Autonomous Crack Monitoring

Part 1: Comparison of Measured Crack Response in Diverse Structures to Dynamic Events and Weather Phenomena
Part 2: Qualification of Autonomous Crack Monitoring Systems

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Comparison of Measured Crack Response in Diverse Structures to Dynamic Events and Weather Phenomena

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This thesis consists of the data and analysis of structural responses for two different studies: the Office of Surface Mining (OSM) study of the velocity response of “atypical” residential structures and the Autonomous Crack Monitoring (ACM) study. The main basis of this thesis was to do additional analysis on a select four “atypical” structures instrumented during the OSM study conducted by Dr. Cathy Aimone-Martin at New Mexico Tech. In addition, crack response between these four structures and three ACM structures was compared in order to further expand the study of crack response on structures due to long term environmental phenomena and dynamic events.

The four OSM structures were instrumented with crack displacement sensors, in addition to the standard velocity transducers employed for the entire OSM study, in order to compare measured and predicted response of crack displacement for long term and dynamic events. Chapters 2 through 6 present the data and results associated with these comparisons. In Chapters 7 and 8, additional analyses conducted on two of the three ACM structures is presented. Chapter 7 describes the improved monitoring system of one of the ACM structures, were two different displacement sensors were instrumented and their responses compared. Chapter 8, describes the second ACM structure included in this thesis, which was instrumented in June of 2001. The third ACM structure is not discussed individually in this thesis; further details can be found in Seibert 2000. Finally, Chapter 9 provides a synthesis of the data with a comparison of all responses, in order to identify any common responses among the seven structures.
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CHAPTER 1

INTRODUCTION

This thesis synthesizes the data and analyses of structural and crack response of seven different structures from two different studies: the Office of Surface Mining (OSM) “Comparative Study of the Structure Response to Coal Mine blasting – Non-traditional Residential Structure” and the Autonomous Crack Monitoring (ACM) study. The objective of the OSM study was to measure the structure response of atypical structures to surface coal mine, blast-induced, ground motions and air vibrations. Velocity transducers were installed to measure whole structure and midwall response in 33 structures at 11 sites. As part of a continuing effort to predict trends in the crack response of various structures, this thesis presents crack response to long term (weather and environmental) and short term (transient) effects of 4 of the 11 OSM structures. Displacements calculated from the structures’ motion response were compared to the crack displacements measured by these displacement sensors, in order to evaluate any correlations between the estimated and measured values.

The objective of the ongoing Autonomous Crack Monitoring (ACM) study is to compare crack changes produced by short term blasting or construction vibrations with those produced by long-term environmental effects (such as temperature and humidity) in an easy to understand fashion. The ACM study consists of 3 structures, at 3 different locations that are instrumented to
monitor crack response and ground. Data collected at these sites are remotely accessed via a phone line and converted accordingly to display over the internet.

This thesis, which presents and compares the crack response of seven, is organized into 10 chapters and four appendices. Chapter 2 presents typical response velocity OSM instrumentation and introduces crack response instrumentation with further detail described in each individual chapter. Chapters 3 through 6 presents the data and analyses associated with the 4 OSM structures, in chronological order of monitoring. Each chapter includes the following:

- description of the structure and the location of instrumentation,
- summary of measurements recorded for each blast detected during the respective monitoring periods and a representative comparison of time histories for at least one of the observed blasts,
- determination of dominant/natural frequencies of the structure,
- crack response to environmental long-term effects,
- crack response to household activities, where measured, and
- comparison of calculated displacements with measured crack displacements.

Chapters 7 through 8 present measurements from two of the three ACM structures. The structure in Chapter 7 was most similar to the those in the OSM study as it was subjected to ground motions from quarry blasting. Crack responses were measured with two different sensors at this structure. The structure in Chapter 8, and the third ACM structure mentioned in Chapter 9, involved measurements of crack response only to long term, weather and occupant events. A synthesis of the responses measured at all seven structures is presented in Chapter 9. Chapter 10 provides a summary of the study and conclusions. The three appendices contain figures and tables that support the data presented in this thesis.
CHAPTER 2

INSTRUMENTATION

This thesis presents crack response data collected in conjunction with the Office of Surface Mining (OSM) study of the velocity response of “atypical” residential structures, and Autonomous Crack Monitoring (ACM) studies. Measurement of ground, structural, and wall response with velocity transducers allows comparison of standard velocity–based calculation estimates with the measured crack response. Responses of three of the four OSM structures were measured during a three-day to one-week period, which is relatively short compared to the months to a year observational periods for other Autonomous Crack Monitoring (ACM) studies. The fourth OSM structure (in New Mexico) was monitored over a period of several weeks, which allowed measurement of response to an extreme weather event. Velocity transducers were not employed at any of the ACM structures, therefore, comparisons with velocity-based estimations of structural response were not feasible. This chapter includes descriptions of instrumentation, which were typically the same at all of the OSM sites. Differences in instrumentation found at the ACM structures are described in each structure’s respective chapter.
**Instrumentation**

This chapter describes the common instruments employed to measure structural and wall response, as well as crack response. Emphasis is placed on the crack response instrumentation since velocity instrumentation for structural response is described in greater detail in Volume I of Aimone-Martin (2002). Instruments can be divided into three main categories based on the following measurements: 1) structural response using velocity transducers, 2) crack response using eddy current sensors, and 3) environmental changes using a dual temperature and humidity sensor.

**Configuration of Velocity transducers**

All four structures from the OSM study were fitted with velocity transducers to measure structural responses and were arrayed in the same basic configuration illustrated in Figure 2.1. (Outdoor velocity transducers are not included in this illustration, but were located at the same corner of the house outside, with the seismograph contained in a sealed container.) Two basic measurements were provided by the velocity transducers- ground excitation and structural response. Deployment for each will be discussed separately.

![Figure 2.1 Typical indoor velocity transducer and seismograph set-up](image)
Excitation ground motions were measured with standard three-axis Larcor velocity geophones in the radial (R), transverse (T), and vertical (V) directions. These excitation geophones were typically placed within three to ten feet of the structure corner and buried approximately 4 to 6 inches in the ground. In all cases, except the bungalow in Indiana (House 1), the arrow on the geophone, which indicates the radial direction pointed away from the blast, but along the long axis of the structure. At the bungalow in Indiana, the arrow pointed along the long axis of the structure, but towards the blast. The Larcor seismograph geophones report the first arriving radial component of ground motion as positive if moving in the direction of the arrow on the geophone cylinder. For other axes, positive motions are downward for the vertical and to the right (looking in the direction of the arrow).

A standard, Larcor seismograph air blast transducer was installed outside, adjacent to the three-axis ground geophones, attached three feet above the ground and pointed toward the location of blasting. The seismograph provided a resolution of 0.005 ips for ground motion and 0.02 millibars for the air overpressure. (For the first five blasts at the New Mexico structure, the ground motion time histories were twice as large, because the resolution on the machine was set incorrectly.) The seismograph, for all cases, was configured so that any ground motion equal to or greater than 0.02 ips, on any axis, would trigger data collection of excitation and response motions. The seismograph was further configured to record for the allotted time period defined for each structure (7 to 12 seconds), starting with the 0.5 seconds of ground motion that occurred before the seismograph was triggered.

Response motions were measured at the structure interior corners corresponding with the exterior three-axis geophones as shown in Figure 2.1, using two seismographs, each with four single axis velocity transducers. Each seismograph, S1 and S2, serviced three single-axis velocity transducers installed at the bottom and top corners of the structure and installed in the middle of the adjacent walls. Figure 2.2 shows a typical S1 cluster at the lower corner and Figure 2.3 shows a typical S2 cluster at the top corner. Of the three single axis transducers installed in the corners, one detected motion in the vertical direction (V), and two detected motion in the horizontal direction (R and T). Of the remaining midwall transducers, one was placed on the transverse wall, therefore detecting radial motion, and the other was placed on the radial wall, therefore detecting transverse motion.
Figure 2.2 Typical S1 cluster of transducers in the lower corner with S1 and S2 seismographs

Figure 2.3 Upper corner velocity transducers connected to the S2 seismograph

All seismographs were connected with a common trigger cable. The interior seismographs were set on manual mode. When the exterior seismograph triggered an event, all three recording units turned on. The excitation threshold used at all sites was set to 0.2 ips (0.5 mm/sec), therefore, whenever the ground geophone detected this level of motion, the whole system was set to record a prescribed length of data. Data files for all three seismographs
contained 4 channels. The four channels on the exterior seismograph, G, were air pressure and radial, vertical, and transverse ground motion, corresponding to the acoustical, vertical, radial, and transverse labels, respectively, in the data files. The four channels on the S1 and S2 seismograph were vertical and radial motion of the structure, transverse or radial motion detected from the midwall, and transverse motion of the structure, which correspond with the acoustical, vertical, radial, and transverse labels, respectively, in the data files.

**Concept of Comparative Crack Displacement**

Crack displacements of typical wall cracks were measured using displacement sensors. The change in an existing crack width in response to structure motions is illustrated in Figure 2.4. The total crack width itself is not actually measured, but rather the change (or variation) in crack width. The change in crack width is hereafter referred to as the crack displacement. By measuring the crack displacement instead of the crack width, it is possible to install the sensor without disturbing the crack itself during installation and monitoring. Further details of this concept are available in Dowding and Seibert (2000) and at [http://www.iti.northwestern.edu/acm](http://www.iti.northwestern.edu/acm).

![Figure 2.4 Definition of crack displacement (Siebert, 2000)](image)
Changes in crack width occurred from many different phenomena that include both long-term (environmental) effects and short-term (dynamic or vibration) effects. As with the ACM studies, both long-term and short-term effects were measured simultaneously with the system deployed during this study. The instrumentation system for crack displacement measurement was linked with the triggering exterior seismograph so that measurements of crack responses were recorded simultaneously with structure and ground motions. In addition, crack displacement measurements were obtained on an hourly basis in order to monitor the long-term movement of the cracks.

The concept of measuring crack displacements from both long-term and short-term effects with the same sensor is not dependent on the type of sensor. (Dowding and Seibert, 2000) Therefore, any number of sensor types can be employed. To date, two have been employed in the typical ACM studies; an eddy current proximity sensor (Kaman SMU9000 2U), and a Linear Variable Differential Transformer (LVDT DC 750 Series) sensor. These transducers have differing attributes as described in Siebert (2000). However, only Kaman transducers were employed in the OSM study.

Measurement of long-term crack displacements may involve long-term drift and temperature responses. In order to track such effects, a sensor (the null) can be affixed to a non-cracked section of the wall. The response of the null sensor can then be subtracted from the crack sensor response in order to obtain the true crack displacement. This concept is described further in Siebert (2000) and Dowding and Seibert (2000). Additional study has shown that null sensor response is typically small. (Louis 2001) A null sensor was employed in two of the four OSM study structures for verification.

**Instrumentation for Measurement of Crack Response**

**Data Acquisition System**

The Data Acquisition System (DAS) in the OSM study, employed to record crack response, was similar to the Somat platform that was employed by Seibert (2000) and Louis (2000) in the ACM studies - the Somat 2100 Field Computer System which contained three signal-conditioning modules and three filter modules. A sampling rate of the system was 1000 samples per second was used. Two signal-conditioning layers, 12-bit analog to digital converters
(A/D), were designated for the crack displacement sensors. A third signal-conditioning layer, an 8-bit A/D converter, was designated to receive the trigger signal from the exterior seismograph. Time histories of vibratory crack response were the same length as those for the structural and ground motions. The pre-trigger recording time ranged from 0.1 to 0.5 seconds.

The DAS was also configured to record long-term crack measurements in addition to measurements during dynamic events. During the monitoring period, the DAS would record a single “burst” (1/1000th of a second) sample every hour during a running test. As a result, the single crack displacement measurements from these “hourly” readings generated long-term crack displacement time histories.

To download the recorded data, a field computer loaded with the Somat Test Control Software for Windows (WinTCS v2.0.1 software), was connected to the DAS and data was retrieved either daily or weekly during the monitoring period.

**Crack Displacement Sensors**

**Kaman Displacement Measurement Sensor**

The Kaman SMU-9000 2U, single channel, displacement measurement sensor is shown in Figure 2.5.

![Figure 2.5 Kaman SMU-9000 2U eddy current displacement measuring sensor mounted across crack on an aluminum anchor block](image)
The 9000 2U sensor has a displacement range of 20 mils (0.02 inches, or 508 micrometers), with a voltage range of 5 volts. According to the manufacturer, the sensor has a resolution of 0.1 micrometers and a frequency response of 10,000 Hertz. Each sensor is independently calibrated to convert from voltage to mils (0.001 inches).

The Kaman gauge senses changes in an 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 produced by the sensor. The initial distance between the target and the sensor is set to approximately 10 mils (0.254 mm). The sensor is connected to the DAS and is powered by a separate 15-volt DC power supply.

**LVDT Displacement Measurement Sensor**

LVDTs (or Linear Variable Differential Transformers) have also been employed, in ACM studies. The sensors employed to date were the DC 750-050 and DC 750-125 LVDTs produced by MacroSensors. The 050’s have a displacement range of ±1.3 millimeters (±3.17 millimeters for the 125’s) with a voltage range of ±10 volts. Each sensor is deployed in the same configuration. The manufacturer does not give the sensor resolution or frequency response. However, the calculated resolution for the sensor based on an A/D converter system is 0.6 micrometers per A/D unit. The system used for these studies relies on A/D converters, therefore, 0.5 micrometers is the minimum resolution that the sensor is capable of producing with such a system. Each sensor has a constant factor to convert from voltage to displacement. The conversion factor for the 050 is 7.87 volts/millimeter and that for the 125 is 3.15 volts/millimeter. A photo of the 050 is shown in Figure 2.6. The body of the LVDT cannot be seen in this Figure directly because it is contained within an aluminum casing for mounting purposes (Seibert 2000).

A schematic drawing of the DC 750 Series LVDT is shown as Figure 2.7. The LVDT consists of two parts: a moveable magnetic core that is threaded onto a stainless steel screw and attached to the aluminum bracket; and a circular body with an cylindrical inner opening in which the core is able to translate parallel to the cylindrical axis. The core is centered within the body of the sensor, without contact, and moves relative to the body. This relative displacement
changes the magnetic field in the core, which in turn changes the output voltage. As with the Kaman gauge, the LVDT is connected to the DAS, and has its own 15-volt DC power supply.

Figure 2.6 LVDT displacement measurement sensor

Site specific considerations

In two of the OSM study structures, the one in Pennsylvania and New Mexico, only one Kaman sensor was employed. At the two sites in Indiana, two Kaman sensors were employed. One sensor was placed over a crack, while the other (the null) spanned an un-cracked surface area near the instrumented crack. At least two LVDTs were installed at all three of the ACM
study structures. In the Wisconsin structure, two Kaman sensors and two LVDT sensors were employed.

System resolutions are governed by either A/D resolution or sensor resolution; however, in these cases the two were similar. The sensor resolution for the Kaman sensor was 0.1 micrometers, while none was provided for the LVDT sensor. Since the dynamic response of the LVDT is similar to that of the Kaman, as shown in Chapter 7, it was assumed to be equal to that of the Kaman. A/D resolutions of all Kaman systems (OSM and Wisconsin) were between 0.065 and 0.083 micrometers/A/D division. For LVDTs, it was 0.62 for Minnesota (because the voltage range was set high) and 0.099 for Illinois. A/D resolution is the voltage range times the given conversion factor (micrometers/volts) divided by the A/D conversion rate (divisions/range or $2^{12}$ in all cases).

**Measurement of Temperature and Humidity**

A Supco DataLogger Temperature and Humidity (DLTH) sensor, shown as Figure 2.8, was used to record temperature and humidity every 10 minutes. At the Pennsylvania site and one of the houses in Indiana, the datalogger was installed indoors, and at New Mexico site and the other Indiana house, the datalogger was installed outdoors. Data were retrieved from the sensor by directly downloading the files from the sensor with the Supco software. These long-term weather data were then compared with the long-term crack response.

![Figure 2.8 Supco temperature and humidity data logger](image.png)
CHAPTER 3

DOUBLE-WIDE TRAILER - PENNSYLVANIA

The Pennsylvania structure, shown in Figure 3.1, is a double-wide trailer located approximately 1400 feet from surface coal mining in Kittanning, Pennsylvania. Data collected on-site from 19 to 24 May 2001 are summarized in Table 3.1. Four blasts with maximum charge weights/delay between 486 and 612 lbs (221 and 278 kg) produced ground motions of 0.07 to 0.32 inches per second (ips) (1.78 to 8.13 mm/sec), maximum structure responses of 0.19 to 0.42 ips (4.83 to 10.67 mm/sec), and maximum wall responses of 0.27 to 1.08 ips (6.86 to 27.43 mm/sec). In addition, a number of household activities were simulated in order to obtain comparative structure and crack responses. Weather data varied cyclically each day with inside temperatures ranging between 68 and 81 °F (20 to 27 °C) to and inside humidity ranging between 40 and 58%.

Figure 3.1 Pennsylvania double-wide trailer
Table 3.1 Summary of structural and crack response for Pennsylvania double-wide trailer

<table>
<thead>
<tr>
<th>Time of blast</th>
<th>Distance</th>
<th>Charge Weight/ Delay</th>
<th>Scaled Distance</th>
<th>Peak Particle Velocity (ips)</th>
<th>Structure response in S1 cluster (ips)</th>
<th>Structure response in S2 cluster (ips)</th>
<th>Midwall responses (ips)</th>
<th>Air Blast (dB)</th>
<th>Measured Crack Displacement above arch in kitchen (µin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/22/2001 10:38</td>
<td>1437</td>
<td>612</td>
<td>58.1</td>
<td>0.07</td>
<td>0.31</td>
<td>0.42</td>
<td>0.98</td>
<td>117</td>
<td>36</td>
</tr>
<tr>
<td>5/22/2001 12:16</td>
<td>1458</td>
<td>486</td>
<td>66.1</td>
<td>0.10</td>
<td>0.22</td>
<td>0.30</td>
<td>0.90</td>
<td>119</td>
<td>31</td>
</tr>
<tr>
<td>5/23/2001 14:19</td>
<td>1483</td>
<td>612</td>
<td>59.9</td>
<td>0.07</td>
<td>0.33</td>
<td>0.27</td>
<td>0.47</td>
<td>119</td>
<td>36</td>
</tr>
<tr>
<td>5/24/2001 10:51</td>
<td>1390</td>
<td>504</td>
<td>61.9</td>
<td>0.12</td>
<td>0.22</td>
<td>0.19</td>
<td>1.08</td>
<td>122</td>
<td>27</td>
</tr>
</tbody>
</table>
Structure Description

Plan and elevation drawings are shown for the Pennsylvania double-wide trailer in Figures 3.2 and 3.3. The structure is approximately 24 feet wide and 48 feet long (7.3 x 14.6 m), seven feet (2.1 m) in height, with a basement space approximately ten feet (3 m) in height. The exterior of the structure is covered with vinyl siding. The interior walls are four inches thick (102 mm) and are paneled or covered with wallpaper. The interior “marriage” wall along the long axis of the structure is constructed of wood studs and gypsum drywall. This dividing wall, shown in Figure 3.2, is the only wall in which a crack was found upon preblast inspection.

Basement photographs given in Figure 3.4, show standard-sized, concrete masonry blocks and a concrete slab floor. As shown in Figure 3.4a, metal posts, spaced 12 feet (3.7 m) apart, connected to a central ceiling beam, provide support along the radial axis of the structure; while steel floor joists, shown in Figure 3.4b, support the structure along the transverse axis of the structure.

As shown in Figure 3.4c, a portion of the trailer floor beam has been removed. The location of this cut out is near the stairway to the basement, which is located near the bathroom. As shown in Figure 3.3, this area is near the crack in the center wall. It appears as though the pipe post to the left of the cut was installed to support the load carried by the severed beam. When structural elements are altered, adverse effects (such as differential settlement, cracks, etc.) are likely. The crack studied in this structure may be related in some way to the alteration of the foundation system.
Figure 3.2 Plan view of the Pennsylvania trailer

Figure 3.3 Elevation view of the Pennsylvania trailer
(a) Central ceiling beam spanning in the radial direction
(b) Steel floor joists in transverse direction
(c) Area of trailer floor beam with portion removed from stairway

Figure 3.4 Basement of double-wide trailer
Location of instrumentation

Locations of all instruments are shown in Figures 3.2 and 3.3. Eleven velocity transducers were installed on and outside of the southwest corner of the structure, closest to the mining activity. The crack displacement sensor was located above the archway of the interior wall in the kitchen of the structure, as shown in Figure 3.5. Further details on placement and description are given in Chapter 2.

Figure 3.5 shows the wall with the Kaman crack displacement sensor and the Supco temperature and humidity datalogger. The crack monitored is located approximately six inches (152 mm) from the ceiling and is vertically oriented as shown by the magnified inset in Figure 3.5. Its width was estimated from photographs to be approximately 700 micrometers (27,700 µin).

For each blast, time histories were recorded for a total of 6.5 seconds. Time correlated (within 1/1000 second) time histories of dynamic crack displacement were also collected from the Kaman sensor for five seconds.
**Transient Responses**

Figure 3.6 shows radial velocity time histories of excitation ground motions and structure response, as well as crack response, associated with the blast on 22 May 2001 at 10:38. This blast was typical of the four blast events that were observed during the monitoring period. The top graph shows crack displacement, followed by the ground excitation, and the lower, S1, and upper, S2, structure corner response. The difference of the integrated lower and upper velocity responses follows, and is labeled as S1-S2 (R). This difference of integrated time histories represents an estimated relative displacement time history for the structure. Finally, the air blast response, in millibars, is shown. This blast produced a peak crack displacement of 0.91 \( \mu \text{m} \) (36.0 \( \mu \text{in} \)) and a peak ground motion, parallel to the wall direction, of 0.24 ips (6.1 mm/sec).

The radial responses shown are parallel to the plane of the wall containing the crack. Thus, they can be employed to predict displacements (or strain) and compare to the measured crack displacements.

In Figure 3.7, the time histories of all three components of ground motion (R, T, and V) along with the air blast response are compared to the crack response. In addition, the upper corner responses (S2) of the structure, both radial and transverse, are also shown. All time histories have a common time base. All significant structural response, including that from the air blast, occurred within the first three seconds.

As mentioned previously, structure response was used in order to compute relative displacements from transient events. To do this, in some instances, it is necessary to estimate a dominant frequency of the structure. Ground motions of a certain dominant frequency typically do not exhibit the same relative displacements in structures of differing dominant frequencies. (Dowding 1996) The dominant frequency of the structure was estimated two ways: 1) the zero-point-crossing frequency determination method and 2) Fourier Frequency Spectra (Dowding 1996). Where free response occurred, as shown in Figure 3.8, the zero-crossing method was employed on the S2 time histories. The inverse of twice the time between successive zero-crossings resulted in an estimated dominant/natural frequency of the structure. Estimations of dominant frequencies calculated from the S2 time histories (in both R and T directions) were averaged, therefore, giving the structure an estimated natural frequency of 8 Hz.
Figure 3.6 Time history of crack displacement on 22 May at 10:38 compared to ground excitation, S1 and S2 response, calculated relative displacement of structure (R1-R2), and air blast.
Figure 3.7 Time history of crack displacement on 22 May at 10:38 compared to ground excitation in the radial, transverse, and vertical directions, air blast response, and S2 radial and transverse structure response
The Fourier frequency approach is most useful when there is little or no free response detected in the response time histories. To obtain dominant frequencies, Fourier Frequency Transforms (FFTs) can be determined using dedicated software such as White Seismograph Data Analysis (White Industrial Seismology, Inc. (1998) or NUVIB (Huang, 1994) for any of the velocity time histories. Only NUVIB can be employed to obtain FFT spectra for the crack displacement time histories, since White only analyzes data files recorded from the seismographs. The ratio of the FFT spectra of the structure response at S2 divided by the ground motion for the same component provides a means to determine the dominant frequency, as shown in Figure 3.9 for the event on 22 May at 12:16. Here the upper corner velocity (S2) Fourier spectrum (b) is divided by that of the ground velocity (c) to produce the ratio (a). False peaks may develop when small structural amplitudes are divided by much smaller ground motion amplitudes. To prevent large ratios of insignificant response and excitation, broad-frequency-band, low amplitude noise should be added to both the structural and ground motion amplitudes to eliminate these false transfer function peaks. (Dowding 1996) Alternatively these peaks can be filtered out by replacing any amplitude less than ten percent of the peak amplitude of a given FFT with ten percent of the peak amplitude. The second approach was followed in this study. FFTs produced for all structures can be found in Appendix A.

Dominant response frequencies estimated from ratios of these moderated FFT spectra of upper structure response and ground motion were approximately 8 to 10 Hz for all responses in the radial direction. As seen in Figure 3.9a, the dominant response frequency for the blast on 22 May at 12:16 was 10 Hz. For this case both the FFT and zero crossing methods yielded the same dominant frequency, 8 to 10 Hz.
Figure 3.9  Spectra of ratio of S2 velocity FTT and ground velocity FFT, S2 FFT, and ground FFT
Single Degree of Freedom analyses were performed on all radial ground motions produced by the blast events. The Single Degree of Freedom model (SDOF) has been used to predict cracking potential of structures subjected to excitation motions in the ground. A spectrum curve is generated from a SDOF analysis that represents the response of structures (of varying natural frequencies) to the same ground motion. (Dowding 1996) Further detail on the background of the SDOF model can be found in Appendix B.

The SDOF response spectrum for the radial ground motion produced by the 22 May blast at 10:38 is displayed as Figure 3.10. A damping coefficient of 5% was assumed in determining the response spectra for all of the ground motions analyzed in this thesis, based on average values from previous studies. By calculating this coefficient from some of the time histories exhibiting free response, this assumption proved to be valid. The approximate dominant (natural) frequency of the Pennsylvania trailer was 8 Hertz (as determined above), therefore, the estimated displacement of the structure relative to this ground motion was 9600 µin (243 µm), as shown by the intersection of the vertical 8 Hertz line with the response spectrum.

Figure 3.10 Single Degree of Freedom response spectrum of radial motion produced by blast on 5/22/2001 at 10:38, showing estimated relative displacement of an 8 Hz structure
Crack Response to Household and Blast Events

Table 3.2 presents the measured crack displacement corresponding to all dynamic events. Household activities such as closing doors and windows, hitting walls, jumping in the house, and dropping a chair, were performed to measure crack responses and compare them to responses from the blasts. Blast-induced displacements are included for comparison. Approximate distances between the location of the activity and the crack are also presented in the table.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Approximate distance from crack (feet)</th>
<th>Peak crack displacement (micro-inch)</th>
<th>Peak crack displacement (micrometers)</th>
<th>Approximate distance from radial midwall (feet)</th>
<th>Peak Radial Midwall Response (ips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bathroom door</td>
<td>gentle</td>
<td>10 to 11</td>
<td>8.9</td>
<td>0.23</td>
<td>8</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>hard</td>
<td></td>
<td>22.3</td>
<td>0.57</td>
<td></td>
<td>2.14</td>
</tr>
<tr>
<td>bedroom door</td>
<td>gentle</td>
<td>5 to 6</td>
<td>8.9</td>
<td>0.23</td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>hard</td>
<td></td>
<td>18.4</td>
<td>0.47</td>
<td></td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>slam</td>
<td></td>
<td>97.7</td>
<td>2.48</td>
<td></td>
<td>1.46</td>
</tr>
<tr>
<td>front screen door</td>
<td>moderate</td>
<td>14</td>
<td>22.3</td>
<td>0.57</td>
<td>12</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>hard</td>
<td></td>
<td>26.7</td>
<td>0.68</td>
<td></td>
<td>0.46</td>
</tr>
<tr>
<td>front door</td>
<td>gentle</td>
<td></td>
<td>4.4</td>
<td>0.11</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>hard</td>
<td></td>
<td>6.9</td>
<td>0.18</td>
<td></td>
<td>0.35</td>
</tr>
<tr>
<td>kitchen door</td>
<td></td>
<td></td>
<td>26.8</td>
<td>0.68</td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td>jump</td>
<td>bedroom</td>
<td>10 to 11</td>
<td>58.4</td>
<td>1.48</td>
<td></td>
<td>0.42</td>
</tr>
<tr>
<td>vacuum hit wall</td>
<td>bedroom</td>
<td></td>
<td>22.5</td>
<td>0.57</td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>chair fall back</td>
<td>dining room</td>
<td>5</td>
<td>49.2</td>
<td>1.25</td>
<td>15</td>
<td>0.09</td>
</tr>
<tr>
<td>hammer</td>
<td>bedroom wall</td>
<td>10 to 11</td>
<td>8.8</td>
<td>0.22</td>
<td>5</td>
<td>0.06</td>
</tr>
<tr>
<td>close window</td>
<td>bedroom S. wall</td>
<td>27</td>
<td>4.4</td>
<td>0.11</td>
<td>2</td>
<td>0.16</td>
</tr>
<tr>
<td>shot 1</td>
<td>5/22/2001 10:38</td>
<td>1450</td>
<td>35.9</td>
<td>0.91</td>
<td>1430</td>
<td>0.98</td>
</tr>
<tr>
<td>shot 2</td>
<td>5/22/2001 12:16</td>
<td>1560</td>
<td>31.3</td>
<td>0.79</td>
<td>1450</td>
<td>0.90</td>
</tr>
<tr>
<td>shot 3</td>
<td>5/23/2001 14:19</td>
<td>1500</td>
<td>36.3</td>
<td>0.92</td>
<td>1475</td>
<td>0.47</td>
</tr>
<tr>
<td>shot 4</td>
<td>5/24/2001 10:51</td>
<td>1400</td>
<td>26.6</td>
<td>0.68</td>
<td>1380</td>
<td>1.08</td>
</tr>
</tbody>
</table>

In many instances, the crack responded at a greater amplitude of displacement to the household activities than to the highest ground motions from blasting. Crack responses associated with the four blasts ranged between 0.68 and 0.92 micrometers (26.9 and 36.3 µin). The smallest response occurred when the window in the far bedroom was shut, which resulted in a peak crack displacement of 0.11 micrometers (4.3 µin); this event was approximately 30 feet (9.1 m) away from the instrumented crack. The largest response occurred when the master bedroom door (approximately 5 ft, or 1.5 m, from the crack in an adjacent room) was slammed shut; this resulted in a peak crack displacement of 2.48 micrometers (90.5 µin). Other responses greater than those associated with the blasts occurred when a person jumped in the middle of the master bedroom and when a chair was dropped in the dining room (another adjacent room).
Closing most of the doors in the structure resulted in peak crack displacements close to the crack displacement associated with the smallest intensity blast. Only when doors were closed gently did the crack displacements remain around 0.2 µm (7.9 µin).

**Crack Response to Environmental Effects**

Figure 3.11 compares the long-term action of weather indicators (temperature and humidity) with the long-term crack response. Temperature, crack displacement, and humidity were plotted with thin solid lines along the same time scale to illustrate interrelationships. Long-term crack displacement was measured hourly during the monitoring period and temperature and humidity were measured every 10 minutes. Sharp changes were observed in the temperature, crack displacement, and humidity throughout the monitoring period. At the time of monitoring, an air conditioning unit was functioning, which produced severe changes in temperature on a regular basis. In addition, rainfall was observed intermittently, producing concentrated periods of high humidity. Consequently, these conditions, more than likely, were the cause of sharp changes in crack displacement.

Average values of crack displacement (and temperature and humidity) were systemically calculated at every hourly measurement taken (and are shown in Figure 3.11 with diamond-constructed lines). These 24-hour “rolling” averages consisted of the measurements from 12 hours before and 12 hours after each hourly measurement. For example, at 12:00 p.m. on 22 May 2001, a 24-hour average crack displacement was calculated from the 24 measurements recorded between 12:00 a.m. on 22 May to 12:00 on 23 May. For the first and last 12 rolling averages computed, the first and last measurement recorded was counted more than once in the respective averages, in order to have 24 measurements included in every average. For this monitoring period, the 24-hour rolling averages of temperature remained relatively constant, but slightly mirrored those of displacement and humidity. The 24-hour averages of humidity increased gradually during most of the observed period, while slightly declining at the end. The 24-hour averages of crack displacement followed those of humidity, but lagged slightly behind.

Overall averages, shown with the thick solid lines in Figure 3.11, were computed for crack displacement, temperature, and humidity throughout the whole monitoring period. Hourly measurements from the first to last hour were included in these averages.
Figure 3.11 Long-term crack displacement and weather versus time
Collectively, the actual measurements, 24-hour averages, and overall averages were used to determine crack response to weather effects. Weather effects have three distinct contributors: 1) frontal movements that change overall temperature and humidity for periods of several days to several weeks, 2) daily responses to changes in average temperature and solar radiation, and 3) weather fronts that contain extremes of unusual weather or other environmental effects. Table 3.3 lists all of the average and maximum values for the frontal, daily, and weather effects. Values of crack response to typical and maximum ground motions associated with coal mine blasts are also included in this table, in order to compare the difference in magnitude between weather-induced and blast-induced crack response.

The first contributor, the frontal effect, is defined as the deviation of the peak 24-hour average value from the overall computed average. In between each instance when the 24-hour average line crossed the overall average line, the frontal effect was calculated at the peak 24-hour average value and taken as an absolute value. The average and maximum of the calculated frontal effects (for temperature, crack displacement in both $\mu$m and $\mu$in, and humidity) were included in Table 3.3.

The second contributor, the daily effect, is defined as the difference of the peak actual measurement from the 24-hour average. In between each instance when the actual measurement line crossed the overall average line, the daily effect was calculated (actual minus 24-hour average) and taken as an absolute value. The average and maximum of the calculated daily effects (for temperature, crack displacement in both $\mu$m and $\mu$in, and humidity) were also included in Table 3.3.

The third contributor, the weather effect, was defined as the difference in the peak actual measurement from the overall computed average. In between each instance when the actual measurement crossed the overall average line, the weather effect was calculated (actual minus overall average) and taken as an absolute value. The average and maximum of the calculated weather effects (for temperature, crack displacement in both $\mu$m and $\mu$in, and humidity) were also included in Table 3.3.
Table 3.3 Computed crack displacements due to long-term weather phenomena

<table>
<thead>
<tr>
<th></th>
<th>Temperature Change (DegF)</th>
<th>Crack Displacement (µin)</th>
<th>Crack Displacement (µm)</th>
<th>Humidity Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal Effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviation of 24 hr average from</td>
<td>0.2</td>
<td>381</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>overall average</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max deviation of 24 hr average from</td>
<td>0.4</td>
<td>451</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>overall average</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of deviations from 24 hr average</td>
<td>2</td>
<td>414</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>trend</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max deviations from 24 hr average trend</td>
<td>4</td>
<td>639</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>Weather Effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviations from overall average</td>
<td>3</td>
<td>419</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>Max deviations from overall average</td>
<td>5</td>
<td>962</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>Vibration Effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Ground motion (PPV=0.10 ips)</td>
<td>-</td>
<td>12</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Max ground motion (PPV=0.32 ips)</td>
<td>-</td>
<td>36</td>
<td>0.9</td>
<td>-</td>
</tr>
</tbody>
</table>

In Figure 3.12, the crack displacements due to different weather phenomena measured over the entire monitoring period are compared to those from the blasts. The magnitude of each dynamic response to a blast event corresponds to the absolute, maximum zero-to-peak displacement of the crack during the five seconds of resulting vibratory motion. In order to display the relatively, small responses associated with the blasts, the blast-induced responses (illustrated with vertical lines) are encircled and the two day period of blasting is magnified in Figure 3.12(b). The zero-to-peak values are shown originating from the overall average line in order to emphasis the large difference in magnitude (between long term and dynamic response) pictorially. The maximum dynamic crack displacement of 0.92 µm or 36.3 µin (associated with a peak radial ground motion of 0.32 ips from the blast on 23 May 2001 at 14:19) is small compared to the average and maximum crack displacements due to computed weather effects of 7 and 24 µm (277 and 948 µin), respectively. The maximum weather front is almost 25 times this particular crack response.
Figure 3.12 Typical crack displacements due to long-term phenomena and maximum zero to peak dynamic blast events
Comparison of computed displacements with measured crack displacements

The maximum measured crack displacement produced by each shot is compared in Table 3.4 to various computed wall displacements based on structure responses, and peak ground motion measured in the direction parallel to the cracked wall. Structure/wall displacements were computed using a number of methods such as the integration of velocity time histories, the Single Degree of Freedom response spectrum method, and estimation based on sinusoidal approximation. All computed displacements were based on structure and ground responses in the direction parallel to the wall containing the crack, since crack displacement was measured in the plane of the wall. All comparisons are presented graphically in Figures 3.13 and 3.14. Details pertaining to these methods to compute structural displacements are presented below.

Integration of time histories

Displacement time histories can be calculated by integrating velocity time histories. By subtracting perfectly time correlated (±0.001 sec) pairs of these integrated velocity time histories, a relative displacement time history was created. This was done for two different pairs - upper corner, S2, minus lower corner, S1, and S2 minus ground, G. The peak relative displacements were determined from these resulting time histories and used as a representative values of computed displacement. Comparisons between measured crack displacements and these (S2-S1)_{max} and (S2-G)_{max} displacements are presented graphically in Figure 3.13 (a) and (b), respectively.

Displacements were also estimated from the integrated ground velocity time histories, exclusively. The peak values from these time histories were used as representative values of computed displacement. The comparison between measured crack displacements and these G_{max} displacements are presented graphically in Figure 3.13 (c).
Table 3.4 Summary of computed and measured displacements

<table>
<thead>
<tr>
<th>Date of Shot</th>
<th>(S2-S1)_{max}</th>
<th>(S2-G)_{max}</th>
<th>G_{max}</th>
<th>From response spectra for f_{n} of 8 Hz</th>
<th>Estimated from V and f at S2_{max} and S2_{max}</th>
<th>Estimated from V and f at S'<em>{max} and S2</em>{max}</th>
<th>Peak ground motion in the radial direction ((\mu\text{in/sec}))</th>
<th>Measured crack displacement ((\mu\text{in}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/22/01 10:38</td>
<td>5914</td>
<td>8403</td>
<td>4755</td>
<td>9557, 7209</td>
<td>6784, 4970</td>
<td>7926, 7380</td>
<td>0.24</td>
<td>36</td>
</tr>
<tr>
<td>5/22/01 12:16</td>
<td>3921</td>
<td>5747</td>
<td>3246</td>
<td>6784, 4970</td>
<td>259, 6301</td>
<td>2519, 7148</td>
<td>0.19</td>
<td>31</td>
</tr>
<tr>
<td>5/23/01 14:19</td>
<td>5317</td>
<td>6323</td>
<td>3320</td>
<td>7926, 7380</td>
<td>2519, 7148</td>
<td>1058, 5508</td>
<td>0.32</td>
<td>36</td>
</tr>
<tr>
<td>5/24/01 10:51</td>
<td>2802</td>
<td>3967</td>
<td>2337</td>
<td>4639, 4382</td>
<td>1685, 1210</td>
<td>1635, 1210</td>
<td>0.20</td>
<td>27</td>
</tr>
</tbody>
</table>
Figure 3.13 Correlations between measured crack displacement and computed displacements and peak radial ground motions
Figure 3.14 Correlations between measured crack displacement and computed relative displacements
**Single degree of freedom response spectrum method**

As described earlier in this chapter, by analyzing SDOF response spectra of blast-induced ground motions, relative displacements can be estimated for structures of different dominant frequencies. Two approaches were made in picking these estimated relative displacements. The first was to find the relative displacement associated with the estimated dominant frequency of the structure. These values were used as representative values of computed displacements, and are equated to peak displacements that the structure would experience. Comparisons between measured crack displacements and these computed displacements are presented graphically as Figure 3.13 (d).

The second approach to finding structure/wall displacements based on this method was to average a range of estimated displacements based on a range of dominant frequencies. As reported in previous studies, the 10 to 15 Hz range is the average range of dominant frequencies for one to two story structure walls. Therefore, estimated displacements for dominant frequencies between 10 and 15 Hz were averaged in order to find representative values of computed displacement for the structure wall. These values were desired since the crack was located on the wall, and were expected to have a stronger correlation with the measured displacements than those computed using the estimated dominant frequency of the structure. Comparisons between the measured crack displacements and these computed displacements are presented graphically as Figure 3.13 (e).

**Estimation based on sinusoidal approximation**

Relative displacements can be estimated visually from time histories by assuming that velocity time histories approximate sinusoidal waveforms. Displacement, $\delta$, can be estimated using the following equation:

$$\delta = \frac{V}{2\pi f},$$

where $V$ is a given velocity in a time history and $f$ is the dominant frequency of the velocity at the time it occurs. The frequency is determined by taking the inverse of twice the time between the zero-crossings enclosing the given velocity. Displacements approximated in this manner can be determined for both upper and lower bounds of the structure and subtracted in order to obtain various measures of relative displacement.
Approximated relative displacements have been produced from the following pairs of velocity time histories: 1) ground motion, G, and the upper corner, S2, at the time of peak G, 2) G and S2 at the time of peak S2, 3) peak G and peak S2, regardless of the time at which each occurs. For the two time-correlated pairs, (1) and (2), displacement is still computed at the same time, regardless of the magnitude of the velocity at that point in time, for either of the time histories. In other words, if the velocity on one of the time histories is 0.0 in/sec and the velocity on the other is 0.3 ips, then the displacement of the first time history would be considered zero, and the relative displacement would be equal to that computed from the second time history. These resulting values from $\delta(S2) - \delta(G_{\text{max}})$, $\delta(S2_{\text{max}}) - \delta(G)$, and $\delta(S2_{\text{max}}) - \delta(G_{\text{max}})$, were all used as representative values of computed displacements. Figure 3.15 displays the calculation of relative displacement using ground motion and S2 response, at the time of peak ground motion, for the blast on 22 May at 10:38. Comparisons between measured crack displacements and the computed displacements are presented graphically as Figure 3.14 (a), (b), and (c), respectively.

![Figure 3.15 Calculation of relative displacement using method of approximation](image)

Relative displacement = $\delta(S2) - \delta(G_{\text{max}})$

Relative displacement = \[\frac{0.24 \text{ ips}}{2\pi \times (1/2 \times 0.03 \text{ sec})} - \frac{0.30 \text{ ips}}{2\pi \times (1/2 \times 0.07 \text{ sec})} = 4607 \mu\text{in or 117} \mu\text{m}\]
In addition, three more pairs were analyzed, where velocity in the lower corner, S1, was used in place of ground motion, G. (G and S1 at the time of peak G, G and S1 at the time of peak S1, and peak G and peak S1, regardless of the time at which each occurs) These resulting values from $\delta(S1) - \delta(G_{\text{max}})$, $\delta(S1_{\text{max}}) - \delta(G)$, and $\delta(S1_{\text{max}}) - \delta(G_{\text{max}})$, were also used as representative values of computed displacements. Comparisons between measured crack displacements and these computed displacements are presented graphically as Figure 3.14 (d), (e), and (f), respectively.

The last pair, in both sets of three is not as precise as the others, as it fails to take into account the necessity of simultaneity of the motions. Such values do not depict the displacement at a given time, but rather, a maximum possible displacement. Therefore, it would be expected that the first two pairs of both sets would yield better correlations with the measured displacements than would the last pairs.

Based on the data shown in Figures 3.13 and 3.14, the best correlation was produced between the measured displacements and the displacements from the difference of integrated velocities, S1-S2, as shown in Figure 3.13 (a). The trend line for this relationship exhibits a regression coefficient, $R^2 = 0.95$. The estimated displacements from SDOF analyses also resulted in high regression coefficients, with the displacement representing the average range of wall frequencies having a tighter trendline, as expected ($R^2 = 0.92$), than the displacement corresponding with the estimated dominant frequency ($R^2 = 0.87$). These correlations were shown in Figure 3.13 (d) and (e), respectively. The lowest regression coefficients were seen from the approximated displacements computed at the times of $G_{\text{max}}$ and $S1_{\text{max}}$, and also when no time correlation was involved in the computation (Figure 3.14 (a), (d), (c), and (e), respectively).

In this thesis, the square of the regression coefficient, $R^2$, was employed to describe the tightness of data to a best-fit trendline. Microsoft Excel defines the $R^2$ value as the square of the Pearson product moment correlation coefficient, which is the proportion of the variance in y, depending on the variance in x. The tightness of fit (of the data to the best-fit trendline) was also calculated with standard deviations, using the y-distances, as well as the perpendicular distances, of the data points from their respective trendline. Only one of these comparisons, $R^2$, was presented in this thesis, as the conclusions did not change with varying methods of calculating tightness of data about best-fit trendlines.
The New Mexico structure, shown in Figure 4.1, is an adobe brick structure located approximately 5000 feet (1533 m) from surface coal mining in Farmington, New Mexico. Data collected onsite from 21 June to 26 July 2001 are summarized in Table 4.1. Nine blasts with maximum charge weights/delay between 300 and 13,047 lbs (136 and 5930 kg) produced ground motions of 0.01 to 0.16 ips (0.3 to 4.1 mm/sec), maximum structure response of 0.02 to 0.22 ips (0.5 to 5.6 mm/sec), and maximum wall response of 0.03 to 0.31 ips (0.8 to 7.9 mm/sec). Weather data varied cyclically each day with outside temperatures ranging between 52 and 103°F (11 to 39 °C) and outside humidity ranging between 10 and 92%.
Table 4.1 Summary of structural and crack response for New Mexico adobe structure

<table>
<thead>
<tr>
<th>Time of Blast</th>
<th>Distance (ft)</th>
<th>Charge Weight/ Delay (lb)</th>
<th>Scaled Distance (ft/lb(^{1/2}))</th>
<th>Peak Particle Velocity (ips)</th>
<th>Structure response in S1 cluster (ips)</th>
<th>Structure response in S2 cluster (ips)</th>
<th>Midwall responses (ips)</th>
<th>Air Blast (dB)</th>
<th>Measured Crack Displacement under outdoor window frame ((\mu)in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/22/01 14:20</td>
<td>5333</td>
<td>13047</td>
<td>46.7</td>
<td>0.09 0.16 0.11</td>
<td>0.13 0.11</td>
<td>0.19 0.14</td>
<td>0.19 0.25</td>
<td>128</td>
<td>90.1</td>
</tr>
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<td>6/26/01 15:57</td>
<td>5186</td>
<td>1708</td>
<td>125.5</td>
<td>0.01 0.01 0.01</td>
<td>0.01 0.01</td>
<td>0.02 0.02</td>
<td>0.03 0.05</td>
<td>112</td>
<td>11.8</td>
</tr>
<tr>
<td>6/28/01 15:03</td>
<td>4816</td>
<td>300</td>
<td>278.1</td>
<td>0.03 0.04 0.05</td>
<td>0.05 0.06</td>
<td>0.06 0.06</td>
<td>0.06 0.06</td>
<td>100</td>
<td>23.6</td>
</tr>
<tr>
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<td>4478</td>
<td>300</td>
<td>258.5</td>
<td>0.05 0.09 0.05</td>
<td>0.05 0.06</td>
<td>0.06 0.08</td>
<td>0.08 0.08</td>
<td>100</td>
<td>23.6</td>
</tr>
<tr>
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<td>4941</td>
<td>9591</td>
<td>50.5</td>
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<td>0.11 0.11</td>
<td>0.17 0.17</td>
<td>0.20 0.26</td>
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<td>166.7</td>
</tr>
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<td>11183</td>
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<td>0.10 0.12 0.14</td>
<td>0.12 0.11</td>
<td>0.15 0.22</td>
<td>0.28 0.31</td>
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<td>94.0</td>
</tr>
<tr>
<td>7/23/01 11:22</td>
<td>4621</td>
<td>300</td>
<td>266.8</td>
<td>0.05 0.07 0.06</td>
<td>0.07 0.07</td>
<td>0.09 0.08</td>
<td>0.13 0.08</td>
<td>110</td>
<td>37.9</td>
</tr>
<tr>
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<td>5565</td>
<td>1200</td>
<td>160.6</td>
<td>0.04 0.11 0.07</td>
<td>0.11 0.08</td>
<td>0.13 0.09</td>
<td>0.17 0.09</td>
<td>106</td>
<td>54.8</td>
</tr>
<tr>
<td>7/26/01 14:55</td>
<td>4593</td>
<td>7455</td>
<td>53.2</td>
<td>0.07 0.07 0.11</td>
<td>0.06 0.09</td>
<td>0.08 0.17</td>
<td>0.19 0.17</td>
<td>120</td>
<td>90.9</td>
</tr>
</tbody>
</table>
**Structure Description**

As shown by plan and elevation drawings in Figures 4.2 and 4.3, the structure is approximately 32 feet wide and 70 feet long (9.7 x 21.3 m). The structure is a one-story residential unit, eleven to sixteen feet in height (3.3 to 4.9 m), with no basement space. The walls of the house are comprised of adobe laid brick, and are approximately 10 inches (254 mm) thick (both exterior and interior). Adobe is constructed from a mixture of clay and straw that is compacted into a mold. For this structure, the individual adobe bricks were approximately 6 in. x 3 in. by 12 in. (152 x 76 x 76 mm)

**Location of Instrumentation**

Locations of all instruments are shown in Figures 4.2 and 4.3. Eleven velocity transducers were installed on and outside of the southeast corner of the structure, closest to the mining. The crack displacement sensor was located on the exterior of the house, spanning a crack that formed a 45° angle from a window frame on the south wall of the house as shown in Figure 4.4. The width of the crack was approximated from the photograph as approximately 800 µm (31,600 µin). Further details on placement and description of the instrumentation are given in Chapter 2.

The sensor is located approximately three feet above ground surface on the exterior wall of the house, was placed outside in order to monitor crack displacement during extreme temperature and humidity swings typical of a desert environment. The Supco temperature and humidity sensor was placed adjacent to the Kaman sensor on the exterior wall to record weather changes.

For each blast, time histories were recorded for a total of 13 seconds. Time correlated (within 1/1000 second) time histories of dynamic crack displacement were also collected from the Kaman sensor for nine seconds.
Figure 4.2 Plan view of New Mexico adobe

Figure 4.3 Elevation view of New Mexico adobe
Figure 4.4 Kaman crack displacement sensor

Transcient Responses

Figure 4.5 shows the velocity time histories of excitation ground motions and structure response, as well as crack response, associated with the blast on 5 July 2001 at 15:03. The responses shown are radial since the plane of the wall containing the crack is radial. This blast produced a peak crack displacement of 4.2 µm (165.9 µin) and a peak radial ground motion of 0.13 ips (3.3 mm/sec). This blast produced the largest dynamic crack displacement during the monitoring period.

In Figure 4.6, the time histories of all three components of ground motion, along with the air blast response, are compared to crack response (for the same blast). In addition, the upper corner (S2) responses of the structure, both radial and transverse, are also shown. All significant structural response from this blast, as well as from the air blast, occurred within the first nine seconds. This also was the case for every each blast during the monitoring period.
Figure 4.7 shows the velocity time histories of excitation ground motions and structure response, as well as crack response, associated with the blast on 17 July 2001 at 12:51. This blast produced a crack response that was typical during the monitoring period.

In Figure 4.8, the time histories of all three components of ground motion, along with the air blast response, are compared to crack response (for the same blast). In addition, the upper corner (S2) responses of the structure, both radial and transverse, are also shown. This blast produced a peak crack displacement of 2.4 µm (94.8 µin) and a peak radial ground motion of 0.12 ips (3.0 mm/sec).
Figure 4.5 Time history of 5 July 2001 crack displacement compared to ground excitation, S1 and S2 response, calculated relative displacement of structure (R1-R2), and air blast
Figure 4.6 Time history of 5 July 2001 crack displacement compared ground excitation in the radial, transverse, and vertical directions, air blast response, and S2 radial and transverse structure responses.
Figure 4.7 Time history of crack displacement at 17 July 2001 at 12:51 compared to ground excitation, S1 and S2 response, calculated relative displacement of structure (R1-R2), and air blast
Figure 4.8 Time history of crack displacement on 17 July 2001 compared to ground excitation in the radial, transverse, and vertical directions, air blast response, and S2 radial and transverse structure responses
The dominant response frequencies of the structure required calculation of the FFT ratio because of the lack of free response in the S2 time histories. Ratios were calculated with radial crack response and excitation displacements in order to directly identify the response of the exterior wall in which it was located. It was necessary to employ crack rather than structural response because the upper and midwall velocity transducers were located far from the crack. Further details on the method of calculation for FFT ratios can be found in Chapter 3. Examples of the FFT crack displacement ratios for the 5 July and the 17 July events that correspond to the ground motions in Figures 4.5 and 4.7 are shown in Figures 4.9 and 4.10, respectively. The ground motion causing the greatest crack (and presumably wall) response, 5 July, produced high ratios at 8.5 and 14 Hz. For the 17 July event, high ratios were produced around 7.5 and 9 Hz. Examples of superstructure response FFT ratios are shown in Figures 4.11 and 4.12, respectively. The overall structure responds most to motion in the 5 Hz range. For the two events shown in Figures 4.11 and 4.12, the dominant frequencies were approximately 5.5 and 7 Hz, respectively. Higher dominant frequencies were observed with the crack to ground ratios than with the structure to ground ratios, as was expected, since the dominant frequencies of walls are typically higher than the dominant frequency of the structure.

The response spectra of radial ground motions from the 5 and 17 July 2001 (at 15:03 and 12:51, respectively) blasts are displayed as Figure 4.13. The estimated relative displacements of the structure, with a dominant frequency of 5 Hz, are 8200 µin (208 µm), and 9200 µin (234 µm), as shown in Figure 4.13. The estimated relative displacements of the wall, with a dominant frequency is 9 Hz, are shown in Figure 4.13, as 4500 µin (115 µm) and 6200 µin (157 µm).

The effect of the higher response frequency for the wall is illustrated on the response spectra of the radial ground motions in Figure 4.13. At 14 Hz, the dominant frequency of the wall, the response spectrum of the 17 July radial ground motion is significantly less than that of the 5 July ground motion. This difference corresponds to the difference in measured crack displacements as reported in Table 4.1. The effect of the lower response frequency for the overall structure is also illustrated in Figure 4.13. In the 5 Hz range, the 5 July ground motion also produces its largest response spectra amplitudes. This difference corresponds to the measurements of radial structural response reported in Table 4.1.
Figure 4.9 FFT Crack displacement ratio, crack displacement FFT, and ground displacement FFT for 5 July blast
Figure 4.10 FFT crack displacement ratio, crack displacement FFT, and ground displacement FFT for 17 July blast
Figure 4.11 FFT superstructure response ratio, S2 response FFT, and ground motion FFT for 5 July blast.
Figure 4.12 FFT superstructure response ratio, S2 response FFT, and ground motion FFT for 17 July blast
Crack Response to Environmental Effects

Figure 4.14 compares the long-term action of weather indicators (temperature and humidity) with the long-term crack response. 24-hour averages of temperature, crack displacement, and humidity were computed as they were in Chapter 3. Since the monitoring period covered a significant amount of time, actual patterns of temperature, crack displacement, and humidity were observed.
Figure 4.14  Long-term crack displacement and weather versus time
The 24-hour average temperature fluctuated mainly within the 70 to 80 degree range (21.1 to 26.7 °C) during the monitoring period, dipping below and above twice, respectively. The temperature exhibited daily changes of 40 degrees Fahrenheit (4.4 °C) between the morning and evening hours. The 24-hour humidity was more variable. Typical daily changes in humidity were around 30%. Four significant increases in humidity, relative to the rest of the data, occurred during the monitoring period - the most significant occurring between 9 and 11 July. During the night of 11 July, the humidity changed almost 80%. According to NOAA climatological observation records for San Juan County, 0.60 in (15.2 mm) of rain was measured from 9 to 12 July 2001. This is a significant amount of rain for the region and explains the large change in humidity.

The effects of the unusual rain event are also reflected in the 24-hour average crack displacements. Around the time of the significant rainfall, the sensor experienced a permanent shift in readings of approximately 20 µm (790 µin). This change is probably not a response to changes in temperature and humidity, but more likely the result of direct wetting of the adobe or expansion of soil due to increased water content. This is a dramatic change that illustrates the importance of long-term monitoring to facilitate the observation of the effects of change in foundation conditions.

Table 4.2 lists all of the average and maximum values for the frontal, daily, and weather effects; an example of each type is displayed graphically in Figure 4.15. Because of the dramatic shift in crack displacement, effects were based upon two overall averages; before and after the significant rainfall. The temperature and humidity variations were not subdivided, as the shift was not as dramatic. Values of crack response to typical and maximum ground motions associated with coal mine blasts are also included in this table, in order to compare the difference in magnitude between weather-induced and blast-induced crack response.
Table 4.2  Computed crack displacements due to long-term weather phenomena

<table>
<thead>
<tr>
<th></th>
<th>Temperature Change (DegF)</th>
<th>Crack Displacement (µin)</th>
<th>Crack Displacement (µm)</th>
<th>Humidity Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frontal Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>3</td>
<td>118</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Max</td>
<td>9</td>
<td>354</td>
<td>9</td>
<td>18</td>
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<td><strong>Daily effect</strong></td>
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<td></td>
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<tr>
<td>Average</td>
<td>15</td>
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</tr>
<tr>
<td>Average</td>
<td>15</td>
<td>669</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>Max</td>
<td>24</td>
<td>984</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td><strong>Vibration Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Ground motion (PPV=0.10 ips)</td>
<td>-</td>
<td>91</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td>Max ground motion (PPV=0.13 ips)</td>
<td>-</td>
<td>165</td>
<td>4.2</td>
<td>-</td>
</tr>
</tbody>
</table>

In Figure 4.15, the crack displacements resulting from different weather phenomena measured over the entire monitoring period are compared to those resulting from blasts. Blast responses are circled on the figure, to locate the relatively small events. The maximum dynamic crack displacement of 4.2 µm or 166 µin (produced by ground motions associated with an average blast from the surface coal mine) is small compared to the average and maximum crack displacements daily and weather effects of 17 and 25 µm (672 and 988 µin). The average dynamic crack displacement experienced during blast events was less than 1/6 of the maximum daily and weather effect crack displacement.
Figure 4.15 Typical crack displacements due to long-term phenomena and maximum zero to peak dynamic blast
Comparisons of computed displacements with measured crack displacement

The maximum measured crack displacement produced by each shot is compared in Table 4.3 to various computed wall displacements based on structure responses, and peak ground motion measured in the direction parallel to the cracked wall. All responses analyzed were those in the radial direction. All comparisons are presented graphically in Figures 4.16 and 4.17. Details of the methods used to compute displacements are presented in Chapter 3.

The best correlation found was that between the measured crack displacements and the approximated relative displacements, $\delta(S2) - \delta(S_{1_{\text{max}}})$ ($R^2=0.91$). This comparison is shown in Figure 4.17 (d). Correlations between the measured crack displacements and the displacements from the difference of integrated velocities, $S1-S2$, as well as those correlations with the displacements estimated from response spectra for the 10 to 15 Hz wall frequency range, were also high ($R^2=0.86$ and $R^2=0.81$, respectively). These correlations are displayed in Figure 4.16 (a) and (e), respectively. A higher correlation was found with the average relative displacements from the SDOF, than with the relative displacements corresponding the dominant frequency of the structure. The correlation found with the estimated displacements for a 5 Hz dominant frequency was very poor, reinforcing the conclusion that the dominant frequency of structural components responsible for crack deformations are in the 10 to 15 Hz range.
Table 4.3 Summary of computed and measured displacements

<table>
<thead>
<tr>
<th>Date of Shot</th>
<th>(S2-S1)$_{\text{max}}$</th>
<th>(S2-G)$_{\text{max}}$</th>
<th>$G_{\text{max}}$</th>
<th>$\delta$ from SDOF method</th>
<th>Approximation with $\delta = V/2\pi f$</th>
<th>Peak ground motion in the radial direction ($\mu $ in/sec)</th>
<th>Measured crack displacement ($\mu $ in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/22/01 14:20</td>
<td>1660</td>
<td>9890</td>
<td>4535</td>
<td>9802</td>
<td>11410</td>
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<td>3446</td>
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<td>0.20</td>
</tr>
<tr>
<td>7/5/01 15:03</td>
<td>1940</td>
<td>8730</td>
<td>3885</td>
<td>8207</td>
<td>2091</td>
<td>205</td>
<td>0.24</td>
</tr>
<tr>
<td>7/17/01 12:51</td>
<td>1630</td>
<td>10900</td>
<td>5040</td>
<td>9193</td>
<td>6875</td>
<td>721</td>
<td>0.19</td>
</tr>
<tr>
<td>7/23/01 11:22</td>
<td>900</td>
<td>6290</td>
<td>3150</td>
<td>5593</td>
<td>6131</td>
<td>75</td>
<td>0.32</td>
</tr>
<tr>
<td>7/26/01 11:04</td>
<td>960</td>
<td>9470</td>
<td>3150</td>
<td>7703</td>
<td>9218</td>
<td>928</td>
<td>0.20</td>
</tr>
<tr>
<td>7/26/01 14:55</td>
<td>1140</td>
<td>4280</td>
<td>3150</td>
<td>3721</td>
<td>528</td>
<td>506</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Figure 4.16 Correlations between measured crack displacements and computed displacements and peak radial ground motions
Figure 4.17 Correlations between measured crack displacements and computed relative displacements
CHAPTER 5

CONCRETE BLOCK FOUNDATION – INDIANA 1

The Indiana (1) structure, shown in Figure 5.1, is a one-story residential bungalow with a basement, located approximately 1500 ft (457 m) east of a surface coalmine in Francisco, Indiana. Data collected on-site from 18 to 21 August 2001 are summarize in Table 5.10. Four blasts with maximum charge weights/delay between 150 and 584 lbs (68 and 265 kg) produced ground motions of 0.04 and 0.23 ips (1.0 and 5.8 mm/sec), maximum structure responses of 0.06 and 0.29 ips (1.5 and 7.4 mm/sec), and maximum wall responses of 0.19 and 0.51 ips (4.8 and 13.0 mm/sec). Weather data varied cyclically each day with outside temperatures ranging between 59 and 89 °F (15 and 31.7 °C) and outside humidity ranging between 41 and 99%.

Figure 5.1 Indiana house 1
### Table 5.1 Summary of structural and crack response for bungalow in Indiana

<table>
<thead>
<tr>
<th>Time of Blast</th>
<th>Distance (ft)</th>
<th>Charge Weight/ Delay (lb)</th>
<th>Vertical (ft/lb(^{1/2}))</th>
<th>Radial</th>
<th>Transverse</th>
<th>Structure response in S1 cluster (ips)</th>
<th>Radial</th>
<th>Transverse</th>
<th>Midwall responses (ips)</th>
<th>Structure response in S2 cluster (ips)</th>
<th>Radial</th>
<th>Transverse</th>
<th>Air Blast (dB)</th>
<th>Measured Crack Displacement on masonry block ((\mu)in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/18/01 17:33</td>
<td>1439</td>
<td>451</td>
<td>67.8</td>
<td>0.16</td>
<td>0.18</td>
<td>0.23</td>
<td>0.13</td>
<td>0.26</td>
<td>0.21</td>
<td>0.23</td>
<td>0.51</td>
<td>0.47</td>
<td>117</td>
<td>11</td>
</tr>
<tr>
<td>8/19/01 13:27</td>
<td>1906</td>
<td>584</td>
<td>78.9</td>
<td>0.09</td>
<td>0.13</td>
<td>0.18</td>
<td>0.14</td>
<td>0.21</td>
<td>0.29</td>
<td>0.15</td>
<td>0.44</td>
<td>0.29</td>
<td>112</td>
<td>7</td>
</tr>
<tr>
<td>8/20/01 12:30</td>
<td>3540</td>
<td>451</td>
<td>166.7</td>
<td>0.04</td>
<td>0.05</td>
<td>0.07</td>
<td>0.04</td>
<td>0.08</td>
<td>0.06</td>
<td>0.08</td>
<td>0.19</td>
<td>0.22</td>
<td>116</td>
<td>4</td>
</tr>
<tr>
<td>8/20/01 16:05</td>
<td>1035</td>
<td>150</td>
<td>84.5</td>
<td>0.12</td>
<td>0.21</td>
<td>0.20</td>
<td>0.13</td>
<td>0.23</td>
<td>0.20</td>
<td>0.17</td>
<td>0.49</td>
<td>0.47</td>
<td>118</td>
<td>10</td>
</tr>
</tbody>
</table>
Structure Description

As shown by plan and elevation drawings in Figures 5.2 and 5.3, the structure is approximately 22 feet wide by 40 feet long (6.7 x 12.2 m). It is a one-story structure, eight feet (2.4 m) in height, with a basement approximately eight feet in height. The exterior of the structure is covered with aluminum siding; the interior walls, approximately six inches (152 mm) thick, are paneled and covered with wallpaper. The basement walls are constructed of standard-sized concrete masonry blocks.

Location of instrumentation

Locations of all instruments are shown in Figures 5.2 and 5.3. The velocity transducers were installed on and outside of the southeast corner of the structure, closest to the mining activity. The Kaman crack displacement sensor was located on the north side of the structure, on the exposed concrete block foundation, as shown in Figure 5.4. Further details on placement and description are given in Chapter 2.

The foundation of the structure extends above the ground surface on the western end of the structure. The sensor was attached to the foundation for a number of reasons. The interior walls were all paneled and wallpapered without any cracks to instrument. The exterior walls were covered with aluminum siding. Crack response on concrete blocks had not been measured in this study. The monitored crack was chosen because it cut across a unit and appeared to be the most recent and active compared to others observed on the foundation units. The approximate width of the crack is 500 µm (19,800 µin). As shown in Figure 5.4, it is located approximately 2 feet (0.6m) above the porch deck (3 to 4 ft, or 0.9 to 1.2 m, from the ground surface), to the right of the porch screen door. A close-up of the crack can be seen in the inset of Figure 5.4.
Figure 5.2 Plan view of Indiana house 1

Figure 5.3 Elevation view of Indiana house 1
In addition to the Kaman crack displacement sensor, a Kaman null sensor was also employed on a non-cracked section nearby the crack on the same concrete block unit. The null sensor allowed an in-situ comparison of the instrument response and crack response. This second, “null” sensor can be seen, to the right of the crack sensor, in the magnified inset in Figure 5.4. As described in the introduction, the null response is that of only the material and the sensor itself.

A Supco temperature and humidity datalogger, the same used in all of the OSM studies, was placed to the right of the Kaman sensors and can be seen in Figure 5.4.

Figure 5.4 Kaman crack displacement sensors and Supco weather logger
For each blast, time histories were collected from the eleven velocity transducers inside and outside of the house for a total of thirteen (13) seconds. Time correlated (within 1/1000 second) time histories of dynamic crack displacements were also collected from the Kaman sensors for twelve (12) seconds.

Structure and crack responses to household events were not observed. The crack was located in the opposite corner of the house from the velocity transducers. Thereby eliminating the possibility of comparing the two different responses to localized household activities.

**Transient Responses**

Figure 5.5 shows velocity time histories of excitation ground motions and structure responses, compared to the crack response, associated with the blast on 18 August 2001 at 17:34; as shown, this blast produced a peak crack displacement of 0.29 μm (11.5 μin) and a peak radial ground motion of 0.18 ips (4.6 mm/sec). This blast event produced a typical crack response, representative of those measured during the monitoring period.

In Figure 5.6, the time histories of all three components of ground motion, along with the air blast response are compared to the crack response. In addition the lower corner, S1, response of the structure, both radial and transverse, are also shown. Lower response is compared in this case, because the crack is in the foundation rather than the superstructure. All significant structure response, as well as air blast response, occurred within the first seven seconds.
Figure 5.5 Time history of crack displacement on 18 August at 17:34 compared to ground excitation, S1 and S2 response, calculated relative displacement of structure (R1-R2), and air blast.
Figure 5.6 Time history of crack displacement compared to ground excitation in the radial, transverse, and vertical directions, air blast response, and S1 radial and transverse structure response (18 August)
The dominant frequency of the structure was estimated using both the zero-crossing method and FFT method. Details on these methods can be found in Chapter 3. The dominant frequency of the structure was computed as 6 Hz using the zero-crossing method, and 9 Hz using the FFT method. The dominant frequency of the structure was taken to be 9 Hz, because that value resulted in stronger correlations with the measured crack displacement, and it was within the typical response range of one-story residential structures. Plots of the computed FFT ratios can be found in Appendix A.

The response spectrum of the radial ground motion, from the blast on 18 August 2001 at 17:33 is displayed as Figure 5.7. The estimated relative displacement from this ground motion relative to the computed dominant frequency of the structure, was 5800 $\mu$m (148 $\mu$m), as shown by the intersection of the vertical 9 Hertz line with the response spectrum.

![Figure 5.7 Single Degree of Freedom response spectrum of radial motion produced by blast on 8/18/01 at 17:34, showing the estimated relative displacement of a 9 Hz structure](image)

Figure 5.7 Single Degree of Freedom response spectrum of radial motion produced by blast on 8/18/01 at 17:34, showing the estimated relative displacement of a 9 Hz structure
Crack Response to Environmental Effects

Figure 5.8 compares the long-term action of weather indicators (temperature and humidity) with the long-term crack response. 24-hour averages of temperature, crack displacement, and humidity were computed as they were in Chapter 3. Data were only collected during a three-day period, therefore, significant long-term trends were not exhibited. The 24-hour averages of the temperature and the corrected crack displacement remain relatively constant, but the 24-hour averages of humidity show a slight decrease during the monitoring period. The higher average humidity values at the start of the monitoring period is most likely a result of the 0.44 in (11.2 mm) of rain that fell on 18 August 2001 (NOAA); this was the only significant precipitation during the monitoring period.

Table 5.2 lists all average and maximum values for frontal, daily, and weather effects for temperature, corrected crack displacement, and humidity. Corrected crack displacements, as opposed to displacement measured from the crack sensor exclusively, were included in the table even though values were the same or nearly the same. Values of corrected crack response to typical and maximum ground motions associated with coal mine blasts are also included in this table, in order to compare the difference in magnitude between weather-induced and blast-induced crack response.

Table 5.2 Computed crack displacements due to long-term weather phenomena

<table>
<thead>
<tr>
<th></th>
<th>Temperature Change (F)</th>
<th>Corrected Crack Displacement (µin)</th>
<th>Corrected Crack Displacement (µm)</th>
<th>Humidity Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frontal Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviation of 24 hr average from overall average</td>
<td>2</td>
<td>79</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Max deviation of 24 hr average from overall average</td>
<td>3</td>
<td>118</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td><strong>Daily effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of deviations from 24 hr average trend</td>
<td>7</td>
<td>276</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Max deviations from 24 hr average trend</td>
<td>12</td>
<td>354</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td><strong>Weather Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviations from overall average</td>
<td>7</td>
<td>315</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Max deviations from overall average</td>
<td>11</td>
<td>472</td>
<td>12</td>
<td>31</td>
</tr>
<tr>
<td><strong>Vibration Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Ground motion (PPV=0.10 ips)</td>
<td>-</td>
<td>8</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>Max ground motion (PPV=0.23 ips)</td>
<td>-</td>
<td>12</td>
<td>0.3</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 5.8 Long-term crack displacement and weather versus time
In Figure 5.9, the crack displacements due to different weather phenomena over the entire monitoring period are compared to those due to the blasts. The responses due to the blasts are so minuscule, they cannot be identified by eye on the plot; these blasts are enclosed within the circles on the figure. In comparison, the largest blast vibration of 0.23 ips (5.8 mm/sec) induced a maximum crack displacement of 0.29 µm (11.5 µin), which was less than 1/30 of the maximum weather response of 12 µm (490 µin).

In Figure 5.10, the crack displacements of the null and crack sensors as well as the corrected crack displacements are shown. The purpose of the null sensor is to provide information regarding temperature effects and drift of the sensor itself. It is attached to the uncracked material to incorporate the uncracked material response as well. As can be seen, little to no displacements were recorded by the null sensor. Nonetheless, these displacements were subtracted from the crack sensor displacements and used as the appropriate displacements for this study.
Figure 5.9 Typical crack displacements due to long-term phenomena and maximum zero to peak dynamic blast events

Figure 5.10 Long-term displacements of both crack and null sensors and the resulting corrected crack displacement
Comparisons of computed displacements with measured crack displacement

The maximum measured crack displacement produced by each shot is compared in Table 5.3 to various computed wall displacements based on structure responses, and peak ground motion measured in the direction parallel to the cracked wall. All responses analyzed were those in the radial direction. All comparisons are presented graphically in Figures 5.11 and 5.12. Details of the methods used to compute displacements are presented in Chapter 3.

There were no significant correlations between predicted relative displacements and measured crack displacements. The largest correlation was found from the relationship between measured crack displacement and peak radial ground motion (regression coefficient of $R^2=0.90$), shown in Figure 5.11 (f). The regression values resulting from the relationships between measured displacements and SDOF relative displacements were computed as $R^2=0.62$ and $R^2=0.67$. These relationships are shown in Figure 5.11 (e) and (f), respectively. The lowest regression coefficients were produced by the relationships with approximated relative displacements. The highest coefficient among all six approximated relative displacements was $R^2=0.56$, for the non-time correlated between S2 and G ($S_{2_{\text{max}}}-G_{\text{max}}$), as shown in Figure 5.12 (c).

Given the location of the crack, little correlation would be expected with the same measures found with other structures. The methods of computed displacement all incorporate the assumption that the crack is located in the superstructure. This crack was located in the foundation, and response would be expected to correlate with ground strain. As described by others (Dowding 1996), ground strain is proportional to the peak particle velocity. As was mentioned above, the highest correlation was found between the measured crack displacement and the ground motion, which further supports these expectations.
Table 5.3 Summary of computed and measured displacements

<table>
<thead>
<tr>
<th>Date of Shot</th>
<th>(S2-S1)$_{\text{max}}$</th>
<th>(S2-G)$_{\text{max}}$</th>
<th>$G_{\text{max}}$</th>
<th>$\delta$ from SDOF method</th>
<th>Approximation with $\delta = V/2\pi f$</th>
<th>Peak ground motion in the radial direction ($\mu$in/sec)</th>
<th>Measured crack displacement ($\mu$in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/18/01 17:33</td>
<td>1970</td>
<td>5470</td>
<td>2690</td>
<td>5836</td>
<td>2218</td>
<td>1078</td>
<td>0.24</td>
</tr>
<tr>
<td>8/19/01 13:29</td>
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<td>7190</td>
<td>3780</td>
<td>6810</td>
<td>3328</td>
<td>1663</td>
<td>0.19</td>
</tr>
<tr>
<td>8/20/01 12:30</td>
<td>750</td>
<td>1570</td>
<td>1020</td>
<td>851</td>
<td>647</td>
<td>388</td>
<td>0.32</td>
</tr>
<tr>
<td>8/20/01 16:05</td>
<td>2470</td>
<td>4430</td>
<td>2400</td>
<td>7811</td>
<td>79</td>
<td>499</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Figure 5.11 Correlations between measured crack displacement and computed displacement and radial ground motion
Figure 5.12 Correlations between measured crack displacement and computed relative wall displacements
The Indiana (2) structure, shown in Figure 6.1, is a one and a half story wood frame house located approximately 3000 ft (914 m) from surface coal mining in Francisco, Indiana. Data collected on site from 22 to 24 August 2001 are summarized in Table 6.1. Four blasts with maximum charge weights/delay between 301 and 1051 lbs (137 and 478 kg) produced ground motions of 0.06 to 0.30 ips (1.5 to 7.6 mm/sec), maximum structure responses of 0.05 to 0.25 ips (1.3 to 6.4 mm/sec), and maximum wall responses of 0.06 to 0.84 ips (1.5 to 21.3 mm/sec). In addition, a number of household activities were simulated in order to obtain comparative structure and crack responses. Weather data varied cyclically each day with inside temperatures ranging between 72 and 89 °F (22.2 to 31.7 °C) and indoor humidity ranging between 54 to 91%.

Figure 6.1 Indiana (2) structure
<table>
<thead>
<tr>
<th>Time of Blast</th>
<th>Distance</th>
<th>Charge Weight/</th>
<th>Scaled Distance</th>
<th>Peak Particle Velocity (ips)</th>
<th>Structure response in S1 cluster (ips)</th>
<th>Structure response in S2 cluster (ips)</th>
<th>Midwall response on kitchen wall (ips)</th>
<th>Air Blast (dB)</th>
<th>Measured Crack Displacement above kitchen sink (µin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/22/01 17:30</td>
<td>2081</td>
<td>1051</td>
<td>64.2</td>
<td>0.23 0.30 0.28</td>
<td>0.14 0.18 0.24 0.25</td>
<td>0.23 0.84* 0.23 0.25</td>
<td>126 537</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/23/01 13:00</td>
<td>3730</td>
<td>301</td>
<td>215.0</td>
<td>0.04 0.07 0.06</td>
<td>0.04 0.05 0.05 0.07</td>
<td>0.06 0.05 0.06 0.07</td>
<td>110 131</td>
<td></td>
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</tr>
<tr>
<td>8/23/01 17:40</td>
<td>4163</td>
<td>447</td>
<td>196.9</td>
<td>0.05 0.07 0.06</td>
<td>0.05 0.05 0.05 0.07</td>
<td>0.06 0.06 0.06 0.07</td>
<td>106 101</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/24/01 12:10</td>
<td>3358</td>
<td>301</td>
<td>193.7</td>
<td>0.05 0.06 0.05</td>
<td>0.05 0.06 0.05 0.06</td>
<td>0.06 0.07 0.07 0.08</td>
<td>114 90</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*For the first shot this midwall measured the transverse direction on the west living room wall
Structure Description

As shown by plan and elevation drawings in Figures 6.2 and 6.3, the structure is approximately 28 feet wide and 38 feet long (8.5 x 11.6 m). It is a one and a half story, wood-framed residential structure, 9 feet to 20 feet (2.7 to 6.1 m) high, with a 7-foot (2.1-meter) high basement. The wood-stud, clapboard covered, exterior walls are covered with aluminum siding. They are approximately 6 inches (152 mm) in thickness. The first story interior walls are comprised of plaster and lath and are approximately 4 inches (102 mm) thick. The upper story was left unfinished and did not have any walls, which left all of the structural components exposed. The basement walls were constructed with concrete block masonry units, as shown in Figure 6.4. Two by eights were placed 16 inch (406 mm) center-to-center as floor joists, with cross ties connecting them, to support the structure.

Location of Instrumentation

Locations of all instruments are also shown in Figures 6.2 and 6.3. Eleven velocity transducers were installed on and outside of the southwest corner of the structure, closest to the mining activity. The crack displacement sensor was located in the kitchen above the window looking out at the blasting, as shown in Figure 6.5. Further details on placement and description of the instrumentation are given in Chapter 2.

This crack whose width was estimated from photographs to be approximately 1200 µm (47,400 µin) in width, was chosen for instrumentation because it was on the wall facing the mine and was obviously active. The crack spanned the entire distance (approximately 18 in or 457 mm) from the window frame to the ceiling and was uniformly open for this entire distance. The sensor was placed 5 in (127 mm) above the window frame. Cracking continued on the same wall, underneath the kitchen sink to the floorboard. The wall opposite the instrumented, on the other side of the kitchen, also had similar cracking, spanning from the ceiling to the floorboard, in the same plane of space. Cracking in this location was also apparent on the basement walls. The basement floor slab appeared to have been poured in sections, where the division of the slab lined up with the large crack.
Figure 6.2 Plan view of Indiana house 2

Figure 6.3 Elevation of Indiana house 2
Figure 6.4 Basement walls of Indiana house 2

Figure 6.5 Crack displacement sensors and Supco datalogger
As shown in Figure 6.5, a Kaman “null” sensor was installed nearby an uncracked wall material. The purpose of the null sensor is explained in Chapter 2. The Supco temperature and humidity datalogger was placed adjacent to the displacements sensors, to the right. In addition, two velocity transducers were installed adjacent to the Kaman sensors as well; one measuring the vertical, one measuring the radial. A third radial transducer was attached near the floor in line with the other two transducers.

For each blast, time histories were collected from eleven velocity transducers inside and outside of the structure for a total of twelve seconds. After the first shot, the two midwall transducers were moved into the kitchen, one adjacent to the crack sensor, above the window, and the other right above the floorboard, in line with the other midwall transducer. Time correlated (within 1/1000 second) time histories of dynamic crack displacement were also collected from the Kaman sensor for a total of ten seconds.

**Transient Responses**

Figure 6.6 shows velocity and displacement time histories of excitation ground motions and structure response, as well as crack response, associated with the blast on 22 August 2001 at 17:30. As shown, this blast produced a peak crack displacement of 13.6 µm (537 µin) and a peak transverse ground motion (parallel to the wall) of 0.25 ips (6.4 mm/sec). Unlike the three previous structures, the crack monitored was not located on a radial wall but rather on a transverse wall, therefore all time histories are those in the transverse direction. This blast produced the largest crack response during the monitoring period, as well, as the largest crack response observed in all four OSM structures. However, it is important to note that this crack was also the largest crack of the four instrumented.

In Figure 6.7, the time histories of all three components of ground motions, along with the air blast response are compared to the crack response (for the same blast). In addition, the upper corner, S2, responses of the structure, both radial and transverse, are also shown.

Figure 6.8 shows velocity and displacement time histories of excitation ground motions and structure response, as well as the crack response, associated with the blast on 23 August 2001 at 13:00; this blast produced a peak crack displacement of 3.3 µm (130 µin) and a peak
transverse ground motion of 0.06 ips (1.5 mm/sec). This crack displacement was more representative of an average crack response. All significant response, including that from the air blast, occurred within the first seven seconds.

In Figure 6.9, the time histories of all three components of ground motions, along with the air blast response are compared to the crack response. In addition, the upper corner, S2, responses of the structure, both radial and transverse, are also shown.
Figure 6.6 Time history of crack displacement on 22 August 2001 at 17:30 compared to ground excitation, S1 and S2 response, calculated relative displacement of structure (R1-R2), and air blast.
Figure 6.7 Time history of crack displacement on 22 August 2001 at 17:30 compared to ground excitation in the radial, transverse, and vertical directions, air blast response, and S2 radial and transverse structure response
Figure 6.8 Time history of crack displacement on 23 August 2001 at 13:00 compared to ground excitation, S1 and S2 response, calculated relative displacement of structure (R1-R2), and air blast
Figure 6.9 Time history of crack displacement on 23 August 2001 at 13:00 compared to ground excitation in the radial, transverse, and vertical directions, air blast response, and S2 radial and transverse response
The dominant frequency of the structure was estimated using both the zero-crossing method and FFT method. Both methods resulted in the same dominant frequency for the structure, 8 Hz.

The response spectra of the transverse ground motion, from the 22 August 2001 blast at 17:30 and the 23 August 2001 blast at 13:00 are displayed as Figure 6.10. The estimated displacements of the structure with a dominant frequency of 8 Hz were 5900 µin (150 µm) and 2400 µin (61 µm), respectively, as shown by the intersection of the vertical 8 Hz line with each response spectrum.

Figure 6.10 Single Degree of Freedom response spectra of transverse motions produced by blasts on 22 August 2001 at 17:30 and 23 August 2001 at 13:00, showing estimated relative displacement of a 8 Hz structure.
Crack Response to Household and Blast Events

Table 6.2 presents the measured crack displacements corresponding to all significant dynamic events during the monitoring period. Household events, such as, hammering the wall, shutting windows, slamming doors, jumping, and moving furniture, were performed in order to measure the responses of the crack and compare them to responses from the blasts. Blast-induced displacements are included for comparison. Approximate distances between the location of the activity and the crack are also presented in the table.

Displacements for the household events and the blast-induced events, were very similar. Blast-induced events were typically around 3 µm (119 µin), with the exception of the first blast, which was around four times larger. Household activity closest to the crack produced some of the largest displacements, as expected. The largest household activity displacement recorded was that of 10.8 µm (427 µin). This displacement was produced when a corner of the living room couch was lifted up and dropped to the ground. The remaining household events averaged around 2 µm (51 µin).

Table 6.2 Summary of measured crack displacements associated with dynamic events

<table>
<thead>
<tr>
<th>Activity</th>
<th>Approximate distance from crack and transverse midwall (feet)</th>
<th>Peak Crack Displacement (µin)</th>
<th>Peak Crack Displacement (µm)</th>
<th>Midwall Transverse response (in/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammering next to crack</td>
<td>1</td>
<td>87.2</td>
<td>2.2</td>
<td>N/A</td>
</tr>
<tr>
<td>Shutting window below crack</td>
<td>3</td>
<td>161.2</td>
<td>4.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Slam kitchen window on East wall</td>
<td>8</td>
<td>78.1</td>
<td>2.0</td>
<td>0.14</td>
</tr>
<tr>
<td>Drop couch in living room</td>
<td>14</td>
<td>425.2</td>
<td>10.8</td>
<td>0.04</td>
</tr>
<tr>
<td>Jumping at landing of second story stairs</td>
<td>27</td>
<td>56.3</td>
<td>1.4</td>
<td>0.03</td>
</tr>
<tr>
<td>Slam basement screen door</td>
<td>14</td>
<td>65.0</td>
<td>1.6</td>
<td>0.02</td>
</tr>
<tr>
<td>Shut drawer in kitchen, next to sink</td>
<td>5</td>
<td>43.0</td>
<td>1.1</td>
<td>0.11</td>
</tr>
<tr>
<td>Shut upper cupboard door (adjacent to crack)</td>
<td>2</td>
<td>174.0</td>
<td>4.4</td>
<td>0.01</td>
</tr>
<tr>
<td>Close upper cupboard door (adjacent to crack)</td>
<td>2</td>
<td>51.9</td>
<td>1.3</td>
<td>0.07</td>
</tr>
<tr>
<td>Jump in living room</td>
<td>16</td>
<td>73.0</td>
<td>1.9</td>
<td>0.02</td>
</tr>
<tr>
<td>Shot 1 (8/22/01 at 17:30)</td>
<td>2085</td>
<td>535.4</td>
<td>13.6</td>
<td>0.23</td>
</tr>
<tr>
<td>Shot 2 (8/23/01 at 13:00)</td>
<td>3735</td>
<td>129.9</td>
<td>3.3</td>
<td>0.06</td>
</tr>
<tr>
<td>Shot 3 (8/23/01 at 17:40)</td>
<td>4170</td>
<td>102.4</td>
<td>2.6</td>
<td>0.06</td>
</tr>
<tr>
<td>Shot 4 (8/24/01 at 12:10)</td>
<td>3365</td>
<td>90.6</td>
<td>2.3</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Crack Response to Environmental Effects

Figure 6.11 compares the long-term action of weather indicators (temperature and humidity) with the long-term crack response. 24-hour averages of temperature, crack displacement, and humidity were computed as they were in Chapter 3. Since the monitoring period was so short, large weather front changes were not expected. However, the humidity and crack displacement do exhibit an increase over the three days. The 24-hour average humidity increased from 70% to 90% over the course of the measured period. The typical daily temperature change appears to be around 25°F (-3.9 °C) and the daily humidity change appears to be around 25%.

Table 6.3 lists all average and maximum values for frontal, daily, and combined weather effects for temperature, crack displacement, and humidity. Values of crack response to typical and maximum ground motions associated with coal mine blasts are also included in this table, in order to compare the difference in magnitude between weather-induced and blast-induced crack response.
Figure 6.11 Long-term crack displacement and weather versus time
Table 6.3 Computed crack displacements due to long-term weather phenomena

<table>
<thead>
<tr>
<th></th>
<th>Temperature Change (DegF)</th>
<th>Corrected Crack Displacement (µin)</th>
<th>Corrected Crack Displacement (µm)</th>
<th>Humidity Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frontal Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviation of 24 hr average from overall average</td>
<td>3</td>
<td>591</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Max deviation of 24 hr average from overall average</td>
<td>3</td>
<td>630</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td><strong>Daily effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of deviations from 24 hr average trend</td>
<td>3</td>
<td>551</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>Max deviations from 24 hr average trend</td>
<td>4</td>
<td>984</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td><strong>Weather Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviations from overall average</td>
<td>6</td>
<td>1299</td>
<td>33</td>
<td>11</td>
</tr>
<tr>
<td>Max deviations from overall average</td>
<td>9</td>
<td>2042</td>
<td>52</td>
<td>18</td>
</tr>
<tr>
<td><strong>Vibration Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Ground motion (PPV=0.10 ips)</td>
<td>-</td>
<td>181</td>
<td>4.6</td>
<td>-</td>
</tr>
<tr>
<td>Max ground motion (PPV=0.30 ips)</td>
<td>-</td>
<td>535</td>
<td>13.6</td>
<td>-</td>
</tr>
</tbody>
</table>

In Figure 6.12, the crack displacements due to different weather phenomena measured over the three days are compared to that produced by the four blasts. Since blast responses are relatively small, they are encircled. The blast that occurred at 13:00 on 23 August 2001, with ground motion measuring 0.06 ips (1.5 mm/sec) in the transverse direction, produced a crack displacement of 3.3 µm (130 µin). The largest blast that occurred during the three days, on 22 August 2001, with a ground motion measuring 0.25 ips (6.4 mm/sec) in the transverse direction, produced a crack displacement of 13.6 µm (535 µin). The estimated crack displacement of 4.6 micrometers, which corresponds with a typical ground motion of 0.10 ips (2.5 mm/sec), is less than 1/10 of the crack displacement due to the maximum weather effect of 52 µm (2117 µin). This ratio would more than likely be smaller if there had been more time to capture the true weather variation.

Also in Figure 6.12 are the displacements measured by the Kaman crack and null sensor, as well as the corrected crack displacement. Details on the purpose of the null sensor can be found in Chapter 2. All crack displacements used for the long-term analysis of this structure are those of the corrected crack displacements. The null sensor exhibited little to no variation over the three days, however, to be certain, any displacement that did occur was subtracted from the crack reading at the appropriate time. Again the short period of observation limits the conclusions regarding typical behavior, as the first 12 hours of data represent the accommodation of the instrument to the wall.
Figure 6.12 Typical crack displacements due to long-term phenomena and maximum zero to peak dynamic blast events
**Comparisons of computed displacements with measured crack displacement**

The maximum measured crack displacement produced by each shot is compared in Table 6.3 to various computed wall displacements based on structure responses, and peak ground motion measured in the direction parallel to the cracked wall. All responses analyzed were those in the transverse direction. All comparisons are presented graphically in Figures 6.13 and 6.14. Details of the methods used to compute displacements are presented in Chapter 3.

For this structure, all of the relationships yielded almost perfect correlations, with the exception of one; none of the other structures had regression coefficients as high. Perhaps the reason for this, is the large range in blast response. The first blast that was monitored was much larger than the other three and contained a different frequency contour, as shown in the response spectrum. This blast was the closest and had the largest charge/delay out of all four blasts. For the other three blasts, the crack responses were all fairly similar in magnitude.
Table 6.4 Summary of computed and measured displacements

<table>
<thead>
<tr>
<th>Date of Shot</th>
<th>Upper corner - Lower corner</th>
<th>Upper corner - Ground</th>
<th>Ground</th>
<th>From response spectra</th>
<th>Estimated from V and f at fn of 8 Hz ( g_{\text{max}} )</th>
<th>Estimated from V and f at ( S_1_{\text{max}} )</th>
<th>PPV (in/sec)</th>
<th>Measured crack displacement above kitchen window (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/22/2001 17:30</td>
<td>75</td>
<td>133</td>
<td>97</td>
<td>150</td>
<td>104</td>
<td>43</td>
<td>0.28</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>259</td>
<td>32</td>
<td>93</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>53</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/23/2001 13:00</td>
<td>18</td>
<td>25</td>
<td>17</td>
<td>61</td>
<td>12</td>
<td>7</td>
<td>0.06</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56</td>
<td>22</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/23/2001 17:40</td>
<td>13</td>
<td>22</td>
<td>15</td>
<td>37</td>
<td>11</td>
<td>9</td>
<td>0.06</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>54</td>
<td>25</td>
<td>12</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/24/2001 12:10</td>
<td>10</td>
<td>23</td>
<td>14</td>
<td>22</td>
<td>7</td>
<td>9</td>
<td>0.045</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
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<td>11</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.13 Correlations between measured crack displacements and computed displacements and peak transverse ground motions
Figure 6.14 Correlations between measured crack displacements and computed relative displacements
CHAPTER 7

CONCRETE BLOCK HOUSE – WISCONSIN

The Wisconsin structure, shown in Figure 6.1, is a stone-faced, concrete block house, adjacent to a limestone quarry. Blasting operations are conducted approximately 1500 to 2000 feet (457 to 609 m) away from the back of the structure. Data has been collected intermittently, on-site since August of 2000. (Louis 2000) Data presented in this chapter were collected from 29 November 2001 to 15 January 2002 to compare the responses of two different crack sensors. As shown in Table 7.1, fifteen blasts produced ground motions of 0.03 to 0.18 ips (0.8 to 4.6 mm/sec), which produced crack displacements of 0.9 to 23.7 µm (35.6 to 936 µin) at three different cracks. In addition, a number of household activities were simulated in order to obtain comparative responses of two different types of displacement sensors. Weather data varied cyclically each day with outdoor temperatures ranging between 23 °F and 68 °F (-5 to 20 °C), and outside humidity ranging between 26% and 95%.

This chapter compares the measurements recorded by the two different types of sensors, for both long-term and dynamic effects. In November of 2001, two LVDT sensors were installed in the structure, one adjacent to the Kaman null sensor, and the other adjacent to the Kaman Crack 1 sensor, shown in Figures 7.2, 7.3, and 7.4. This change enabled the comparison of LVDT and Kaman sensor response to the dynamic and long-term behavior of Crack 1. Previous analyses have compared crack response to dynamic and long-term effects. (Louis 2000)
Figure 7.1 Wisconsin concrete block house

Table 7.1 Summary of crack response for concrete block house in Wisconsin

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>R (in/sec)</th>
<th>T (in/sec)</th>
<th>V (in/sec)</th>
<th>Peak air pressure (dB)</th>
<th>Crack 1 - LVDT (µin)</th>
<th>Crack 1 - Kaman (µin)</th>
<th>Crack 2 (µin)</th>
<th>Crack 3 (µin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/30/01 8:17</td>
<td>0.15</td>
<td>0.10</td>
<td>0.11</td>
<td>114</td>
<td>131</td>
<td>106</td>
<td>157</td>
<td>332</td>
</tr>
<tr>
<td>11/30/01 10:59</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>106</td>
<td>81</td>
<td>80</td>
<td>92</td>
<td>176</td>
</tr>
<tr>
<td>11/30/01 11:29</td>
<td>0.15</td>
<td>0.10</td>
<td>0.09</td>
<td>114</td>
<td>175</td>
<td>150</td>
<td>202</td>
<td>235</td>
</tr>
<tr>
<td>12/5/01 9:03</td>
<td>0.06</td>
<td>0.05</td>
<td>0.03</td>
<td>106</td>
<td>119</td>
<td>76</td>
<td>98</td>
<td>338</td>
</tr>
<tr>
<td>12/7/01 12:02</td>
<td>0.09</td>
<td>0.10</td>
<td>0.06</td>
<td>105</td>
<td>112</td>
<td>79</td>
<td>157</td>
<td>115</td>
</tr>
<tr>
<td>12/7/01 12:28</td>
<td>0.18</td>
<td>0.13</td>
<td>0.07</td>
<td>107</td>
<td>187</td>
<td>156</td>
<td>171</td>
<td>933</td>
</tr>
<tr>
<td>12/17/01 8:36</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>104</td>
<td>56</td>
<td>57</td>
<td>93</td>
<td>144</td>
</tr>
<tr>
<td>12/17/01 10:15</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
<td>98</td>
<td>106</td>
<td>89</td>
<td>54</td>
<td>195</td>
</tr>
<tr>
<td>12/17/01 11:53</td>
<td>0.07</td>
<td>0.07</td>
<td>0.05</td>
<td>100</td>
<td>125</td>
<td>89</td>
<td>65</td>
<td>288</td>
</tr>
<tr>
<td>12/18/01 10:01</td>
<td>0.15</td>
<td>0.10</td>
<td>0.09</td>
<td>108</td>
<td>131</td>
<td>102</td>
<td>128</td>
<td>408</td>
</tr>
<tr>
<td>12/18/01 10:31</td>
<td>0.11</td>
<td>0.08</td>
<td>0.09</td>
<td>105</td>
<td>112</td>
<td>87</td>
<td>90</td>
<td>384</td>
</tr>
<tr>
<td>1/4/02 9:33</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>113</td>
<td>44</td>
<td>36</td>
<td>162</td>
<td>145</td>
</tr>
<tr>
<td>1/4/02 13:06</td>
<td>0.12</td>
<td>0.06</td>
<td>0.10</td>
<td>106</td>
<td>87</td>
<td>71</td>
<td>136</td>
<td>514</td>
</tr>
<tr>
<td>1/15/02 10:15</td>
<td>0.15</td>
<td>0.06</td>
<td>0.12</td>
<td>108</td>
<td>150</td>
<td>110</td>
<td>132</td>
<td>223</td>
</tr>
<tr>
<td>1/15/02 10:45</td>
<td>0.08</td>
<td>0.08</td>
<td>0.10</td>
<td>107</td>
<td>81</td>
<td>76</td>
<td>141</td>
<td>580</td>
</tr>
</tbody>
</table>

Structure Description

As shown in Figure 7.1, the structure is a one-story, concrete masonry block structure with a concrete masonry block basement that opens out to a backyard, one story below the front yard. A garage is located South of the house. As shown, the exterior walls are faced with stone. Figure 7.2 displays the plan and elevation view of the structure.
The first floor joists are supported by a wooden principal beam running lengthwise in the radial direction. The ceiling is supported by transverse wooden joists, which are supported at the center by the lengthwise center wall, which in turn rests on the basement support beam. This center wall was removed in the computer room, which lead to the ceiling crack, Crack 2. The openings between the kitchen and living room, as well as that between the entry way and living room appear to be supported by beams. These beams seem to be unusually connected to the opening walls, which have lead to Cracks 1 and 2.
Figure 7.2 Plan view and elevation view of Wisconsin concrete block house
**Location of Instrumentation**

Locations of all crack displacement sensors are shown in Figure 7.2. Kaman sensors span three different cracks and a Kaman null sensor is mounted on an uncracked wall section. Of the LVDT sensors, one spans Crack 1, adjacent to the Kaman sensor, as shown in Figure 7.3; the other, a null sensor, is located over the uncracked wall section, adjacent to the Kaman null sensor, as shown in Figure 7.4.

Crack 1, shown in Figure 7.3, is located in the living room at the top of the wall separating the kitchen and the living room. It spans a crack that seems to be created by expansion and contraction of the beam supporting ceiling joists above the entrance to the living room from the kitchen. While the crack is approximately 500 µm (19,800 µin) wide, it is constrained in a raised dimple that might be as wide as 5000 µm (198 mm). This raised dimple implies that this crack has been repeatedly repaired, as a result of its high weather response.

The location of the null sensors, as shown in Figure 7.4, is above the doorway separating the main entrance hall and the computer room, on an uncracked wall section. This location was originally chosen for the Kaman null sensor because it was an uncracked portion of wall close to the other Kaman sensors, as well as, at the same approximate height on the wall. As stated in Chapter 1, a null sensor is employed to separate the non-crack response of the sensor from the crack response. Null responses are typically small and negligible. This was verified by the Kaman sensors in the 2000 Louis study, and again in this study, with the LVDT sensors. Figure 7.5 displays the minute displacement measured by the null sensor in comparison to that measured by the crack sensor.

All three outdoor sensors have been replaced or moved since the 2000 Louis study. A new outdoor temperature and humidity sensor (a Vaisala HMD/W50), is now located on the North face of the house on the bottom of the window sill. The current range of the sensor is 23 to 131°F (-4 to 55 °C); therefore, the minimum temperature recorded is 23 °F (-4 °C), even though the temperature has more than likely gone below this value during the monitoring period. In addition, a new three-axis Geosonics geophone, as shown in Figure 7.6, was installed due to the failure of the radial axes, and the air pressure transducer has been replaced with a Larcor
overpressure microphone, as shown in Figure 7.7. Due to improper wiring of the microphone, however, accurate measurement of air pressure has not been recorded.

Figure 7.3 Kaman and LVDT displacement sensors spanning Crack 1

Figure 7.4 Kaman and LVDT null displacement sensors
The Data Acquisition System (DAS) has remained in the same location since the original installation of this site. Details on the Somat 2100 DAS employed at this site can be found in Louis (2000).

**Extent of Monitoring**

For each blast, time histories were collected from the three-axis geophone, the air pressure transducer, the three Kaman crack sensors, and the LVDT crack and null sensors for a total of three seconds. Motion of 0.02 ips (0.5 mm/sec) triggered the DAS to record these time histories simultaneously.
Long-term data were also recorded during this time period. Every hour, readings of temperature and humidity (indoor and outdoor), and crack response from the three Kaman crack sensors and the LVDT crack and null sensors were recorded by the DAS.

In addition, crack displacements and ground motions were measured in response to the simulation of household activities, after the installation of the LVDT sensors.

**Comparative Responses to Ground Motions**

Figure 7.8 shows the time histories of excitation ground motions and crack response associated with the blast on 7 December 2001 at 12:02. As shown, this blast produced peak displacements of 2.0 and 2.9 μm (79 and 115 μin) for Crack 1 from the Kaman and LVDT sensors, respectively. The peak particle velocity of 0.09 ips (2.3 mm/sec) associated with this blast is typical of blasting operations.

Time histories associated with the remaining fourteen blasts can be found in Appendix C.

The natural frequency of the structure was previously estimated using the FFT method in the Louis study (2000). Response spectra for two blasts, one on 30 November 30 2001 at 11:29 and one on 15 January 2002 at 10:15 are displayed as Figure 7.9. The relative displacements of the structure with an estimated dominant frequency of 11 Hz from the two blasts were 1600 μin (40 μm) and 700 μin (18 μm), respectively, as shown by the intersection of the vertical 11 Hz line with each response spectrum.
Figure 7.8 Time histories of crack displacements, ground motion, and air blast recorded for blast on 7 December 2001 at 12:02
Figure 7.9 Single Degree of Freedom response spectra of radial motions produced by blasts on 11/30/01 and 1/15/02, showing estimated relative displacement of an 11 Hz structure

Peak, in-plane displacements of Crack 1 associated with the fifteen blast events measured by the Kaman and LVDT sensors are compared, in Figure 7.10. As displayed and enumerated in Table 7.1, the LVDT measurements were consistently larger than the Kaman sensor for all fifteen blasts; however, the difference between the two sensors was relatively small for any single event. A regression coefficient of 0.91 was found as the relationship between the two sensor types. This high correlation of peak responses, along with the almost duplicate time histories recorded by each crack sensor, shows that little difference exists between the measuring capabilities (and/or restrictions) of each sensor for blast events that excite the entire structure.
Crack Response to Environmental Long-term Effects

Long-term displacements measured by the two sensors over the same crack were also compared. Figures 7.11 and 7.12 compares the long-term action of weather indicators (temperature and humidity) with the long-term crack responses of the Kaman SMU-9000 sensor and LVDT DC750 sensor, respectively. 24-hour averages of temperature, crack displacement, and humidity were computed as they were in Chapter 3. Table 7.2 lists the average and maximum displacements for the frontal, daily, and weather effects for temperature, crack displacement (for both the Kaman and LVDT sensors), and humidity. Values of crack response to typical and maximum ground motions associated with coal mine blasts are also included in this table, in order to compare the difference in magnitude between weather-induced and blast-induced crack response.
As seen in the two figures, the long-term response of Crack 1 as measured by the two sensors was remarkably similar. Figure 7.13 displays the long-term response of the two different sensors in the same plot. Over the seven week period of observation, the two sensors display the exact same pattern. Each begins at \(-5\, \mu m (-198\, \mu in)\) and ends at \(-22\, \mu m (-869\, \mu in)\). The ratio of LVDT to Kaman response was approximately 5 to 4 for both the weather and blast effects.

As with the other cases, displacements associated with weather effects are much larger than those associated with blast events. The maximum weather effect displacement of 47 \(\mu m (1850\, \mu in)\) determined during the monitoring period for the LVDT sensor is more than 25 times the peak displacement of 5 \(\mu m (197\, \mu in)\) associated with a typical ground motion of 0.09 ips (2.3 mm/sec). For the Kaman sensor, the maximum weather effect displacement of 37 \(\mu m (1457\, \mu in)\) was measured as more than 10 times the same dynamic displacement.

Table 7.2 Computed crack displacements due to long-term weather phenomena

<table>
<thead>
<tr>
<th></th>
<th>Temperature Change (DegF)</th>
<th>Indoor Crack Displacement ((\mu m))</th>
<th>Indoor Crack Displacement ((\mu in))</th>
<th>Outdoor Crack Displacement ((\mu m))</th>
<th>Outdoor Crack Displacement ((\mu in))</th>
<th>Humidity Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frontal Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviation of 24 hr average from overall average</td>
<td>12</td>
<td>1696</td>
<td>43</td>
<td>904</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td>Max deviation of 24 hr average from overall average</td>
<td>31</td>
<td>6111</td>
<td>155</td>
<td>3102</td>
<td>79</td>
<td>27</td>
</tr>
<tr>
<td><strong>Daily Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of deviations from 24 hr average trend</td>
<td>5</td>
<td>1977</td>
<td>50</td>
<td>927</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>Max deviations from 24 hr average trend</td>
<td>12</td>
<td>3956</td>
<td>100</td>
<td>2245</td>
<td>57</td>
<td>25</td>
</tr>
<tr>
<td><strong>Weather Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviations from overall average</td>
<td>12</td>
<td>2422</td>
<td>62</td>
<td>1214</td>
<td>31</td>
<td>14</td>
</tr>
<tr>
<td>Max deviations from overall average</td>
<td>34</td>
<td>8556</td>
<td>217</td>
<td>4226</td>
<td>107</td>
<td>37</td>
</tr>
</tbody>
</table>
Figure 7.11 Long-term Kaman crack displacement and weather versus time
Figure 7.12 Long-term LVDT crack displacement and weather versus time
Figure 7.13 Comparison of LVDT long crack displacement with Kaman SMU 9000 sensor
Comparative Response to Occupant Activities

Table 7.3 presents the measured crack displacement resulting from occupant-induced events, which were simulated in order to compare sensor response nearby localized deformation. Time histories of these events are shown in Figure 7.14. A few select displacements measured during blasting events were also tabulated, in order to compare the differences in measurements between both sensors, corresponding to dynamic events of varying intensity. Once again, the magnitudes of displacements measured by the LVDT sensor were larger than those measured by the Kaman sensor. However, the differences between sensor responses were much larger for the localized events that originated closer to the sensors’ location.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Approximate distance from Crack 1 (feet)</th>
<th>Peak Crack 1 Displacement - Kaman (µm)</th>
<th>Peak Crack 1 Displacement - Kaman (µin)</th>
<th>Peak Crack 1 Displacement - LVDT (µm)</th>
<th>Peak Crack 1 Displacement - LVDT (µin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pound on wall near crack 1</td>
<td>1</td>
<td>5.5</td>
<td>218</td>
<td>20.7</td>
<td>815</td>
</tr>
<tr>
<td>Pound on wall near crack 3</td>
<td>6</td>
<td>0.8</td>
<td>32</td>
<td>1.9</td>
<td>74</td>
</tr>
<tr>
<td>Running through house</td>
<td>-</td>
<td>10.3</td>
<td>404</td>
<td>17.6</td>
<td>691</td>
</tr>
<tr>
<td>Slam front door</td>
<td>12</td>
<td>1.7</td>
<td>68</td>
<td>3.1</td>
<td>123</td>
</tr>
<tr>
<td>Blast of PPV=0.09 ips</td>
<td>2000</td>
<td>2</td>
<td>79</td>
<td>3</td>
<td>118</td>
</tr>
<tr>
<td>Blast of PPV=0.18 ips</td>
<td>2000</td>
<td>4</td>
<td>157</td>
<td>5</td>
<td>197</td>
</tr>
</tbody>
</table>

These large differences for nearby localized events may have resulted from a variety of factors. They no doubt provide higher mode responses as indicated by the spiked time history recorded when pounding on the wall near Crack 1, which is shown in Figure 7.14. Time histories of localized events also do not exhibit the same symmetry as do the whole structure responses resulting from ground motions, such as that shown in Figure 7.8.
Figure 7.14 Time histories of occupant activities listed in Table 7.3
Comparisons of measured crack displacement with common estimates of structural response

The maximum measured crack displacement produced by each shot is compared in Table 7.4 to various computed values of displacements and peak radial ground motions. These comparisons were made in order to determine the correlation that exists between the measured crack displacement and these various responses, and are graphically presented in Figure 7.15. Fewer correlations were determined for this structure because response velocities were not measured. All responses analyzed were those in the radial direction.

The best correlation found was that between the measured crack displacements and the peak ground motions in the radial direction (regression coefficient of $R^2=0.73$), as shown in Figure 7.15 (e). The correlations found between the measured displacements and the three types of computed displacement, were relatively the same (regression coefficients between 0.51 and 0.65).

Table 7.4 Summary of computed displacements and measured displacements

<table>
<thead>
<tr>
<th>Date of Shot</th>
<th>Integration of Ground Velocity</th>
<th>$\delta$ from response spectras at $f_n$ of 11 Hz</th>
<th>$\delta$ from response spectras Avg for $10 &lt; f_n &lt; 15$</th>
<th>PPV (in/sec)</th>
<th>Measured Kaman crack displacement ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/30/01 8:17</td>
<td>24</td>
<td>37</td>
<td>32</td>
<td>0.15</td>
<td>2.7</td>
</tr>
<tr>
<td>11/30/01 10:59</td>
<td>11</td>
<td>22</td>
<td>21</td>
<td>0.08</td>
<td>2.0</td>
</tr>
<tr>
<td>11/30/01 11:29</td>
<td>25</td>
<td>40</td>
<td>44</td>
<td>0.15</td>
<td>3.8</td>
</tr>
<tr>
<td>12/5/01 9:03</td>
<td>19</td>
<td>32</td>
<td>30</td>
<td>0.06</td>
<td>1.9</td>
</tr>
<tr>
<td>12/7/01 12:02</td>
<td>12</td>
<td>20</td>
<td>19</td>
<td>0.09</td>
<td>2.0</td>
</tr>
<tr>
<td>12/7/01 12:28</td>
<td>46</td>
<td>97</td>
<td>82</td>
<td>0.18</td>
<td>4.0</td>
</tr>
<tr>
<td>12/17/01 8:36</td>
<td>14</td>
<td>18</td>
<td>17</td>
<td>0.08</td>
<td>1.5</td>
</tr>
<tr>
<td>12/17/01 10:15</td>
<td>13</td>
<td>41</td>
<td>36</td>
<td>0.08</td>
<td>2.3</td>
</tr>
<tr>
<td>12/17/01 11:53</td>
<td>13</td>
<td>49</td>
<td>40</td>
<td>0.07</td>
<td>2.3</td>
</tr>
<tr>
<td>12/18/01 10:01</td>
<td>25</td>
<td>70</td>
<td>56</td>
<td>0.15</td>
<td>2.6</td>
</tr>
<tr>
<td>12/18/01 10:31</td>
<td>22</td>
<td>35</td>
<td>33</td>
<td>0.11</td>
<td>2.2</td>
</tr>
<tr>
<td>1/4/02 9:33</td>
<td>5</td>
<td>9</td>
<td>9</td>
<td>0.03</td>
<td>0.9</td>
</tr>
<tr>
<td>1/4/02 13:06</td>
<td>8</td>
<td>16</td>
<td>14</td>
<td>0.12</td>
<td>1.8</td>
</tr>
<tr>
<td>1/11/02 10:15</td>
<td>13</td>
<td>18</td>
<td>20</td>
<td>0.15</td>
<td>2.8</td>
</tr>
<tr>
<td>1/11/02 10:45</td>
<td>14</td>
<td>33</td>
<td>28</td>
<td>0.08</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Figure 7.15 Correlations between measured crack displacement and computed displacements and peak radial ground motion
A Kaman and LVDT sensor were affixed over the same crack adjacent to each other to compare the responses to ground motion, weather events, and occupant activities. The ratio of LVDT to Kaman response was consistently 1.25, or 5 to 4, for the maximum ground motion and weather effects. The long-term time histories of responses were remarkably consistent without correction from the null sensors. Both reported similar crack width change over the seven-week interval of observation. Only for the localized occupant activities did the consistency diminish. More research is necessary to identify the reason for the difference in response to the localized events.

The consistency in the ratios of response to transient ground motion and long-term weather effects indicates that each sensor could be employed to compare the effects without prejudice. While the LVDT might report higher dynamic response, it would also report higher response to environmental factors. To determine which sensor measures displacements more accurately, further studies involving the implementation of different sensor types would be necessary. However, for the purpose of the ACM and OSM studies, both sensors prove accurate and adequate to measure crack displacements in this structure and others.
The Minnesota structure, shown in Figure 8.1, is a stucco-faced, tile block structure, located 180 feet (55 m) from anticipated pile driving for road and bridge construction. In June of 2001, autonomous crack monitoring instrumentation was installed to collect data in order to compare effects of ground motions produced by pile driving and weather on interior and exterior cracks. The instrumentation includes the following channels of observation: 3 axes of ground motion, 1 noise (air blast) transducer, 4 channels of crack displacement (static and dynamic), and indoor and outdoor temperature and humidity. The four channels of crack displacements are allocated in pairs. Each pair, indoor and outdoor, consists of a sensor spanning a crack and a companion null sensor spanning a non-cracked portion of the wall adjacent to the crack. The purpose of autonomous crack monitoring is to display via the internet to interested parties the comparison of crack movements produced by dynamic events to those produced by environmental changes or household activities.

Structure Description

The sixty-year old chapel, shown in Figure 8.1, is located on the corner of East Diamond Lake Road and Stevens Avenue in Minneapolis, Minnesota, adjacent to I35W. It is constructed of hollow tile covered with stucco on the outside and a combination of stucco and plaster and lath wall cover on the inside. The structure consists of two main sections, the main chapel space,
which faces East Diamond Lake Road, and the church school rooms at the North end of the structure. The monitored cracks are located in and on the chapel as it is closer to the anticipated construction.

As shown in Figures 8.2 and 8.3, the chapel is 2 ½ stories high with a basement. The height of the structure at the nave is approximately 33 to 44 feet (10.0 to 13.4 m), while the height in the vestibules is approximately 22 feet (6.7 m). The area of the chapel is approximately 80 feet by 40 feet (24.4 x 12.2 m).
Figure 8.2 Plan view of chapel

Figure 8.3 Elevation view of chapel
**Location of instrumentation**

LVDTs (or Linear Variable Differential Transformers) have been employed for this ACM study. The sensors employed, are the DC 750-050 and DC 750-125 LVDTs produced by MacroSensors. The 050’s, illustrated in the schematic drawn in Figure 8.4, have a stroke range of ± 1.3 mm or ± 0.05 in (± 3.17 mm or ± 0.12 in for the 125’s) and voltage range of ± 10 volts. Each sensor is deployed in the same configuration. The conversion factor for the 050 is 7.87 volts/millimeter (0.31 volts/in) and that for the 125 is 3.15 volts/millimeter (0.12 volts/in).

The LVDT consists of two parts: a moveable magnetic core that is threaded onto a stainless steel screw and attached to the aluminum bracket; and a circular body with an cylindrical inner opening in which the core is able to translate parallel to the cylindrical axis. The core is centered within the body of the sensor, without contact, and moves relative to the body. This relative displacement changes the magnetic field in the core, which in turn changes the output voltage.

![Figure 8.4 Schematic of DC 750 series LVDTs](image-url)

As noted in Figure 8.2, two of the LVDTs were placed inside of the structure over plaster, while the other two were placed outside of the structure over stucco. Of each of the two pairs, one of the sensors was placed over a crack, while the other was placed nearby, over an un-cracked portion of the wall.

As shown in Figure 8.5, the indoor sensors were placed in the southwest portion of the chapel, at the center of an archway at the East end of the chapel, approximately 12 ft (3.7 m) above the floor. All of the arches along the nave are cracked at the top center. This location was
chosen because it was at the East end of the chapel, closest to the proposed construction, and also because the crack appeared to be active. There were obvious attempts to repair the crack. The crack, which spans vertically from the arch to the ceiling, is approximately 800 µm (31,600 µin) wide.

As shown in Figure 8.6, the outdoor sensors were placed along the East wall of the structure, to the left of the large stained glass window, approximately six feet from the ground surface. The crack spans horizontally, and is approximately 1000 µm (39,500 µin) wide. The crack is stained, which indicates long-term activity. This location east of the interior crack, was chosen because of its proximity to the proposed construction, 100 to 200 ft (30 to 61 m) from the East wall.

![Figure 8.5 Indoor LVDTs in Minnesota chapel](image)
In addition to the displacement sensors and ground motion transducers, indoor and outdoor temperature and humidity sensors, and a Larcor overpressure microphone were installed. The locations of these additional sensors are indicated in Figures 8.2 and 8.3. The block of three transducers that measure vertical and two components of horizontal ground motion was buried approximately one foot under the ground surface, approximately seven feet (2.1 m) away from the East wall of the chapel. The orientation of the block is the same as that employed at the OSM structures and in Wisconsin. One Vaisala Temperature and Humidity Measurement instrument was placed in the vicinity of the indoor displacement sensors, directly in the corner, above the heating duct, approximately seven feet (2.1 m) above the floor surface. The other Vaisala was placed outside near the outdoor displacement sensors at the corner of the large stained glass window, which is approximately five feet (1.5 m) above the ground surface. The
The overpressure microphone is located adjacent to the outdoor Vaisala instrument, as shown in Figure 8.6. Due to improper wiring of the microphone, however, accurate measurement of air pressure has not been recorded.

The Data Acquisition System (DAS) was placed in the southwest corner of the chapel under the archway on which the indoor transducers was fixed. It was attached to the bottom of a pew seat, oriented parallel to the nave of the chapel as shown in Figure 8.7. The industrial modem and 12V power supply were also attached underneath the pew. All details on instrumentation and configuration of the system can be found in Appendix D.

![Data acquisition system](image)

**Figure 8.7 Data acquisition system**

**Extent of Monitoring**

The data being collected by the DAS consist primarily of hourly readings from the LVDTs and the weather sensors. Once an hour, nine samples are taken from each channel, at a rate of 1000 samples per second, and averaged to return a single value. In addition, threshold values have been set to trigger the collection of dynamic data when certain levels of ground motion are detected. Currently, this threshold value is set at 0.02 ips (0.5 mm/sec). Therefore, whenever ground motions of 0.02 ips (0.50 mm/sec) are detected, a three second stream of data
are recorded by the DAS. These three-second data streams record the ground motions, crack displacements, and air pressure.

The DAS is also configured to record manual burst data during an ongoing test, at any given time, for any given amount of time. Therefore, if any dynamic events are expected to occur, it would be possible to collect a constant stream of data during a specified time interval.

**Crack Response to Environmental Effects**

Figures 8.8 and 8.9 compare the long-term action of weather indicators (temperature and humidity) with the long-term crack response of the indoor and outdoor sensors, respectively. Temperature, crack displacement, and humidity are plotted on the same time scale to illustrate interrelationships. Long-term crack displacement, temperature, and humidity were all measured hourly during the monitoring period. The outdoor crack appears to be less active than the indoor crack. During the colder months of December and January, greater cyclic crack displacements can be observed for both outside and inside cracks.

Table 8.1 lists the average and maximum values for the frontal, daily, and combined weather effects for temperature, crack displacement, and humidity. The overall averages for temperature, indoor crack displacement, outdoor crack displacement, and humidity are 60 °F (15.6 °C), 66 µm (2607 µin), -66 µm (1817 µin), and 63%, respectively. Further details on the technique of calculating weather displacements can be found in Chapter 3.

<table>
<thead>
<tr>
<th></th>
<th>Temperature Change (DegF)</th>
<th>Indoor Crack Displacement (µm)</th>
<th>Outdoor Crack Displacement (µm)</th>
<th>Humidity Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frontal Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviation of 24 hr average from overall average</td>
<td>12</td>
<td>43</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td>Max deviation of 24 hr average from overall average</td>
<td>31</td>
<td>155</td>
<td>79</td>
<td>27</td>
</tr>
<tr>
<td><strong>Daily effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of deviations from 24 hr average trend</td>
<td>5</td>
<td>50</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>Max deviations from 24 hr average trend</td>
<td>12</td>
<td>100</td>
<td>57</td>
<td>25</td>
</tr>
<tr>
<td><strong>Weather Effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average deviations from overall average</td>
<td>12</td>
<td>62</td>
<td>31</td>
<td>14</td>
</tr>
<tr>
<td>Max deviations from overall average</td>
<td>34</td>
<td>217</td>
<td>107</td>
<td>37</td>
</tr>
</tbody>
</table>
Compared to the other structures in previous chapters, the displacements due to weather effects are much larger for this structure. However, it is important to note that the time of observation was much larger than were the times for some of the previous structures. By monitoring the structure response over a greater time period, the structure is affected by more extreme weather fronts, as well as, seasonal changes. The OSM structures in Chapters 3, 5, and 6 were monitored for less than a week; which is too short a time to reliably observe a significant frontal effect. To faithfully compare the magnitude of the displacements, the structures should be monitored for the same length of time during a transition season such as spring or fall.

Figure 8.10 displays a shorter period of time to magnify the changes measured with the crack sensors and to investigate the need for null sensor correction. The top plot defines the maximum displacements from frontal, daily, and weather effects described above. The lower two plots show the crack displacement measured by each crack sensor compared to the displacement corrected by the null sensor. The corrected crack displacement is calculated by subtracting the measurement recorded by the null sensor from its respective crack sensor. These comparisons show that the corrections made with the null sensor are minimal and do not change the variations in long-term response. In this case, they are so minimal as to be unnecessary.
Figure 8.8 Long-term indoor crack displacement and weather versus time
Figure 8.9 Long-term outdoor crack displacement versus time
Figure 8.10 Typical crack displacements due to long-term phenomena
CHAPTER 9

SYNTHESIS

This chapter synthesizes the long-term and vibration response of seven structures. Four of the eleven atypical structures instrumented during the Office of Surface Mining 2000-2001 investigation (Aimone-Martin, 2002) were fitted with special instrumentation to monitor crack response. This thesis reports the findings structure by structure in separate chapters, and synthesizes the results by comparing measurements from all four atypical structures as well as that from three other ACM structures. Specially programmed data acquisition devices were employed to detect and compare both long-term, or weather, and transient, or blast effects on the cracks for all seven. Combination of this crack response with the velocity response of the baseline OSM study provides additional insight into the relation between structural, wall, and crack response to vibratory excitation.

The four OSM structures vary widely, and include a double-wide trailer (T), an adobe brick ranch house (A), a concrete block basement wall of a bungalow (B), and a highly distressed wood-framed house (D). The three ACM structures include a stone block house (C), a Victorian wood framed house (V), and a stucco over hollow tile Chapel (S). Observation of the unique, atypical structures extends the database on the response of cracks in relation to both environmental and vibratory effects. Location of the cracks also varies widely, and includes cracks on: 1) interior drywall (T) and (C) and plaster and lath (D) and (V), as well as, 2) exterior concrete block (B), adobe (A), and stucco over hollow tile (S). All structures were one story,
with the exception of the chapel (S) and the Victorian house (V), and all but the adobe house (A) were founded on a basement.

Environmental and Vibratory Effects

Environmental and vibratory responses of cracks for the four atypical houses are compared with those from three other houses in Table 9.1, and the bar chart in Figure 9.1. Response is defined as the micrometer change in crack width. All comparisons in this synthesis are based on data within this thesis, with the exception of one structure, (V). Responses presented in this chapter for the Victorian structure (V) were obtained during the development of the data acquisition device (Siebert, 2000).

The seven homes geographically were widely distributed in central Pennsylvania (T), northern New Mexico (A), southern Indiana (B & D), southern Wisconsin (C), northern Illinois (V), and eastern Minnesota (S). Data were collected during all seasons of the year. In addition to the weather and vibratory crack responses, responses to occupant activities were measured at four of these structures.

Weather effects were monitored over widely variable time periods. Three of the four “atypical” structures were monitored for periods of a week or less. The adobe (A) was observed for nearly a month. The (C), (V), and (S) structures were observed for longer periods, 2 months, 3 months, and 4 months, respectively. The short, week-long periods of observation most likely do not include extreme weather and thus probably under-report weather effects.

Maximum weather effects are at least an order of magnitude greater than the vibratory effects produced by ground motions of 0.1 ips (2.5 mm/sec) for all six of the structures studied. In one case, (T), the maximum weather-induced response is even greater, 40 times greater. As described earlier, the maximum weather effect is defined as the maximum of deviations of the peaks from the overall average crack width change during the study period. The vibratory response is the maximum, zero to peak change in crack width during the vibratory response. Both, the long-term, weather, and transient, vibratory responses are measured by the same sensor and are thus directly comparable.
### Table 9.1 Summary of measured displacements due to static and dynamic events

<table>
<thead>
<tr>
<th>Event</th>
<th>(T) Trailer Interior Drywall</th>
<th>(A) Ranch Exterior Adobe</th>
<th>(B) Bugalow Exterior Concrete Block</th>
<th>(D) Distressed Frame Interior Plaster/Lath</th>
<th>(C) Block/Stone Interior Drywall(1)</th>
<th>(V) Victorian Frame Interior Plaster/Lath(2)</th>
<th>(S) Chapel Stucco Exterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of crack (micrometers)</td>
<td>700</td>
<td>800</td>
<td>500</td>
<td>1200</td>
<td>500</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Max Frontal Effect</td>
<td>11</td>
<td>9</td>
<td>3</td>
<td>16</td>
<td>35</td>
<td>100</td>
<td>155</td>
</tr>
<tr>
<td>Max Daily effect</td>
<td>16</td>
<td>25</td>
<td>9</td>
<td>25</td>
<td>10</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Max Weather effect</td>
<td>24</td>
<td>25</td>
<td>12</td>
<td>52</td>
<td>44</td>
<td>-</td>
<td>217</td>
</tr>
<tr>
<td>Days of observation</td>
<td>5</td>
<td>35</td>
<td>4</td>
<td>3</td>
<td>37</td>
<td>92</td>
<td>126</td>
</tr>
<tr>
<td>ΔT (deg F)</td>
<td>13</td>
<td>51</td>
<td>30</td>
<td>17</td>
<td>44</td>
<td>41</td>
<td>63</td>
</tr>
<tr>
<td>Max Blast event (ppv in ips)</td>
<td>0.9 (0.32)</td>
<td>4.2 (0.13)</td>
<td>0.3 (0.23)</td>
<td>13.6 (0.30)</td>
<td>7 (0.13)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Blast event at 0.10 ips</td>
<td>0.3</td>
<td>2</td>
<td>0.2</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Slamming door (distance to crack in ft)</td>
<td>2.5 (6)</td>
<td>-</td>
<td>-</td>
<td>1.6 (14)</td>
<td>3.5 (7)</td>
<td>10 (5)</td>
<td>-</td>
</tr>
<tr>
<td>Jumping (distance to crack in ft)</td>
<td>1.5 (10)</td>
<td>-</td>
<td>-</td>
<td>1.9 (16)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hammering (distance to crack in ft)</td>
<td>0.2 (11)</td>
<td>-</td>
<td>-</td>
<td>2.2 (1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shutting window (distance to crack in ft)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.1 (3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Walking on Stairs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>Foundation Response</td>
<td>-</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Seasonal Heating</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300</td>
</tr>
</tbody>
</table>

Notes:
(1) Crack #1 (Louis, 2000)
(2) Crack #2 located under stairwell (Seibert, 2000)
Figure 9.1 Comparison of measured displacements due to static and dynamic events
**Crack Response to Environmental Effects and Occupant Activities**

There is a weak correlation of crack response with crack width for those cracks in wall covering. The widest crack, 1200 µm (47,400 µin), in the distressed frame, D, displayed the largest weather response as well as the largest response to vibratory excitation. That with the thinnest, 500 µm (19,800 µin), the trailer, T, displayed the least response again to both weather and vibratory excitation. Crack widths were estimated from photographs (by scaling off of known distances) shown in the previous descriptive sections for each structure.

Response to occupant activity can be as large as that produced by vibratory excitation as shown in Table 9.1 and Figure 9.1. Responses presented are a common subset of the widely variable activity tests conducted. Distances to the activity are shown along with the crack responses produced. Those activities closest to the crack produced the greatest response. The greatest response, 40 µm (1580 µin), is produced by walking or running past the crack in a stairway (V), which may contain a construction defect.

Responses to two unique events, a rain storm in New Mexico (A) and seasonal heating in Illinois (V), created large and relatively permanent crack responses. A half-inch rainfall at the adobe home (A) produced a permanent displacement 16 micrometer change that remained for the duration of the observation. This is 8 times greater than the response of the crack to 0.1 ips (2.5 mm/sec) blast-induced ground motions. Over the period of December to March, heating of the wood frame house (V) changed the crack width of a basement crack by 300 µm (11,900 µin). This house is not located near a blast vibration source. However, a comparison can be made through occupant-induced motions. Slamming a door 5 ft (1.5 m) away produced 10 µm. Thus the seasonal heating response is some 30 times greater than that to an adjacent door slam.

**Crack Response to Vibratory Ground Motion**

Aggregating the crack width response for all homes into a single graph allows comparison of the variability of vibratory response by crack type and/or structure type. The same format has been employed for aggregated data in Figures 9.2 and 9.3, as for each structure individually. The maximum measured crack displacement produced by each shot is compared to
various parameters employed for correlation with calculated, estimated, or approximated relative displacements and/or visual observation of the threshold of cosmetic cracking. The responses analyzed were those motions parallel to the wall containing the crack because the crack displacement was measured in the plane of the crack. Table 9.2 summarizes the regression coefficients determined for these comparisons, which are individually presented in the appropriate chapters. Details of the methods of calculation, estimation, and approximation can be found in Chapter 3. Figure 9.2 contains the correlations with the calculated and estimated displacements, while Figure 9.3 contains the correlations with the approximated displacements.

Table 9.2 Summary of correlations between measured crack displacement and calculated, estimated, and approximated relative wall displacements and PPV parallel to plane of crack

<table>
<thead>
<tr>
<th>Regression coefficients determined between measured displacement and:</th>
<th>(T) Trailer Interior Drywall</th>
<th>(A) Ranch Exterior Adobe</th>
<th>(B) Bugalow Exterior Concrete Block</th>
<th>(D) Distressed Frame Interior Plaster/Lath</th>
<th>(C) Block/Stone Interior Drywall</th>
<th>(V) Victorian Frame Interior Plaster/Lath</th>
<th>(S) Chapel Stucco Exterior</th>
<th>Average correlation from OSM structures (T-D)</th>
<th>Average correlation from all structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated displacement: Integrated top-integrated bottom</td>
<td>0.95</td>
<td>0.87</td>
<td>0.29</td>
<td>0.99</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>Calculation displacement: Integrated top - Integrated ground</td>
<td>0.75</td>
<td>0.39</td>
<td>0.28</td>
<td>0.99</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Estimated displacement: Integrated ground velocity</td>
<td>0.62</td>
<td>0.51</td>
<td>0.22</td>
<td>0.99</td>
<td>0.65</td>
<td>-</td>
<td>-</td>
<td>0.59</td>
<td>0.63</td>
</tr>
<tr>
<td>Estimated displacement: SDOF ( f_n ) of structure</td>
<td>0.87</td>
<td>0.44</td>
<td>0.62</td>
<td>0.96</td>
<td>0.51</td>
<td>-</td>
<td>-</td>
<td>0.72</td>
<td>0.63</td>
</tr>
<tr>
<td>Estimated displacement: SDOF ( 10&lt;f_n&lt;15 \text{ Hz} )</td>
<td>0.91</td>
<td>0.84</td>
<td>0.67</td>
<td>0.99</td>
<td>0.64</td>
<td>-</td>
<td>-</td>
<td>0.85</td>
<td>0.69</td>
</tr>
<tr>
<td>PPV parallel to wall of crack</td>
<td>0.58</td>
<td>0.6</td>
<td>0.9</td>
<td>0.99</td>
<td>0.73</td>
<td>-</td>
<td>-</td>
<td>0.77</td>
<td>0.73</td>
</tr>
<tr>
<td>Approximated displacement: ( (PV_{max}^2\pi f)^{top}-(PV_{max}^2\pi f)^{bottom} )</td>
<td>0.35</td>
<td>0</td>
<td>0</td>
<td>0.99</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>Approximated displacement: ( (PV_{max}^2\pi f)^{top}-(PV_{max}^2\pi f)^{ground} )</td>
<td>0.88</td>
<td>0.28</td>
<td>0.13</td>
<td>0.68</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>Approximated displacement: ( (PV_{max}^2\pi f)^{bottom}-(PV_{max}^2\pi f)^{ground} )</td>
<td>0.19</td>
<td>0.36</td>
<td>0.56</td>
<td>0.98</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>Approximated displacement: ( (PV_{max}^2\pi f)^{top}-(PV_{max}^2\pi f)^{bottom} )</td>
<td>0.35</td>
<td>0.07</td>
<td>0.03</td>
<td>0.98</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>Approximated displacement: ( (PV_{max}^2\pi f)^{top}-(PV_{max}^2\pi f)^{ground} )</td>
<td>0.83</td>
<td>0.91</td>
<td>0.46</td>
<td>0.99</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Approximated displacement: ( (PV_{max}^2\pi f)^{bottom}-(PV_{max}^2\pi f)^{ground} )</td>
<td>0.16</td>
<td>0.03</td>
<td>0.01</td>
<td>0.98</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 9.2 Comparison of correlations between measured crack displacement and predicted displacements and peak parallel ground motions
First consider the crack location. The crack in the bungalow (B) was located at the top of the concrete block basement wall, only 3 ft (0.9 m) from the ground surface. It has the least response even though it sustained peak particle velocities as high as 0.2 ips (5.1 mm/sec) as shown in Figure 9.2 (f). The low response is expected, as the basement wall moves with the ground and thus is not free to selectively amplify motions as is the superstructure. Such measured displacements of this crack would not be expected to correlate with other measures, which presume free response of the structure. Crack displacement in this basement wall best correlates to peak particle velocity because it is most directly related to ground strains. It has the worst correlation with calculated displacement (between the top and bottom corners of the structure), as these responses are for the above ground, freely responding portion of the structure.

Next consider crack response. The most active of the three cracks in wall covering of the superstructure was also the widest, (D). As can be seen in the crack photographs, this crack was different from the others. It was significantly wider and more uniform in width. The correlations for D are uniformly the highest; however, these high correlations may result from the large range of measured crack width changes as seen in the detailed presentation of D data.

The graphs in Figures 9.2 and 9.3 have been truncated at 5 µm (198 µin) for measured crack displacement, to illustrate the comparative trend of all the data. Therefore, the point that represents the crack response (at house D) of 14 µm (553 µin), at a peak particle velocity of 0.28 ips (7.1 mm/sec), is not visible in these figures.

Cracks that are most active when perturbed by ground motion are also seen to be the most active when perturbed by changes in the weather. The most active crack is defined as that which has the steepest slope in Figures 9.2 and 9.3. Cracks in structures C and D would be the most active, and that in B would be the least. Comparison of the slope with the maximum weather effects in Table 9.1 shows that D is twice as responsive to weather changes as T and A. There are too few data points to draw a numerical correlation between these three structures, as the one-week observation period for weather effects was too short to ensure that extreme events were captured. Further insight can be gained when comparing structures A and C, which were monitored for the same length of time. Structure C exhibits the steeper slope in three of its correlations, as well as the higher response to weather effects. This higher response further supports the link between large vibratory response and large weather response. As for the
remaining structure, while the crack in structure B was the least active, its location on a basement wall so close to the ground renders it particularly insensitive to daily changes in weather.

Consider the three cracks that were located above ground, where superstructure response was possible (T, A, and D). Measured crack displacement correlated best with the difference in displacements calculated from motions measured at the top and bottom of the structure, parallel to the plane of the crack. This correlation is shown in Figure 9.2 (a). High correlation is expected, as this difference is the relative displacement of the wall, which is proportional to the gross, in-plane, shear strain in the wall. As such the calculated difference in displacement also could be considered as a direct measurement of the gross wall strain.

The second best correlation with the measured crack displacement is obtained from the pseudo velocity response spectrum (PVRS), for the frequencies between 10 and 15 Hz. The PVRS is a derivative of calculated relative displacement that accounts for the structural response frequency, as well as, the full excitation time history (Dowding, 1996). These correlations are almost identical to that between the two direct measures of wall strain. The single point for a range of frequencies was obtained by averaging the relative displacement responses for each frequency between 10 and 15 Hz. This frequency range corresponds to that of the walls. Correlations are lower with PVRS displacements for the natural frequency of each superstructure, but are still higher than those for other estimates in Figure 9.2, with the exception of structure C.

Typical structural response monitoring is commonly undertaken with motions measured in the ground and upper structure, non-time correlated, and with separate vibration monitors. It is instructive to gauge the effectiveness of various estimates of displacements made with these types of data. Estimates of wall strain can be made from sinusoidal approximations of displacement, which are peak velocities divided by two times Pi times the associated frequency (PV/2πf), as explained earlier. Displacements approximated from the velocity time histories at various locations can be subtracted to obtain various measures of relative displacement. Approximated relative displacements have been produced from the following pairs of velocity time histories: 1) ground and top corner motions at the time of peak ground motion, 2) ground and top corner motions at the time of peak top corner motion, 3) peak ground and peak top corner motions, regardless of the time at which each occurs. Figures 9.3 (a) to (c) show the
correlations of measured crack displacements with these approximated relative displacements. None of the three possibilities with the top response and the ground response display high correlations as uniformly as the calculated and estimated values in Figure 9.2 identified above.

Another alternative is to measure top and bottom response and ignore ground motion. Approximated relative displacements were also analyzed, where velocity in the bottom corner was used in place of ground motion. These approximations are shown in Figures 9.3 (d) to (f). The highest correlation is found in Figure 9.3 (e). Here, the approximation is computed at the time of maximum top corner response. This approximation of relative displacement differs only from the direct calculation (Figure 9.3 (a)) by the manner in which displacement is obtained.

Structural response velocity measurements were made with small single axis transducers glued to the walls at the corners of the structures. When mounted on cantilevered brackets, large multi-axial devices from commercial vibration monitors may not yield the same quality in data. Even though the standard configuration of velocity transducers is a triaxial block, it is recommended to employ single, uniaxial transducers to simplify mounting difficulties.

These differences in response described above are small compared to the large impact of weather related response demonstrated in Figure 9.1. Changes in crack width produced by ground motions between 0.10 and 0.30 ips (2.5 and 7.6 mm/sec) were less than 5 µm (198 µin), except in one instance; whereas, the maximum weather responses during one week (or smaller) periods of observations were 10 to 50 µm (395 to 1975 µin). The crack in structure D that showed the exceptionally large vibratory response (14 µm or 553 µin), also showed the largest weather response (52 µm or 2054 µin).
Figure 9.3 Comparison of correlations between crack displacement and calculated relative displacements
REFERENCES


Nomis Seismographs Data Analysis, Version 6.0.0, Nomis Seismographs, Birmingham, AL.


Somat Ease version 3.0 (1999). Somat Corporation, Champaign, IL.

Somat TCE eDAQ version 3.5.1 (2001). Somat Corporation, Champaign, IL.

Somat TCS for Windows, version 2.0 (1999). Somat Corporation, Champaign, IL.

APPENDIX A
FOURIER FREQUENCY SPECTRA
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity

5-6 Hz
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) Crack displacement/Ground Displacement

(b) Crack Displacement

(c) Ground displacement
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) Crack displacement/Ground Displacement

(b) Crack Displacement

(c) Ground displacement

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-6 Hz</td>
<td></td>
</tr>
</tbody>
</table>
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) Crack displacement/Ground Displacement

(b) Crack Displacement

(c) Ground displacement
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
Distressed House - 8/24/01 12:10

(a) S2 Velocity/Ground Velocity

(b) S2 Velocity

(c) Ground velocity
APPENDIX B
SINGLE DEGREE OF FREEDOM MODEL & RESPONSE SPECTRUM
B1. STRUCTURAL ANALOGY

The cracking potential of ground borne vibrations can be discussed most accurately in terms of the response of structures to the passing of the vibration wave form. One of the critical response factors is the amount of differential movement that occurs between structural members or between different points on the same structural member because it causes strains which, in turn, cause cracking.

To compute the differential displacements that may occur in an actual structure or structural component, it is necessary to simplify a structure so that computations are practical. The simplest model that accounts for the dynamic interaction of the three simplified characteristics is the single degree of freedom (SDF) system shown in Figure B-1. The concentrated mass is analogous to the masses of the main components (floors); the spring represents the stiffness of the main components (walls), and the dashpot, through viscous resistance, models the dissipation of energy (connections). The differential movement, \( \delta \), is the difference between the absolute displacement of the mass, \( x \), and the absolute displacement of the ground, \( u \). Even multiple degree of freedom systems such as multiple storied structures may be idealized as a single-degree-of-freedom system if one is interested in the dominant or fundamental mode of response. Greater detail on the response of multiple degree of freedom systems can be found in tests on structural dynamics and earthquake engineering.

B2. MATHEMATICS OF THE SDF MODEL

The equation of motion for the SDF system in Figure B-1, when subjected to ground excitation, is

\[
m \ddot{x} + c_1 \dot{\delta} + k \delta = 0 \tag{B-1}
\]

excitation, is where \( x \) is the absolute acceleration of the mass, \( m \); \( c_1 \) the damping coefficient; the velocity of the mass relative to the ground; \( k \) the linear spring constant; and \( \delta \) the
relative displacement between the ground and the mass. Using the relationship for the
relative displacement \( \delta = x - u \), shown in Figure I-1, Equation B-1 becomes

\[
m \ddot{\delta} + c \dot{\delta} + k \delta = - m \ddot{u}
\]

(B-2)

The circular natural frequency of the undamped spring-mass system, \( p \), is equal
to \( \sqrt{k/m} \). The fraction of critical damping, \( \beta \), is equal to \( \frac{c}{2 \sqrt{mk}} \). If the mass is
displaced from its equilibrium position, it will not oscillate when released but will simply
return to its equilibrium position when \( c_1 = 2 \sqrt{mk} \). Under this condition the
system is said to be critically damped. The circular natural frequency of the damped
system, \( p_d \), is equal to \( p \sqrt{1 - \beta^2} \). Equation B-2 can be recast as

\[
\ddot{\delta} + 2\beta p \dot{\delta} + p^2 \delta = \ddot{u}
\]

(B-3)
in terms of percentage critical damping, \( \beta \), and circular natural frequency, \( p \). The
ground-acceleration time history, which is to be integrated from time zero to time \( t \), is
represented by \( u(t) \).

Thus if a structure's undamped natural frequency, \( p \), and its fraction of critical
damping, \( \beta \), are known, it is not necessary to define particular values of \( m, k \), and \( c_1 \) in
order to model the structure accurately. Furthermore, dynamic properties, \( p \) and \( \beta \), can
be more accurately measured from a free vibration time history of the building response
than calculated from estimates of \( m, k \), and \( c_1 \). These measured parameters
automatically account for the factors that are difficult to quantify, such as the degree of
fixity of the columns (which affects \( k \)) and the damping coefficient, \( c_1 \).

The preceding discussion dealt with the response of a particular structure to a
particular ground motion. However, to distinguish different types of ground motions
and their differing cracking potentials, it is necessary to compare the effect of the wave
on a wide variety of structures. The response spectrum, which can be calculated from
solutions to Equation B-3, provides a mechanism for this comparison.

Solution to Equation B-3 for relative displacements at any time may be expressed in

\[
\delta(t) = -\frac{1}{p \sqrt{1 - \beta^2}} \int_0^t (\tau) e^{\beta p(t-\tau)} \sin[p_d(t-\tau)] d\tau
\]

(B-4)
terms of the Duhamel integral of the absolute ground acceleration time history as
where \( \delta \) and \( u \) are zero at \( t_0 \) (Veletsos and Newmark, 1964).

Equation B-4 yields the relative displacement response of an SDF system from a
ground-acceleration time history. If a velocity time history is used as the input time
history, the relationship between \( u \) and \( \delta \) can be found by integrating Equation B-4 by
parts and combining terms (Veletsos and Newmark, 1964). The resulting equation can
be expressed as
\[
\delta(t) = -\int_0^t \dot{u}(\tau) e^{\beta p_d (t-\tau)} \left[ \cos \left( \frac{p_d (t-\tau)}{\sqrt{1-\beta^2}} \right) \right] d\tau \quad (B-5)
\]

when \( \delta \) and as well as displacement, velocity, and acceleration are zero at \( t_0 \).

### B3. CONSTRUCTION OF THE RESPONSE SPECTRUM

When a particle velocity time history such as that of the radial ground motions shown in Figure B-2b is processed by computer with Equation B-5, a relative displacement, “\( \delta \)”, time history is calculated. In the calculated relative displacement time history there will be a maximum, \( \delta_{\text{max}} \).

![Response spectrum](image)

Figure B2. Response spectrum (a) calculated from excitation ground motions (b) showing responses of systems with natural (fundamental) frequencies of 10 and 20 Hz

If that maximum relative displacement is multiplied by \( p \), the structure's circular natural frequency (or \( 2\pi f_s = 2\pi / (1/T) \)),

\[
PV = 2\pi f_s \delta_{\text{max}} = p \delta_{\text{max}}
\]

is called the pseudo velocity (PV). This pseudo velocity is a close approximation of the relative velocity, \( \dot{u} \), if the pulse associated with \( \delta_{\text{max}} \) is approximately sinusoidal.
The pseudo velocity response spectrum of a single ground motion, such as that of the seven pulse motion in Figure B2a, is generated from the $\delta_{\text{max}}$ values of a number of different SDF systems when excited by that motion. Consider two different components of the same structure, a 10-Hz superstructure and the 20-Hz floor. If the ground motions, $u(t)$, of the seven pulse motion are processed twice by Equation B-5 with $\beta$, damping, held constant at 3%, and $f_s = 10$ and 20 Hz, two $\delta_{\text{max}}$ values will result.

The first computation is made with the 10-Hz system, which has a circular natural frequency of

$$p = 2\pi(10)$$

and results in

$$\delta_{\text{max}} = 0.25 \text{ mm (0.01 in.)}$$

This $\delta_{\text{max}}$ is then converted to PV as

$$\text{PV}_{10} = p\delta_{\text{max}} = 2\pi(10)(0.25) = 15.7 \text{ mm/s (0.62 in./sec)}$$

and is plotted as point 1 in Figure B-2a. The same computation is then repeated for the 20-Hz system.

$$p = 2\pi(20)$$

$$\delta_{\text{max}} = 0.5 \text{ mm (0.02 in.)}$$

$$\text{PV}_{20} = 2\pi(20)(0.5) = 63.5 \text{ mm/s (2.5 in./sec)}$$

and PV$_{20}$ is plotted as point 2 in Figure B2a. If the ground motions are processed a number of times for a variety of $f_s$'s with $\beta$ constant, the resulting pseudo velocities will form the solid line in Figure B2a.

The response spectrum in Figure B2b is plotted on four-axis tripartite paper. These four axes take advantage of the sinusoidal approximation involved in calculating a pseudo velocity. The axis of the maximum relative displacement, $\delta$, is inclined upward to the left and is the pseudo velocity (PV) divided by $2\pi \phi_c$. The pseudo acceleration (PA) axis is inclined upward to the right and is PV times $2\pi \phi_c$. PA and PV are called pseudo acceleration and pseudo velocity because they are sinusoidal approximations. However, these simplifications closely approximate the absolute acceleration of the mass and the relative velocity for systems with small $\beta$ values (Veletsos and Newmark, 1964).
APPENDIX C
TIME HISTORIES recorderD AT WISCONSIN STRUCTURE
Displacement (µm)

Sensor 1

Sensor 2

Sensor 3

PV (in/sec)

Ground R

Ground T

Ground V

Air Pressure (dB)

Air Blast

Time (sec)
Displacement (\(\mu m\))

Sensor 1

Sensor 2

Sensor 3

PV (in/sec)

Ground R

Ground T

Ground V

Air Pressure (dB)

Air Blast

Time (sec)
Displacement (µm)

Sensor 1

Sensor 2

Sensor 3

Ground L

Ground T

Ground V

Air Blast

LVDT-crack

C10
Displacement (µm)

Sensor 1

Sensor 2

Sensor 3

PV (in/sec)

Ground R

Ground T

Ground V

Air Pressure (dB)

Air Blast

Time (sec)
APPENDIX D
INSTALLATION AND CONFIGURATION OF MINNESOTA INSTRUMENTATION
D1. INSTALLATION OF SYSTEM

Installation Process

Installation was conducted from 3 to 5 June 2001. Members of the installation team included: Dan Hogan and Dan Marron, of the Infrastructure Technology Institute, and Laureen McKenna, Civil Engineering graduate student.

The following equipment were installed:

- Somat eDAQ Data Acquisition System
- Blackbox MD3450 Industrial Modem
- 12 Volt Power Supply
- Macrosensors DC750 Series LVDTs (4 – 2 Indoor, 2 outdoor)
- Geosonics Triaxial 4.5 Hz Geophone (3 components of motion)
- Vaisala HMD/W50 Temperature and Humidity Measurement Instruments (indoor and outdoor)
- Larcor Pressure transducer, Model 1289-02
- Belden Multi-conductor cable
- Junction box

For this project, a Somat eDAQ Data Acquisition System (DAS) polls all sensors and transducers, and stores and transmits the data when called. All sensors were wired to the DAS with multi-conductor cables. Wiring of the outdoor sensors required running a multi-conductor cable through the heating duct, located in the southwest corner of the chapel, down into the basement, along the basement ceiling, out the window, and into a junction box. The outdoor sensors were then connected together in the junction box. The metal junction box currently rests in the window well near the outdoor sensors. A schematic of the wiring in the junction box is shown as Figure D1.
Figure D2. Junction strip connecting eDAQ to sensors
System Capacity

Settings of the system components are listed in Table D1. The transducers record ground motion in three directions (Longitudinal, Vertical, and Transverse) with the output in volts. The Vaisala’s measure temperature in degrees and relative humidity in percent. The LVDTs record displacements in voltage. Since the sensors spanning over the cracked portion of the walls span the width of the crack, the displacements are those of the changes in the crack’s width. These sensors are referred to as the Outdoor Crack and Indoor Crack. The sensors spanning over the un-cracked portion of the two walls, which are referred to as the Outdoor Null and Indoor Null, record displacement, if any, from expansion or contraction of the sensor or wall material. The Null sensors are included in this system as an accuracy check and typically do not exhibit any significant displacement. The air pressure sensor measures air pressure in volts. However, the wiring of the sensor is incorrect and does not return accurate measurements. Rewiring of the sensor will take place at some later date.

As long as power is supplied to the DAS, it is constantly recording voltage output from the ground motion, crack displacement, temperature, humidity, and air pressure sensors. However, what the DAS stores in its memory depends on how the system is configured for each channel. The latest version of the configuration file can be found in Section D3, WinTCS Configuration File.

<table>
<thead>
<tr>
<th>Table D1. System Settings</th>
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<tbody>
<tr>
<td><strong>Channel</strong></td>
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<td>12</td>
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</tbody>
</table>
D2. AUTOMATION PROCESS

Data Retrieval

In order to retrieve data from the DAS, a modem has been installed to establish a remote connection between the DAS and a PC at the Infrastructure Institute at Northwestern University. Everyday, the PC dials the modem at the chapel and connects to the DAS. Using the Somat software, Windows TCE eDAQ v.3.5.1, the test currently running is stopped, data is uploaded, the memory is cleared and another test is reconfigured, and started. This process can be done either remotely or by direct attachment to the DAS. Currently, a program called Automate is employed to induce the PC to automatically control Windows TCE. The program also induces the PC to convert the raw data uploaded from the DAS to text files, for importation into Microsoft Excel.

Currently, the success rate of this automatic process is not very high. Ongoing trials of different automation techniques continue in order to find a self-sufficient program. Meanwhile, uploads continue on a regular basis with the help of ITI staff. Detailed instructions necessary to connect with the DAS and upload data can be found in Table D2.

Displaying the data via the internet

In addition to retrieving data from the DAS, an additional automation process has been employed for this project. Everyday, the following website, http://iti.birl.northwestern.edu/acm/minneapolis/, is updated to reflect the data collected from the DAS. At a designated time, text files (which have been saved from the raw data files) are automatically copied to the ITI webserver and converted to display over the internet via Java programming scripts. Plots of long term weather versus time and crack displacement versus time can be displayed simultaneously on the website. In addition, time histories of dynamic events can be viewed independently or they can be viewed in comparison to long term crack displacement versus time, on the same plot as described in Siebert (2000). The conversion factors used by the webserver to translate the output voltage to preferred units are listed in Table D3.
Table D2. Communicating with Minneapolis Data Acquisition System (Somat eDAQ)

Dialing the modem:

1) Start WinTCE, enter IP address of eDAQ – 192.168.55.55 (Preferences, Communications)
2) From windows start up menu, start Dial-Up Networking
3) Make new connection, pick modem, configure (19200 if possible to connect only at this speed) under connection (defaults) and options
4) Enter phone number for site (Minneapolis Enga Chapel) : 612-827-1184
5) Once new connection created, edit properties:
   a. Server types – PPP, Inter.
   b. Check log on network, and enable software, Only TCP/IP (under settings specify IP address – current 192.168.55.100)
   c. Server assigned – leave two options checked
      Dial with username as ‘ppp’ and password ‘123’

Automate commands:

- Open network dialing, click Minneapolis link and dial
- Open TCE and open latest .tce file
- Stop test
- Upload test
- Automate closes TCE and reopens b/c it usually gives a busy command so you have to open again
- End test
- You usually need to purge the disk so I have included the manual way to purge
- Hit F1 (to get the hardware tab, press configure and then purge
- Now initialize test
- Restart test when you know you have gotten any data that exists
- Hang up phone call
- Exit TCE and open Ease (either through TCE or start menu or desktop)
- Open Ease
- Go to view channels (this just sets up ease so that you are focused on the channels, manually this doesn’t really make a difference, but if there is left over data on the channels automate needs some direction to clear it)
- Delete anything in Ease that may be remaining by highlighting and pressing the delete key
- Open data file for that which was just uploaded (or anything)
- Automate focuses on Ease again to make sure it continues
- Highlight channels in order and save as text file (with Ease header) in corresponding text file with same naming convention
Here’s where Minneapolis is a little different: you will want to highlight one channel and go to plot and display channel information. When text box shows on screen you can do two different things: either save as text file and save as c:\minneapolis\headers\minH{FORMATDATETIME "YYMMDD"}.txt or copy all text and paste into text file for that data file  
Either way, you will need to open wordpad and open text file for day  
For the first way you need to open the header file and copy and paste it at the top of the text file or you can just paste it in if you are taking it directly from Ease (it is not really important to make sure there is a header file every day, it just is easier for automate to save as and then retrieve the header from a file – There isn’t a way to automatically copy and paste from that text window in ease)…You need the header because you need the run date.  
Highlight all channels again and delete to clear ease channels  
Exit Ease
Table D3. Conversion Factors for Sensors in Minneapolis

**Air Blast Conversion**

1 mB = 500 mV = 0.5 V (Transducer calibration)

\[ dB = 20 \log_{10} \left( \frac{P}{P_o} \right), \text{ where } P_o = 20 \times 10^{-6} \text{ N/m}^2 \] (Dowding)

Air Pressure in dB = \(20 \log_{10}\frac{\text{input in volts}}{1 \times 10^{-7}}\)

**LVDT Macrosensors**

DC750 Series – Used for Indoor Crack and Null Sensor and Outdoor Null Sensor
7.87E-3 volts/µm

LVDT used for Outside Null Sensor
3.15E-3 volts/µm

**Temperature and Humidity Sensor – Vaisala**

Temperature
Range - 23° to 131° F
Zero – 23
Scale - 154
Relative Humidity
Range 0 to 100%
Zero – 0
Scale - 10
(Converted in set-up file)
D3. WinTCS Configuration File

[Main]
TCEVersion=V3.5.1
FileVersion=1.2
TargetFCS=eDAQ
IdenDifined=1
HardNameEDaq=ENGA
MasterSampleRate=100000
NumHardItems=3
NumChanItems=12
NumSoftItems=16
NumDataItems=2

[IdenInfo]
Prefix=IDSTD
Title=Enga Memorial Chapel, Minneapolis
Operator=Laureen McKenna
Date=06/08/01
NumCommLines=3
CommLine_1=Vibration Monitoring
CommLine_2=First .TCE setup file attempt.
ObjectID=0

[HardItem_1]
Prefix=MS_MPBM
ID=MPB
Code=v1.9
SN=MSMPB.06-2224
ECNCount=9
ECNNumber_1=001220
ECNeDate_1=020901
ECNNumber_2=001238
ECNeDate_2=020901
ECNNumber_3=001241
ECNeDate_3=020901
ECNNumber_4=001243
ECNeDate_4=020901
ECNNumber_5=001244
ECNeDate_5=020901
ECNNumber_6=001245
ECNeDate_6=020901
ECNNumber_7=001247
ECNeDate_7=020901
ECNNumber_8=001249
ECNeDate_8=020901
ECNNumber_9=001254
ECNeDate_9=020901
PCMCardState=3
PCMModelNum=M-SYSTEMS
PCMSerialNum=None

[HardItem_2]
Prefix=MS_HILEV
ID=HiLev_1
Code=n/a
SN=MSHLA.03-2145
ECNCount=1
ECNNumber_1=001235
ECNeDate_1=011901
BadCharData=0

[HardItem_3]
Prefix=MS_MPBSER
ID=MPBSer
Code=n/a
SN=MSMPB.06-2224
ECNCount=9
ECNNumber_1=001220
ECNeDate_1=020901
ECNNumber_2=001238
ECNeDate_2=020901
ECNNumber_3=001241
ECNeDate_3=020901
ECNNumber_4=001243
ECNeDate_4=020901
ECNNumber_5=001244
ECNeDate_5=020901
ECNNumber_6=001245
ECNeDate_6=020901
ECNNumber_7=001247
ECNeDate_7=020901
FPGAVersion=n/a
NumHardInterfaces=0
[ChanItem_1]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_1
Connector=HiLev_1.c01
SampleRate=1000
Description_1=Longitudinal
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1.00000000e+000
FS_Max_1=1.00000000e+000
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-1
CalSigValue_1=-1
CalMode_2=Defined Value
CalEngValue_2=1
CalSigValue_2=1
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_2]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_2
Connector=HiLev_1.c02
SampleRate=1000
Description_1=Vertical
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1.00000000e+000
FS_Max_1=1.00000000e+000
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-1
CalSigValue_1=-1
CalMode_2=Defined Value
CalEngValue_2=1
CalSigValue_2=1
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_3]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_3
Connector=HiLev_1.c03
SampleRate=1000
Description_1=Transverse
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1.00000000e+000
FS_Max_1=1.00000000e+000
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-1
CalSigValue_1=-1
CalMode_2=Defined Value
CalEngValue_2=1
CalSigValue_2=1
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_4]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_4
Connector=HiLev_1.c04
CalSteps=2
SampleRate=1000
Description_1=Outside Temperature
Type_1=Temperature
Units_1=Deg F
ChanDataType=784
FS_Min_1=2.30000000e+001
FS_Max_1=1.31000000e+002
CalDate=07/06/01
CalSlope=1.08000000e+001
CalIntercept=2.30000000e+001
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=23
CalSigValue_1=0
CalMode_2=Defined Value
CalEngValue_2=131
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_5]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_5
Connector=HiLev_1.c05
SampleRate=1000
Description_1=Outside Humidity
Type_1=Humidity
Units_1=%RH
ChanDataType=784
FS_Min_1=0.00000000e+000
FS_Max_1=1.30000000e+002
CalDate=06/08/01
CalSlope=1.00000000e+001
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-10
CalSigValue_1=-10
CalMode_2=Defined Value
CalEngValue_2=10
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_6]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_6
Connector=HiLev_1.c06
SampleRate=1000
Description_1=Outside Crack
Type_1=Voltage
Units_1=volts
ChanDataType=32
FS_Min_1=-1.00000000e+001
FS_Max_1=1.00000000e+001
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-10
CalSigValue_1=-10
CalMode_2=Defined Value
CalEngValue_2=10
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_7]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_7
Connector=HiLev_1.c07
SampleRate=1000
Description_1=Outside Null
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1.00000000e+001
FS_Max_1=1.00000000e+001
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-10
CalSigValue_1=-10
CalMode_2=Defined Value
CalEngValue_2=10
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_8]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_8
Connector=HiLev_1.c13
SampleRate=1000
Description_1=Outside Air
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1.00000000e+001
FS_Max_1=1.00000000e+001
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-10
CalSigValue_1=-10
CalMode_2=Defined Value
CalEngValue_2=10
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_9]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_9
Connector=HiLev_1.c09
SampleRate=1000
Description_1=Inside Temperature
Type_1=Temperature
Units_1=Deg F
ChanDataType=784
FS_Min_1=2.30000000e+001
FS_Max_1=1.31000000e+002
CalDate=07/06/01
CalSlope=1.08000000e+001
CalIntercept=2.30000000e+001
CalExpSpan=2.30000000e+001
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=23
CalSigValue_1=0
CalMode_2=Defined Value
CalEngValue_2=131
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[ChanItem_10]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_10
Connector=HiLev_1.c10
SampleRate=1000
Description_1=Inside Humidity
Type_1=Humidity
Units_1=%RH
ChanDataType=784
FS_Min_1=0.00000000e+000
FS_Max_1=1.30000000e+002
CalDate=06/08/01
CalSlope=1.00000000e+001
CalIntercept=0.00000000e+000
CalExpSpan=1.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-10
CalSigValue_1=-10
CalMode_2=Defined Value
CalEngValue_2=10
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

D12
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=0
CalSigValue_1=0
CalMode_2=Defined Value
CalEngValue_2=100
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=1
ObjectID=0
TransducerID=0

[ChanItem_11]
Prefix=XDMS_HILEV
NumIDs=1
ID_1=CH_11
Connector=HiLev_1.c11
SampleRate=1000
Description_1=Inside Crack
Type_1=Voltage
Units_1=volts
ChanDataType=32
FS_Min_1=-1.00000000e+001
FS_Max_1=1.00000000e+001
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=-10
CalSigValue_1=-10
CalMode_2=Defined Value
CalEngValue_2=10
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0

[SoftItem_1]
Prefix=TRIG_INT
NumIDs=1
ID_1=Int_Trig
Description_1=
Type_1=Logical
Units_1=
ChanDataType=264
FS_Min_1=0
FS_MAX_1=0
InputChs=1
InputCh_1=CH_1
TrigIndex=1
TrigInvert=0
ObjectID=0

[SoftItem_2]
Prefix=TIMECHAN
NumIDs=1
ID_1=Elapsed_Time

ID_1=CH_12
Connector=HiLev_1.c12
SampleRate=1000
Description_1=Inside Null
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1.00000000e+001
FS_MAX_1=1.00000000e+001
CalDate=06/08/01
CalSlope=1.00000000e+000
CalIntercept=0.00000000e+000
CalExpSpan=0.00000000e+000
CalSteps=2
CalMode_1=Defined Value
CalEngValue_1=10
CalSigValue_1=10
CalMode_2=Defined Value
CalEngValue_2=10
CalSigValue_2=10
PrerunZeroMode=Undefined
PrerunZeroValue=
XdcrMode=0
ObjectID=0
TransducerID=0
Description_1=
Type_1=Time
Units_1=sec
ChanDataType=288
FS_Min_1=0
FS_Max_1=604800
InputChs=1
InputCh_1=CH_1
ObjectID=0

[SoftItem_3]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_L
Description_1=Longitudinal
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1
FS_Max_1=1
InputChs=1
InputCh_1=CH_1
TapCount=9
ObjectID=0

[SoftItem_4]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_V
Description_1=Vertical
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1
FS_Max_1=1
InputChs=1
InputCh_1=CH_2
TapCount=9
ObjectID=0

[SoftItem_5]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_T
Description_1=Transverse
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-1
FS_Max_1=1
InputChs=1
InputCh_1=CH_3
TapCount=9
ObjectID=0

[SoftItem_6]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_OT
Description_1=Outside Temperature
Type_1=Temperature
Units_1=Deg F
ChanDataType=784
FS_Min_1=23
FS_Max_1=131
InputChs=1
InputCh_1=CH_4
TapCount=9
ObjectID=0

[SoftItem_7]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_OH
Description_1=Outside Humidity
Type_1=Humidity
Units_1=%RH
ChanDataType=784
FS_Min_1=0
FS_Max_1=130
InputChs=1
InputCh_1=CH_5
TapCount=9
ObjectID=0

[SoftItem_8]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_OC
Description_1=Outside Crack
Type_1=Voltage
Units_1=volts
ChanDataType=32
FS_Min_1=-10
FS_Max_1=10
InputChs=1
InputCh_1=CH_6
TapCount=9
ObjectID=0

[SoftItem_9]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_ON
Description_1=Outside Null
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-10
FS_Max_1=10
InputChs=1
InputCh_1=CH_7
TapCount=9
ObjectID=0

[SoftItem_10]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_OA
Description_1=Outside Air
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-10
FS_Max_1=10
InputChs=1
InputCh_1=CH_8
TapCount=9
ObjectID=0

[SoftItem_11]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_IT
Description_1=Inside Temperature
Type_1=Temperature
Units_1=Deg F
ChanDataType=784
FS_Min_1=23
FS_Max_1=131
InputChs=1
InputCh_1=CH_9
TapCount=9
ObjectID=0

[SoftItem_12]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_IH
Description_1=Inside Humidity
Type_1=Humidity
Units_1=%RH
ChanDataType=784
FS_Min_1=0
FS_Max_1=130
InputChs=1
InputCh_1=CH_10
TapCount=9
ObjectID=0

[SoftItem_13]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_IC
Description_1=Inside Crack
Type_1=Voltage
Units_1=volts
ChanDataType=32
FS_Min_1=-10
FS_Max_1=10
InputChs=1
InputCh_1=CH_11
TapCount=9
ObjectID=0

[SoftItem_14]
Prefix=SMOOTH
NumIDs=1
ID_1=Avg_IN
Description_1=Inside Null
Type_1=Voltage
Units_1=volts
ChanDataType=784
FS_Min_1=-10
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D16
QUALIFICATION OF AUTONOMOUS CRACK MONITORING SYSTEMS

A Thesis

Submitted to the Graduate School In Partial Fulfillment of the Requirements

For the Degree

MASTER OF SCIENCE

Field of Civil Engineering

By

Brandon G. Hughes

EVANSTON, IL

June 2006
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Abstract

This thesis summarized the qualification and testing of two commercial Autonomous Crack Monitoring (ACM) systems for use in measuring micrometer displacement of cracks. Qualification involved the assessment of both laboratory and field performance in a residential structure subjected to nearby quarry blasting for the production of roadway aggregate. Aggregate and construction industries are dependant on procedures that cause vibratory ground motion and would benefit from a commercial ACM system. Currently, only research grade equipment is available for ACM monitoring which is expensive, unwieldy and requires specialized knowledge to operate.

Performance at three levels of monitoring has been evaluated. During level I monitoring only long term crack displacement response to environmental effects was recorded. During level II monitoring both long term and dynamic (triggered by ground motion) crack displacements are recorded. At the highest level of monitoring, level III, long term and dynamic crack displacements are recorded with dynamic response triggered by crack response and/or ground motion. Crack displacement triggering allows recording of crack responses to occupant activities or other non ground motion events such as wind gusts.

Qualification showed that each system was able to sufficiently operate at monitoring and collecting level I crack and environmental responses. Additionally, each system also showed continued progress towards adequate level II operation. Finally, one of the systems was evaluated as a level III system and captured both occupant and environmentally induced crack responses during qualification.
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Chapter 1

Introduction

This thesis describes the qualification and testing of two commercial Autonomous Crack Monitoring (ACM) systems for use in measuring micrometer displacement of cracks. Qualification involved the assessment of both laboratory and field performance. The commercial ACM systems were installed in a residential structure subjected to nearby quarry blasting for the production of roadway aggregate. Aggregate and construction industries are dependant on procedures that cause vibratory ground motion and would benefit from a commercial ACM system. Currently, only research grade equipment is available for ACM monitoring, which is expensive, unwieldy and requires specialized knowledge to operate. This research was sponsored by the Infrastructure Technology Institute (ITI) at Northwestern University through a grant from the United States Department of Transportation.

ACM equipment includes hardware such as geophones for monitoring ground motion, crack sensors for determining one dimensional crack response and data loggers for recording and transmitting the results. An ACM system also includes software for transforming the data into a useful format. As ACM technology has been developed, three levels of monitoring have been created to optimize system capability. Level I monitoring records only the long term crack response to environmental effects at low sampling rates to determine daily or weekly trends. At this level of performance blast effects manifest themselves by a change in the crack response at the time of the blast. Level II monitoring records both long
term crack displacement and high sample rate dynamic data during seismic events. Level II monitoring requires a geophone to monitor ground vibration and then trigger the system to measure crack displacement during an event. Level III monitoring records long term crack displacement and high sample rate data during events triggered by ground motion and/or crack response. Crack response can include that resulting from occupant’s activity or other non-seismic dynamic events such as wind gust induced response. Crack triggered response from these other dynamic events can then be compared to blast induced movements.

Previous work with ACM systems has included the development and installation of experimental systems in blasting and construction environments. Past work by (Louis, 2000; Siebert, 2001; McKenna 2002; Baillot 2004; Waldron 2006) have demonstrated the effectiveness of research grade ACM technology in monitoring crack displacement during level I and II operation. Previous work by (Petrina 2004; Ozer 2005; Waldron 2006) has further developed laboratory methods for the qualification of ACM sensors and equipment for various modes of monitoring. The thrust of this thesis, the commercialization of ACM systems, is another step in moving ACM technology from the laboratory to practice.

This thesis which describes the commercialization of two ACM systems is divided into seven Chapters. There is not a background Chapter included in this work since the information can be found in the many previous theses enumerated above. The first commercial ACM system, system X, was evaluated in Chapters 2 through 4. The second commercial ACM system, system Y, was evaluated in Chapters 5 through 7. Chapters 2 and 5, describe the equipment and installation procedures followed for systems X and Y, respectively. Additionally, the software and manuals included with each system are evaluated for ease of use. Chapters 3 and 6 describe the laboratory qualification of systems
X and Y, respectively. Laboratory qualification included evaluation of both long term and dynamic capabilities of the system. Long term qualification was completed by mounting the sensors on a homogeneous plate with a known linear thermal expansion coefficient. The recorded displacement of the sensor was then compared to the theoretical expansion of the plate. Chapters 4 and 7 describe the field qualification of systems X and Y, respectively. During field qualification, each system was installed in a residential structure to determine the system’s capability to measure crack response from blasting. System X was evaluated to monitor crack displacement during operation as a level I, II and III system. System Y was evaluated to monitor crack displacement during operation as a level I and II system. The final Chapter of this thesis, Chapter 8, summarizes the conclusions made for each system.
Chapter 2

Installation, Software and Literature of Crack Monitoring System X

In this chapter, the installation, software and literature of a commercial Autonomous Crack Monitoring (ACM) system X are summarized. Specifically software and manuals of system X, were reviewed to ascertain their ease of use by the average field technician. Additionally, electromagnetic noise interference was measured and methods for reducing and removing noise were evaluated.

Installation

This section describes the general installation method that was followed for installation in both the laboratory and field. The physical installation of system X including the crack sensor can be completed in one day. Figure 2.1 shows the wiring diagram for the two component system X crack monitor as it was installed in the test house. The first component measures ground motion and air blast and the other measures crack response. Each component consists of a processor (computer), data logger and sensors. Transducers for the first component measure ground motion, while those for the second, measure the crack response. The ground motion component triggers the crack sensor component when the system obtains both long-term and dynamic crack response (level II operation).
Geophone Monitor

Installation began by the placement of the geophones and related equipment in the basement of the test house. An out of the way location for the geophone was needed to minimize triggering by activity from the house’s residents. A storage area under the stairway was selected. Normally, the geophone would be installed by burying, anchoring, sandbagging or spiking in the ground outside. However, in this case since it was not employed to ensure regular compliance, it was installed in the basement. Other measurements of ground motion were available to establish compliance. The geophone can be anchored to a concrete surface, and in this case, a plaster coating on the bottom of the geophone block was used. Figure 2.2 shows the completed installation of the geophone. Plaster was advantageous because after the testing was completed, the remaining plaster can be scraped away without leaving any residue or mounting holes.
Once the geophone was mounted, the downstairs data logger was then placed on the floor under the stairway within 5 feet of the geophone. The geophone cable was then connected to geophone port on the side of the geophone data logger. The geophone data collector contained an internal battery that could be used for short term monitoring or an A/C adapter for long term deployment. Since system X was to be deployed in the test house for at least six months, the unit was powered by the A/C adapter. The internal battery remained useful as a backup power supply in case of a power outage or accidental unplugging of the unit. The trigger cable, attached to the auxiliary port on the geophone data logger, was routed to the auxiliary port on the crack monitor upstairs. A standard serial cable was then employed to connect the geophone data logger to an “Nport”, to allow remote communication and control via the internet. Figure 2.2 shows the installation of the geophone and geophone data logger.

Figure 2.2 Installation of the geophone (left) and the downstairs data logger (right).
Crack Monitor

The second step of installation was attachment of the crack sensors across the crack. Two LVDTs supplied with the system were mounted at the crack. The first LVDT was mounted directly across the crack to measure crack movement; and the second LVDT was mounted on a nearby uncracked section of the drywall to measure environmental effects of the sensor and uncracked wall materials. LVDTs were attached to the wall surface with a 90 second quick setting epoxy. The sensors were placed at least 30 centimeters apart to prevent interference between the sensors.

The system X literature recommended the use of hot glue to attach the crack sensor across the crack on the wall. Previous work by (Petrina, 2004) found that using a adhesive such as hot glue was found to be deformable, have nonlinear expansion, and have a high coefficient of expansion. The hot glue was replaced with the 90 second epoxy to reduce these effects. According to lab testing done by (Petrina, 2004) the 90 second epoxy was found to be both stable and quick setting.

LVDT displacement sensors were mounted across a crack in a drywall ceiling as shown in Figure 2.3. The coil housings of the LVDTs were first epoxied in place and then connected to the crack monitor. The monitor was turned on and the core was centered in the coil housing to allow maximum travel of the sensor during operation in both directions. The crack monitor was then placed in setup mode and a voltmeter was placed across the test points to determine the exact location of the core inside the attached coil housing. The core assembly was then joined by threading the shaft of the core into the core bracket. Jam nuts, were also used for subsequent adjustment of the core position. The core assembly was then fixed in position with the quick-set epoxy. As the epoxy was setting, slight adjustments were
made to move the core assembly within the coil to the manufacturer’s specified position. Adjustments were made by sliding the assembly in the setting epoxy based on the readout of the voltage meter. Finally, Loctite adhesive was applied to the jam nuts to prevent them from loosening over time. Figure 2.3 shows the completed LVDTs mounted across the crack and on the uncracked drywall.

![Image of LVDT installation](image)

**Figure 2.3** Installation of the system X crack and null lvdt’s on the crack. The core being epoxied (left), the final installation (middle) and a close-up of sensor showing the size relation to the crack.

The crack and null displacement sensors were connected to the crack monitor data logger and placed in a small closet. Another data logger similar to the one in Figure 2.2 was placed on the bottom shelf of the closet and the crack sensor cables were then routed through a small hole in the wall and connected. The crack monitor data logger, like the geophone data logger, can be powered by both an internal battery and A/C adapter, and like the geophone data logger, was powered by the A/C adapter. The auxiliary port on the crack monitor received the external trigger cable from the geophone data logger. As with the
geophone data logger, a standard serial cable was employed to connect with the Nport for internet communication.

**Sensors**

System X crack monitors employ LVDT sensors to measure micrometer opening and closing of the crack and geophones to measure the particle velocity of the ground motion. All LVDT displacement sensors were exercised in the laboratory both statically and dynamically to ensure that they operated properly and that their response compared to previously calibrated sensors. External SUPCO temperature and humidity sensors were used to monitor the environmental effects during selected testing. Future ACM systems should include integrated temperature and humidity sensors.

**Geophone Sensors**

Geophones measure ground motion in terms of particle velocity. Since there are longitudinal, transversal and vertical principal directions; three geophones are necessary. In this case all three components are housed in a single geophone block. During a dynamic event, a geophone records the time history of the ground motion for a preset duration. During normal monitoring, the geophone is programmed to monitor ground motion constantly. When the ground motion exceeds a user defined trigger value, the geophone data logger then records for a preset duration. In addition to recording the particle velocity-time history after triggering, the geophone data logger will also record a preset amount of time prior to triggering. This is called the pretrigger. A pretrigger of 0.5 seconds was set for all
measurements. The particle velocity trigger level was set to 1.02 mm/sec. The unit records ground motion at 1000 samples per second for the preset pre and post trigger record time. For blast monitoring, the recorded time length for an event is normally three seconds. Figure 2.4 compares the typical three components of the particle velocity during a time history. During this blast, the geophone was triggered on the vertical channel and the maximum peak particle velocity (PPV) was 4.75 mm/second.

![Graph of ground motion record by the system X geophone](image)

Figure 2.4 Typical ground motion record by the system X geophone. Blast occurred on May 27, 2005.
**Crack Sensors**

The opening and closing of a crack during a blast event are very small and often only a few micrometers of displacement will be recorded. System X was qualified with Transtek series 200 LVDTs to collect crack displacement. Thus, the crack displacement sensors must have a small range and a high resolution. The range of the Transtek sensor was approximately 2.5 times the benchmark Kaman sensor (McKenna, 2001). A direct comparison of the specifications of Transtek LVDT with the Kaman eddy current sensor is shown in Table 2.1 The Transtek sensors proved to be easy to install with little disturbance to the homeowner. According to Petrina, (2004) the displacement sensors were selected based on surface attachment, mechanical design and operational configuration. Qualification of the Transtek LVDTs dynamically and statically and a comparison with the Kaman sensors is presented in Chapter 3.

The crack sensor on system X, is monitored on both a AC and DC coupled channels. The null sensor is only monitored on a DC channel. AC coupled channels measure only dynamic response while DC coupled channels measure both long term and dynamic response. The AC coupled channel should be employed versus the DC coupled channel to define the dynamic response time histories because it is highly resolved. DC coupled channels follow the long term displacement response in reference to the initial value.
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<td>SMU-9000-2U</td>
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Table 2.1 Specifications comparison for the Transtek LVDT to the Kaman eddy current sensor.

**Noise Levels and Electromagnetic Interference (EMI)**

Electromagnetic Interference (EMI) can mask the signal from a sensor measuring crack displacement in an Autonomous Crack Monitoring (ACM) system. EMI induces voltage fluctuations, which are superimposed over the sensor output. ACM systems employ highly sensitive sensors that produce a voltage proportional to changes in displacement. Thus, small crack movements result in small voltage changes. Any introduction of EMI during these measurements results in significant voltage spikes and noise as shown in Figure 2.5. Crack displacement recorded during a transient event can be obscured by noise. EMI is emitted from most electronic devices and therefore measuring equipment should be designed to operate in a noisy environment. Most EMI occurs at the 60 Hz frequency, common for AC power in residential and commercial buildings.

Initial testing of system X in the test house was completed with the NU system operating at the same time. With the NU system operating, system X noise was 2.3µm peak
to peak. It was found during testing that the high noise levels were directly related to EMI production by the NU system. For this reason testing was completed on system X with and without the concurrent operation of the NU system. Table 2.2 shows the noise levels of the system with and without the operation of the NU system. System X was found to operate at an acceptable noise level of 0.8 µm peak to peak in a standard residential environment.

The most significant reduction of the noise levels of system X was attained when the NU System was deactivated. While the cause of noise in this testing environment was easy to pinpoint and eliminate, in some field environments this may not be possible. Figure 2.5 demonstrates the noise levels before and after the NU equipment was disabled.

<table>
<thead>
<tr>
<th>System X Historical Noise Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>1/20/2005</td>
</tr>
<tr>
<td>6/9/2005</td>
</tr>
<tr>
<td>6/30/2005</td>
</tr>
</tbody>
</table>

Table 2.2 Historic noise levels for system X during testing
Computer Interface and Software

In this section the computer interface and software supplied with system X are evaluated to determine adequacy and ease of use. After the long-term and dynamic data have been collected by an ACM system, it must be displayed properly to allow comparison. The primary function of the computer interface and software for the equipment is to allow the operator to organize, sort, store, remove and process the data. A well designed ACM system should include quality software, which would aid in automating typical data processing tasks and reduce the amount of time spent working with data by the operator. Poorly designed or
insufficient software would cause the operator of a system to spend a large amount of time and expense processing the data before it could be used as intended.

**System X Programming & Connection**

System X can be programmed both on-site and remotely. A serial connection is used by system X to send and receive data from the unit. On-site, the unit can be programmed with the external key pad and LCD screen located on the crack monitor by cycling through the system menus and changing setting points such as monitoring modes, trigger levels and text notes. In Figure 2.6 the external key pad on the crack monitor is shown. The system can also be programmed on-site with a computer connected to the serial port. Using a serial port to program the unit may require a USB to serial converter, since most laptop computers do not have a native serial port. Programming is accomplished through the Microsoft program HyperTerminal, which is standard with most windows operating systems. There are two methods for programming the system with a computer. The first method, called TTY, simulates the LCD screen on the crack monitor. The computer keyboard is used to program the unit. The second method for programming the unit from a computer is called “gets and sets.” A get command followed by a parameter code will return the current value stored in that field. A set command followed by a parameter code and value will store the new value in that field. A get command should always follow a set command to confirm that a setting change has been made.
Remote communication with system X can be accomplished with a modem or over the internet. To connect to the system over a modem, both the crack and geophone unit require a serial to telephone conversion cable, external modem and an active phone line. Once the system has been connected to a modem any computer with a modem can dial into the system. For security, both the crack and geophone units require a password before setting changes or data removal can take place. During field testing, data was retrieved from the unit over the internet connection. The serial cable from the unit was connected to an Nport (Moxa), to allow access over the internet. The Nport creates a virtual serial port for the unit over the internet. The virtual serial port can be accessed using HyperTerminal on a remote computer. Once connected to the unit by modem or over the internet the TTY or get and set method can be used to program the unit.
HyperTerminal can also start, stop and retrieve data from system X. HyperTerminal allows an operator to collect data from the unit remotely and limit costly site visits. Additionally, the remote download process can also be automated to further reduce the operating cost, limit human interaction and enable downloads when events are least likely to occur. During field testing, data were downloaded in the middle of the night when blast events and occupant activity were least likely to occur.

Programming system X, with the keypad or TTY mode was found to be the simplest and is the recommended method for programming because it does not require a list of parameter codes, as does the “get and set” method. One advantage of the “get and set” method of programming is that it allows the user to change and review settings quickly. The manufacturer of system X recommends only using TTY mode when on-site. If an interruption in communication occurs during programming in the TTY mode, the unit can become “lost” or lock up, and require a manual restart. For this reason, when simple setting changes are programmed remotely, the user should employ the “get and set” method. During the six months of evaluation of system X, a “lost” or locked up unit was only encountered once during heavy remote operation using the TTY mode.

Layout and display of the command settings in the TTY mode allowed for easy access to the different settings. Figure 2.7 shows the complete layout of the command windows an operator would see during programming in the TTY mode. Most commonly used sections of the TTY windows shown in Figure 2.7 are sections A and B. Section A shows the windows used to set the monitoring mode, record lengths and trigger levels. A detailed description of the menus found in section A is presented in Figure 2.8. The window shown in Section B is where an operator can change the text displayed on each event. Text
notes included information such as equipment ID, client name, operator and location.

Sections of the TTY layout used less frequently include sections C, D, E and F. Section C shows the menu used to set the timer and to turn the unit on and off. Utilities such as displaying the time and date in the unit and to clear the memory are located in section D. Utilities for communication and alarms are shown in section E. Section F includes commands for selecting recording templates and shutting the unit off.
Figure 2.7 System TTY mode layout for programming.
The **Recording mode** selection is used to pick how the unit will record.
- **Dual**: Records both dynamic and long-term data.
- **Trigger**: Records dynamic data when triggered.
- **Histogram**: Used to record peak particle velocities over long periods of time.

**Trigger Setup**: This selection is not used to trigger recording.

**Trigger Setup**: This selection is used to set crack trigger.
The crack trigger will allow the unit to record data when the crack sensor exceeds output trigger value for four consecutive data points.

**Trigger Setup**: This selection is used to set the time length of the dynamic event.
- This can be set between 1 and 15 seconds.

**Hist Interval**: Selects the method of long-term collection.
- **Short**: Records in seconds.
- **Long**: Records in minutes.

**Hist Interval**: The duration between the recording of histogram data.
- When **Hist Interval** is set to **Short**, the **Hist Interval** can be set to record every 1, 2, 5, 10, 15, or 30 seconds.
- When **Hist Interval** is set to **Long**, the **Hist Interval** can be set to record every 1, 2, 5, 10, 15, or 30 minutes.

---

**Figure 2.8 Detailed description of the trigger settings for system X.**
Data Analysis Software

Once the monitoring has been completed, or during regular intervals data collected by system X can be removed and processed. Two software packages are employed to analyze the data collected during monitoring. The first software package is called “Event Manager” and is used to view the file summaries and export dynamic data files. Figure 2.9 is a typical screenshot from the Event Manager software main menu, that allows review of the file summary which includes date, time and peak recorded values.

![Event Manager Software Interface](image)

Figure 2.9 System X, Event Manager Software interface

The second software package for analyzing and processing the data is called “Seismic Analysis.” The original intended use of the Seismic Analysis software package was for processing and viewing ground motion time histories. This software package
enables the user to view and print the time histories of both ground motion and crack motion captured by the geophone and crack sensor, respectively. The software was also capable of creating event reports, which described the key points of an event and frequency content analysis. Figure 2.10 shows a typical screenshot from the Seismic Analysis software when creating a crack time history. When reviewing a crack or ground motion time history, any areas of interest can be isolated and enlarged for further review. An ACM specific software application or adaptation of the Seismic Analysis software is currently unavailable.

Figure 2.10 Seismic Analysis Software screenshot when creating a crack time history
Literature and Manuals

The literature and manuals supplied with an ACM system should include thorough documentation to allow a new user to install and operate the system independently. Without the proper manuals, setup and operation of an ACM system would be very difficult. System X was supplied with three core documents. These documents included an operator’s manual for the Seismic Analysis software, 3000 series seismographs and a beta version of the crack monitor installation guide. Additionally, system X was supplied with a quick start card, located in the case of the crack monitor, for on-site programming.

Study of the manual entitled “Basic Compliance Software” was necessary to learn more about the Seismic Analysis software package prior to its use. Files removed from both the crack and ground motion monitor could be processed and viewed with this software. The first section of the manual details the requirements to operate Seismic Analysis, the layout and keys used in the software package. The second section of the manual describes how to handle files. Both dynamic or triggered and static or histogram events are reviewed. Methods for plotting the events and creating reports are shown.

The manual entitled “Safeguard Seismic Unit” was used to learn about the operation and programming of the series 3000 seismograph. This manual describes the methods for installing a seismograph and step by step key-pad programming. Key-pad programming was reviewed in the Computer Interface and Programming section. The manual also reviews typical system capacities, operation durations & limitations and capacities.

ACM specific literature supplied with system X, included the quick start card and the manual entitled “Additional Resources for Portable Crack Response Monitor.” This
manual reviews installation methods and programming steps for ACM system. The first section of the manual included recommended installation methods for the crack sensors and geophone. This includes detailed instruction for attaching and centering the LVDTs. The second section of the manual described the methods for programming the unit. The quick start card, located in the crack monitor case top, included a brief review of the setup information included in the manual. The card also included instructions for setting the triggers. This included triggering off both the crack and seismograph.
Chapter 3

Laboratory Qualification of Crack Monitoring System X

This chapter presents the qualification evaluation of system X. System X was first operated in the laboratory to ensure proper operation and then in the field to evaluate the system’s ability to collect valid data under real field conditions. Laboratory operation was undertaken to verify that the displacement of the crack monitoring system operated within the acceptable standards established with the benchmark sensors. Performance was evaluated for both static and dynamic response.

Long Term or Static Response

Long term response was evaluated to verify the proper operation of the sensors when used in a field environment. Previous work by (Petrina 2004) had been completed to determine that the system X sensors operate correctly in terms of sampling rate, linearity, noise and resolution. Prior to the evaluation of system X as a complete crack monitoring system, the sensors were tested statically. To verifying the linearity of the sensor output, they were first calibrated. Calibration was needed to determine the conversion equations used to change the sensor voltage output into displacement. Calibration results can then be used to verify that the existing equations are correct and within acceptable tolerances.

Qualification of a sensor to measure micrometer crack opening and closing due to long term environmental influences should be completed in a similar manner in which the
sensor is expected to perform in the field. In order to determine if the sensor will respond linearly during cyclic use, the sensors were tested under cyclic loading when attached to a plate of known thermal properties. The sensors were attached to a plastic plate and then exposed to varying temperatures to allow the plate and the sensor to expand and contract. The expansion and contraction of the plate allowed the sensor to record changes in displacement of the sensor core to the housing. During testing the sensors were attached to a plastic plate made of Ultra-High Molecular Weight Polyethylene (UHMW-P). This material was used previously by (Petrina 2004) and provides a large thermal response that approximates a cracked wall’s thermal behavior. The coefficient of thermal expansion (CTE), $\alpha$ for UHMW-P is $\alpha=198.0 \, \mu m/\text{m}/\text{oC}$. The CTE for the sensors made of steel is $\alpha=13.0 \, \mu m/\text{m}/\text{oC}$ and approximately 15 times smaller than UHMW-P plastic. During this study since the CTE or steel is an order of magnitude lower then that of the UHMW-P, the expansion of the sensor was ignored. Since the expansion and contraction of the actual sensor components were ignored, the accuracy attained in this calibration is limited by this effect.

**Calibration**

Prior to long term testing, each sensor was calibrated to determine its voltage to displacement relationship. The relationship between voltage and displacement for the tested Transtek LVDT is a linear relationship. The system X crack monitor has an internal setup file that can be factory adjusted for the calibration of the sensors. A Kaman metric calibration fixture, with a sensitivity of 0.01 millimeters was used to calibrate the sensors. Figure 3.1 shows the Kaman calibration fixture used to determine displacement and a voltmeter for displaying the corresponding sensor voltage output.
Before calibrating a sensor, the manufacturer specifications should be reviewed to determine the expected working range. In the case of the Transtek LVDT, the voltage output range was found in the sensor coil and core literature to be ±1.5 volts. Next the LVDTs, were mounted in the calibration fixture and locked it into place. A voltmeter was then attached to the test points of the system X data logger to determine the LVDT voltage output during testing. The displacement of the core is then increased incrementally with the calibration fixture and the corresponding voltage is recorded. During calibration, the displacement was increased at 0.05 mm per each reading. The calibration process was completed three times to insure repeatability.

Once the calibration process was completed three times for each sensor, the data collected were entered into a computer and plotted to determine a best fit line for the data. Figure 3.2 shows the plotted voltage versus displacement data collected during calibration. It can be seen in Figure 3.2 that both LVDTs tested have a linear fit, as would be expected.
Sensor calibration showed that the LVDTs had a displacement range of approximately 3mm, which corresponds to the working voltage range of ±1.5 volts.

Statistical analysis can be completed on the data collected during sensor calibration to gauge the consistency of the sensors during repeated use. Additionally, an equation or slope can be found to convert the voltage output to displacement. Table 3.1 shows a summary of the data and statistics found during the calibration process. The first LVDT tested, called the null gauge, was found to have an average slope of 0.985 V/mm. The crack gauge or second LVDT tested, showed similar results to the null gauge. The average slope found for the crack gauge was 0.991 V/mm. During the three rounds of testing the standard deviation for the null and crack LVDTs was minimal and found to be 0.0006 and .0052 respectively. Furthermore, the R² values recorded for the linear best fit line for each sensor were very close to a unity value. The worst R² case found during evaluation was 0.999957.

![Figure 3.2 Voltage vs. displacement for calibration of the Transtek LVDTs](image-url)
Table 3.1 Calibration test summary data, equation slope, average slope, R² and standard deviation.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Null Slope</th>
<th>Null R²</th>
<th>Crack Slope</th>
<th>Crack R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9853451</td>
<td>0.999972</td>
<td>0.99424109</td>
<td>0.999957</td>
</tr>
<tr>
<td>2</td>
<td>0.9842311</td>
<td>0.999975</td>
<td>0.99425171</td>
<td>0.999960</td>
</tr>
<tr>
<td>3</td>
<td>0.9852917</td>
<td>0.999976</td>
<td>0.98529173</td>
<td>0.999976</td>
</tr>
<tr>
<td>Average</td>
<td>0.9849560</td>
<td></td>
<td>0.99126151</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.0006284</td>
<td></td>
<td>0.00516998</td>
<td></td>
</tr>
</tbody>
</table>

**Long Term or Static Testing Equipment Setup**

Once the sensors have been calibrated to ensure that system X has a proper conversion factor from output voltage to displacement, the sensor can be subjected to typical environmentally induced wall displacements and temperatures to determine the hysteresis loops and drift (Patrina 2004, Baillot 2004). The LVDTs were mounted on a flat piece of UHMW-P, approximately 400 mm square. During the mounting process, the relatively smooth surface of the UHMW-P was roughened with sandpaper to allow a proper bond between the epoxy and the UHMW-P. Each sensor was mounted at least 30 cm apart from another LVDT to limit sensor to sensor interference. Evaluation of system X was completed outdoors to take advantage of the natural temperature swings similar to those found during field operation. To prevent any possibility of water damage and direct contact with the sun, all equipment was placed in a weather resistant enclosure. Figure 3.3 shows the equipment setup used during the static testing.

System X does not have the ability to measure temperature changes along with crack displacement. Temperature and humidity were monitored with a SUPCO data logger, which
was set to record the temperature once per minute. The humidity readings recorded during
testing were ignored because UHMW-P does not respond to changes in humidity as do
construction material such as wood or drywall.

Figure 3.3 Static response qualification equipment layout.

To measure long term response of system X LVDTs, a simple procedure was
followed. First, the system was assembled as described previously. The internal clocks in
both the system X data logger and the SUPCO temperature data logger were synched to the
local computer clock. The sampling rate for system X and the SUPCO temperature data
logger were set to record the sensor displacement once per minute. Early testing of both
system X and the SUPCO logger were helpful in determining a reasonable sampling rate for
operation during testing. Early tests showed that system X and the SUPCO logger were able
to return a value with four significant Figures. Because of the limited ability to record data at
a higher precision, collecting data at higher sample rates would not be meaningful and only increase file sizes and reduce the length of time at which the equipment could record. Once both data loggers were programmed, they were then activated to start the data collection process. The weather resistant enclosure was then sealed and the entire unit was allowed to operate outdoors for approximately three to four days. During this period of evaluation, the UHMW-P plate with the attached sensors endured daily temperature swings from 17°C to 33°C.

**Long Term or Static Response Results**

At the completion of the testing period, the recorded data were removed from the individual data loggers to be processed and merged into one time history. Prior to merging the data collected, individual time histories can be plotted for each displacement sensor and temperature with respect to time; this can be seen in Figure 3.4. From the time histories shown in Figure 3.4 it can be seen that peak temperatures recorded correspond to peak in sensor displacement. It is expected that during peak temperatures, the UHMW-P plate would expand and cause larger LVDT displacements. During the static testing, as expected, the highest temperatures occurred during the early afternoon and the lowest during the early morning.
To determine graphically the effect of temperature on the cyclic expansion and contraction of the system X sensors, the collected data needed to be merged as shown in Figure 3.5. Figure 3.5 illustrates the relationship between temperature and displacement. Additionally, the theoretical expansion of the plate can be plotted along with experimental results to validate the process. The calculated displacement can be found based on the materials CTE and the initial gap measurement between LVDT housing and core bracket. The measured sensor displacement that was collected during the static evaluation of system X, was found to be in good agreement with both the theoretical calculations and temperature data collected during testing. Additionally, the hysteresis loops created by the sensors during testing were small and within the limits of previously tested sensors (Petrina 2004 & Balliot 2004).
Figure 3.5 Measured and calculated displacement vs. temperature for sensor 1 and 2.

**Short Term or Dynamic Response**

This section describes the dynamic qualification of system X to verify the system’s ability to capture dynamic activity in the lab prior to its placement in a field environment. Previous work in dynamic testing by (Ozer 2005) had been completed on other types of sensors. Testing methods by (Ozer 2005) were used as a foundation for further development of an apparatus for validating ACM sensors dynamically. Validation of system X was assessed in two categories; frequency and amplitude.

During a dynamic event, the displacement sensor must record a transient waveform. Because this event will only occur in limited numbers or only once during the monitoring period it is important for an ACM system to sample the waveform at an adequate sampling rate. The structural response frequency of most buildings measured in the field is normally
in the range of 10 to 15 Hz. (Dowding 1996). This frequency range required the ACM system to sample at 1000 Hz to define the dynamic response of the crack. During dynamic testing, the testing apparatus was vibrated at frequencies up to 100 Hz, this allowed at least ten data points per excitation cycle. In addition to the ability to capture events with high frequencies, ACM systems must be able to capture events with small amplitudes. Field testing has shown that interior cracks in residential structures can respond with displacements between 2 to 5 \( \mu m \) zero to peak during a dynamic event. During the dynamic testing of system X, the sensors were driven at amplitudes ranging from approximately 2 to 15 \( \mu m \) zero to peak.

**Dynamic Testing Equipment Setup**

Ozer, (2005) verified the potentiometer as an ACM displacement sensor by measuring the response of two aluminum blocks stacked upon each other to a drop weight. The blocks were separated by a thin rubber sheet which modeled an interior crack. The control Kaman sensor was then mounted on one side of the blocks and the sensor to be tested on the other. A small weight could then be dropped at varying heights on the upper block. Varying the height of the drop varied the amplitude of the crack movement. The resulting movement of the upper aluminum block with respect to the lower block was then record by both systems and compared.

As shown in Figure 3.6, the system was modified in order to accommodate larger sensors and increase the controllability of excitation frequency and amplitude. The initial testing device was adapted to include larger aluminum blocks and a small electric motor with an eccentric weight. The addition of the electric motor allowed for the frequency of the upper block to vary with the angular velocity of the motor. The amplitude was varied with
an eccentric weight attached to the electric motor. During dynamic testing, small amounts of putty were attached to a cardboard wheel which served as an eccentric weight. Excitation was completed in seven intervals, reducing the eccentric weight from approximately 0.60 to 0.20 grams.

Dynamic response of system X was compared to that of the Kaman eddy current displacement sensor and the Edaq mobile field computer and data logger as described in Ozer (2005). The Kaman eddy current sensor has been used for experimental crack monitoring projects for years and are accepted to be the most reliable and sensitive sensors available.

Considerations taken during dynamic testing included limiting electromagnetic noise, preventing movement of the lower block and ensuring the proper adjustment of the sensors/upper block combination before each test. Any excess equipment in the laboratory that may induce electromagnetic noise during testing was turned off or moved away from the devices. To limit the movement of the lower block during dynamic excitation, it was attached to the edge of the more massive lab table. During test runs 3 through 7, the electric motor was run prior to the test to ensure the aluminum blocks were adequately seated upon each other and any slack in the system was removed. During test runs 1 and 2 this pre-running of the electric motor prior to testing was not completed which resulted in a baseline offset in the recorded waveforms.

Dynamic testing of system X was accomplished by following a simplified procedure. First, the aluminum blocks were assembled with a small foam spacer between them. Guide plates were then installed on the lower block to limit horizontal translation of the upper block. A front and right view of the modified testing apparatus can be seen in Figure 3.6.
The sensor to be tested and the control Kaman sensor were each attached to opposite sides of the block assembly. Both systems were set to record dynamic data for a three second time period. The electric motor was activated by a 1.5 volt source to vibrate the upper block. The corresponding dynamic crack movement was then recorded by each system. The first attempt at dynamic testing was done with the largest eccentric weight. Sequential tests were run after the removal of small amounts of the eccentric weight until a crack amplitude of 2 \( \mu \text{m} \) was reached.

During testing, differences in the dynamic response of the control sensor and test sensor were found. Differences in the sensor responses such as non-uniform displacements and phase shifts could be attributed to limitations in the testing equipment, including equipment alignment, connection and size effects. Uniform displacement of the upper block with respect to the lower block was anticipated. However, lack of horizontal support or difficulty in the alignment of the eccentric motor to the center of gravity of the upper block...
was encountered. This eccentricity caused a small rocking motion of the upper block and non-uniform displacements at the face of the upper block. Any slight deviations in the alignment affected the magnitudes of the displacements measured by the sensors. This misalignment of the eccentric motor was found to cause a phase shift in the waveform. When the eccentric weight oscillates, it functions as a vibrator and creates a net upward and downward force. This changing force causes the upper block to move relative to the lower block and simulates crack movement. However, the eccentric movement of the eccentric weight produced a rocking motion which produced a 180° phase shift between the two transducers, as shown in Figure 3.7.

![Figure 3.7 Description of how a phase shift was created in the waveforms, during dynamic testing.](image)

In addition to equipment alignment, sensor size and type of connection could affect the amplitude of the recorded waveform. The Kaman control sensor is advantageous for crack monitoring because it does not require a cross crack connection between the sensor tip
and target. However, because Kaman sensors have limited durability, it is recommended for only research use. The inertia of the wall is orders of magnitude greater than that of the sensors, so that the sensor differences are irrelevant across a crack. The connection of the LVDT core to the core housing can dampen the response of the system when out-of-plane movement occurs. During dynamic testing, because of the slight rocking motion that occurs from the eccentric weight, the LVDT core can bind in the core house, creating frictional losses. Any binding that would occur during testing should reduce the amplitude of the waveform recorded by system X.

**Dynamic Qualification Results – Amplitude Comparison**

Dynamic responses of the LVDT from system X, were compared to that of the control system in terms of both frequency and amplitude. Figure 3.8 shows a typical waveform captured by both the control system and system X. This Figure shows both the DC coupled channel 3 used for waveforms with baseline shifts and the AC coupled channel 4 used for waveforms without baseline shifts. Table 3.2 summarizes a comparison of the maximum amplitudes collected during the dynamic tests completed on system X. During dynamic tests, when a baseline shift did not occur, the amplitude of the AC coupled channel was used to compare to the control waveform.
Figure 3.8 Typical waveform recording during the dynamic testing of system X.

<table>
<thead>
<tr>
<th>Event #</th>
<th>Eccentric Weight (g)</th>
<th>System X Trigger Level (µm)</th>
<th>Kaman Max Amp. (µm)</th>
<th>CH.3 Max Amp. (µm)</th>
<th>CH.4 Max Amp. (µm)</th>
<th>Amp. Ratio CH3/Kaman (Floating Center)</th>
<th>Amp. Ratio CH4/Kaman (Zero Centered)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.60</td>
<td>3.175</td>
<td>4.2</td>
<td>14</td>
<td>11.5</td>
<td>3.3</td>
<td>2.7</td>
<td>Offset</td>
</tr>
<tr>
<td>2</td>
<td>0.46</td>
<td>3.175</td>
<td>2.5</td>
<td>8.7</td>
<td>8</td>
<td>3.5</td>
<td>3.2</td>
<td>Offset</td>
</tr>
<tr>
<td>3</td>
<td>0.46</td>
<td>3.175</td>
<td>2.7</td>
<td>9</td>
<td>8.4</td>
<td>3.3</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.39</td>
<td>1.905</td>
<td>2</td>
<td>5.5</td>
<td>4.8</td>
<td>2.8</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>1.905</td>
<td>1.4</td>
<td>4</td>
<td>3.7</td>
<td>2.9</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.21</td>
<td>0.635</td>
<td>0.6</td>
<td>2</td>
<td>1.3</td>
<td>1.1</td>
<td>2.2</td>
<td>Late Trigger</td>
</tr>
<tr>
<td>7</td>
<td>0.29</td>
<td>0.635</td>
<td>1.1</td>
<td>2.8</td>
<td>2.5</td>
<td>2.5</td>
<td>2.3</td>
<td></td>
</tr>
</tbody>
</table>

|                      | Standard Deviation All Data | 0.4 | 0.4 |
|                      | Average Ratio During an Offset Event | 3.0 |
|                      | Average Ratio During Non-Offset Event | 2.9 |

Table 3.2 Summary of the dynamic tests completed for system X.
An average ratio of the maximum amplitude of the system X to the control was 2.9 with a standard deviation of 0.4. During dynamic excitation when a baseline shift did occur, the amplitude of the DC coupled channel was compared to the control waveform. Testing determined that the average ratio of the maximum amplitude of system X to the control was 3.0, with a standard deviation of 0.4. Testing showed that on average, the system X LVDT recorded three times more crack displacement than the control sensor. The ratio of the maximum crack displacement was found to be relatively constant throughout a wide range of amplitudes tested. The large difference in crack movement collected by system X was compared to the control and attributed to the testing apparatus and not the sensor. The larger crack responses are most likely due to the location of the eccentric weight, in comparison to the center of gravity of the blocks. Field testing in Chapter 4 shows that across the same crack the two systems responded similarly. This observation has also been made by (Mckenna, 2002)

**Dynamic Qualification Results – Frequency Comparison**

Measured response frequency of system X was compared to the Kaman standard. During testing, the apparatus was operated at a frequency of approximately 100 Hz, this is well above the 10 – 50 Hz range that the equipment will be exposed to in the field. Equipment that can capture waveforms accurately at a high frequency can readily capture waveforms at lower frequencies. Thus lower frequency excitation was not necessary to capture the same frequency as the Kaman standard as shown in Figure 3.9. During the start-up of the eccentric weight, the frequencies that were encountered by the sensors were lower
than during constant operation. During both start-up and at a constant angular velocity, the frequency of system X was comparable to the control system.

Figure 3.9 Frequency comparison of system X to the control system.
Dynamic Qualification Results – Offsets

Baseline shifts or temporary offsets of a crack during a dynamic event occur from time to time. Use of the AC coupled response of system X eliminates this temporary response as shown in Figure 3.10. The waveform of the DC coupled channel on system X was able to capture the same crack offsets reported by the Kaman sensor. Data presented in Chapter 4, shows that the LVDT has tendency for temporary baseline shifts, whereas the Kaman has less of a tendency. As described in Patrina, (2004) and McKanna, (2002), the LVDT shifts may be due to misalignment between the core and coil.

Figure 3.10 Typical waveform time history of the control system and system X during a baseline shift.
Chapter 4

Field Testing of Crack Monitoring System X

This chapter describes the field testing of Autonomous Crack Monitoring (ACM) system X. Field performance of the system was evaluated in three modes of monitoring operation or levels of trigger operation; 1) every hour to measure long term crack movement; 2) upon exceeding a preset intensity of ground motion; and 3) upon exceeding a preset change in crack width. System X’s field installation was across a crack in a house located near an active limestone quarry. All procedures were reviewed to ensure that the system was easy to use by the average field technician.

Field Trial Blast Vibrations

System X was evaluated in a real blasting environment. The system was installed in a house near an active limestone quarry where blasting occurred approximately once per week during the blasting season. During testing, system X was operated as a level I, II and III system. A level I system records only long term crack response, which can be compared to long term changes in temperature and humidity. A level II system records both long term and dynamic crack response during blasting. A level II system directly measures the magnitude of the crack movement during blasting. A level III system records long term data, as well as dynamic response during blasting and dynamic data produce by other forms of
excitation. A level III system records all forms of crack excitations including blasting, occupant and weather (wind) induced.

**Level I Operation**

System X was first evaluated for level I operation by Petrina (2004). According to Petrina, the system was found to be adequate for long-term data collection. Level I systems record peak micrometer changes in crack width at selected time intervals. System X has 13 different time intervals to choose from when programming. Different time intervals allow data to be collected from every second to every hour, depending upon the need. Long term patterns of crack response to environmental effects can be compared to determine if dynamic excitation has caused permanent changes. Level I system operation does not include measurement of dynamic crack response. During level I operation and testing the system was verified and compared to the results collected by Petrina, (2004).

**Level I Equipment Setup**

In order to continue the evaluation of system X as a level I system, the unit was installed in the Milwaukee test house to monitor long-term crack movement. The Northwestern University (NU) system was used to monitor the same crack concurrently with system X to directly compare response. System X was setup to record level I as described in Chapter 3. The histogram function on the unit was set to record the peak crack displacement every 15 minutes.
Level I Data Collection

Level I data were collected from January to July of 2005, which allowed the units functionality to be evaluated during the extreme changes in temperature and humidity observable during both heating and cooling seasons. During the winter months low temperature and humidity were observed. During the spring and summer months the system was operated at higher temperatures with varying levels of humidity. Varying levels humidity could be expected when windows are opened in the spring.

During monitoring the inside temperature and humidity were maintained within a cyclically small range, which is normal for homes with a furnace and air conditioner. Both the indoor and outdoor temperature and humidity were recorded for comparison. Figure 4.1 shows the indoor and outdoor temperature and humidity readings collected during the monitoring period between January 1, 2005 and March 12, 2005. The grey lines in Figure 4.1 depict the raw data that was collected every 15 minutes. The black line shown in Figure 4.1 is a 24 hour average of the data. The data collected every 15 minutes illustrates the large daily variations in temperature and humidity that were encountered.
Figure 4.1 Environmental data from a three-month monitoring period. Gray jagged lines are a one-hour rolling average while the black lines are 24-hour rolling average.
The 24-hour average removes the extreme hourly fluctuations and produces a long-term representation of the weather trends. The patterns in humidity and temperature are similar for both outdoor and indoor results. From the temperature plots it can be shown that the indoor and outdoor temperatures are much more comparable than those for humidity. On average the home was maintained at a temperature of 20°C and a relative humidity of 30%.

To compare with data collected from system X, data were also obtained from the NU LVDT. Figure 4.2 compares the crack displacements recorded by the NU LVDT and system X LVDT to the indoor temperature during monitoring. Any thermal expansion effects experienced by the ceiling crack would be expected to be heavily influenced by the change in indoor temperature. In Figure 4.2 peak displacements in the NU LVDT and system X LVDT occur at approximately the same times. Maximum peaks in displacement also occur at the same time at minimum indoor temperatures. When comparing the 15 minute data it can be shown that the magnitude of the system X peaks and valleys were only slightly smaller than those of the NU LVDT. The shape of the 15 minute graph shown in grey for system X LVDT does not appear as sharp, in comparison to the NU LVDT. The peaks in the 24 hour averaged data tend to be similar in magnitude for both LVDTs. The following example comparison of 24 hour averaged crack response can be made. On 2/19/05 a minimum value of 35µm and 20µm were recorded on the NU and System X LVDTs, respectively. On 2/20/05 a maximum value 58µm and 43µm were recorded on the NU and System X LVDTs, respectively. Net change in crack width on both systems was similarly found as approximately 23µm. Similar trends and magnitudes in data of system X compared to the NU LVDT indicate comparable responses.
Figure 4.2 Comparison of the displacement time histories for the NU LVDT, System X LVDT crack gauge and indoor temperature. Gray jagged lines are a 1 hour rolling average; and the black lines are a 24-hour rolling average. (red dots indicate points used to calculate the long term static ratio.)

During operation, an ACM system must be able to maintain a constant ratio or long term to dynamic movement. A constant ratio is needed to directly compare dynamic crack excitation to long term crack movement to determine the significance of dynamic events. During level I or long term data collection, the ratio of the NU LVDT to the system X sensor
was found. The peak data points collected, denoted with (red dots), in Figure 4.2 are presented in Table 4.1 and graphically in Figure 4.3. The NU LVDT has been used previously in ACM applications and has been tested for compliance therefore used as baseline for comparison. The NU LVDT to system X ratio was found to be 1.32 during long term operation.

![Graph showing Y=1.32X with R = 0.975](image)

### Table 4.1 System X and NU LVDT

<table>
<thead>
<tr>
<th>NU LVDT ΔDisplacement (μm)</th>
<th>System X ΔDisplacement (μm)</th>
<th>Ratio NU/X</th>
</tr>
</thead>
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<td><strong>Slope linear best line</strong></td>
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</tr>
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</table>

To determine if the thermal expansion of the ceiling material or the crack was causing the recorded results on system X, the null gauge must be compared to the crack gauge. Figure 4.4 is a comparison of the displacements recorded by the crack and null gauge in the same environment. The System X null gauge was mounted on an uncracked section of
ceiling. As expected the null gauge showed little to no response during testing. Any small
spikes in data could be attributed to electronic noise. The displacement of the intact portion
of the ceiling was found to be a fraction of the displacements of the crack and insignificant.
Since the readings of the null gauge were so low, it was confirmed that the crack sensor was
measuring the displacement of the crack, not the displacement of the ceiling material or
temperature response of the sensor.

![Graph showing comparison of Crack and Null Displacement](image_url)

Figure 4.4 Comparison of the System X Crack and Null gauges over two-month duration of
testing

For materials that are considered non-homogeneous and nonlinear, such as sheetrock
nailed to wood, the crack behavior was expected to be influenced by many factors. Figure
4.5 compares the indoor temperature to crack displacement for system X data collected from
Patrina, (2004) and this study. Also shown in Figure 4.5 is a straight line representing the
theoretical displacement for the thermal expansion for an uncracked portion of gypsum drywall.  (Gypsum drywall CTE, United States Gypsum USG) Data from this study and Patrina, (2004) had similar relative crack movement with respect to temperature. Historical data such as Figure 4.5 shows that the crack movement is cyclical and occurs in a constant displacement zone over the two year period. The relative crack movements of both data sets were also found to be greater than theoretical thermal expansion. This difference is no doubt heavily influenced by the effect of humidity on the wood wall frame.

Figure 4.5 Temperature versus crack displacement data compared to the theoretical thermal expansion of gypsum, the main component of drywall.

Level II Operation

Level II systems normally are triggered by ground motions, which in turn initiate the recording of the crack response. Crack responses are measured as micrometer changes in
crack width at high sampling rates (normally 1000 Hz). Long term crack width is also recorded at regular time intervals ranging from every 15 minutes to once an hour for comparison with the long term environmental and dynamic effects. Collection of the long term data is also accomplished with the operation of a Level I system.

Level II evaluation was conducted in a quarry blasting environment in Milwaukee, WI by comparing system X response with that of the NU system. During simultaneous operation of system X and the NU system, it was found that the NU system introduced higher noise levels to system X. As a result system X was operated both with the NU system and independently. Data collected during the operation of system X was only compared to the historical data collected from the NU system.

**Level II Equipment Setup**

To evaluate operation of system X at level II, it was installed to record data as described in Chapter 3. Level I operation was also enabled by setting the histogram function to record the peak crack displacement every 15 minutes. The geophone data logger was set to record ground motion and trigger the crack monitor data logger when ground motion exceeded 1.02 mm/sec (0.04 in/sec).

**Level II Data Collection**

Level II data were collected over six months of operation from January to June of 2005. During the winter months of operation, blasts occurred approximately once every few weeks; during spring and summer, blasts occurred about once a week. On days when blasting did occur, two or three individual blasts would be observed within approximately an
As shown in Table 4.2, 37 blasts were recorded during Level II evaluation of system X. The ground motion measured during monitoring ranged in PPV from 1.09 to 6.60 mm/sec with an average PPV of 1.81 mm/sec. The largest and smallest blasts recorded during monitoring occurred on the same date, May 19, 2005. During the largest event the system X geophone, spaced farthest from the blast, recorded a PPV of 6.60 mm/sec. The closer NU geophone position outside of the test house, recorded a PPV of 8.20 mm/sec and the even closer quarry geophone recorded a PPV of 9.73 mm/sec. The smallest blast recorded during monitoring resulted in a PPV of 1.09, 1.40 and 1.96 for the system X, NU, and quarry geophones, respectively. In both cases of the smallest and largest blasts, it was found that PPV attenuated as ground motion approached the test house. Since the design of system X is considered as known and trusted for capturing ground motion, measurement of ground motion will not be reviewed.

Records obtained from the quarry indicated 49 blasts occurred during the months of evaluation of system X. Approximately 75% of blasts were large enough to trigger system X. Any blast that did not trigger system X during testing had attenuated below the trigger value of 1.02 mm/sec by the time the ground motion reached the test house basement.

During the level II testing of system X, the unit was operated in two electronic noise environments while in the same blasting environment. The first noise environment occurred when the NU equipment was operating and the noise levels averaged 2.3 µm. Any data collected when the NU equipment was operating required frequency filtering before it could be analyzed. When the nearby NU equipment was deactivated, the noise level decreased to 0.8 µm.
| Date       | Longitudinal | Transverse | Vertical | Max PPV | Crack Displacement
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Table 4.2 Summary of blast data collected during Level II testing of system X. *Denotes events that did not require noise filtering. (NU system inactive)
Level II Performance

The peak crack displacements measured by the system X LVDT were compared to the NU LVDT and Kaman sensor. The evaluation of the sensors included a direct comparison of the shape and amplitudes of the waveforms. Figure 4.6 compares the NU LVDT sensor to the system X LVDT. To create a direct level II comparison of system X to the NU system, system X waveform was filtered to remove frequencies above 50 Hz. The shape of the waveform captured in Figure 4.6 by system X, was similar to the waveform captured by the NU LVDT. Both waveforms showed a peak crack vibration 0.5 seconds. Additionally, both waveforms have a large low frequency peak at approximately 1.75 seconds from the air overpressure wave of the blast event. The system X waveform displayed a lower peak crack displacement after filtering.

![System X, 50 Hz Filtered Time History](image)

![NU LVDT Time History](image)

Figure 4.6 Direct comparison of crack time histories for system X, and NU LVDT, blast April 18, 2005. System X, data filtered to remove all content greater than 50 Hz.
During evaluation, all waveforms captured by system X were of smaller amplitude than those captured by the NU system. While system X and the NU system were installed on the same crack, they were spaced approximately 16 inches apart from each other and their responses should have similar ratios of long term to dynamic displacement. Figure 4.7 compares time correlated significant dynamic responses to ground motion and air over pressure recorded by both the NU LVDT and AC coupled channel on system X during five different blasts. This comparison was made with eight different blasts that occurred between March and May of 2005. During all eight blasts reviewed the NU LVDT was active, and the NU Kaman gauge was only active for two blasts, due to equipment constraints.

Interpretation of ratios of the NU LVDT to system X response is complicated. For instance, the ratio for long term effects (shown in Figure 4.3 as 1.32), is 25% of the ratio of dynamic effects (shown in Figure 4.7 to be 1.75). While these ratios could be used to adjust the dynamic response to be comparable to the long term response, it may not be the proper adjustment because of filtering and the difference in noise compared to signal for dynamic and long term response. Unfortunately, to obtain a comparison requires simultaneous operation of the NU system, which induces high noise levels.

The required filtering of the system X waveforms to reduce the effects of noise reduces the amplitude of the signal. Thus, had filtering not been required, the resulting waveforms would have had larger system X crack response amplitudes and thus, a smaller dynamic ratio of the NU LVDT to system X. In other words, the 1.75 dynamic ratio of the NU LVDT to system X would have been smaller and thus closer to the 1.32 long term ratio.

The noise level of system X while the NU system was operational was much larger then the dynamic crack response amplitude but small with respect to the to the long term
crack response amplitudes. For example during a blast event with a ground motion of 0.1 PPV there was only 1 µm of crack displacement (zero to peak) while the noise with the NU system operational was 1.1 µm (zero to peak) or a 110% of the signal. This high noise level shown in Figure 2.5 of Chapter 2 required filtering to obtain any signal relating to crack displacement, which complicates the comparison as discussed above. On the other hand the noise level is only 3% of the signal for a typical long term, weather induced crack response shown in Figure 4.2.

Figure 4.7 (Top) Comparison of the displacements of system X to the NU LVDT sensor during dynamic recording. (Five individual blasts denoted by symbols.) (Bottom) Example of how the dynamic ratio was selected for a given filtered waveform.
To determine the overall effectiveness of the system’s ability in capturing level II data as an independent system, two different types of data captured by the system, an AC and DC coupled response, are reviewed. Consider the event shown in Figure 4.8, which is a blast event that occurred on June 9, 2005 with a PPV of 2.62 mm/sec on the vertical channel. The corresponding crack displacement produced by the ground motion was less than 2µm, peak to peak. Crack responses captured on the DC coupled channel 3 differ with those from the AC coupled channel 4 of system X. As described in chapter 2, the AC coupled channel 4 waveform is more highly resolved and is zero centered during a blast. One disadvantage of a zero centering sensor is that a temporary shift would not be visible in the time history, as is seen in the DC coupled waveform, which displays a temporary offset of 2 µm.
Figure 4.8 System X, recorded crack displacement from a blast occurring June 9, 2005 were a temporary offset occurred.

The importance of the temporary offset in figure 4.8, can be assessed by comparing with the long term response shown in figure 4.9. The 2 µm offset, while seeming significant in figure 4.8, is seen in figure 4.9 to be small compared to the large swings in crack displacement. In addition, this event does not change long term crack response pattern.
System X’s ability to capture air pressure response is shown in Figure 4.10. This blast event was recorded with system X, on June 20, 2005 and is more typical of the blasts seen during monitoring. The system X geophone recorded a PPV of 1.27 mm/sec on the vertical channel of the geophone. This blast has a smaller peak crack displacement due to the blast vibration compared to the June 9th blast, but a larger low frequency crack displacement due to the air overpressure wave associated to the blast event. Like the June 9th blast, a small temporary crack offset could be noticed on the DC coupled channel 3 of Figure 4.10. Also, similar to the June 9th event, this event’s temporary offset is overwhelmed by the environmentally induced crack response.
Figure 4.10 System X, recorded crack displacement from a blast occurring June 20, 2005 during which the crack responded to primarily to the air blast.

**Level III Operation**

System X was evaluated for level III operation by triggering the unit off the crack movement. The unit was set to trigger off the crack when the crack displacement exceeded a threshold value more than four times in a row. An example of the triggering logic of system X is shown in Figure 4.11. Crack triggering operation is very similar to level II operation.
when the unit is triggered off the ground motion. Unlike ground motion the zero point or trigger reference shifts on the AC coupled channel with long term crack response. The “zero” for the AC coupled channel is taken as to the mid scale of the signal A/D range. The system triggers when the AC coupled channel displacement exceeds the current zero by a user defined amount for four consecutive samples. Once the trigger level is exceeded, the dynamic crack response is recorded at a frequency of 1000 Hz.

![Displacement vs. Time Graph](image)

Figure 4.11 Example of the crack triggering logic for system X, when operating as level III system.

Level III ACM operation can be implemented by trigging of the crack (without the geophone) to record both blast and occupancy-triggered events. Occupancy-triggered data included events caused by door slams, dropped objects and high winds, which can cause the crack to respond. The prime advantage of being able to measure crack movement from
occupancy events was the ability to compare blast to occupancy-induced crack movements that occur at unforeseen times. In level III operation crack width was also recorded at intervals of 15 minutes to one hour for comparison with long term environmental effects obtained during the level I and II operation.

**Level III Equipment Setup**

In order to evaluate system X during level III operation, the crack data logger was installed as described in Chapter 3. The histogram function was set to record the peak crack displacement every 15 minutes. The geophone data logger was set to record the ground motion when it exceeded 1.02 mm/sec. If desired, system X could be operated at level III without the geophone data logger and record only data from the crack. The geophone trigger function on the crack monitor data logger was allowed to remain active.

When both trigger mechanisms are activated each response will be recorded regardless of the type of excitation. The only time when an event would not be recorded during level III monitoring would be if the unit triggers twice within a 20 – 30 second period. System X, requires a short period of time between dynamic events to reinitialize, before another event can be recorded. If an occupant induced event occurs within the 20 – 30 second period before a blast event, there is a possibility that the crack monitor will not be prepared to record dynamic data during the event, and the crack will be lost. However, when the crack trigger has been properly set the potential for losing data can be minimized by reducing the number of crack triggered events to only those which are significant.

During testing, the crack trigger level was varied between 0.36 to 0.75 µm of movement, zero to peak. The lower the trigger value was set, the more events the unit
recorded. When reviewing crack triggered events on system X, the waveform recorded on the AC coupled channel 4 was used for analysis. The waveform captured on the DC couple channel 3, was only used when a baseline shift in the time history was assumed.

Level III Data Collection

System X was operated as a level III system for approximately three weeks, from late June through the end of July 2005. During the 20 days of testing as a level III unit, system X recorded almost 300 crack triggered events. As shown in Figure 4.12 the number of events recorded per day plotted as a function of the crack trigger level. The more sensitive the crack trigger was set, the more events were recorded. To determine the optimal trigger level shown in Figure 4.12, an algorithm was run on the data collected over a two day period when the trigger was set to 0.014 mils or 0.36 \( \mu \)m. A trigger level of 0.014 mils is the lowest possible trigger level for system X and not recommended for during a standard installation. Trigger levels below this would fall below the system’s noise level. The test algorithm determined the number of events the system would have recorded had the trigger level been set higher.
Figure 4.12 Number of events recorded by system X as function of the trigger level. Specific to the Milwaukee test house, data collected on July 8-9, 2005, with a trigger level of 0.36 µm.

Trigger data shown in Figure 4.12 shows a few interesting trends. A vertical asymptote occurred at a trigger level of 0.36 µm and a horizontal asymptote of one event per day began at a trigger level of 0.75 µm. The system was therefore able to capture most events when the trigger level was set between 0.36 µm and 0.75 µm. During these two days of testing, no events triggered at a level greater than 2.50 µm. Trends in the data show that as the trigger level approaches 0.36 µm, the number of events approaches infinity. This trend means that the crack is beginning to trigger off the system’s noise, rather than actual events. The average noise level of system X was previously found in Chapter 2 to be approximately 0.40 µm, zero to peak. As shown in Figure 4.13, when the trigger level was set to 0.36 µm, any noise fluctuations in the waveform greater than 0.04 µm would cause the unit to trigger. This very small trigger level could be exceeded easily by environmental noise.
During testing, the optimal trigger level was found to be 0.53 \( \mu \text{m} \). At this trigger level, most of the noise spikes and insignificant events were eliminated. When the trigger level is less than the optimal trigger level of 0.53 \( \mu \text{m} \), the number of events collected per day increases quickly. To identify legitimate events, when the trigger is set to a low value becomes labor intensive and may not be the most efficient method of monitoring.

![Graph showing crack displacement vs. time with trigger threshold](image)

**Figure 4.13** Example of the typical system X noise during monitoring in comparison to the smallest crack trigger level. Trigger level of 0.036 \( \mu \text{m} \) shown in red.

**Level III Performance**

Many different types of crack responses can occur during dynamic excitation. Occupant events can vary both in frequency and magnitude. Figure 4.14 shows a variety of deliberately induced occupant events at the monitored house, in Milwaukee, WI (Waldron, 2006). The first event, labeled A, was created by quickly closing the kitchen door of the house. This event has a high frequency and was small in amplitude. The second event, B
resulted from pushing on the ceiling near the crack. This event shows large amplitude and 
low frequency with periods as long as a second. The third event labeled event C, was proved 
by lightly striking the ceiling near the crack. This event has a large frequency and small 
amplitude and is comparable to the size and shape of the event recorded when the kitchen 
doors were being closed. Examples of occupancy events with known causes, such as those 
found in Figure 4.14, are useful in determining the significance of a blast induced response.

![Graph showing displacement over time](image)

**Figure 4.14** Examples of created occupancy activity recorded on the NU system, for 
comparison of the actual events from system X. (Waldron 2006)

Most of the crack triggered response collected during level III evaluation of system X 
could be classified as either high or low frequency events. Low frequency events were 
classified as having a frequency lower than 4 Hz. Shown in Figure 4.15 are two examples of 
low frequency waveforms collected by system X. These events have a single peak in crack 
displacement. The crack displacement waveform rises and falls slowly as the crack opens
and closes. In most cases the crack returned to its original position within approximately half a second.

Natural wind gusts exert dynamic air overpressure forces on structures. It was hoped that this type of response would be detectable during crack triggered events with high winds. Wind gusts of 20 mph were observed on the 15th and 20th of July at nearby Mitchell airport as shown in Figure 4.16 (NOAA, 2005). In Figure 4.16 the constant line indicates the average hourly wind speed while the red dots depict the 5 second peak wind speed during gusts. Wind gust data can be compared to crack responses like those in Figure 4.16 to determine the magnitude of the wind response.

Figure 4.15 Low frequency (4 Hz or less) crack triggered movement recorded during system X, monitoring in Milwaukee, WI.
The natural wind gust data collected from the nearby Mitchell airport (NOAA) can be compared to the crack triggered events to determine the effect that the wind has on the crack displacement. Wind induced response is compared to the wind gust speed on the 15th and 20th of July, 2005 in Figure 4.17. A similar study was conducted by Aimone-Martin (2005) in Henderson, NV, and her data are shown in this graph for comparison. In both the Henderson, NV study and in this study, it was found that the crack displacement increased with an increase in wind gust speed. Additionally, in both cases the crack displacement provided by wind gusts was larger than the average displacement from local blasting. Due to the differing types of structures, varying wind directions, the individual building response to the wind is expected to vary.
High frequency crack movement was classified as crack responses with a frequency greater than 4 Hz. Two examples of high frequency crack time histories recorded during system X level III monitoring are shown in Figure 4.18. When high frequency waveforms are encountered, at least 3 to 4 cycles of opening and closing occurred before the waveform returns to its original baseline. The higher frequency waveforms shown in Figure 4.18 are comparable to the door closing and striking the ceiling shown in Figure 4.14.
Crack triggered events can be used to determine time dependent trends in the data. Figure 4.19 represents the frequency of occurrence of crack triggered data. These data were collected for 12 consecutive days of monitoring with the crack trigger level set to 0.36 μm.
Time dependant data like Figure 4.19 is a valuable tool for correlating the relationship between triggered events and the actions of the building’s occupants. When reviewing the plot of the 12 consecutive days it could be noticed that a peak in the number of events occurred at 5 am and then again from 9 am to 6 pm at night. These events appeared to correlate well with the time of day in which most people are active in their homes. Late in the evening and during the middle of the night, few crack triggered events occurred.

To further determine the cause the events, the data were divided into seven working and five weekend days. The plot of working days shown in Figure 4.19, indicated that a large number of events occurred at approximately 5 am and at 2 pm. This could be attributed to the comings and goings of the building’s occupants. The plot of the weekend days shown in Figure 4.19 indicated that a large number of crack triggered events occurred from 9 am to 6 pm. Interestingly, on the weekends, early morning events are eliminated and more activity occurred in the late morning.

One possible scenario for these trends in the data could be attributed as follows:

On weekdays: Occupant A leaves the building for work at approximately 5 am each morning. Occupant B leaves the building at approximately 9 am and returns at 2 pm. The building remained active from 2 pm until 9 pm when the occupants went to bed.

On weekends: The building’s occupants wake between eight and nine in the morning. They were active in the house throughout day, with peaks at 12 noon and 5 pm. Activity reduced throughout the evening until the occupants went to bed at approximately 10pm.
Figure 4.19 Number of events occurring in the Milwaukee test house as function of time of day. Data collected from June 30 to July 11, 2005.
Chapter 5

Installation, Software and Literature of Crack Monitoring System Y

In this chapter, the installation, software and literature of a commercial Autonomous Crack Monitoring (ACM) system, hence called system Y, are reviewed and summarized. Specifically, the software and manuals of system Y were reviewed to ensure their ease of use by the average field technician. Additionally, the effects of electromagnetic noise interference on system Y were measured. Methods for reducing and removing electromagnetic noise were also evaluated for system Y.

Installation

The general installation methods that were followed for installation of system Y in both the laboratory and the field are described in this section. The physical installation of system Y in a residential structure can be completed in approximately one day. Figure 5.1 shows the general wiring diagram and equipment location for the complete system Y crack monitor as it was installed in the test house. During this specific installation the geophone was mounted in the basement of the house and the crack sensors placed across a crack on the ground floor ceiling.

During monitoring the ACM system Y was capable of measuring ground motion, air overpressure and crack response. For this installation air overpressure was not monitored.
The central components of system Y were contained within the monitor enclosure and included a micro processor, a data logger, battery and display screen. The crack and ground motion sensors were then attached to the monitor. System Y included a geophone, which monitored ground motion and then triggered the system to record crack displacement and ground velocity time histories when the system was programmed to operate as a level II system.

![System Y wiring diagram](image)

**Figure 5.1 System Y wiring diagram**

**Geophone**

The first step in the installation of system Y was to install the geophone in the basement of the test house. A storage area under the basement entry stairway was chosen, due to its remoteness. Normally, the geophone would be installed by burying, anchoring, sandbagging or spiking in the earth outdoors. The best location for the geophone is to place it between the structure being monitored and the blast. In this installation, since it was not
employed to ensure regulatory compliance it was adhered to the existing concrete slab. A plaster coating on the bottom of the geophone block. Figure 5.2 shows the completed installation of the geophone adhered to the basement slab. Plaster was found to be advantageous when compared to other types of mounting because, after the testing was completed, the remaining plaster could be scraped away without leaving any residue or mounting holes. Once the plaster cured, the geophone cable was then connected to the geophone port on the side of the system Y monitor.

![Figure 5.2 Installation of the geophone in the downstairs of the test house.](image)

**Crack Monitor**

The second step of the installation of system Y was to attach the crack sensors across the drywall crack. Two linear potentiometers sensors supplied with the system, shown in figure 5.3, were mounted across the crack using a 90 second quick setting epoxy. The sensors were placed 30 centimeters apart. The first sensor was mounted directly across the crack to measure crack movement. The second sensor was mounted on a nearby uncracked
section of the drywall to measure environmental effects. System Y uses linear
potentiometers to measure crack displacement.

To install the crack sensors, the first sensor was connected to the crack monitor and
the monitor was turned on. The linear potentiometer was manually placed at the center of its
range of displacement. The lock screw located on the side of the sensor was tightened to
prevent the slider from moving. The crack monitor was turned on and a sensor test was run.
A sensor test verified the sensor was connected properly. Following the sensor test, an
autozero was performed by pressing the “option” and “start monitor” buttons at the same
time. The autozero function made the current position of the sensor equal to zero and
allowed maximum travel of the sensor during operation in both directions. To verify the
current position of the linear potentiometer from the main screen on system Y, the “option”
and “start monitor” buttons were pressed to review the current position of the sensor. If the
sensor had been properly zeroed, the current reading should be approximately zero.

![Figure 5.3 Installation of the system Y crack and null linear potentiometers on the cracked
and uncracked drywall.](image)
Depending upon the expected range of motion the linear potentiometer would encounter in the field, it could be set to record displacement in the normal or sensitive mode. In normal mode, the system Y sensor will have a range of ±5.22 mm and a resolution of 2.61 µm. When operating in sensitive mode, the range is reduced to ±0.653 mm and the resolution becomes 0.33 µm. If system Y is installed in an environment where only long term crack information was needed, as in level I operation, the unit should be programmed in normal mode to take advantage of the larger range. If the unit is intended to record both long term and dynamic crack data, the unit should always be operated in sensitive mode to take advantage of the higher resolution. A higher resolution enables the system to define the crack displacement during a dynamic event more closely.

In the test house, the displacement sensors were mounted over a crack in a drywall ceiling using a 90 second quick-set epoxy. With linear potentiometers locked in position, they were installed with quick-set epoxy across the crack. Figure 5.3 illustrates the mounting of the linear potentiometers across the crack and on the drywall ceiling. After the epoxy had set, the setscrews were released to allow the sensors to move and record displacement.

The crack and null displacement sensors were connected to the system Y monitor and placed in a small closet. The system Y equipment was placed on the bottom shelf of the nearby closet and the crack sensor cables were then routed through a small hole in the wall and connected to the unit. The crack monitor was powered by both an internal battery and A/C adapter. During this installation, the unit was powered by the A/C adapter since electrical outlets were available and the internal battery was only used during a power outage. The auxiliary port on the crack monitor was connected to a standard serial cable that was then connected with the Nport for internet communication as shown in figure 5.1.
Sensors

System Y crack monitors employed linear potentiometers to measure micrometer opening and closing of the crack and geophones to measure the particle velocity of the ground motion. The linear potentiometer displacement sensors were evaluated in the laboratory both statically and dynamically to validate their performance and to compare it to the previously calibrated sensors. Laboratory evaluation of the system Y sensors is described in Chapter 6. External SUPCO temperature and humidity sensors were used to monitor the environmental effects during selected testing. Future ACM systems should include integrated temperature and humidity sensors.

Geophone Sensors

Geophones measure ground motion in terms of particle velocity. Since there are three principal directions: longitudinal, transversal and vertical, three geophones are necessary. In this case all three components are housed in a single geophone block. During a dynamic event, a geophone records the time history of the ground motion for a preset duration of 3 seconds. During normal monitoring, the geophone is programmed to monitor ground motion constantly. When the ground motion exceeds a user defined trigger value, the geophone then records. In addition to recording the particle velocity-time history after triggering, the geophone monitor also records time histories prior to triggering, called the pretrigger. A pretrigger setting of 0.25 seconds and a particle velocity trigger level of 1.02 mm/sec were used for all measurements. When the unit records ground motion a sampling frequency of 1024 samples per second is used for both the preset pre and post trigger record time. For blast monitoring, the recorded time length for an event is normally three seconds. Figure 5.4
compares the three components typical of a particle velocity time history during a blast.

During this blast, the geophone was triggered on the vertical channel and the maximum peak particle velocity (PPV) was 6.73 mm/second.

![Graph showing particle velocity time history](image)

**Figure 5.4** Typical ground motion record by the system Y geophone. Blast occurred on May 19, 2005.

**Crack Sensors**

The opening and closing of a crack during a blast event is very small and often only a few micrometers of displacement will be recorded. System Y was qualified with StructureMetrix SMG035A linear potentiometers. These sensors were used to measure crack displacement. Since the displacements measured by an ACM system are very small, the
displacement sensors used must have a small range and a high resolution. When the gain setting is set to 8 or ‘sensitive’, the range of the StructureMetrix sensor at ±653 µm was approximately 1.3 times that of the benchmark Kaman sensor. When the gain is set to 1 or ‘normal’ the range of the sensor was ±5220 µm or 10.4 times that of the Kaman sensor. A direct comparison of the specifications of StructureMetrix linear potentiometers to the Kaman eddy current sensor is shown in Table 5.1. The StructureMetrix linear potentiometers were easy to install, however they were much larger in size compared to other any sensors tested. StructureMetrix linear potentiometers were qualified both dynamically and statically to compare their response to the Kaman sensors, which are discussed in Chapter 6.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>StructureMetrix</th>
<th>Kaman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>SMG035A</td>
<td>SMU-9000-2U</td>
</tr>
<tr>
<td>Type of Sensor</td>
<td>Linear Potentiometer</td>
<td>Eddy Current</td>
</tr>
<tr>
<td>Input, (Volts DC)</td>
<td>7.2 max, 5.5 min</td>
<td>30 max, 7.5 min</td>
</tr>
<tr>
<td>Input, (Current mA)</td>
<td>200 max</td>
<td>15mA</td>
</tr>
<tr>
<td>Output, full Scale (DC)</td>
<td>±1.65</td>
<td>0 to 5</td>
</tr>
<tr>
<td>Scale factor (V/µm)</td>
<td>0.0003085</td>
<td>0.01</td>
</tr>
<tr>
<td>Gain Setting</td>
<td>1x (normal)</td>
<td>8x (sensitive)</td>
</tr>
<tr>
<td>Range (µm)</td>
<td>±5220</td>
<td>±653</td>
</tr>
<tr>
<td>Resolution (µm)</td>
<td>2.61</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 5.1 Specification comparison for the StructureMetrix linear potentiometer to the Kaman eddy current sensor.
Noise Levels and Electromagnetic Interference (EMI)

Electromagnetic Interference (EMI) can be produced by all types of electronics and equipment and can mask the signal from a sensor measuring crack displacement in an Autonomous Crack Monitoring (ACM) system. EMI induces voltage fluctuations, which are superimposed over the sensor output. ACM systems employ highly sensitive sensors that produce a voltage change proportional to changes in displacement. These small crack movements resulted in small voltage changes which can be masked by normal EMI. Any introduction of EMI during these measurements may result in significant voltage spikes. EMI on the crack displacement channel during a transient event can obscure the crack time history by noise. EMI is emitted from most electronic devices and therefore measuring equipment should be designed to operate in environments with moderate levels of noise. Most EMI encountered during testing occurred at the 60 Hz frequency, common for AC power in residential and commercial buildings.

System Y was initially qualified in the test house with the experimental Northwestern University (NU) system operating at the same time. With the NU system operating, system Y recorded an average noise level of 5.3 µm peak to peak. It was found that during testing the high noise levels were directly related to EMI production by the NU system. For this reason, testing was completed on system Y with and without the concurrent operation of the NU system. Table 5.2 shows the noise levels of the system with and without the operation of the NU system. System Y was found to operate at a noise level of 1.3 µm peak to peak in a standard residential environment. The most significant reduction of the noise levels of system Y was attained when the NU System was deactivated. While the cause of noise in this testing environment was easy to pinpoint and eliminate, in some field environments this
may not be possible. Figure 5.5 demonstrates the noise levels before and after the NU equipment was disabled.

<table>
<thead>
<tr>
<th>Date</th>
<th>Noise Level (µm)</th>
<th>Gain</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/4/2005</td>
<td>5.3</td>
<td>1</td>
<td>Blast Triggered Event NU System running.</td>
</tr>
</tbody>
</table>

Table 5.2 Historic noise levels for system Y during testing.

Figure 5.5 Typical system Y noise level visible in the crack velocity-time history with and without NU system in operation.
Computer Interface and Software

In this section, the computer interface and software supplied with system Y are evaluated to determine the adequacy and ease of use. Once the long-term and dynamic data have been collected by an ACM system, it must be displayed properly to allow for review and comparison. The primary function of the computer interface and software for the equipment was to allow the operator to organize, sort, store, remove and process the data. A well designed ACM system should include quality software, which aids in automating typical data processing tasks and reduces the amount of time spent working with data by the operator. One advantage of system Y was that ground velocity and crack displacement time histories for a blast were stored in a single file. Poorly designed or insufficient software would cause the operator of a system to spend extra time and expense processing the data.

System Y Programming & Connection

System Y can be programmed both on-site and remotely. This system uses a serial port to connect for sending and receiving data from the unit. On-site, the unit could be programmed with the external keys and LCD screen or with a computer connected to the serial port. With the key pad and LCD screen, menus can be cycled through and changes made to the system such as switching monitoring modes and trigger levels. In Figure 5.6 the external keys on the crack monitor are shown. The system could also be programmed on-site with a computer connected to the serial port. During evaluation the majority of the on-site programming was done using the software and a laptop computer.
Remote communication with system Y can be accomplished over the internet or by modem. During evaluation, modem communication was only lab tested, and is therefore not discussed. This method was not implemented in the field since it was considered standard practice for system Y. During the field evaluation, data were retrieved from the unit over the internet. The serial cable from the unit was connected to an Nport (Moxa), to allow access over the internet. The Nport creates a virtual serial port for the unit over the internet. Once connected to the unit over the internet, the software can be used as it would have been on site. The only drawback to off-site programming was very slow data transfer rates. However, in almost all situations slow remote data transfers were preferred to site visits.

System Y is capable of recording up to eight waveforms during a dynamic event. This greater flexibility allows for the addition of other sensors to the unit for monitoring. As an ACM system, system Y was capable of monitoring two cracks with a single unit. However, due to the limited number of available sensors, this feature was not used during evaluation. The only side effect of monitoring multiple channels was that the more channels recorded during a dynamic event, the less number of events that can be recorded during a
monitoring period. Once the maximum number of events had been reached, the unit needed to be reset before it could continue monitoring for dynamic events. Table 5.3 describes the relationship between the number of channels recorded and the number of events the unit could record per monitoring period. During evaluation, only five channels were used to maximize the number of dynamic events recorded during a day. This was done since the unit is only capable of being automatically reset once per day. A typical crack monitoring project would use six channels recording ground motion, air overpressure, crack and null movement. During evaluation the equipment setup did not include an air overpressure transducer.

<table>
<thead>
<tr>
<th>Number of Channels</th>
<th>Maximum Events Recorded</th>
<th>Notes/Typical Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>16</td>
<td>3 Channel Geophone</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>Geophone/Air Overpressure</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>Geophone/Air Overpressure/ Crack</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>Geophone/Air Overpressure/ Crack/ Null</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

* All calculations are based on a 3 second recording

Table 5.3 System Y relationship between the number of channels recorded and the number of events the unit can record per monitoring period.

The software can also be used to start, stop and retrieve data from system Y. The software also allows an operator to collect data from the unit remotely and limit costly site visits. During field testing, data were manually downloaded remotely on a weekly basis and only when blast events were least likely to occur. The layout and display of the command settings allowed easy access to the different settings while using the key pad on site. Figure 5.7 shows the layout of the command windows an operator would see during programming.
Figure 5.7 System Y command layout when programming with the keypad. (Company Y Operator Manual)
Data Analysis Software

Once the monitoring had been completed or during regular intervals, the data collected by system Y was removed and processed. To analyze the data collected during monitoring, system Y used the manufacturer supplied software. Figure 5.8 is a typical screenshot from the software main menu that allows review of the files. The files can then be managed and sorted from this screen.

![Figure 5.8 System Y, Event Management software interface](image)

The software can also be used for analyzing and processing the data collected on system Y. The original intended use of the software was for processing and viewing ground motion time histories. This software package enables the user to view and print the time histories of ground and crack motion captured by the crack monitor. The software is also
capable of creating event reports, which describes the key points of an event and frequency content analysis. Figure 5.9 shows a typical screenshot from the software when creating a crack time history. One significant advantage of the software is that ground motion and crack displacement time histories are included in one file. When reviewing a crack and ground motion time history, any areas of interest can be isolated and enlarged on for further review. An ACM specific software application or further adaptation of the software is not available.

Figure 5.9 Software screenshot of a ground motion and a crack time history

**Literature and Manuals**

The literature and manuals supplied with an ACM system should include thorough documentation to allow a new user to install and operate the system independently. Without
the proper manuals, setup and operation of an ACM system would be very difficult and confusing. System Y was supplied with multiple documents to aid in the installation. The primary documents included an operator’s manual for the software and System Y seismographs. Additionally, system Y was supplied with a quick start card, located on the side of the case of the crack monitor, for on-site programming.

Review of the manual entitled “Operator Manual” was required to learn more about the software package prior to its use. The manual describes the process to remove files from the crack monitor. Once removed from the unit they can be processed and viewed with the software. The first section of the manual describes a basic tutorial of how to use the software. The second section of the manual describes the layout and keys used in the software package and how to handle files.

The manual entitled “System Y Operator Manual” was used to learn about the operation and programming. This manual describes the methods for properly installing a seismograph and step by step programming prior to monitoring. The system can be programmed in three modes; compliance, advanced and flex. For crack monitoring, flex programming was used. From the flex setup window the sensor specific information could be entered and sent to the unit. Key-pad programming was reviewed earlier in Chapter 5 in the section on computer interface and programming. The manual also reviews typical system capacities, operation durations and limitations and capacities. The quick start card located on the side of system Y shows the condensed instructions for operating system Y. The quick start card is useful for on-site programming when the manuals are not available.
Chapter 6

Laboratory Qualification of Crack Monitoring System Y

The laboratory qualification evaluation completed on Autonomous Crack Monitoring (ACM) system Y is presented in this chapter. It was important to first operate System Y in the laboratory to ensure proper operation prior to field deployment. This step was undertaken to verify the system’s ability to collect valid data under field conditions. Laboratory operation was undertaken to verify that the displacement of the crack monitoring system operated within the acceptable standards established with the benchmark LVDT and Kaman sensors used by the Northwestern University (NU) system. Performance of the system Y sensors was evaluated for both static and dynamic response. Laboratory testing of system Y, was also evaluated to ensure that the system was easy to use by the average field technician.

Long Term or Static Response

Long term or static evaluation was completed on system Y to verify the proper operation of the sensors when used in a field environment. Prior to the evaluation of system Y as a complete crack monitoring system, the sensors were tested statically.

Qualification of a sensor to measure micrometer crack opening and closing due to long term environmental influences should be completed in a similar manner in which the sensor is expected to perform in the field. This requires the sensors and system to be tested
together so that the complete system can be evaluated. To determine if the sensor will respond linearly during cyclic use, the sensors were plate tested under cyclically changing temperature loading. The sensors were attached to a plate with known material properties and then exposed to varying temperatures to allow the plate and sensors to expand and contract. The expansion and contraction of the plate allowed the sensor to record cyclic changes in displacement. During testing the sensors were attached to a plastic plate made of Ultra-High Molecular Weight Polyethylene (UHMW-P). This material provides a large thermal response that approximates a cracked wall response. The coefficient of thermal expansion (CTE), $\alpha$, for UHMW-P is $\alpha=198.0 \, \mu m/m/°C$. The sensor body is expected to expand slightly during testing. However, the CTE for the sensors made of steel is $\alpha=13.0 \, \mu m/m/°C$ and was approximately 15 times smaller than the CTE for UHMW-P plastic. Therefore the effects from the expansion and contraction of the actual sensor components are an order of magnitude lower and were ignored.

**Long Term Testing Equipment Setup**

The sensors can be evaluated over long time periods (level I operation) to determine the size of the hysteresis loops. The larger the hysteresis loops, the less responsive the sensor is to small changes in displacements. To test the sensors in a level I operation, the linear potentiometer was mounted on a flat piece of UHMW-P, approximately 400 mm square. During the mounting process, the smooth surface of the UHMW-P plate needed to be roughened with sandpaper to allow a sufficient bond between the epoxy and the UHMW-P plate. While testing system Y, the sensors were placed outdoors in a protected enclosure to take advantage of the natural temperature swings. These temperatures changes are similar to what would be found during actual field operation. To prevent any possibility of water
damage and direct contact with the sun, all equipment was placed in a weather resistant
enclosure. Had the sun been allowed to shine on the plate directly, the sensor displacement
would have also been a function of the cloud cover. Figure 6.1 shows the equipment setup
used during the static testing.

System Y as supplied does not have the ability to measure temperature and humidity
changes along with crack displacement. Temperature and humidity were monitored with a
SUPCO data logger. The SUPCO temperature and humidity data logger was set to record the
temperature once per minute. The humidity readings recorded during testing were ignored
because UHMW-P does not respond to changes in humidity like more susceptible
construction materials such as wood or drywall.

Figure 6.1 Static testing equipment layout for system Y
A simple procedure was followed to measure the long term, level I response of the system Y linear potentiometer. First, the system was assembled as described previously in Chapter 5. The internal clocks in both system Y and the SUPCO temperature data logger were synched to the local computer clock. The sampling rate for system Y and the SUPCO temperature data logger were set to record the sensor displacement and temperature at least once per minute. Once both the systems were programmed, they were activated to start the data collection process. The weather resistant enclosure was then sealed and the entire unit was allowed to operate in the outdoor temperatures for approximately three days. During this period of evaluation, the UHMW-P plate with the attached sensor endured daily temperature swings from 18°C to 32°C.

**Long Term Response Results**

At the completion of the testing period, the recorded data were removed from the individual systems to be processed and merged into one time history. Prior to merging the collected data, individual time histories can be plotted for the displacement sensor and temperature with respect to time, as shown in Figure 6.2. During the static testing, as expected, the highest temperatures occurred during the early afternoon and the lowest during the early morning. From the time histories shown in Figure 6.2 it is visible that the peak temperatures recorded correspond to peak in sensor displacement. It was expected that during the peak temperatures recorded, the UHMW-P plate would expand and cause a larger displacements of the linear potentiometer.

The linear potentiometer was found to record larger changes in displacement because of the span of the gauge at 140 mm was rather large. This relatively large span is at least ten
times larger than any other ACM sensor tested. The smaller the span of the gauge the less material effects are included in monitoring.

![Graph showing temperature and displacement comparison](image)

Figure 6.2 Correlation showing the comparison of the temperature and displacement recorded during static testing.

To determine the effect of temperature on the cyclic expansion and contraction of the system Y sensors, displacement was compared to temperature in Figure 6.3. While hysteresis loops are visible they do not drift, but oscillate about a common mean response. This cyclic response is compared to the theoretical expansion of the plate shown as the solid inclined line. The theoretical displacement was calculated by multiplying the coefficient of thermal expansion or (CTE) by the temperature change and initial gap measurement between the brackets of the linear potentiometer. The slope of the calculated displacement was found to be approximately two times larger than the measured value. The sensor was able to
consistently record displacements with approximately half the magnitude compared to the control sensor. The hysteresis loops created by the sensors during testing were slightly larger than those of previously tested sensors such the LVDT and Kaman sensor (Balliot 2004).

![Figure 6.3 Measured and calculated displacement vs. temperature for system Y.](image)

**Short Term or Dynamic Testing**

Dynamic qualification was undertaken to verify the system’s ability to capture dynamic activity in the laboratory prior to its placement in a field environment. Previous work in dynamic testing by (Ozer 2005) had been completed on string potentiometers and served as a basis for development of an apparatus to validate the dynamic response of system Y.

During a dynamic event, the displacement sensor is responsible for capturing a transient waveform. Because this event will only occur once during the monitoring period it
is important for an ACM system to sample the waveform at a high sampling rate. The structural response frequency of most buildings measured in the field is normally in the range of 10 to 15 Hz. This frequency range required the ACM system to sample at 1000 Hz to define the dynamic response of the crack. The standard sampling rate for control system was 1000 Hz and for system Y was 1024 Hz. During dynamic testing, the testing apparatus was vibrated at frequencies up to 100 Hz so that 10 samples were obtained per excitation cycle. In addition to the ability to capture events with large frequencies, ACM systems must be able to capture events with small amplitudes. Field testing has shown that interior cracks in residential structures can respond with displacements between 2 and 5 \( \mu m \) zero to peak during a dynamic event.

Ozer (2005) verified the string potentiometer as an ACM displacement sensor by measuring the response of two aluminum blocks stacked upon each other and vibrated by a drop weight. The blocks were separated by a thin rubber sheet which modeled an interior crack. The control Kaman sensor was then mounted on one side of the blocks and the sensor to be tested on the other. A small weight could then be dropped at varying heights on the upper block. Varying the height of the drop varied the amplitude of the movement between the upper and lower block.

**Dynamic Testing Equipment Setup**

As shown in Figure 6.4 the system was modified in order to accommodate larger system Y sensors and increase the control of the variability of the system’s frequency and amplitude. Larger aluminum blocks then Ozer’s were employed to accommodate the larger sensors. A small electric motor with an eccentric weight was employed to control the excitation frequency. Changing the arm and mass of the eccentric weight allowed the
amplitude of the excitation to be controlled. During dynamic qualification, a copper wheel weighing 5.1 grams served as an eccentric weight. When the eccentric weight oscillates, it functions as a vibrator and creates a net upward and downward force. This changing force caused the upper block to move relative to the lower block and simulated crack movement.

Dynamic response of system Y was compared to the NU system Kaman eddy current displacement sensor and the Edaq mobile field computer and data logger. The Kaman eddy current sensor has been used for experimental crack monitoring projects for years with which there is a great deal of experience.

Considerations taken during dynamic testing included; limiting electromagnetic noise, preventing movement of the lower block and ensuring the proper adjustment of the sensors/upper block combination before each test. Any excess equipment in the laboratory that may induce electromagnetic noise during testing was turned off or moved away from the devices. To further limit electromagnetic noise, it was found that all cable runs for system Y needed to be wrapped in aluminum foil in the laboratory to reduce the noise levels within expectable ranges. To limit the movement of the lower block during dynamic excitation, it was attached to the edge of the more massive table to limit its movement.

Dynamic testing of system Y was accomplished by following a simplified procedure. First, the aluminum blocks were assembled with a small foam spacer between them. Guide plates were then installed on the lower block to limit horizontal translation of the upper block. A front and right view of the modified testing apparatus can be seen in Figure 6.4.
The system Y sensor and the control Kaman sensor were attached to opposite sides of the aluminum block assembly. Both systems were set to record dynamic data for up to 15 seconds. The electric motor was activated by a 1.5 volt source to vibrate the upper block with respect to the lower block and the corresponding dynamic crack movement was then recorded by each system. Dynamic excitation was initiated with the eccentric weight spaced farthest away from the motor shaft. Subsequently excitation was reduced by placing the eccentric weight closer to the motor shaft.

During testing, differences in the dynamic response of the control sensor and test sensor were observed. Differences in the sensor responses such as non-uniform displacements and phase shifts could be attributed to limitations in the testing equipment. These limitations included equipment alignment, connection and size effects. Uniform displacement of the upper block with respect to the lower block was anticipated. However, it appears that either lack of horizontal support or difficulty in the alignment of the eccentric...
motor to the center of gravity of the upper block or both occurred. This caused a small rocking motion of the upper block and non-uniform displacements at the face of the upper block as shown in Figure 6.5. Any slight deviations in the alignment affected the magnitudes of the displacements measured by the sensors as well as a phase shift between time histories of the sensors on opposite sides.

![Diagram](image)

Figure 6.5 Description of how a phase shift was created in the waveforms, during dynamic testing.

In addition to equipment alignment, the size or the sensor and type of connection could affect the amplitude of the recorded waveform during the small force laboratory excitation. System Y sensor required a large force to displace which can dampen the response of the system. During dynamic evaluation it was found that the system Y sensors dampen out the smaller applied forces and only responded to the larger eccentric forces. The much smaller Kaman control sensor, on the other hand, does not require a connection
between the sensor tip and target. Without a direct connection between the tip and housing of the Kaman sensor there are no frictional losses during testing small amplitudes. However, because Kaman sensors are fragile and expensive they are not very field worthy. During dynamic testing, because of the slight rocking motion which occurred from the eccentric weight, the sensor body can bind creating frictional losses. Any binding that would occur during testing should reduce the amplitude of the waveform recorded by system Y.

These lab related damping effects of the system Y sensor during small excitations were not apparent in field testing discussed in Chapter 7. Had the lab evaluation been accomplished on a set of much larger aluminum blocks, this dampening effect would not have been apparent since the inertia of the wall is orders of magnitude greater than that of the sensors. However, during field deployment of this system on a residential crack, the dampening effect of the system Y sensor should be considered when selecting an appropriate crack for monitoring.

**Dynamic Evaluation Results – Amplitude Comparison**

Dynamic response of the linear potentiometer from system Y, was compared to the control system in terms of both frequency and amplitude as shown by the time histories in Figure 6.6. The amplitude of the waveform recorded by system Y was always found to be larger than that recorded by the Kaman sensor. During low amplitude dynamic tests, the system Y sensor was found to absorb typical displacement created by low force excitation and only responded to the larger excitation forces. Table 6.1 summarizes the comparison of the maximum amplitudes collected during the dynamic tests completed on system Y. On average, the system Y linear potentiometer reported 2.8 times the maximum and 2.2 times
the minimum recorded value of the Kaman sensor when using the factory supplied conversion of voltage to displacement. From Figure 6.7 it can be seen that the ratio of the displacement of the linear potentiometer to the Kaman sensor was constant during testing. Since the ratio of the maximum crack displacement was found to be relatively constant throughout a wide range of excitation amplitudes, the sensor was considered to be operating properly and within tolerances. The large difference in crack movement recorded by system Y, compared to the control was attributed to the testing apparatus or the conversion constant of the sensor.

Figure 6.6 Typical waveform recording during the dynamic testing of system Y.
<table>
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<tr>
<th>Test Number</th>
<th>Event Number</th>
<th>Kaman Min Amp. (µm)</th>
<th>System Y Min Amp. (µm)</th>
<th>Amp. Ratio System Y/Kaman</th>
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<td>Min</td>
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<td>7</td>
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<td>-18.65</td>
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Table 6.1 Summary of the dynamic tests completed for system Y.

![Figure 6.7 Maximum and minimum displacements of the Kaman and system Y sensors during dynamic testing.](image-url)
**Dynamic Testing Results – Frequency Comparison**

The measured response frequency of the system Y sensor was compared to the standard Kaman sensor. During testing, the apparatus was operated at a frequency of approximately 100 Hz, this is well above the 10 – 50 Hz range necessary for field operation. Equipment that can capture waveforms accurately at a high frequency can readily capture waveforms at lower frequencies. However, briefly during the start-up of the eccentric weight rotation, the excitation frequencies were lower than during constant operation as shown in Figure 6.8. During both start-up and at constant angular velocity, the measured response frequency of system Y was comparable to that of the control system.
Dynamic Testing Results – Offsets

Baseline shifts or temporary offsets of a crack can occur during a dynamic event. An important feature for crack monitoring devices is being able to capture these events. Use of the data collected can be used as evidence of the magnitude and causes of a crack opening or closing during excitation. Figure 6.9 shows a typical waveform time history when a baseline
shift or offset has occurred. This waveform shows that system Y was able to capture crack offsets during dynamic testing when recorded by the control system.

Figure 6.9 Typical waveform time history of the control system and system Y during a baseline shift.
Chapter 7

Field Testing of Crack Monitoring System Y

The field testing of Autonomous Crack Monitoring (ACM) system Y in a blasting environment is described in this chapter. Two modes of monitoring operations were evaluated for this system. These operation modes or types of trigger operation included both level I and II operation. Level I operation requires recording crack displacement at a regular interval. Level II operation requires the recording of dynamic crack response at unknown times when a preset intensity of ground motion is exceeded. A field installation across a crack in a house located near an active limestone quarry was selected to test the performance of this system in both of these modes. Additionally, all procedures were reviewed to ensure that the system was easy to use by the average field technician.

Field Trial Blast Vibrations

Performance of system Y was evaluated at both levels I & II in the field by installing the equipment in the Milwaukee test house. The active limestone quarry adjacent to the test house blasted more or less weekly during the monitoring period, which provided a realistic environment. As a level I system, the unit recorded only the long term crack response, which could be compared to long term changes in temperature and humidity as well as the long term response of various Northwestern University (NU) benchmark systems. As a level II
system, the unit not only recorded the long term crack response, but also the dynamic crack response to blast induced ground motion and air over pressure.

Level I Operation

During level I operation, the system records peak micrometer changes in crack width at preset time intervals. System Y offers a choice of six different time intervals. These range from every two seconds up to every 15 minutes. Selecting a sampling rate smaller than every minute would not be recommended for remote operation of an ACM system when the data stored on the unit is not downloaded regularly. For most ACM applications sampling every 15 minutes is sufficient for capturing long term trends. Long term patterns of crack response can be compared to environmental effects to determine if dynamic excitation due to blasting, mining or construction activities have caused permanent changes to the crack displacement. However, level I operation alone does not include the needed measurement of the dynamic response of the crack during a blast event.

Level I Equipment Setup

System Y’s performance was evaluated by comparison with the NU system which concurrently monitors the same crack. The temperature and humidity data were collected with the NU system. System Y was setup to record level I responses as described previously in Chapter 5. During setup, the histogram function on the unit was set to record the peak displacement of the crack and null sensor every 15 minutes.
Level I Data Collection

Level I data were collected from February to July of 2005. While collecting level I data the unit’s functionality was evaluated during the extreme changes in temperature and humidity observable during both heating and cooling seasons common for Milwaukee, WI. Temperature and humidity during the winter months were relatively low and in the spring and summer they were higher with varying levels of humidity, which varied with the passage of various weather fronts encountered. Varying levels of indoor humidity were expected during the spring when most people open the windows in their homes. In all cases the indoor temperature fluctuated within a few degrees of 21°C.

During most of the monitoring period, the inside temperature and humidity were maintained within a cyclically narrow range, which is normal for most homes heated with a gas furnace and cooled with a central air conditioner. The temperature and humidity data and the long-term crack data collected by system Y and the NU LVDT are compared in Figure 7.1. This figure shows similar trends in the crack displacements recorded by the NU LVDT and system Y linear potentiometer.

The thermal expansion experienced by the drywall ceiling was found to be heavily influenced by changes in indoor temperature as seen in the comparison of trends in crack displacement and temperature in Figure 7.1. Trends in Figure 7.1 also validate sufficient operation of system Y by comparing the peak displacements of the NU LVDT and system Y linear potentiometer. To remove noise spikes in the data, the time histories are averaged over a 24 hour period. Peaks and valleys in the time histories of the two sensors occur at approximately the same times. Maximum peaks in displacement occur at the same time as minimum indoor temperatures. When comparing the 15 minute data shown in grey in Figure
7.1, it is shown that the magnitude of the system Y peaks and valleys were larger than those of the NU LVDT by a factor of two. The ratio of the peaks in the 24 hour averaged data tends to be similar in magnitude for both sensors, with system Y being only slightly higher.

During operation an ACM system must be to maintain a constant ratio of long term to dynamic movement. A constant ratio is needed in order to directly compare dynamic crack excitation to long term crack movement to determine the significance of dynamic events. During level I or long term data collection the ratio of the NU LVDT to the system Y sensor was found. The peak data points collected, denoted with red dots, in Figure 7.1 are presented in Table 7.1 and graphically in Figure 7.2. The NU LVDT has been used previously in ACM applications and has been tested for compliance and is therefore used as baseline for comparison. The ratio of measure displacement of the NU LVDT to system Y was found to be 0.52 during long term operation.
Figure 7.1 Comparison of the displacement time histories for the NU LVDT, System Y linear potentiometer crack gauge and indoor temperature. Gray jagged lines are a 1 hour rolling average; and the black lines are a 24-hour rolling average. (red dots indicate points used to calculate the long term static ratio.)
Table 7.1 System Y and NU LVDT calculated changes in displacement from the data collected in Figure 7.1.

<table>
<thead>
<tr>
<th>NU LVDT ΔDisplacement (µm)</th>
<th>System X ΔDisplacement (µm)</th>
<th>Ratio NU/X</th>
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</thead>
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</table>

Figure 7.2 Long term system Y versus NU LVDT data used to determine the system X long term or static ratio

Y = 0.52X
R = 0.986
To determine if displacement recorded by system Y is caused by the thermal expansion of the ceiling material or the crack, the response of null gauge must be compared to that of the crack gauge. Figure 7.3 is a comparison of the displacements recorded by both the crack and null sensors mounted on the same piece of drywall and spaced within 0.5m of each other. The System Y null gauge was mounted on an uncracked section of ceiling. As expected, the null gauge showed little to no response during testing. Any small spikes in data as shown by grey line in the null displacement on Figure 7.3, could be attributed to electronic noise. Since the readings of the null gauge were so low, it was confirmed that the crack sensor was measuring the displacement of the crack and not the displacement of the ceiling material or temperature response of the sensor body. Upon removal it was discovered that the null gauge was not operable and therefore it is not absolutely certain that the zero response in Figure 7.3 results from low thermal response of the system.

![Figure 7.3 Comparison of the System Y Crack and Null gauges over two-month duration of testing](image)
Level II Operation

Level II systems record simultaneously long term crack response and ground motion and dynamic crack response during blast events. The system begins recording dynamic response when the ground velocity exceeds the trigger value. Crack responses are measured as micrometer changes in crack width at high sampling rates (normally 1000 Hz). Long term crack width is recorded at regular time intervals ranging from every 15 minutes to once an hour for comparison with the long term environmental and dynamic effects. Collection of the long term data during level II operation was identical to level I system operation.

Level II evaluation was also conducted in the Milwaukee test house by comparing the response of system Y across a ceiling crack with that of the NU system. During simultaneous operation of system Y and the NU system, it was found that the NU system introduced higher noise levels to system Y. As a result of this conclusion, system Y was operated both with and without the NU system. Data collected during the operation of system Y was evaluated by comparing to the historical data from the NU system.

Level II Equipment Setup

To evaluate the operation of system Y at level II, the equipment was installed to record data as described in Chapter 5. Long term data collection was enabled by setting the histogramcombo function to record the peak crack displacement every 15 minutes. The system was set to record ground motion and trigger the crack monitor to dynamic time histories when the ground motion exceeded 1.02 mm/sec (0.04 in/sec).
**Level II Data Collection**

Level II data were collected over two months of operation in May and June of 2005. During the construction season, blasts occurred about once a week. On days when blasting did occur, two or three individual blasts would be observed within approximately an hour. As shown in Table 7.2, 19 blasts were recorded during level II evaluation of system Y. During monitoring, the peak particle velocity (PPV) of the ground motion ranged from 1.02 to 6.73 mm/sec with an average PPV of 1.84 mm/sec. The largest blast recorded during monitoring occurred on May 19, 2005. During the largest event the system Y geophone, inside on the basement floor, recorded a PPV of 6.73 mm/sec. The NU geophone position outside of the test house located closer to the quarry, recorded a PPV of 8.20 mm/sec and the even closer quarry geophone recorded a PPV of 9.73 mm/sec. Since the design of system Y for capturing ground motion is well documented, it will not be evaluated.

Records obtained from the quarry indicated 24 blasts occurred during the two months of evaluation of system Y. Approximately 80% of blasts were large enough to trigger system Y. Any blast that did not trigger system Y during testing had attenuated below the trigger value of 1.02 mm/sec by the time the ground motion reached the test house basement.

During level II testing of system Y, the unit was operated in two crack noise environments while in the same blasting environment. The first noise environment occurred when the NU equipment was operating and the noise levels averaged 5.3 \( \mu m \). At this noise level the crack displacement during an event was completely masked by the noise. Any data collected when the NU equipment was operating required frequency filtering before it could be analyzed. When the nearby NU equipment was deactivated the noise level decreased to 1.3 \( \mu m \).
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<th>Date</th>
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Table 7.2 Summary of blast data collected during level II testing of system Y. *Denotes events record with the gain set to 1x. *Denotes events that did not require noise filtering. (NU system inactive)

**Level II Performance**

Peak dynamic crack displacements measured by the system Y linear potentiometer was compared to the NU LVDT and Kaman sensor. The evaluation of the sensors included a direct comparison of the shape and amplitudes of the waveforms. Figure 7.4 compares the dynamic response of the NU LVDT and Kaman sensors to the system Y linear potentiometer, for the same blast event. To create a direct level II comparison of system Y to the NU system, the system Y waveform was filtered to remove frequencies above 50 Hz. The shape of the waveform captured in Figure 7.4 by system Y, was similar to the waveform captured...
by the NU LVDT and Kaman. All waveforms showed a peak crack displacement due to ground vibration 0.5 second into the blast. Additionally, all waveforms have a large low frequency peak at approximately 1.25 seconds from the air overpressure wave of the blast event. The system Y waveform displayed a larger peak crack displacement than the LVDT and Kaman sensors after filtering.

An adequate ACM system should have a consistent ratio of crack displacement for dynamic and long term responses. In addition, the ratio between one ACM system and another should remain relatively constant. Therefore, there are two measures of consistency
for an ACM system. First consider the average ratio of the dynamic responses shown in Figure 7.5 where four different blasts that occurred on June 2, 2005 are compared. Second, the ratio during long term response found during level I evaluation can be compared. Figure 7.5 shows data points that correspond to the maximum displacement response from ground motion and air overpressure of the system Y and NU LVDT sensors. During each event one of the peaks represents the ground motion induced crack response and the other represents the peak air overpressure induced crack response. In this case, the air blast response is always the largest.

Interpretation of ratios of the NU LVDT to system Y response is very complicated. For instance, the ratio for long term effects (shown in Figure 7.2 as 0.52), is 40% of the ratio of dynamic effects (shown in Figure 7.5 to be 0.32). While these ratios could be used to adjust the dynamic response to be comparable to the long term response, it may not be the proper adjustment because of filtering and the difference in noise compared to signal for dynamic and long term response. Unfortunately, to obtain a comparison requires simultaneous operation of the NU system, which induces high noise levels.

The required filtering of the system Y waveforms to reduce the effects of noise reduces the amplitude of the signal. Thus, had filtering not been required, the resulting waveforms would have had larger system Y crack response amplitudes and thus, a smaller dynamic ratio of the NU LVDT to system Y.

The noise level of system Y while the NU system was operational was much larger then the dynamic crack response amplitude but small with respect to the to the long term crack response amplitudes. For example during a blast event with a ground motion of 0.1 PPV there was only 1 µm of crack displacement (zero to peak) while the noise with the NU
system operational was 5.3 µm (zero to peak) or a 530 % of the signal. This high noise level shown in Figure 5.5 of Chapter 5 required filtering to obtain any signal relating to crack displacement, which complicates the comparison as discussed above. On the other hand the noise level is only 10% of the signal for a typical long term, weather induced crack response shown in Figure 7.3.

Figure 7.5 (Top) Comparison of the maximum and minimum displacements of system Y with the NU LVDT sensor during dynamic recording. These four events (denoted by symbols) occurred on June 2, 2005. (Bottom) Example of how the dynamic ratio was selected for a given filtered waveform.
To illustrate system Y’s ability to capture a complete blast response, two different examples of the data captured by the system are reviewed. These events can be used to determine the overall effectiveness of the system’s ability in capturing level II data as an independent system. The first event shown in Figure 7.6 depicts a blast event that occurred on June 9, 2005 and resulted in a temporary offset of the crack baseline. During this blast the geophone recorded a PPV of 2.79 mm/sec on the vertical channel. The corresponding crack displacement due directly from the ground motion was less than 2µm, peak to peak, which is barely above the noise level of 1.3 µm peak to peak. The larger crack response shown in Figure 7.6 due to the air overpressure wave that reached the structure approximately a second after the ground motion was 2.6 µm peak to peak.

The long term and dynamic data collected with system Y during the day of the June 9th blast, can be compared to determine the significance of magnitude of the dynamic response of this blast to the total crack displacement due to all effects including the weather. The long term movement of the crack and dynamic displacement during the June 9th blast are shown together in Figure 7.7. Peak to peak displacement of the crack due to the blast air over pressure of 2.6µm is relatively insignificant. The dynamic crack movement is an order of magnitude higher compared to the daily movement of the crack at 25 µm due to the various environmental effects.

System Y captured a small temporary baseline shift of 0.9 µm in the crack time history shown in Figure 7.6. The June 9th blast was the second largest recorded during the entire monitoring period with PPV of 2.79 mm/sec. The time history captured showing the offset shown in Figure 7.6 is only three seconds long. As seen in Figure 7.7, temporary offset does not change the overall sinusoidal response pattern and is thus not an offset in any
permanent sense. Compared to the daily long term movement of the crack, the temporary change was only 3.6% of the daily movement in the displacement as shown in the figure.

The second example to illustrate system Y’s ability to capture the cracks response to a blast is shown in Figure 7.7. This blast event recorded with system Y, on June 30, 2005 was more typical of the blasts seen during monitoring and had PPV of 1.14 mm/sec on the vertical channel of the geophone. This blast shows a small peak crack displacement due to the blast vibration when compared to the June 9th blast, but a large low frequency crack displacement due to the air overpressure. The June 30th blast shown in Figure 7.8 which has far lower ground particle velocities compared to the June 9th blast, shown in Figure 7.6, has an equivalent peak to peak crack displacement of 2.4µm due to air overpressure.

Figure 7.6 System Y recorded crack displacement from a blast occurring June 9, 2005 where a temporary offset occurred.
Figure 7.7 Comparison of the crack displacement captured by system Y both long term and dynamically during blasting on June 9, 2005 where an insignificant temporary offset occurred.

Figure 7.8 System Y recorded crack displacement from a blast occurring June 30, 2005 during which the crack responded primarily to the air blast.
Chapter 8

Conclusion

This thesis summarized the qualification and testing of two commercial Autonomous Crack Monitoring (ACM) systems for use in measuring micrometer displacement of cracks. Qualification involved the assessment of both laboratory and field performance in a residential structure subjected to nearby quarry blasting for the production of roadway aggregate. Aggregate and construction industries are dependant on procedures that cause vibratory ground motion and would benefit from a commercial ACM system. Currently, only research grade equipment is available for ACM monitoring which is expensive, unwieldy and requires specialized knowledge to operate.

Performance at three levels of monitoring has been evaluated. During level I monitoring only long term crack displacement response to environmental effects was recorded. During level II monitoring both long term and dynamic (triggered by ground motion) crack displacements are recorded. At the highest level of monitoring, level III, long term and dynamic crack displacements are recorded with dynamic response triggered by crack response and/or ground motion. Crack displacement triggering allows recording of crack responses to occupant activities or other non ground motion events such as wind gusts.

Conclusions regarding each system are subdivided into the following categories: installation, laboratory testing and field testing for each system. Their capabilities are
compared to the Northwestern (NU) system response, which serves as a base line for performance. Evaluation of system X, is summarized first, followed by that of system Y.

**System X**

**Analysis of the installation, software and literature**

- Installation of system X in a residential structure can be completed in one day to measure ground motion, air overpressure and crack response.
- Crack displacements can be recorded in level I, II and III monitoring modes.
- Electromagnetic interference occurred at the 60 Hz, which is a common household power frequency.
- When employed in close proximity with the NU instrumentation system, noise levels increased.
- On-site programming can be completed via the key pad or a laptop computer through a serial connection, which may require a USB to serial converter for most laptops.
- Remote programming can be accomplished with the “get and set” method, because the easier to program TTY mode is less stable.
- Two software packages, Seismic Analysis and Event Manager, are required to view and process the data collected.
- Current literature for operation focused on ground motion monitoring; more ACM specific literature would be helpful.
**Laboratory testing**

- Long term temperature induced displacement responses were linear with minimal hysteresis.
- Dynamic excitation responses were similar to the control system in both frequency and magnitude.
- Temporary offsets in crack displacement can be captured during operation with the DC coupled channel.

**Field testing (by level of operation)**

*Level I*

- Long term crack displacement followed the changes in temperature and humidity in a pattern similar to that followed by the NU control system.
- Ratios of measured long term displacements (NU LVDT/system X) were constant, but greater than one throughout the qualification.
- Long term linearity and hysteresis remained similar during separate studies of the same crack response.

*Level II*

- During level II testing, ground motion triggered crack responses were similar to the NU control system response, yet smaller in magnitude.
- Only filtered dynamic data can be compared to that measured by the NU LVDT, because of the high level of noise produced by the NU system combined with the low signal.
• Two channels must be reviewed during level II operation; a DC coupled channel for long term crack response and an AC coupled channel for dynamic crack response.

• Calculation of ratios of dynamic response required filtering, to remove noise and allow a direct comparison to the NU system.

• Ratios of (NU system/system X) displacements for long term and dynamic responses of the same crack were within 25% of each other, despite the complexities imposed by high noise levels and filtering.

**Level III**

• Many crack responses triggered by occupant and environmentally induced events were captured.

• Crack trigger levels at specific locations may have to be varied because of large numbers of occupant generated events.

• Crack responses with small temporary offsets can be compared to the long term trends in the crack displacement to show their insignificance.

• Deliberate occupancy events were initiated to obtain time histories whose signatures could be correlated with otherwise unknown dynamic event time histories.

• Wind gust velocity, collected from the nearby airport correlated in time with dynamic crack displacement.

• Dynamic crack response studies can be under taken to identify trends in the occupant’s daily activities and their effects on crack displacement.
System Y

Installation, software and literature

- Installation of system X in a residential structure can be completed in one day to measure ground motion, air overpressure and crack response.
- Crack displacements can be recorded in level I and II monitoring modes.
- Electromagnetic interference occurred at the 60 Hz, which is a common household power frequency.
- When employed in close proximity with the NU instrumentation system, noise levels increased.
- On-site programming can be completed via the keypad or a laptop computer through a serial connection, which may require a USB to serial converter for most laptops.
- Remote programming can be accomplished with the system specific software and an internet or mode connection.
- One software package was required to view and process the data collected.
- Current literature for operation focused on ground motion monitoring; more ACM specific literature would be helpful.

Laboratory testing

- Long term temperature induced displacement responses were linear with modest amounts of hysteresis.
- Dynamic excitation responses were similar to the control system in both frequency and magnitude.
• Temporary offsets in crack displacement can be captured during operation with the DC coupled channel.

• It was discovered that the null crack gauge supplied by the manufacturer was inoperable.

• During low amplitude dynamic tests, the system Y sensor was found to absorb typical displacement created by low force excitation and only responded to the larger excitation forces.

Field testing (by level of operation)

Level I

• Long term crack displacement followed the changes in temperature and humidity in a pattern similar to that followed by the NU control system.

• Ratios of measured long term displacements (NU LVDT/system Y) were constant, but less than one throughout the qualification.

• Long term crack displacement was found to follow the changes in temperature and humidity in a pattern similar to that followed by the NU control system.

• Lower than expected null displacement was recorded during monitoring, which may or may not have resulted from a malfunctioning null gauge.

Level II

• During level II testing, ground motion triggered crack responses were similar to the NU control system response, yet smaller in magnitude.
• Only filtered dynamic data can be compared to that measured by the NU LVDT, because of the high level of noise produced by the NU system combined with the low signal.

• Calculation of ratios of dynamic response required filtering, to remove noise and allow a direct comparison to the NU system.

• Ratios of (NU system/system Y) displacements for long term and dynamic responses of the same crack were within 40% of each other, despite the complexities imposed by high noise levels and filtering.

• Each event’s, ground motion, air overpressure and crack displacement are contained within one record.

This study has made significant progress in the commercialization of ACM systems by verifying the operation of two commercial ACM systems in both the laboratory and field. Based on the measured data and the field experience from this study the following recommendations for future work are suggested. Further development of the manuals, literature and software that would accompany a commercial ACM system is needed. Improved literature and software would allow for ACM system to be installed and operated efficiently by a field technician with minimal experience. ACM systems should add the capability of autonomously collecting temperature and humidity data. Integrated temperature and humidity sensors would reduce the current dependency of these systems on external, stand alone temperature and humidity loggers. Finally, improved displacement sensors could reduce signal noise and increase recording resolution.
References


McKenna, L.M. (2002). *Comparison of Measured Crack Response in Diverse Structures to Dynamic Events and Weather Phenomena*, M.S. Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL.


