CRACK MESUREMENT : NEW APPROACH TO ADDRESSING BLASTING COMPLAINTS

by
Charles H Dowding
Professor of Civil Engineering, Northwestern University

INTRODUCTION

Blasting complaints are consuming an increasing amount of time and resources. This worsening situation has spawned new methods for relaying the public's concerns. The direct measurement of crack response to both long term environmental and blast vibration effects with the same sensor exemplifies one new approach, which can be helpful in the process of educating quarry neighbors about the large impact of the environmental changes. This comparison of long-term and vibratory crack response demonstrates that the silent response of cracks to environmental changes is larger than that produced by blasting, which is felt and heard.

Several varieties of crack monitoring systems are presently employed in locations across the United States. The details of these systems are not as important as is their measurement of crack response. Northwestern University operates two experimental systems with full remote operability and Internet display of information. This system is built around a remotely operable field data acquisition computer (Dowding and Siebert, 2000).

This article demonstrates how the use of sensor technology and computerized data acquisition systems can be actively used to address fears of vibration-induced cracking by directly measuring crack response. Relatively inexpensive systems to monitor both crack response and ground motion have been developed that involve the manual down loading of data on a periodic basis. These systems can be combined with telecommunications for autonomous display on the Internet to more directly interact with the public and to add credibility to the data.

As described in this article, a previous study using several different systems and sensors showed that cosmetic cracks in wood framed structures respond more to weekly changes in the weather (temperature and humidity) than ground motions that exceed allowable limits. These same measurement systems show that crack response to household activities and thunder can be greater than those resulting form blast-induced ground motion. Further information can be obtained by visiting a web site that presents response data in real time as well as description of the equipment and structural response.

CURRENT PROBLEMS WITH THOSE SQUIGGLY LINES

Blasting complaints are more often than not focused upon cracks like that shown in Figure 1. Neighbors adjacent to blasting are either afraid of such cracks appearing or feel that they have already occurred. These concerns are heightened by the human sensitivity to motions. Ground motion as low as 0.02 inches per second (ips) can be perceived by humans, and motions as low as 0.1 ips can cause annoyance. Cosmetic cracking has not been observed below 0.8 ips and in most states, allowable ground motions range from 0.5 to 1.0 ips, with some up to to 2.0 ips under certain conditions. Thus responsible blasting still produces motions that can startle people. More importantly, most people interpret response of buildings in their own terms. Thus there tends to be a belief that if it's felt by and annoying to the owner, it will affect and be aggravating to the physical structure as well.

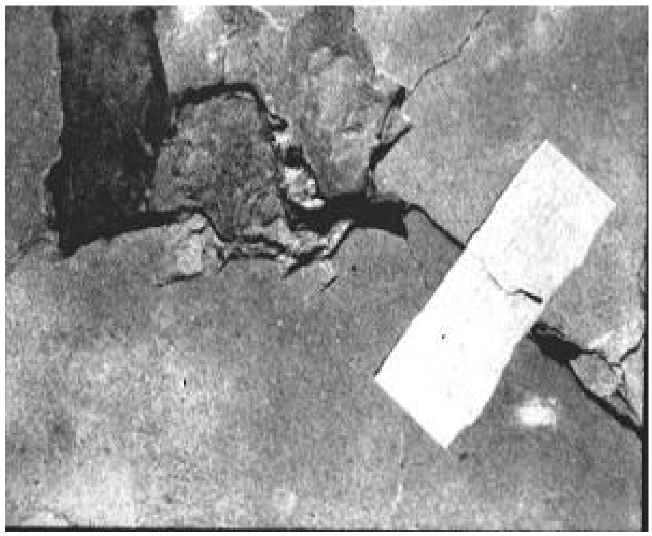

Figure 1: Crack in Mortar Coat Over Rubble Stone.

While the neighbor is concerned about the crack, the seismologist is concerned about the ground and squiggly lines on the time history graph of the ground motion. Currently complaints are addressed by measuring the ground motions outside the structure with an instrument in a black box. These measured peak ground motions are then compared with a standard developed by the Federal or State government. The neighbor is then told that a comparison of the measured motion with a government standard can show whether they are likely to cause cracking. Given the sensitivity of humans to motion, motions they truly believe are harmful turn out to be harmless when compared to the government standard. These references to standards that resulted from studies conducted over 25 years ago by some unknown government officials or researchers are met with skepticism.

Comparing measured ground motion time histories with those that caused cracking in representative structures is 1) inherently complex to understand by the general public, and 2) requires belief in the results of previous studies of critical levels of ground motion. These two requirements sometimes lead to illogical results. Despite volumes of evidence, some juries and regulators ignore the basic physics of the situation. While there are no doubt many reasons for this dismissal of science, the complexity of ground motion's description and the need to believe past reports certainly are at the head of the list. Furthermore it is difficult to convince skeptics that the silent response of cracks to temperature and humidity is more than that produced by a phenomena that is felt and heard.

MEASURE THE CRACK

If the crack is the center of attention for affected neighbors, why not measure its response directly? Since all homes are cracked to some extent, candidates for measurement are present in almost all homes. Measurement of crack response has two attributes not shared by the present approach of measuring ground motion. First, the response of the cracks that are the most worrisome to the neighbors are directly involved. Second, complexities of ground motion and their indirect nature are avoided. Thirdly and most importantly of all, crack response to dynamic events can be compared to that produced by long term events such as changes in the weather. This comparison automatically provides a context for the measured response. As will be discussed in detail later, research is showing that today's vibration controls are so low that ordinary weather induced crack movement is larger than that caused by typical levels of ground motion.

Special sensors can be employed to measure crack response directly. One dual purpose sensor can be placed across a crack as shown in Figure 2 to measure changes that result from both transient (vibration) or long-term (environmental) effects. Full, time histories of vibratorally-induced changes in crack width can be recorded by the same sensor that measures the long-term effect of changes in temperature and humidity. This direct measurement is simple to understand and requires no reliance upon previous work by others.

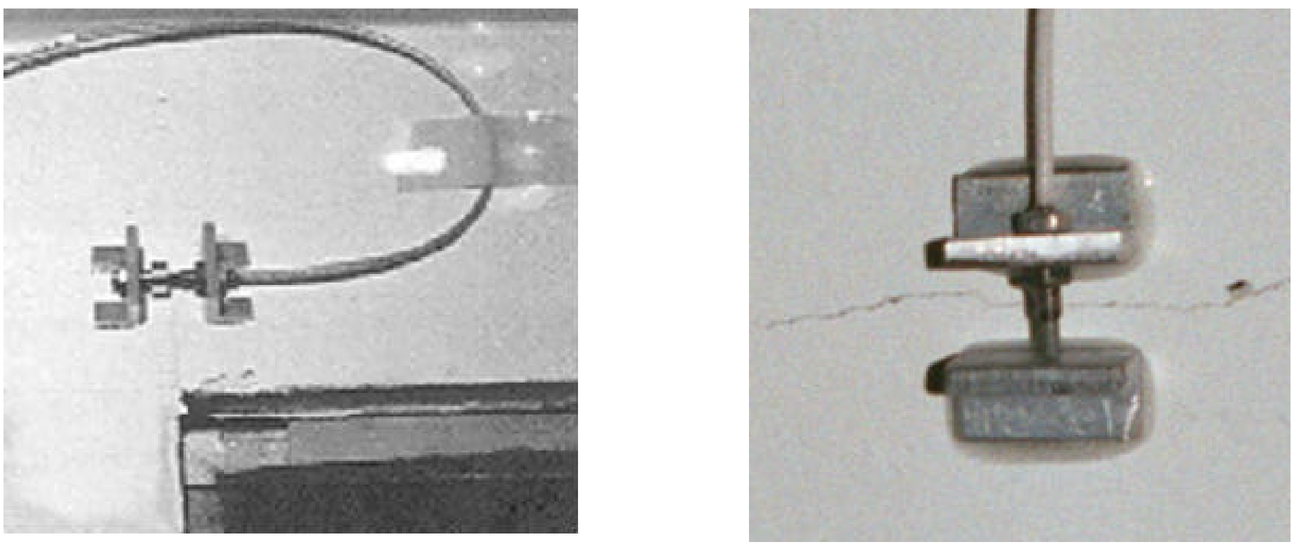

Figure 2: (Left) Eddy Current Sensor Across Hairline Crack in Dry Wall Joint at Door Corner. This Device Can Measure both long-term and Vibratory Changes in the Crack Width. (Right) Enlargement of a Second Generator Sensor Target Spanning Cracking in Dry Wall Ceiling Joint.

Change in crack width is defined with the help of Figure 3. The sensors do not measure total crack width but rather the change in the crack width. As illustrated by the figure, the crack changes width during various events, which are described in greater detail throughout this paper. From this point on, this change in crack width will be referred to as crack displacement.

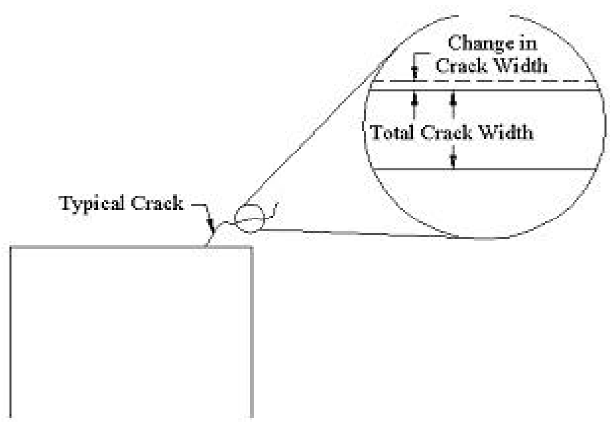

Figure 3 Micro-Inch Crack Width Change Measured by Eddy Current Sensors.

EXAMPLE CASE HISTORY

The test house in Figure 4 was located near an operating surface coal mine and was heavily instrumented to assess the effects of environmental changes upon crack displacement and to compare them with those produced by blast induced vibrations. The house was purchased from its owner, who had constructed the two additions, the original mid section. Thus it was built of materials and is in a condition typical of many older houses.

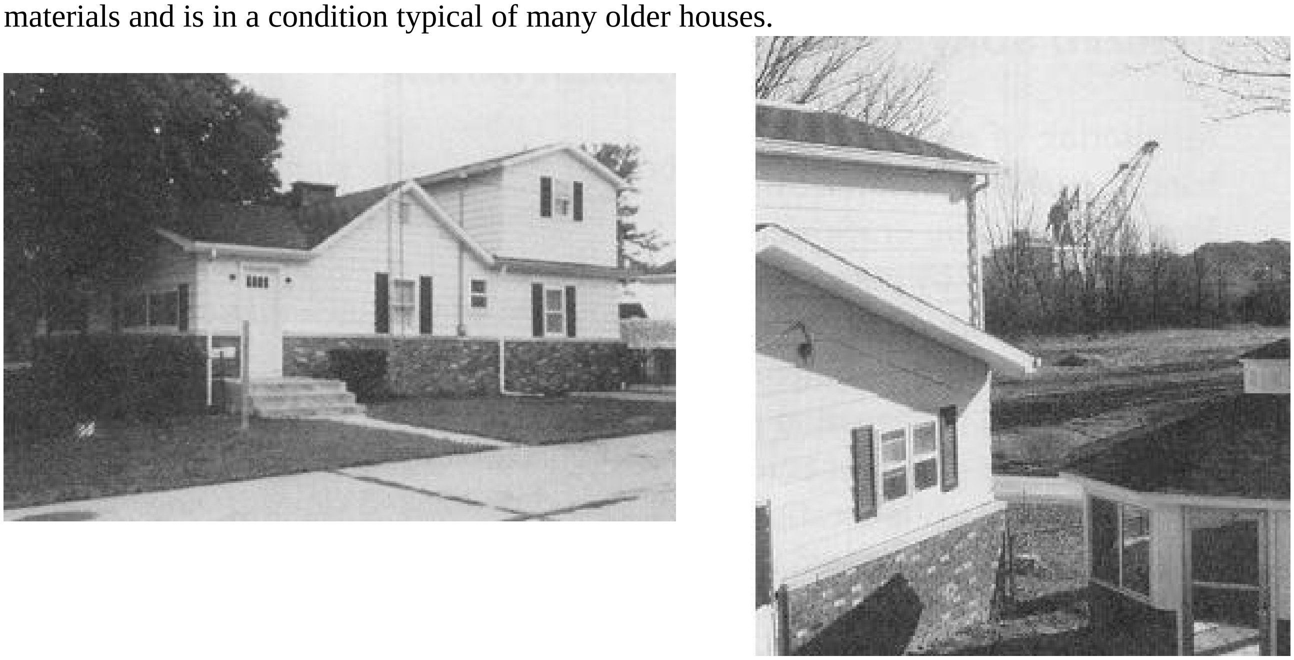

Figure 4: Elevation of Test House Showing Proximity to Mining by Adjacent Shovel and Three Phases of Construction Identified by Roof Lines.

Computerized Surveillance Instrumentation

Fourteen dynamic crack deformation, velocity, and air blast transducers were continuously monitored by computer to record ground vibrations as well as structural vibrations and environmentally induced wall and crack deformations. Location of the transducers and sensors monitored by computer is shown in Figures 5. Crack and wall deformation gauges were concentrated in the living room. Crack displacement sensors c_7, c_9 and c_{10} were placed at cracked (7) and uncracked (9 and 10) joints between drywall sheets, while locations c_2 and c_6 were at uncracked midsections of drywall sheets. Sensor c_8 spanned a large open crack between concrete blocks in the basement. Ground, particle velocity motions (a_1, a_2, a_3 or L, T, and V particle velocities) and air blast (b) were recorded outside at the northwest corner. Wall velocity transducers (d_1 to d_4) were recorded at midheight and midspan of exterior (d_1) and an interior (d_2) first story walls and at an upper corner of the second story (d_3 and d_4). Thus d_1 and d_2 measure wall response while d_3 and d_4 measure superstructure response.

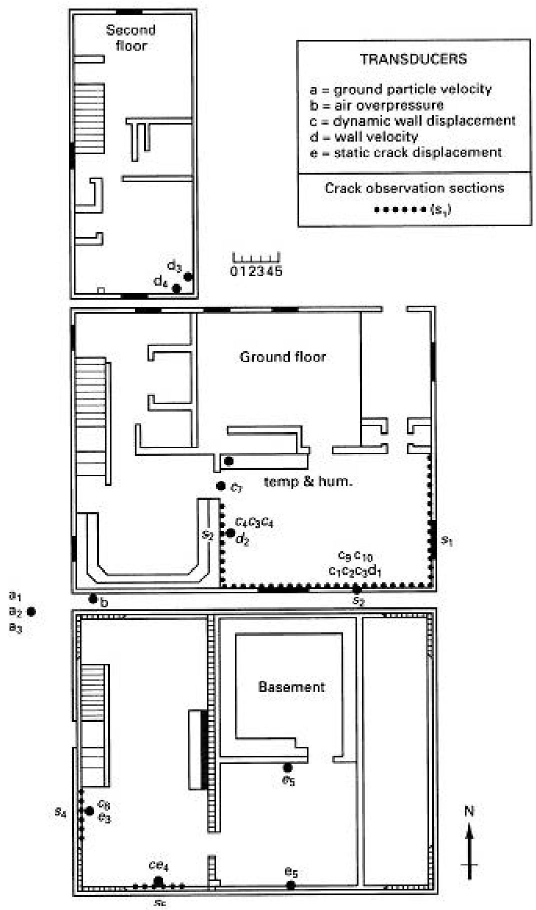

Figure 5: Plan View of House Showing Transducer Locations.

Time Histories of Crack Width Response to Vibratory Excitation

The continuous monitoring of structural response that is caused by either ground or wall motion allowed unattended recording of environmental excitation which heretofore has been impossible. For instance, response of the test house to thunder and human activity has been measured without anyone in attendance. In fact, the system was so sensitive that it was possible to detect in Chicago by modem the arrival of the cleaning service at the test house in central Indiana.

Response of the test house to thunder and a door slam is shown in Figure 6. Thunder produced an air pressure of 113 dB (or 0.0012 psi over pressure) at 14 Hz and the exterior wall (d_1) responded almost twice as much as the interior wall (d_2). The upper story (d_3), representing response of the superstructure, responded even less than the interior wall. Among cracked wall sections, c_7 (drywall) and c_8 (basement concrete block), had the greatest displacement response. All transducers and sensors had maximum responses at the times of peaks in air pressure.

Response of the house to slamming of the front door is shown also in Figure 6. Similar trends as those for the air blast are observed and it appears that a front door slam produces a pressure difference that drives the wall with transducers d_1 and c_{10} some 30 ft away. Vibratory motions on a wall immediately adjacent to the door would be larger as described in U.S. Bureau of Mines studies (Siskind et al, 1980, Stagg et al 1984).

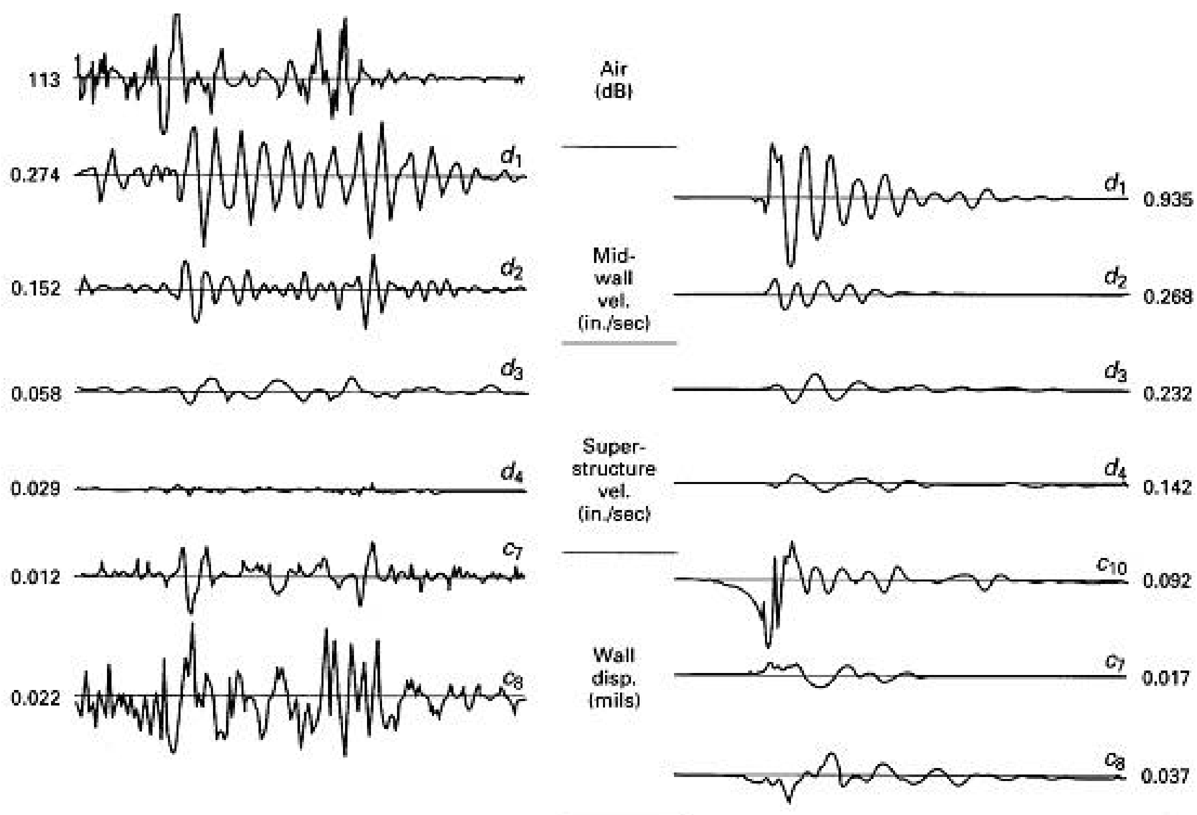

Figure 6: Comparing Velocity and Crack Displacement Response to Thunder and Door Slamming.

Time histories of all 14 transducers responding to a surface coal mine blast-vibration that produced a ground motion peak particle velocity of 0.163 ips in the T (east-west) direction is shown in Figure 7. The ground motion, L, T and V, contains both high (initial) and low (trailing) frequencies. By comparing timing of the peaks it can be seen that the initial higher frequency portion produces the greatest wall velocity response (d_1 and d_2), while the trailing lower frequency portion produces the largest superstructure (d_3 and d_4) response. Crack displacements (c_{10}) away from the upper story are produced somewhat equally by both high and low frequency portions of the motions, whereas that immediately below the upper story (c_7) are larger during the low frequency portion. They were probably driven by the upper story motion as indicated by their synchronous response.

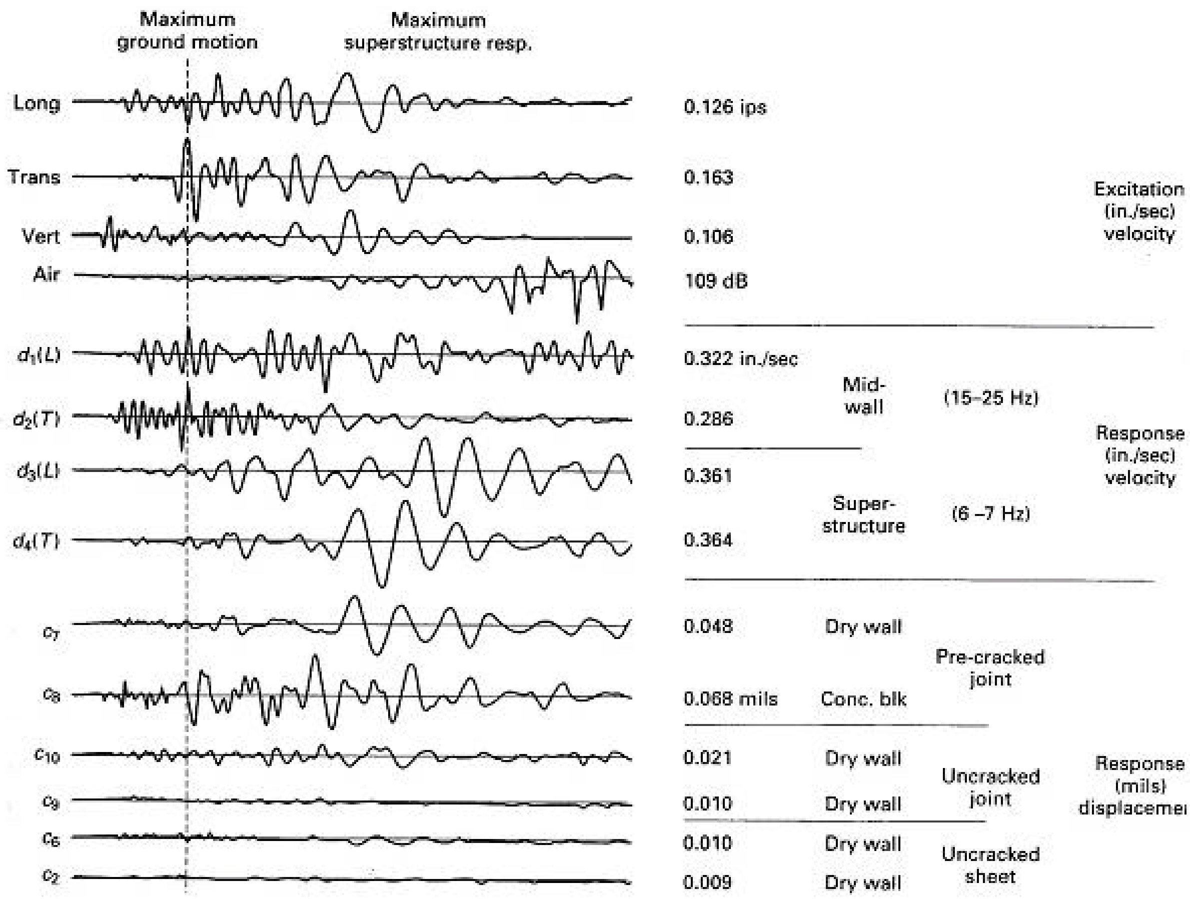

Figure 7: Response of 14 Transducers to 0.163 ips (4 mm/s) Ground Motion That Shows Wall Response to the Early Arriving High Frequency Motions and The Later Arriving Low Frequency Waves.

Crack displacements do not result in permanent offset as can be seen by their oscillatory response in the above example time histories. The measured change in crack width oscillates about zero just like the ground motions, air blast and structure response. As the ground motion passes, excitation dies out and so does the building response as evidenced by both the wall motions (d transducers) and the crack displacements (c sensors). Thus there is no residual or long-term structural effect since the crack width returns to its pre blast span. The same cannot be said for weather and other long-term effects as discussed below.

Weather Induced Changes in Crack Width

The same crack width sensors that responded to vibratory excitation that lasted 1/10 of a second were also able to detect response to chemical-thermal changes produced by changes in the weather conditions. The combination of highly sensitive gauges and computerized monitoring allowed remote monitoring around-the-clock over a period of eight months. Altogether, the six crack displacement sensors were read remotely some 800 times during this time to produce a weather response data bank unequalled in the vibration industry anywhere in the world.

Three sensor positions were chosen to demonstrate the sensitivity of crack displacement to changes in the weather or temperature and humidity during the course of eight months. Position C_6 sits in the middle of a dry wall sheet; C_7 spans the most active dry wall crack; and C_{10} crosses an uncracked dry wall sheet joint on the outside wall and shows the most weather and vibration response of all gauges placed on that wall. The seasonal and frontal variation histories are shown in Figure 8 where crack displacements are compared to outside humidity. Only the relative values of the crack displacements are important as the absolute values were chosen to facilitate plotting three responses on the same graph. Unusually large changes in humidity are circled for comparison with the corresponding displacement response of wall cracks. As shown in the figure the weekly weather induced responses are equal and sometimes greater than the seasonal responses. Of all four possible weather factors, the outside humidity correlated best with the peaks in the wall displacements and is shown by the circles around response peaks for position c_7 and the humidity.

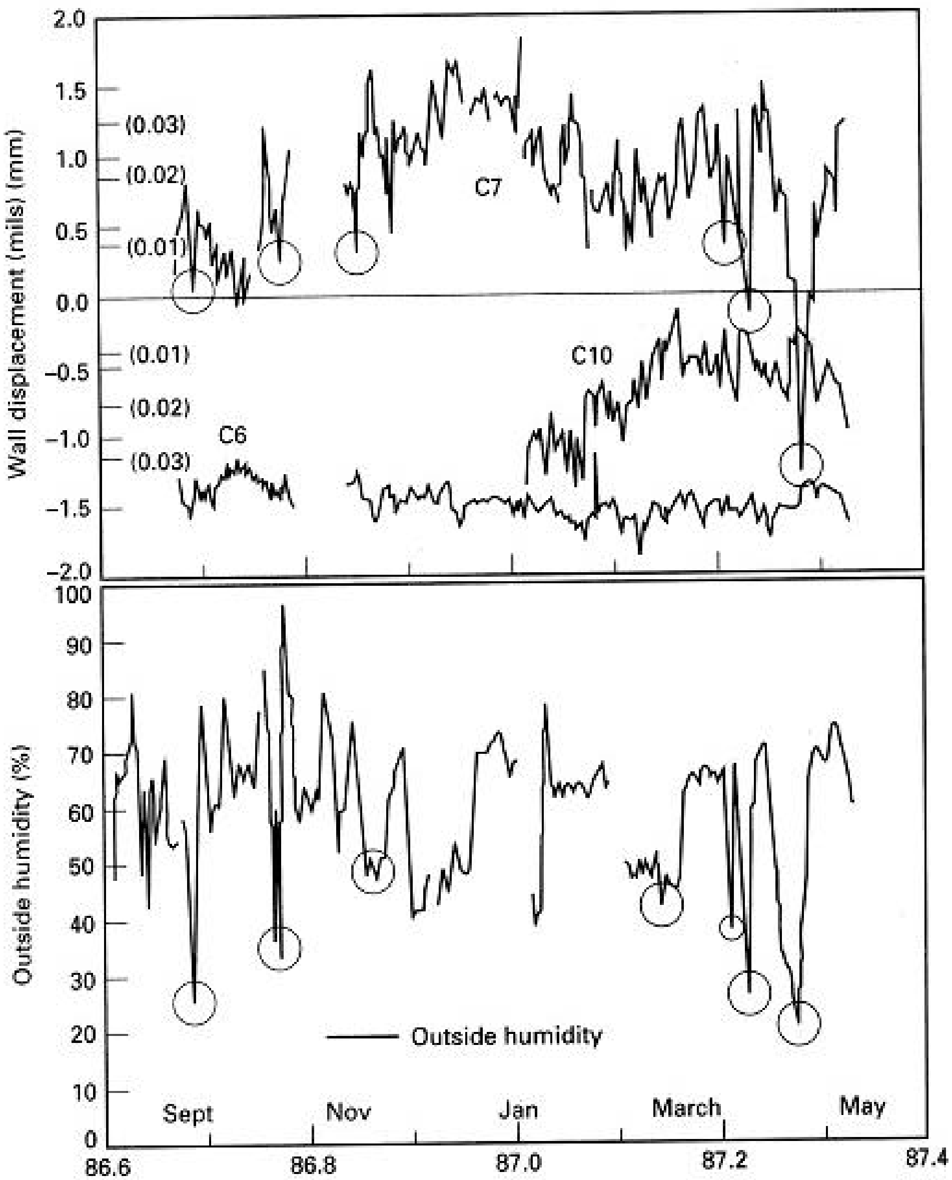

Figure 8: Eight Month History of Displacement and Crack Displacement Showing Greatest Change in Crack Width to Correlate with the most Intense and Longest Drop in Humidity in April.

Comparison of Crack Displacement from Weather and Vibration

The most significant attribute of the system for the comparison of environmental and vibration displacements is their measurement by the same sensor at the same location. The same sensor can detect changes in displacement that have durations from .002 second -blast vibrations- to 6 months, or (16,000,000 seconds) - seasonal changes. Thus, the time sensitivity spans some 9 orders of magnitude. Since the same gauge measures both environmental and blast or vibration effects, their comparison can be made directly without any calculation or conversion.

Environmental and vibration induced displacements are compared directly for transducer location c_7 in Figure 9 in units of mils, where a mil is l/l000'th of an inch or 0.025 mm. Transducer c_7 showed the most response to both environmental and vibration effects and most clearly shows the relative effect of each. This comparison is shown as a function of time and thus the weather effects appear as a continuous function as they were measured 2 to 3 times daily. Blasting occurred on average less than once per day and thus the individual events appear as individual point events marked by the plus signs. During the eight months of observation, mining approached the test house as reflected by the increase in blast induced displacement. The mining took place along a line leading to the structure thus there is a time pattern to the increase in displacement that correlates to the distance between blast and structure as the mining activity proceeded toward and away from the structure.

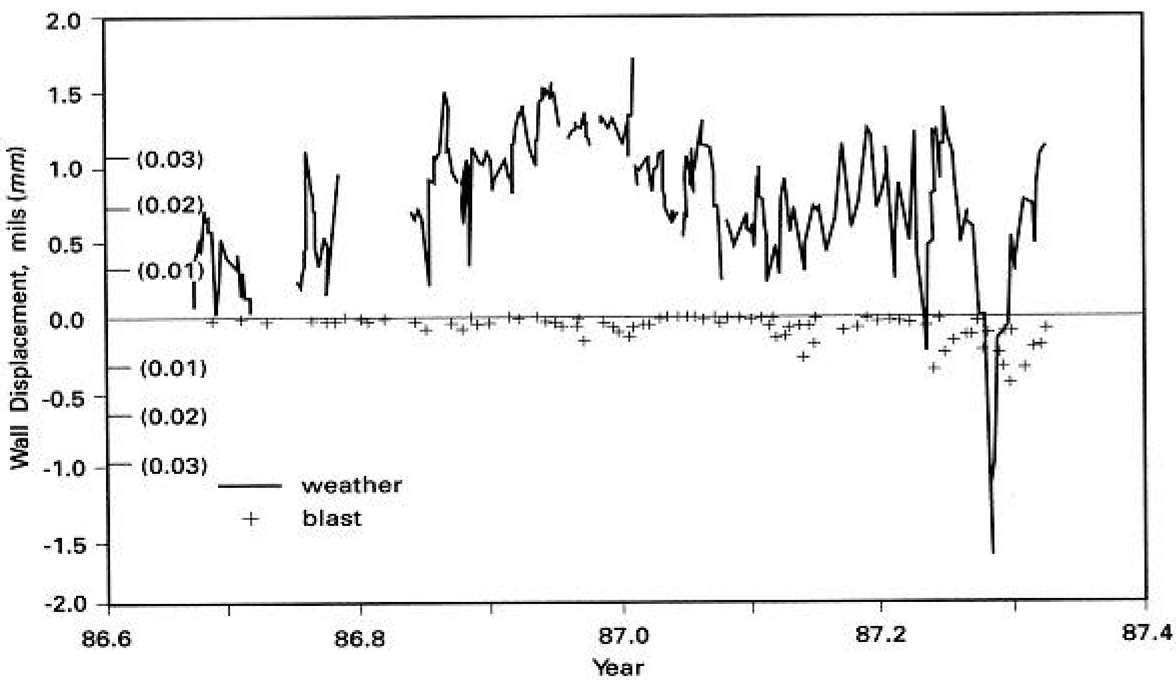

Figure 9: Comparison of Long-Term and vibration Induced Crack Displacement Showing that the Largest Ground Motion ("+" at arrow) of 0.75 ips (19 mm/s) Produced a Crack Displacement Less Than That of the Passage of a Typical Weekly Weather Front.

The greatest blast induced vibration during this period was 19 mm/s (0.75 ips). Despite this significant vibration level, the induced crack displacement was a good deal less than the average change produced by the passage of a significant weather front. For instance the average variation in deformation about the mean seasonal trend was equal to the maximum produced by blasting, and the maximum weather induced deformation was some 3.5 times that of the maximum produced by blasting.

Thus, approximately once a week this house is naturally subjected by changes in the weather to deformations that produce crack displacements that equal those produced by the ground motions of at least 12 mm/s or 0.5 ips. These measurements confirm those observations of weather induced deformations reported by Stagg et al. (1984). Thus every week, season by season, houses deform significantly more than would be produced by a typical blast (eg 2.5 mm/s or 0.1 ips).

The difference between environmental and vibration phenomena is that the weather effect occurs slowly without noise. It is therefore undetectable by the home owner. The blast-induced ground motion can be detected and is accompanied by a noise that also alerts the home owner to the vibration.

It also appears that an energetic door slam may produce deformations on the other side of the house that are similar to those of the above mentioned vibration levels considered annoying by humans. As seen from the USBM test house, door slamming produces strains on the same wall that are five times those of a typical blast (Slskind et. al. 1980).

PUBLIC INTERACTION OVER THE INTERNET

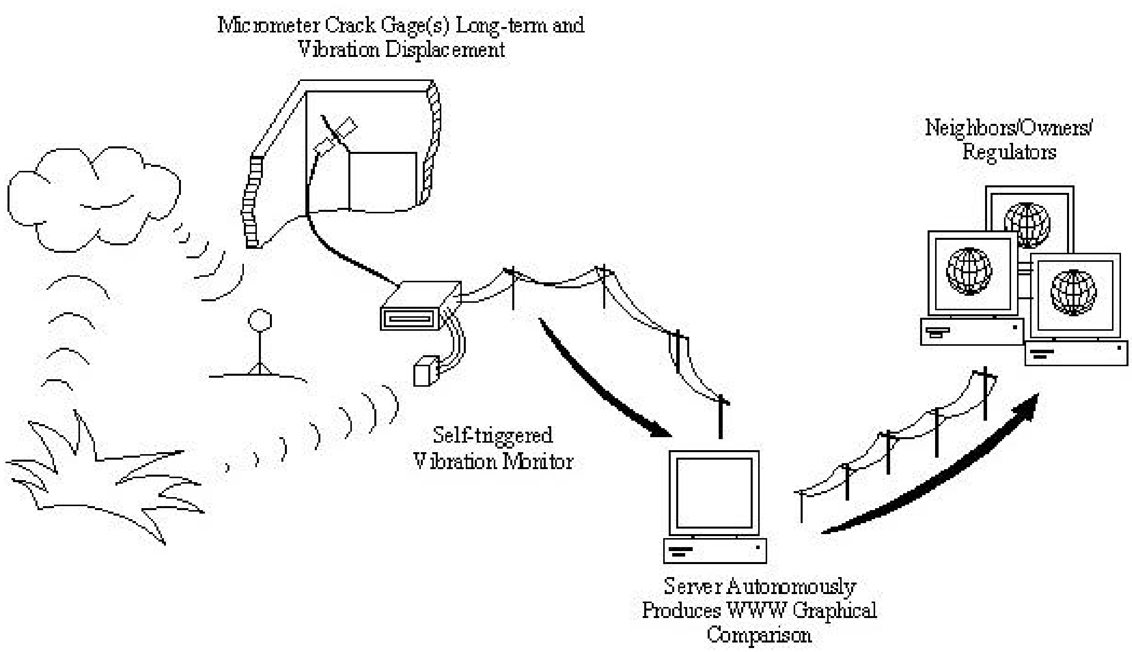

Figure 10: Autonomous Crack Measurement System Automatically produces graphical comparisons of vibration and environmentally-induced crack displacement, which are accessible to interested parties via the Internet.

Comparison of environmental versus vibration effects provided by the measurement of changes in crack width can be further leveraged by an automatic display via the Internet as illustrated by Figure 10. Data are collected and stored locally by an enhanced vibration monitor, which is polled by the Internet server. The server then automatically converts to graphical form both long-term environmental and vibratory response for Internet transmission when requested by neighbors, owners, and/or regulators. This combination of single crack width sensor and display via the Internet is being developed by the Infrastructure Technology Institute at Northwestern University as an Autonomous Crack Comparometer (ACC) system. The ACC provides a visual, graphical comparison of crack response to natural and vibratory forces not heretofore possible.

Access to the most current ACC test sites can be gained through the ITI (Infrastructure Technology Institute at Northwestern University) URL: http://iti.birl.northwestern.edu/acm/ .. The menu of choices for Evanston site is given in the left hand column in figure11, as it would appear on the web page.

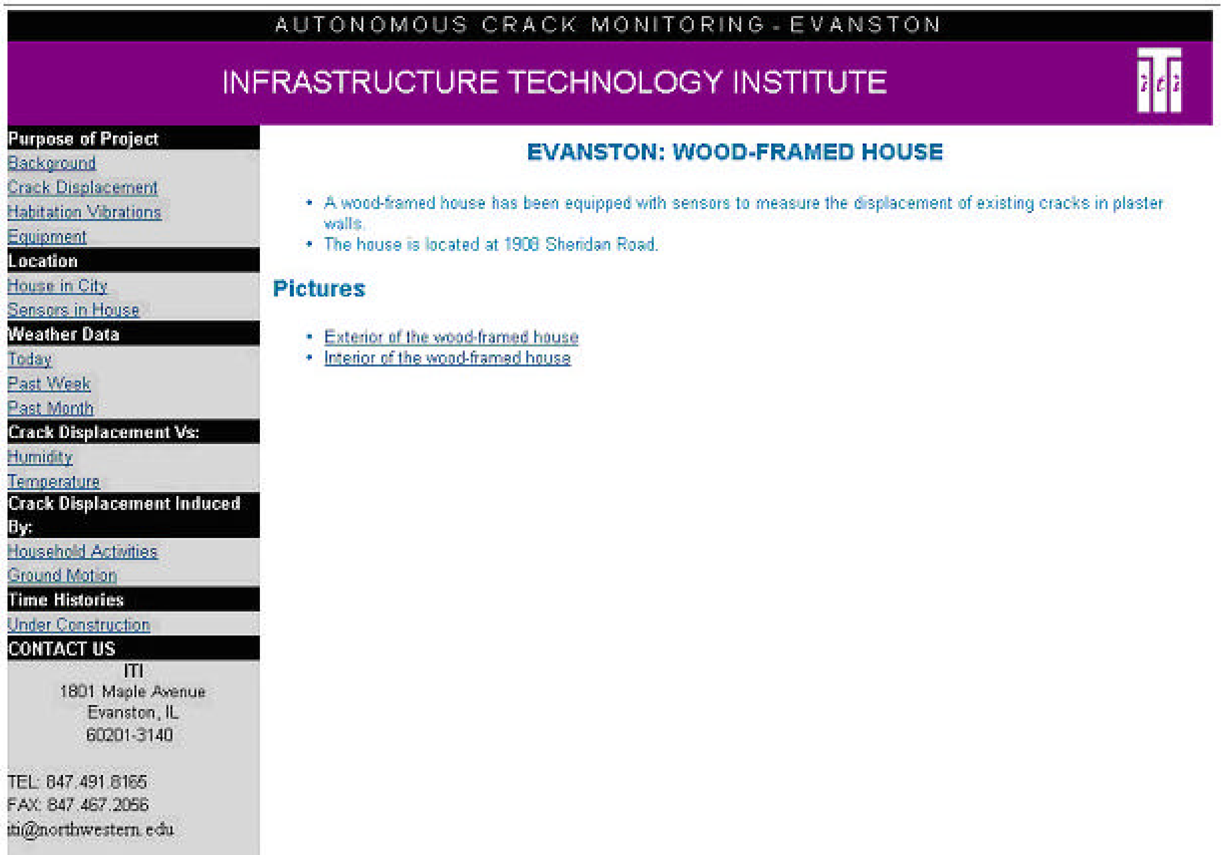

Figure 11: Banner of Crack Monitoring Website for a Specific Structure.

A number of choices are possible at this web site. The first three groups, PURPOSE, LOCATION, WEATHER are general in nature and describe how to interpret the graphs and they supply background information of general interest such as the daily weather. The next two choices present two different comparisons of CRACK DISPLACEMENT. This first comparison with weather related temperature and humidity is presented in a two-graph form like that in Figure 8. The second compares long term and vibratory response in a single graphical form similar to that in Figure 9. The last option is a graphical comparison of ground motion and wall response TIME HISTORIES like that in Figure 7.

CONCLUSIONS

Advances in sensor technology and computerized data acquisition now make it possible to address fears of vibration-induced cracking on a less technical basis by directly measuring crack response. Relatively inexpensive systems to monitor both crack response and ground motion have been developed that involve the manual down loading of data on a periodic basis. These systems can be combined with telecommunications for autonomous display on the Internet to more directly interact with the public and to increase data credibility.

The important concept is the addition of direct measurement of crack response to the traditional measurement of ground motion for correlation with government standards. The vibration monitoring system and measurement sensor can vary and their brand is not fundamental to the approach.

Crack response to both long-term weather effects and vibratory excitation can be measured with the same sensor. Previous study with several different systems and sensors has shown that cosmetic cracks in wood framed structures respond more to weekly changes in the weather (temperature and humidity) than blasting-induced ground motions that exceed allowable limits. Crack response to household activities and thunder can also be greater than typical ground motion.

Crack measurement is most useful where operation is longer lasting and access to a typical home is possible. Under these conditions there will be enough time to collect response to daily, weekly (weather front) and seasonal environmental changes. Furthermore it should be possible to place the equipment in homes that are representative of others.

Direct comparative crack responses will be helpful in the process of educating neutral parties about the large impact of the environmental changes. This comparison of long-term and vibratory crack response directly demonstrates that the silent response of cracks to environmental changes can often be more than that produced by blasting, which is felt and heard.

REFERENCES

Dowding, C. H. (1996), Construction Vibrations, Prentice Hall, Upper Saddle River , NJ.

Dowding, C.H. and Siebert, D. (2000), Control of Construction Vibrations with an Autonomous Crack Comparometer, "Explosives and Blasting Technique", Proceedings of the 1st World Conference on Explosives and Blasting Technique, A.A. Balkema, Netherlands.

Siskind, D.E., Stagg, M. S., Kopp, J.W. and Dowding, C.H. (1980) Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting, RI 8507, US. Bureau of Mines, available from International Society of Explosives Engineers.

Stagg, M.S. Siskind, D.E., Stevens, M. G., and Dowding, C.H. (1984), Effects of Repeated Blasting on a Wood Frame house, RI 8896, US. Bureau of Mines, available from International Society of Explosives Engineers.