

# Control of Construction Vibrations with an Autonomous Crack Comparometer

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**ABSTRACT:** Concern over construction vibration-induced cracking has led to development of a new approach to vibration monitoring, an autonomous crack comparometer (ACC). This paper describes sensor performance and chronicles the first steps in the development of this concept, illustrated in Figure 1. A single sensor 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. Measurements reported herein show that weather-induced response of cracks is greater than that caused by presently allowable construction-induced vibration. Graphic display through the Internet more convincingly compares these differing responses. Visual comparison avoids the abstract complexity of vibration time histories and required belief of past comparisons of vibration levels with crack initiation. Finally, the Internet provides a mechanism of direct public participation in data collection and interpretation.

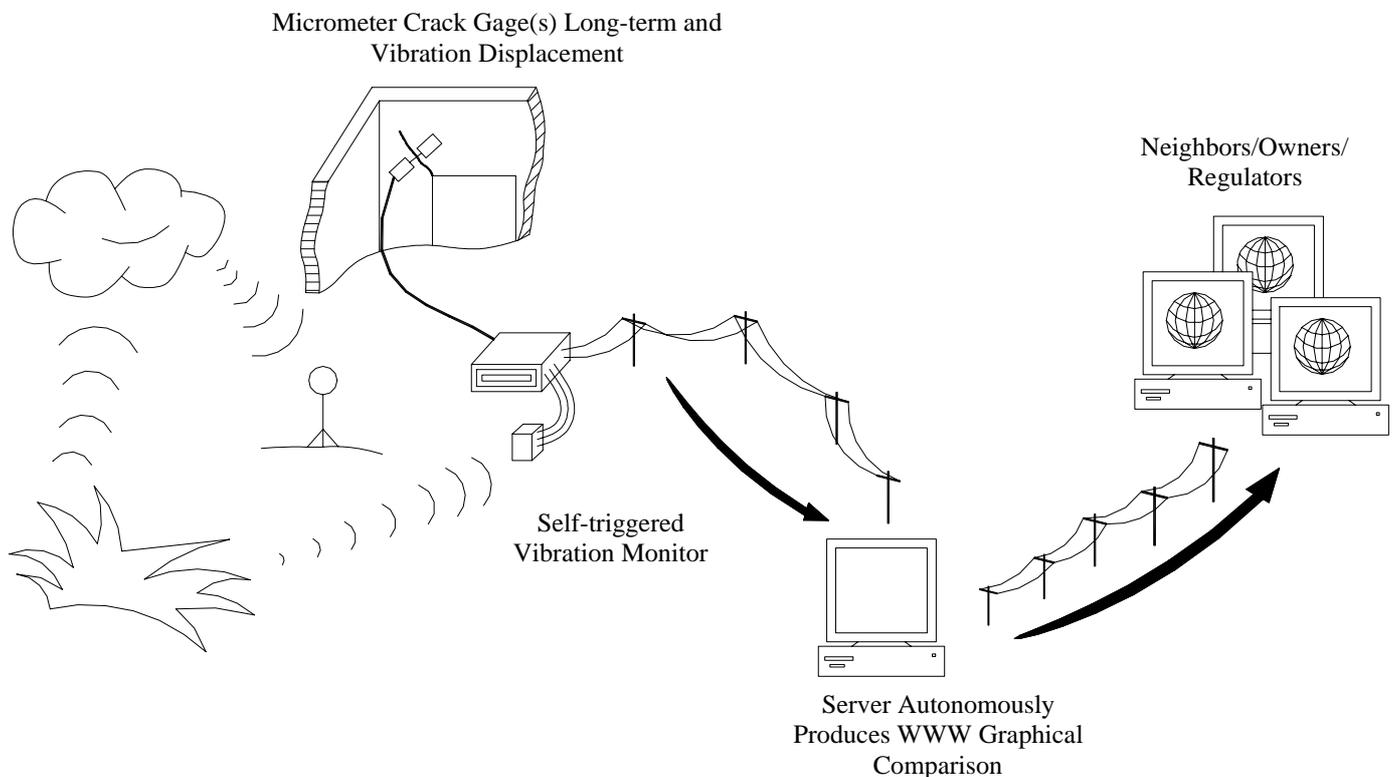


Figure 1 AUTONOMOUS CRACK COMPAROMETER

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

# 1 ADVANTAGES OF PROPOSED TECHNOLOGY AND MARKET POTENTIAL

The Autonomous Crack Comparometer (ACC) concept illustrated in Figure 1 (Siebert, 2000) combines two technologies not heretofore integrated (micrometer measurement of crack response and digital seismographic technology). 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 of the issue of concern. 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. 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.

The current approach of comparing measured ground motion time histories with those that caused cracking in representative structures is 1) inherently complex to understand, 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 less than that produced by a phenomena that is felt and heard.

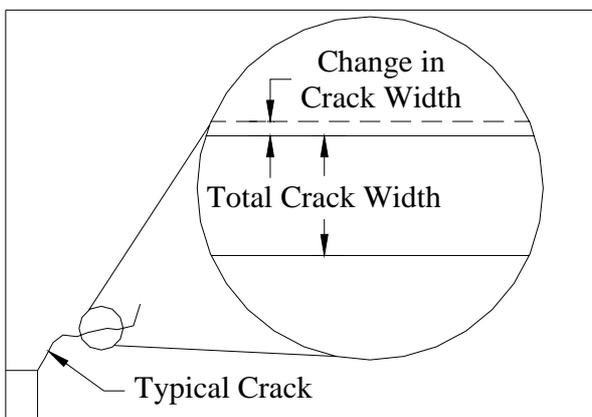


Figure 2 Definition of the change in crack width hereafter called crack displacement.

In the near term, the number of deployed instruments should double each year for the next five to ten years. It is expected that in the first year some two to four units would be deployed. Currently, three primitive, non-autonomous versions of the concept are deployed in Dade County, Florida to illuminate the factors that affect changes in crack width.

## 2 MICROMETER CHANGES IN CRACK WIDTH

Change in crack width is defined with the help of Figure 2. 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 displacement

Micrometer crack displacements are measured with proximity sensors developed in conjunction with computerized, numerically controlled (CNC) manufacturing. The robustness of these systems necessary to survive the manufacturing floor is sufficient for use within structures adjacent to construction projects. These sensors are able to respond statically as well as dynamically. Thus the same gages are able to measure micrometer displacements produced by both long-term changes in temperature and humidity as well as dynamic, construction-induced vibration excitation.

### 2.1 Micrometer Displacement Sensor Requirements

It is envisioned that a number of types and brands of micrometer displacement sensors will be compatible with ACC 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 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. Figure 8 ( in a later section) from past experience illustrates crack displacement over two-thirds of a year that includes the January heating season. The total movement of the crack during the heating season does not exceed 0.1 mm or 100

micrometers. Since not all cracks behave the same, this range could be extended +/-200% 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.

### 2.2 Long Term Effects: Drift and Thermal Hysteresis

Electronic drift and thermal hysteresis pose two major challenges to long-term measurement. In order to quantify the effects of these two phenomena, several sensors and their electronics were subjected to cyclic temperature changes over a three-week period. The sensors were mounted on an aluminum block of a known coefficient of thermal expansion (CTE). Thermocouples, temperature sensors composed of a bi-metallic junction, were also mounted on the block to determine the current temperature. All sensors and electronics together were subjected to temperatures that cyclically ranged between 20°C and 31°C (68° F and 88° F) during daily temperature changes. Readings were taken every five minutes for 19 days. The electronics and the sensors followed the same temperatures during the test by virtue of their identical location.

Figure 3 is a plot of output converted to displacement versus temperature during the 19-day test for two sensors. The increased output at similar temperatures demonstrates the drift. As indicated by the stylized pattern on the graph, the drift is in only one direction for either sensor. It is unknown if this drift would have continued indefinitely, however; it is

assumed that the drift would have switched directions and cycled back. The theoretical displacement is shown for comparison by the thin sloping lines. It was calculated by multiplying the CTE by sensor gap by the temperature change.

In addition to drift, thermal hysteresis is also important. The arrow in the figure points to a one-day cycle for the most temperature sensitive system. This one-day cycle sensor displacement loops around the linear theoretical displacement value. Depending upon the magnitude of this loop or hysteresis, the error of the sensor can be determined. It is difficult to correct for this hysteresis error since it depends upon the direction of the temperature change (heating or cooling).

### 2.3 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

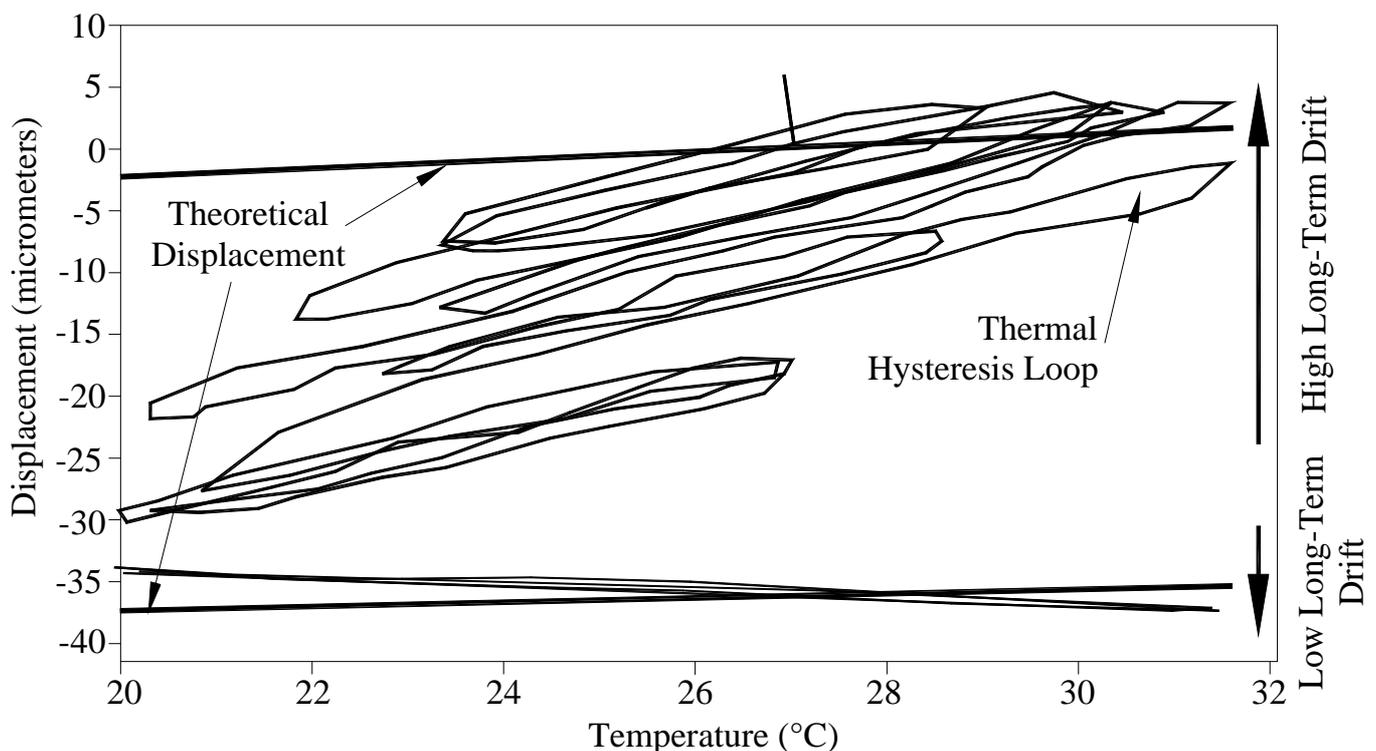


Figure 3 Comparison of sensors with low and high long-term drift and illustration of thermal hysteresis loop.

sensors, 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.

### 3 COMPARISON OF ENVIRONMENTAL AND HABITATION VIBRATION RESPONSE

Autonomous operation of the dual measurement crack sensing system was verified by instrumenting a wood framed structure on the Northwestern campus. The least temperature sensitive system, an LVDT, was employed in this test of the concept. The ability of the system to capture and display both long term and vibratory crack response could be determined with habitation-induced vibrations rather than mining or construction induced vibration. Habitation excitation in this case is the result of walking and running up and down the stairs as well as slamming doors. While habitation induced vibrations are local, they nevertheless provide the randomly timed vibrations necessary to test the dual capabilities of the sensors.

This section describes the results of these verification measurements and compares them with past measurements of crack response on another wood framed house (Dowding, 1996) that was exposed to mine induced ground motion. This comparison shows many similarities and validates the concept of dual measurement with a single sensor.

Figure 4 illustrates the location within a central stairwell of the three crack sensors (basement, stairs & 1<sup>st</sup> floor), a null sensor and a temperature/humidity sensor. These sensors were placed on interior walls within 4 m of each other. Internal wall temperatures are relatively constant which reduces temperature effects. Furthermore, close proximity of the null and crack sensors allows the single null to be employed with all three crack sensors. These sensors were

connected to the data acquisition system and field computer for communication with the central server, this server autonomously produces the graphical data for internal display.

At the time this article was written, the sensors had been in place for some four months during the beginning of the intense heating system. The long-term history of the first floor response is compared with the degree-day heating time history in Figure 5. A degree day is the number of degrees the average daily

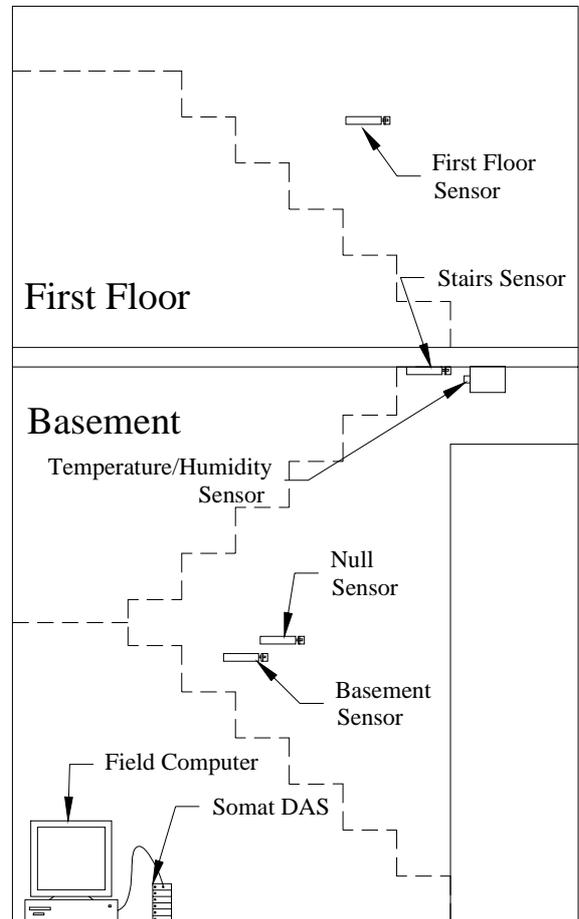


Figure 4 Elevation view of stair well with sensor locations.

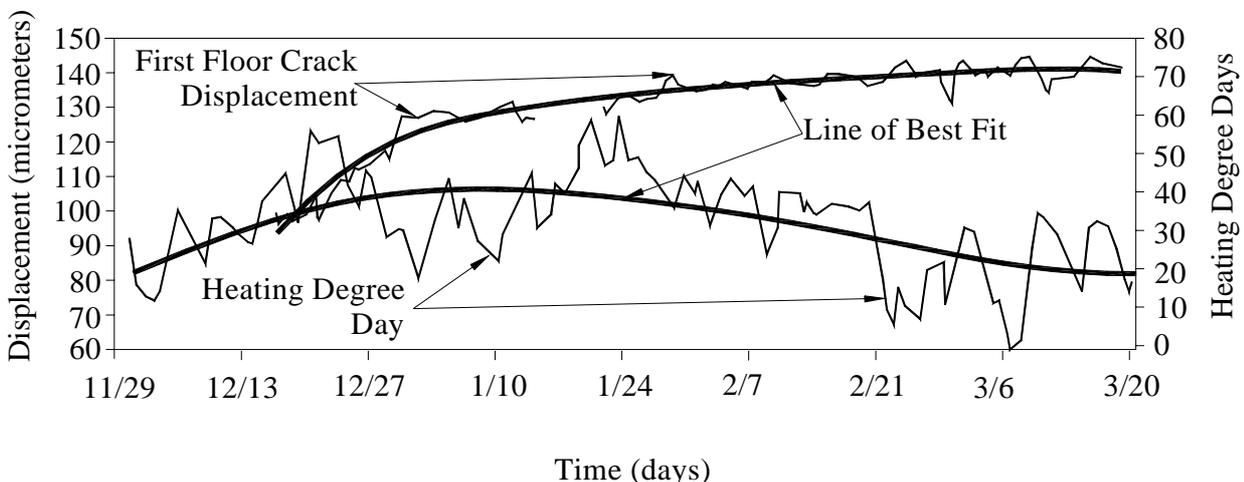


Figure 5 Comparison of time histories of first floor crack displacement with degree heating days shows the large affect of wood desiccation with the onset of continual winter heating.

temperature falls below 68°F (20°C). The number of degree days increases dramatically from early December through several severely cold periods at the end of January, so does the crack response. As will be described later, this same response was observed both on another highly reactive crack in this house as well

as in the earlier test house (Dowding, 1996).

Figure 6 compares long term and habitational vibration response for all three sensors. The stair crack is the most reactive to both long term as well as habitation vibration effects. The stair sensor is placed across a crack at the junction of the stair and wall

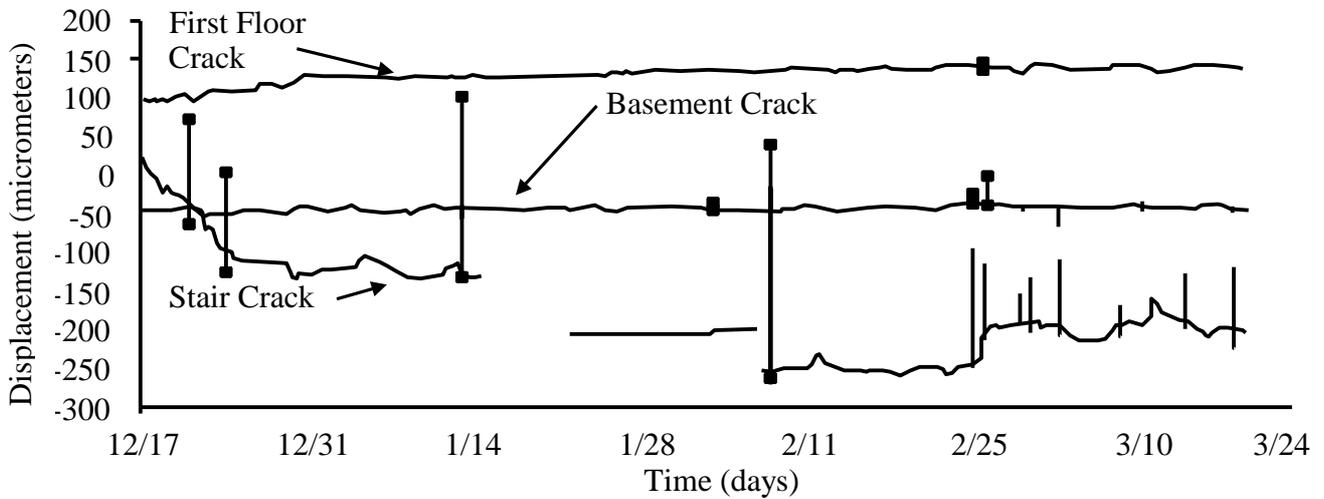


Figure 6 Crack displacements produced by long-term weather effects (continuous line) are equivalent to those produced by habitation vibration (■-----■).

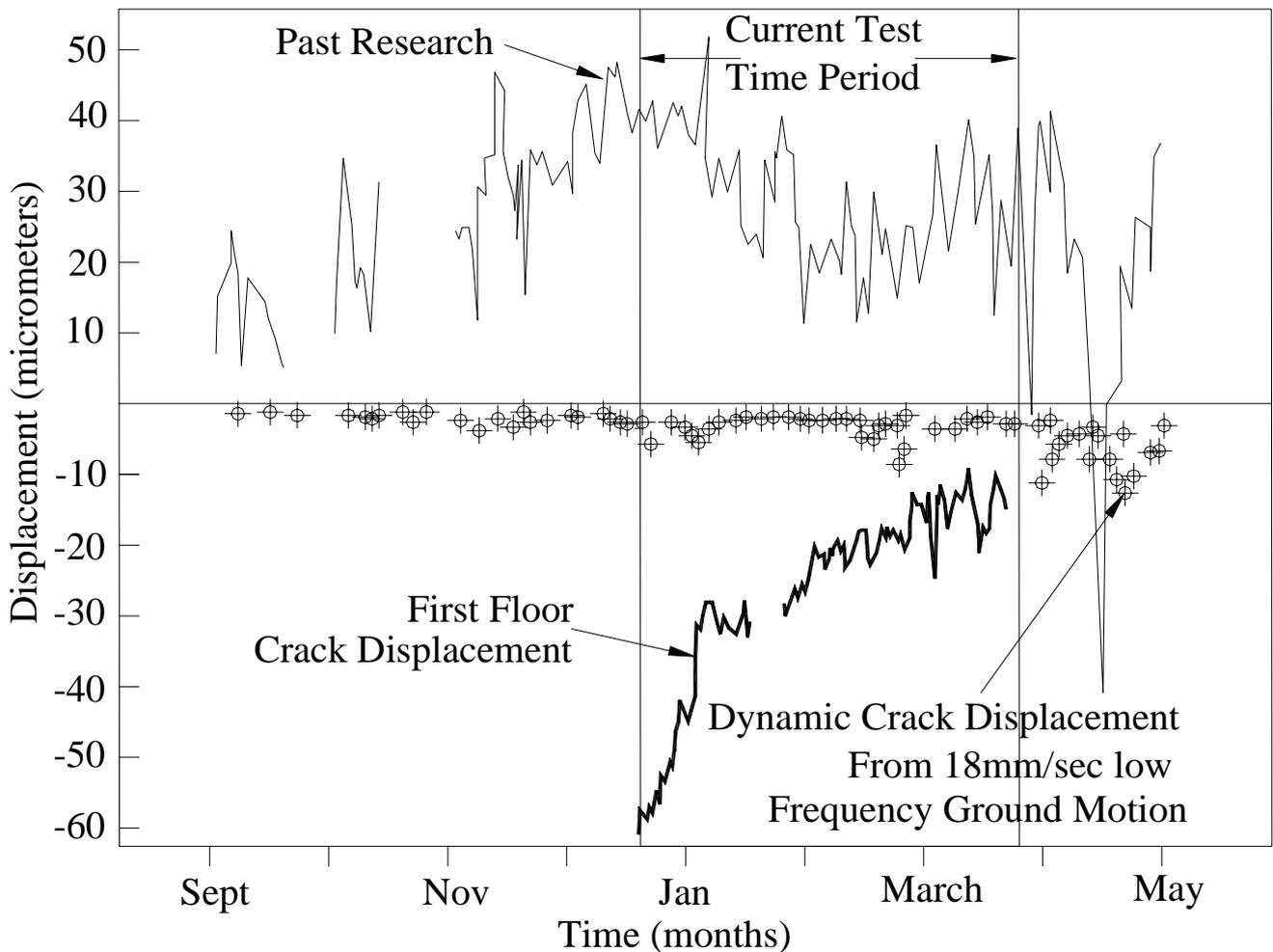


Figure 7 Long term crack displacements from this (---) and past (---) measurement (Dowding, 1996) show similarity of winter heating and weather effects; both of which are far greater than that produced by 18 mm/s ground motion from a near-by surface coal mine blast.

frames, which may not have properly attached to each other. It also displays the greatest change during the onset of the heating season. The basement crack, which is located in the relatively unheated portion of the building has the least long-term response. As was reported before, cracks display differing responses.

Clearly the cracks respond as much to habitation induced excitation as they do to long-term weather response. This importance of habitation excitation has been reported by others (Siskind et al 1980, Siskind, 2000). The stair habitation excitation is the greatest as it results from the full weight impact of a person walking on the stairs at the crack location, which is directly below the stairs.

The 1<sup>st</sup> floor crack responses are compared in Figure 7 with those of another active crack in a wood framed home subjected to mine induced ground motion (Dowding, 1996). Both were highly active cracks in their respective houses. Both changed significantly during the onset of the heating season. Both experience large fluctuations on a weekly time frame. These weekly fluctuations are the result of the passage of weekly weather fronts.

Long term response of both cracks is also compared with mine vibration induced crack response on Figure 7. The largest crack response to vibration was caused by ground motion with a peak particle velocity of 18 mm/s. This crack response to a relatively high ground motion is similar to that from the passage of an average weekly weather front. It is not nearly as intense as might be produced by prolonged heating or the passage of a strong change in weather represented by the large spike in crack response at the end of the 1996 study.

## 4 AUTOMOUS OPERATION

Autonomous operation is achieved simply through employing AutoMate with existing batch processing software. AutoMate (Unisyn, 2000) is a software tool for Windows computers that enables autonomous entry of commands in multiple applications without manually pressing keys or employing macrocodes. AutoMate breaks down common user actions into basic tasks. These tasks are built step by step in logical progressions, and take the place of human induced commands. Once triggered, at a scheduled time, AutoMate carries out "actions" in the order specified during the task without human assistance.

### 4.1 Java Applet for ASCII Text File Analysis

The last task AutoMate performs is to run the Java applets (a web based programming language), which analyze the text file and create graphs for display on the web page. A small script file within the Java applet, called a servlet, extends the functionality of the web server. Text files, created from the original data file by AutoMate and other software, is divided into three sections, header information, four-hour data, and

vibration data. The first section, or header information, contains each channel recorded, the number of data points in each channel, the time the test was started, and other test information. The second section, or four-hour data, contains long-term crack response and weather data. The final section, or vibration data, contains the transient crack response.

### 4.2 Dynamic Generation of Graphs for Internet

Java servlets also dynamically generate graphs for the web site (Kosnik, 2000). They take the place of other server counterparts and eliminate the need for applets on client (or public) computers. Graphing at the clients would require the viewers' web browser to perform this analysis. Elimination of client-side applets allows for quick loading of the web site with any version browser or speed connection.

There are four 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, and 4) Transient crack displacement from construction vibrations superposed on long term changes. Each of these plots is graphed for a variety of time intervals that range from the past twenty-four hours, week, month, and year.

## 5 INTERNET PAGE DESIGN

The Internet web pages are a critical component of autonomous crack monitoring because it enables access to and displays the information for the public. The web 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.

Several requirements were set forth for the initial web design. First, each page must load in less than 10 seconds with a 56k modem. Second, the site must be viewable with any web browser. Third, the site must be easily extensible, as new pages will be added for other monitoring sites. Fourth, the lay public must be able to easily understand and navigate through the site.

A number of features make it possible for the pages to load quickly with modem connections. Rather than designing a few large pages that require scrolling to present data, a sequence of many small pages is employed along with a left side content bar that displays all options. This content bar, shown in Figure 8, can be seen upon accessing the site, whose address is

given in the next section. Each page has a few small or well-compressed images. In some cases, thumbnail images are used, which are smaller versions of a larger image. The viewer can enlarge the image by clicking on the thumbnail version.



### **Purpose of Project**

**Background**

**Crack Movement**

**Equipment Used**

### **Location**

**House in City**

**Sensors in House**

### **Weather Data**

**Today**

**Past Week**

**Past Month**

### **Crack Displacement vs.**

**Humidity**

**Temperature**

**Vibration**

**Ground Motion**

### **Home**

Figure 8 Side bar displayed on all Internet web site pages for ease of navigation

Compression of graphics also improves the download times. The GIF image format is best suited for logos and graphs, whereas JPEG compression is most effective with photographs. The chosen approach with many small pages coupled with compression of images allows for the presentation of graphical information without long download times.

In order for the site to be useful to the general public, it must be compatible with all web browsers. This requirement introduces several constraints to the design. First, no browser-specific hypertext markup language (HTML) can be used. For example, some HTML can only be viewed in Netscape Navigator, Microsoft Explorer, or other designated browser. Furthermore, more recent extensions to the HTML language, which are not supported by older browsers, cannot be employed. These include: frames which divide a web site into several distinct windows; JavaScript, a client-side scripting language which extends the functionality of HTML; and Java applets, client-side program elements that run in the web browser. To avoid any compatibility issues, only standard HTML code is employed to display the site.

A distinction must be made between Java applets, which run in the client's web browser, and server-side Java programs, which run on the web server. The use of applets is disallowed by the design specification, as older web browsers do not support this technology. However, server-side Java programs are used extensively in the back end of the site, as they do not depend on the capabilities of the client's browser.

## 6 INTERNET ACCESS

Access to the most current ACC test site can be gained through the ITI (Infrastructure Technology Institute) URL <http://www.iti.northwestern.edu/>. More information on ACC performance and access to specific sites will be listed on the ITI page entitled "Research Projects".

## 7 AUTONOMOUS OPERATION REDUCES REPORTING EFFORT

The Internet based system provides a mechanism to reduce the labor costs of data compilation. Data are automatically compiled and reduced in the database that resides on the server. With previous systems, presentation of the data in graphical and chart form required a great deal of time and effort. With the integration of the web site, reduction of data to comparative graphical form not only occurs automatically but also is easily accessible. Obviously, expenditures of time and money will be greatly reduced to prepare final reports.

Production of the graphs in Siebert's (2000) thesis provides a comparative example of the savings in effort that results from automatic data reduction. These graphs were produced in only several days from data already reduced to digital/graphical form. For comparison, reduction to graphical and tabular form of the 8 months of separately recorded data (stacked on the right hand side of Figure 9) required six months of a graduate student's time. Thus it appears that the automation required for autonomous display may decrease data reduction efforts by several orders of magnitude.

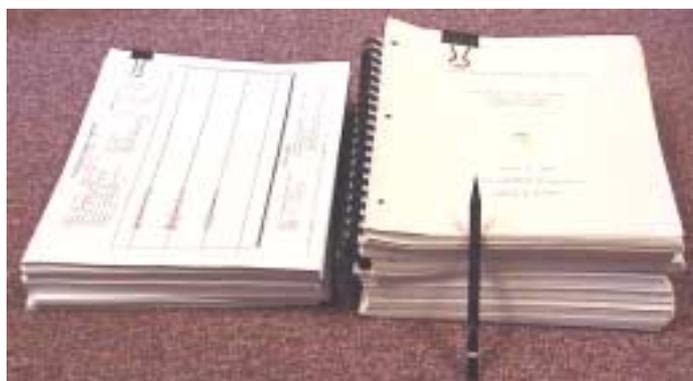


Figure 9 Volume of data captured in non digital form from two crack monitoring projects of six and eight month's duration.

## 8 CONCLUSIONS

Public concern over construction vibration-induced cracking has led to the development of a radically new approach to vibration monitoring and control, an Autonomous Crack Comparometer (ACC). This article chronicles the first step of developing instrumentation and software necessary for this system. The new system automatically compares long-term weather induced micrometer changes in crack width with those produced by habitation or ground motion. This comparison is displayed autonomously in real time via the Internet without human interaction.

The current model of the ACC effectively illustrates that weather cycles have the greatest effect on micrometer changes in crack width. While habitational vibrations cause transient changes in crack width, they return to the same position as the pre-vibration width. When crack displacements induced by vibrations from a surface coal mine are compared with the current data, it is apparent that ground motion produces relatively little crack displacement

Electronic drift and thermal hysteresis affect micrometer displacement sensors to varying degrees. Further research on different sensors is required in order to determine the most accurate sensor for this application. However, changing sensors will not require changes to other portions of the system or the concept. Currently, electronic drift and thermal hysteresis are corrected by subtraction of null sensor response.

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. 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.

Upon complete development, the ACC site and concept will have to be evaluated by installation in a concerned community.

## 9 ACKNOWLEDGEMENTS

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