and faced with drywall. The first floor joists are supported by a wooden principal beam that runs the length of the basement, left to right in the plan and elevation views in Figure 4. Except for the computer room, the first floor ceiling is supported by transverse wooden joists which are supported at the center by a wall that sits on top at the support beam.

Displacement sensor locations in the house

Three eddy current crack sensors (Kaman SMU 9000) span three different cracks and a null sensor is mounted on an un-cracked wall section as shown in Figure 4 in the plan and elevation views. Sensor 1, shown on Figure 5, is mounted at the upper corner of the opening in the wall between the living room and kitchen. It spans a crack that seems to be created by expansion and contraction of the beam supporting ceiling joists above the wide opening between the two rooms. Sensor 3, also shown on Figure 5, is located at the upper corner of the opening separating the entrance hall and the living room. This sensor also spans a crack that seems to be caused by expansion or contraction of the beam spanning the opening. Sensor 2, spans a ceiling crack in the computer room that is located mid span of the ceiling joists above. The null sensor, as shown in Figure 4, is located above the door separating the main entrance hall and the computer room on an uncracked wall section. It was mounted in that location to be as close as possible of the other sensors and at approximately at the same height on the wall.

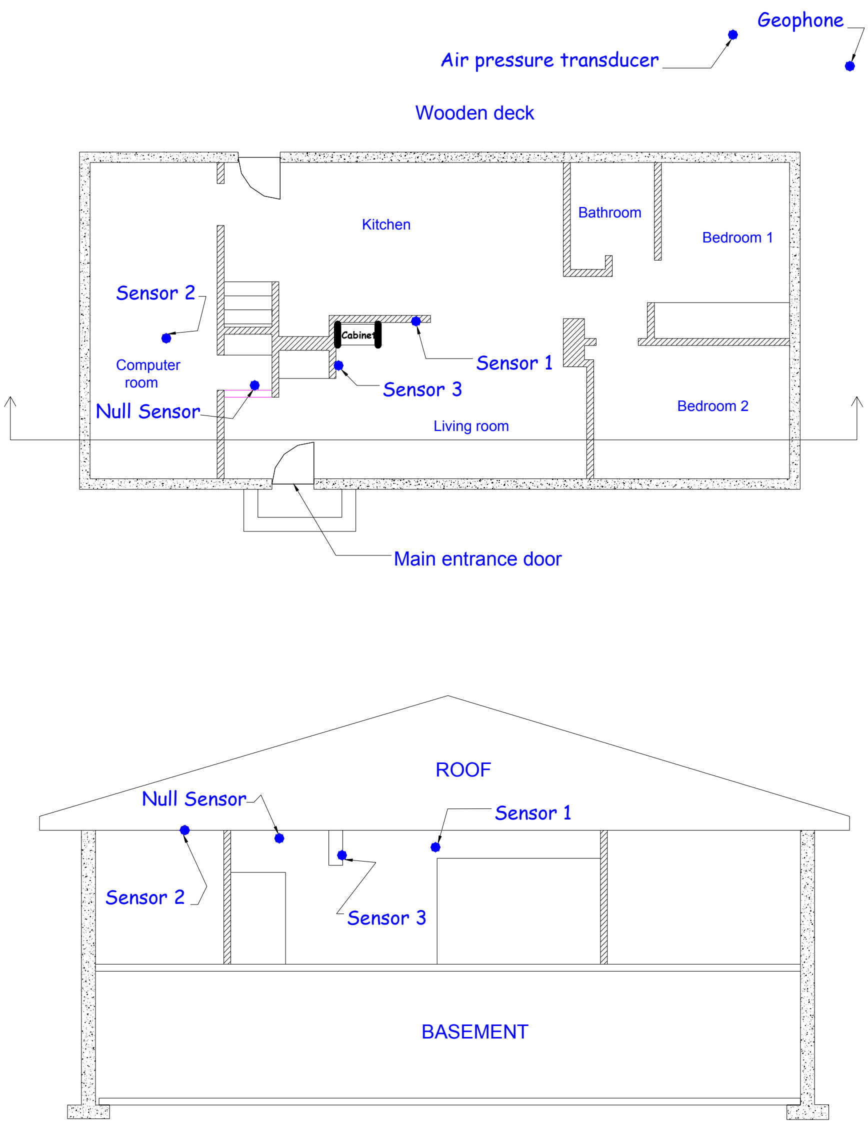

Figure 4 Plan and Elevation views of the test house

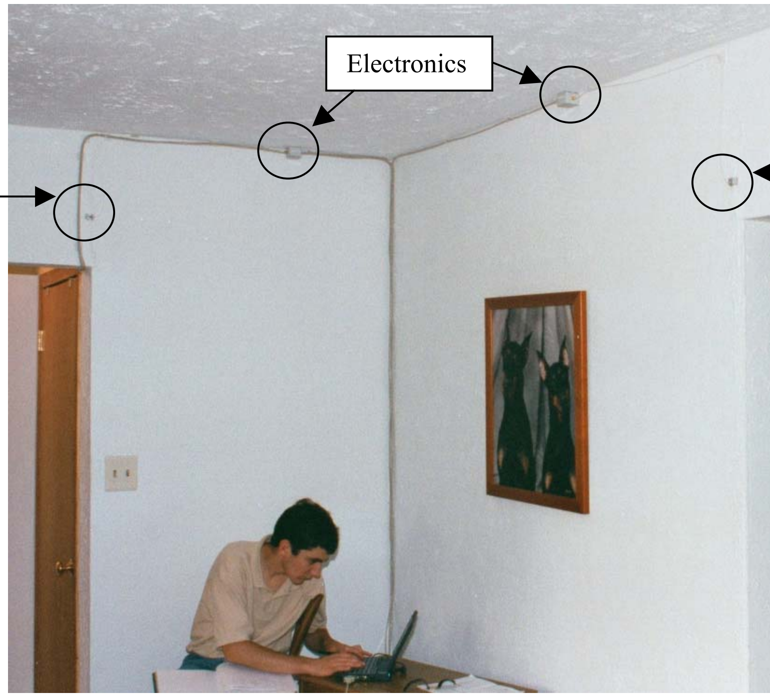

Figure 5 General geometry of crack sensors 3 and 1

CRACK SENSOR CORRECTION WITH NULL SENSOR

While it seems intuitive that crack displacement data may need to be corrected to compensate for thermal hysterisis and an electronic drift of the measuring device, it appears that this correction is small compared to the environmentally induced changes in crack width. Thermal hysteresis is produced by material expansion that includes brackets, plaster and epoxy volume variations. Drift would be the wandering of the voltage associated with the initial measurement. Both of these affects can be compensated with a null sensor placed on an un-cracked section of the wall near the crack sensor. Readings of the null sensor are subtracted from the crack sensor to “null” out instrument response.

Figure 6: Crack 3 Response Corrected for Null Response Showing Relatively Small Effect of the Null Response

Figure 6 compares crack 3 response with that of the null sensor for a 60 day period in the Fall of 2000 with highly variable temperature and humidity. The null response is approximately 1/5 to 1/10 that of the crack sensor, and is thus negligible. To show how little difference the correction makes, the null response is subtracted from the sensor response and is shown as the dotted line in the upper half of Figure 6. For example consider the large response caused by the passage of a weather front during the second week in October. Crack 3 closed some 70 micro meters respectively while the null increased by only 15 micro meters. In this case the null correction increases the crack response. As the test proceeds, the null response and hence its correction declines in significance as shown by the declining difference between the sensor response and the corrected sensor response.

Null sensor behavior in a blast event

During a dynamic event, there should be negligible response in the null sensor. Figure 7 compares time histories of the three crack and null displacement sensors with the "L" component of the ground motion with a peak particle velocity of 0.13 ips. Crack response returns to the initial displacement and the null sensor shows virtually no transient displacement. There are small oscillations around zero (not visible at the scale), that are a result of electrical noise.

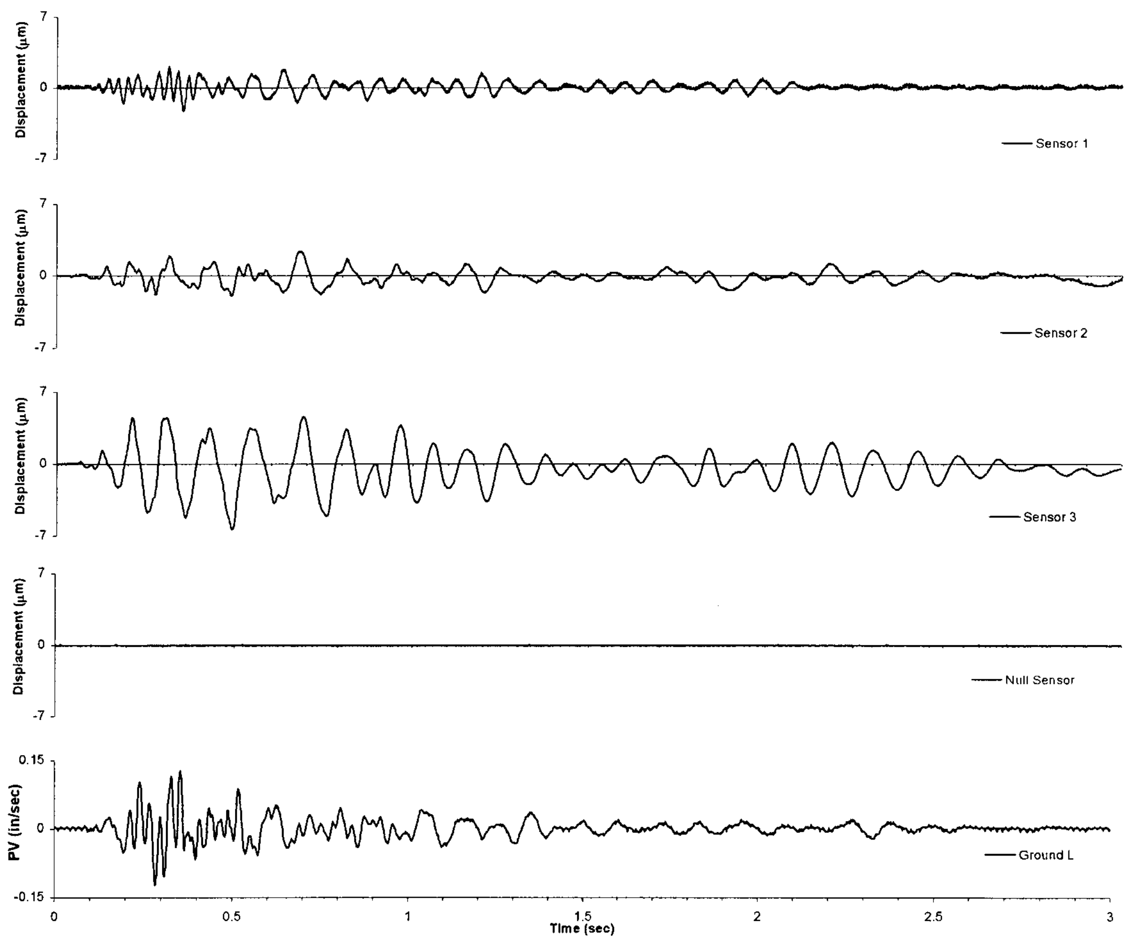

Figure 7 Time histories crack response and ground motion response for blast event oct0-13 for comparison of dynamic response of null sensor

CRACK DISPLACEMENT VERSUS WEATHER AND OTHER ENVIRONMENTAL FACTORS

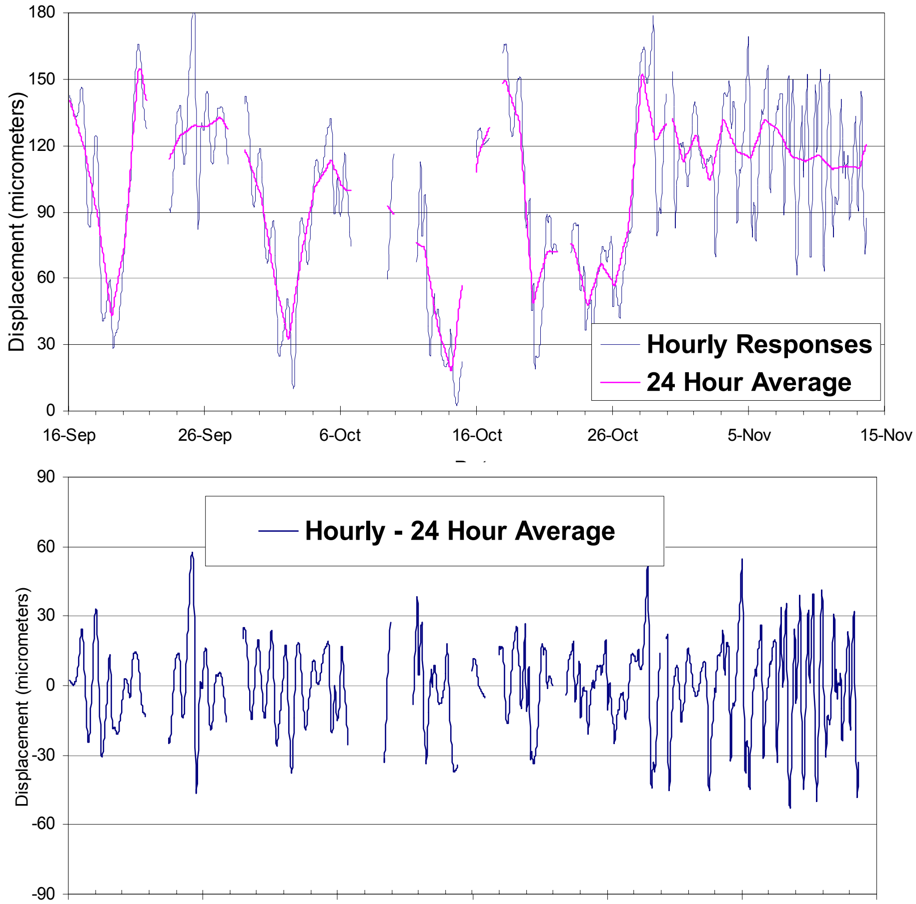

Figure 8: Comparison of Crack Response to Weather Front and Daily Environmental Effects.

Crack response to daily and weather front changes in temperature and humidity can be separated as illustrated in Figure 8 for crack 2 during the study period. In the upper half the 24 hour moving average is compared with changes in crack width measured every hour. Weather front influences are the differences between the “24 hour average” and the overall average during the observation period, which is around 105 micrometers. Thus the weather front that passed by in the second week in October, produced a 70 micro meter response. The daily effects are then filtered from the total response by subtracting the “24 hour average from the total as shown in the lower half of Figure 8. Table 1 summarizes results of this procedure for the three cracks. The table also compares daily and weather front crack displacement with the maximum blast induced displacement. The maximum peak particle velocity (PPV) in Table 1 was associated with the event that produced the maximum displacement for the crack.

		Crack 1	Crack 2	Crack 3
Daily changes	Average	7	24	12
	Std deviation	4	14	8
Weather front changes	Average	14	50	20
	Std deviation	7	16	14
Maximum household activity		3	2.5	3.5
Maximum blast-induced crack displacement		4	7	9
Maximum associated PPV (in/sec)		0.09	0.08	0.09

Table 1 Weather changes effects on the crack displacement in micrometers

COMPARISON OF ENVIRONMENTAL AND BLAST CRACK RESPONSE

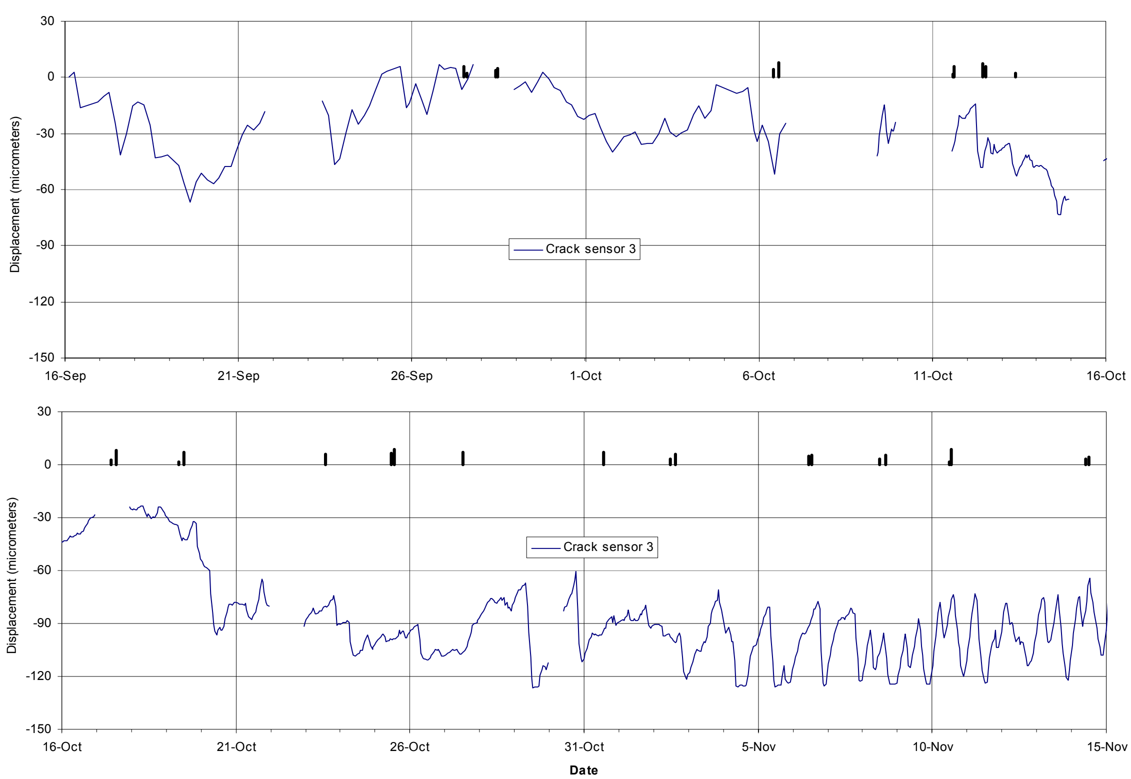

Figure 9: Comparison of Long-Term and Vibratory Response of Crack 3

Comparisons of the environmental and blast effects are presented in Figure 9 for crack 3 as it is the most responsive to vibration excitation. Blast induced responses are shown by the vertical bars plotted along the zero line. Each event is plotted as a single bar. The height is equal to the maximum "zero to peak" displacement response. As discussed before the long term response to weather and heating effects is the undulating line. Comparisons for the other two cracks are contained in Louis's thesis (Louis, 2000). During this period dynamic crack displacements produced by blast-induced ground motions are insignificant compared to displacements produced by environmental effects. This dominance of environmental effects is even more pronounced for the ceiling crack (2), which is greatly affected by weather changes (see previous section) but less by blasting.

Figure 10 compares the maximum induced-blast crack displacement with that caused by daily and the longer term weather front environmental changes for this house and that reported by Dowding (1996) in the book Construction Vibrations (labled "Book" in the Figure)

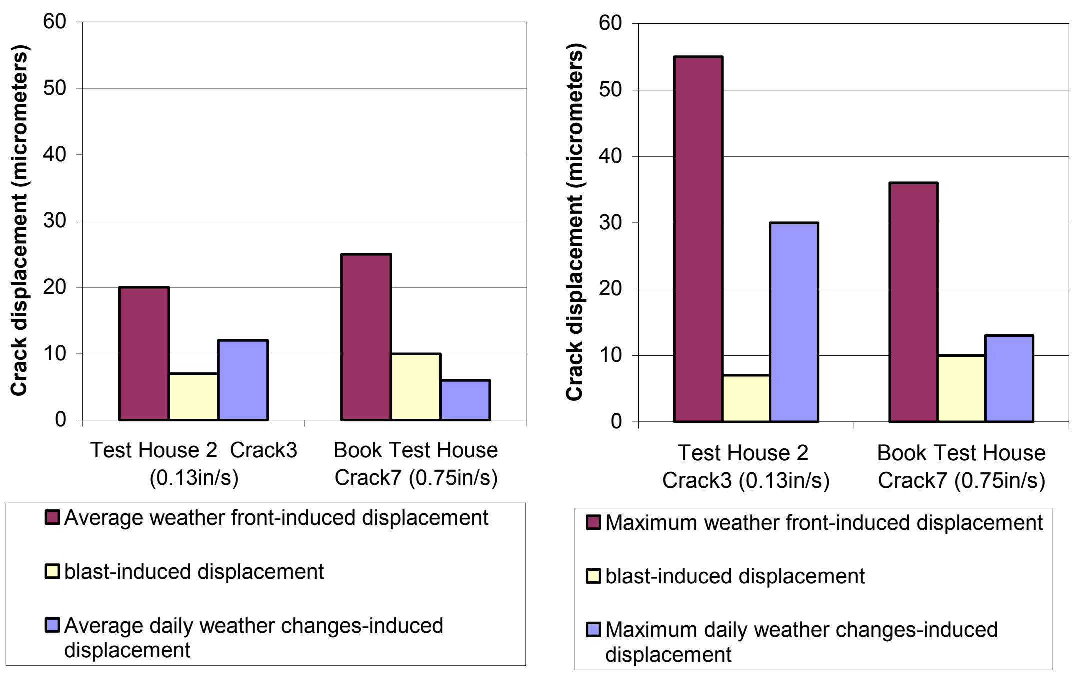

Figure 10 Comparison of Average and Maximum Weather Front and Daily Environmental effects with Those of the Maximum Vibration Effect

Daily and longer term or weather front environmental changes greatly affect crack displacement for both houses. Furthermore they produce larger crack displacements than does blasting, even with relatively high ground motions. The “book” house was subjected to a maximum PPV of 0.75 ips while the test house was subjected to 0.13 ips. Even the *average* weather front induced-crack displacement is 2.5 and 3 times greater than the *maximum* blast-induced displacements for the “book’ and test house, respectively. The *maximum* weather front effect is even more significant and is 8 and 3.6 times the *maximum* blast induced response.

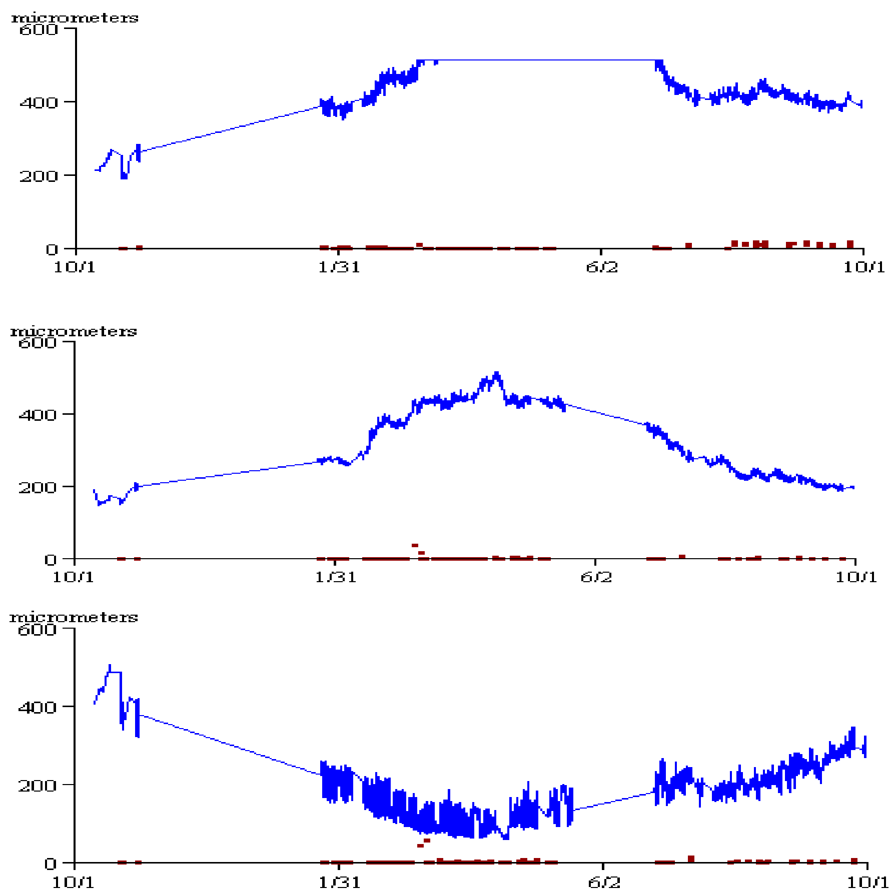

Figure 11: Year-Long and Vibratory Crack Response Comparisons Shows that Long-Term Effects Are an Order of Magnitude Greater than the Maximum Vibratory Effects. Top: Crack 3. Bottom: Crack 2.

YEAR-LONG CRACK RESPONSE

Long-term and vibratory crack response are compared in Figure 11 for an entire year (1 October, 2001 to 1 October 2002) for all three cracks. Maximum displacements for all three were on the order of 300 micrometers, 0.012 in. or about the width of a human hair, and occurred in April at the end of the heating season. This seasonal crack displacement is at least an order of magnitude greater than the maximum vibratory response of the most vibratorily sensitive crack, 3 during this year- long period. This long- term response, while similar for all three cracks, is not an instrument response for several reasons. The null sensor opened only 11 micrometers during this period. Furthermore, crack 2, in the study ceiling, closed while, 1 and 3 at corners of openings in the living room walls, opened.

INTERNET ACCESS AND PAGE DESIGN

Access to the most current ACM test sites can be gained through the Northwestrern University ITI (Infrastructure Technology Institute) URL, http://www.iti.northwestern.edu/acm , The home page contains, background, important links, and operational sites. Information described in this article can be explored at the operational sites by choosing the archived data, which are for the test house described in this paper.

Internet web pages are a critical component of autonomous crack monitoring because they display the information for the public. The current home page is illustrated in Figure 12. These pages must present clearly, assist interpretation, and explain the live data stream to the lay public. Primary viewers of the site are assumed to be those who live near a vibration producer, such as a quarry or construction site, not the scientific community. Furthermore, it is assumed that if area residents have access to computers with Internet capabilities at all, they may not be equipped with the most up-to-date technology. Therefore, the site must be quick to load and be able to operate on older web browsers.

There are five types of plots required for presentation on the Internet. All plots show variation with respect to time of: 1) Long term crack displacement compared to humidity, 2) Long term crack displacement compared to temperature, 3) Transient crack displacement from habitation superposed on long term changes, 4) Transient crack displacement from construction vibrations superposed on long term changes, 5) Time histories of ground motion and crack response. Each of these plots is graphed for a variety of time intervals that range from the past twenty-four hours, week, month, and year (Kosnik, 2000)

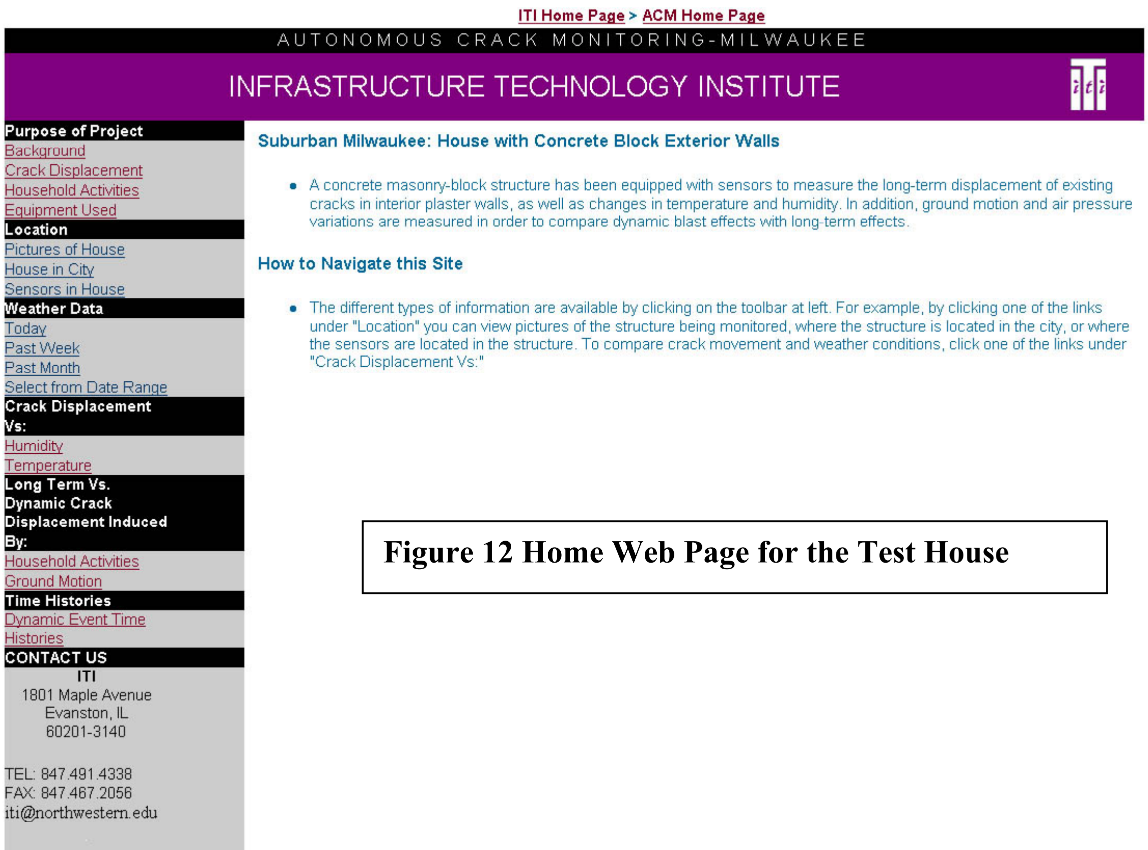

Figure 12 Home Web Page for the Test House

CONCLUSIONS

Public concern over construction vibration-induced cracking has led to the development of a radically new approach to vibration monitoring and control, Autonomous Crack Measurement (ACM).   The ACM system automatically compares long-term weather induced micrometer changes in crack width with those produced by ground motion. This comparison can be displayed autonomously in real time via the Internet without human interaction or it can be obtained through manual downloading for next day or week display.

This paper describes the detail of the ACM concept as well as sensor performance in the first test house fitted an ACM system. Response of three cracks in this concrete masonry unit (CMU) house was measured as part of the system verification.

This ACM research installation effectively illustrates that weather cycles have the greatest effect on micrometer changes in crack width. While vibrations cause transient changes in crack width, they return to the same position as the pre-vibration width. Electronic drift and thermal hysteresis affect micrometer displacement sensors to varying degrees, but can be compensated through the use of a “null” sensor. However measurements indicate that the null sensor may not be needed in most cases. The ACM approach is not limited by the type of micrometer sensor, and several types have been found acceptable provided they and the associated data acquisition devices meet the sensitivity and range requirements.

Internet display allows viewers to compare changes in crack width produced by long-term weather changes to those produced by habitation and vibration motions on a variety of time scales. These comparisons are made graphically and thus should be interperable by a wider range of audiences Data for the web site are automatically recorded and updated daily, which eliminates the costly and time consuming manual data analysis and reduction required with other systems.

ACKNOWLEDGEMENTS

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