

**ADDENDUM I**

**DIRECT MEASUREMENT OF  
CRACK RESPONSE AT FOUR OSM STUDY STRUCTURES**

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## **Introduction**

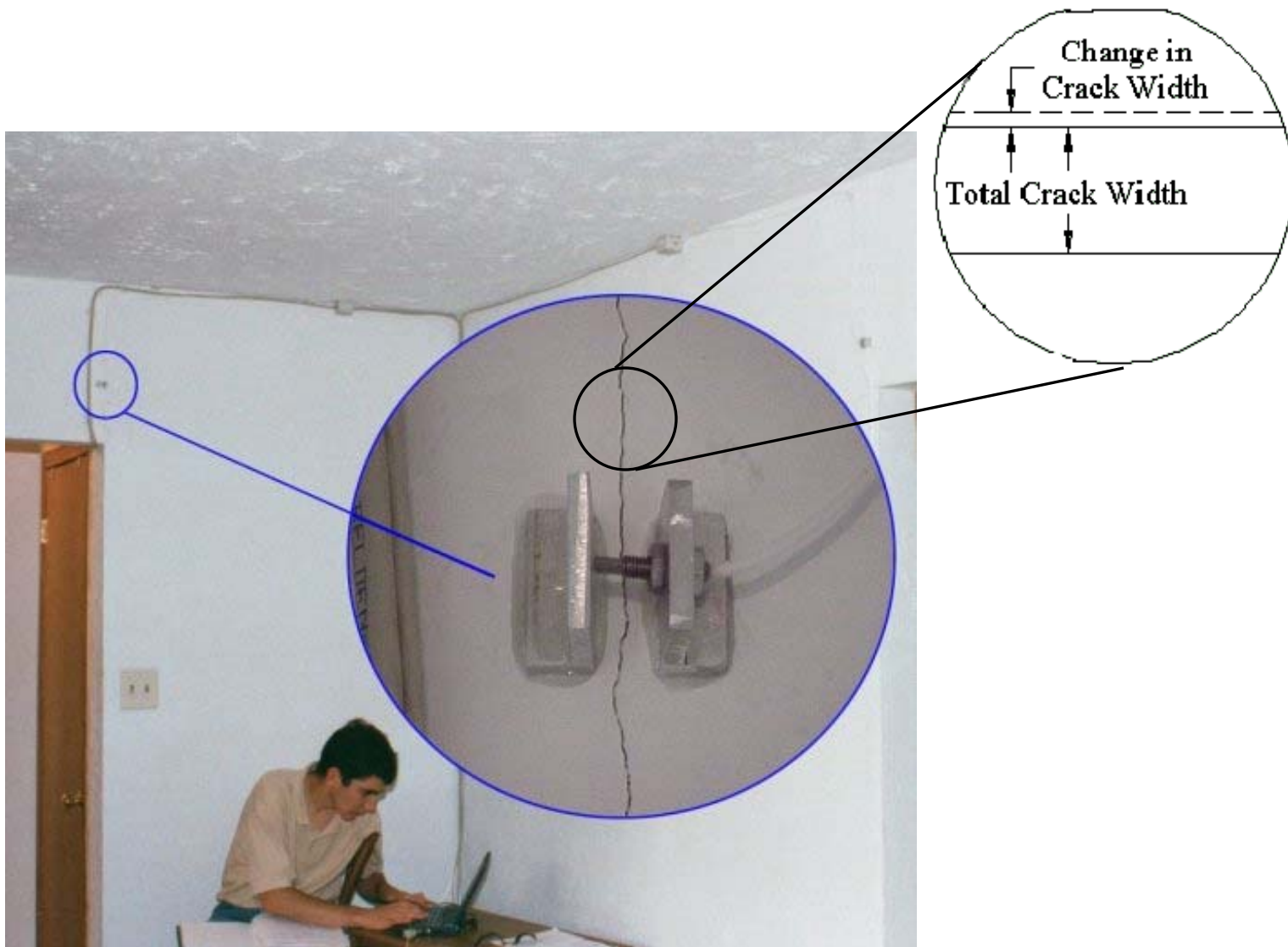
This appendix synthesizes micrometer changes in crack width in response to both long term (environmental) and transient (blast vibration) of four of the structures in the main body. The appendix begins with a description of the genesis of the study and instruments employed. Response of the distressed wood-framed structure in Indiana is then employed to describe a typical suite of measurements. Long term crack response over periods of days to weeks is compared to changes in the temperature and humidity. Transient crack response to blast and occupant induced motions is then compared to peak velocity ground motions and structural response (the traditional approaches to investigation of cracking potential). Finally, the transient and long term changes in crack width are compared.

## **Direct Measurement of the Change in Crack Width**

Currently, complaints are addressed by measuring peak ground motions outside the structure with a blasting or vibration seismograph. These measured peak ground motions are then compared with standards developed by federal or state government agencies. Augmenting the measurement of ground motions, with which the average person may be unfamiliar, with direct measurement of crack response provides another means to discuss what is often of greatest concern, cracking.

Advances in sensor technology and computerized data acquisition now make it possible to simultaneously measure crack response to both long term and vibratory effects. Relatively inexpensive systems that combine measurement of both crack response and ground motion have been developed that involve the manual downloading of data on a periodic basis. They have been employed in this study to investigate their feasibility. These systems can be combined with telecommunications for near real-time display on the Internet to allow access to a wide variety of interested parties.

A special dual-purpose sensor like that shown in Figure 1 can be placed across a crack to simultaneously measure long-term and vibratory response in terms of changes in crack width. This direct measurement, termed "crack displacement" is simple to understand and requires no reliance upon empirical guidelines. As shown by the insert in Figure 1, these sensors do not measure total crack width, but rather the change in crack width. Total crack widths could be



**Figure 1 Typical threshold crack in a one-story concrete block house**

calculated from the change by adding the change to the initial total crack width. For the remainder of this appendix change in crack width will be referred to as change in crack width or crack displacement.

Maximum total crack width is an index of potential extension of a crack. In other words, the greater the increase in total crack width (displacement plus initial crack width) the greater the potential for crack extension. Figure 2 shows the results of special tests (Miller, 1995) to determine the change in crack length with the change in the crack mouth opening. The change in crack mouth opening is analogous to total crack width, as defined above. In the test summarized by Figure 2, a specimen of cement paste like that shown in the insert, was subjected to increasing force,  $F$ , at the mouth of a crack of length “ $a$ ”. As  $F$  was increased, the crack mouth opening, or crack opening displacement (COD), increased, as did the crack length,  $a$ . The main graph portrays the change in COD with the extension of the crack. For instance, as COD increased from 3.5 micrometers (+ 7 to - 7 =  $14 \times 10^{-5}$  inches =  $140 \times 10^{-6}$  inches = 140 micro-inches) to 7.5 micrometers (+ 15 to -15) the crack extended from 1.4 to 1.6 inches (35.5 to 40.6 mm).

Measurements summarized in Figure 2 show the crack extending only when it experiences a displacement that surpasses the maximum total crack width experienced. Thus, if the crack width remains less than its maximum historic value, it will not extend. However by logical extension, it can be said that the greater the crack displacement, the larger is the potential for cracking.

## Crack Displacement Sensors

While the authors have employed both eddy current proximity sensor and linear variable differential transformers, LVDT's in other studies, only the eddy current sensors were employed in this study. The principle of employing the same sensor to simultaneously measure crack displacements produced by both long-term and transient effects is not dependent on the type of sensor. Therefore, any number of sensor types can be employed. Details pertaining to the performance of a variety of different displacement sensors used in crack monitoring can be found in other references (Siebert, 2000) and (Louis, 2000).

Eddy current proximity devices sense the changes in a magnetic eddy current produced by changes in the distance between the sensor and the target. As shown in Figure 1, two aluminum brackets are epoxyed on either side of the crack, at a distance of 0.25 in (6 mm) apart. The eddy current device employed in this study, the Kaman 9000 2U, has a displacement range of 508 micrometers (20 mils) with resolution of 3.9 micro-inches (0.1 micrometers). While the 9000 2U is the more expensive of the Kaman devices, it has the least long-term drift (Siebert, 2000).

A second crack displacement sensor was also affixed to a non-cracked section of the wall in structures W1S-IN and W2S-IN to null out any possible long-term drift and temperature response. The difference in the response of the two sensors (crack minus null) is thus attributed solely to the crack, as described in (Siebert, 2000) and (Dowding and Siebert, 2000). Data presented later will show that null sensor response is typically small and null sensors are often not needed.

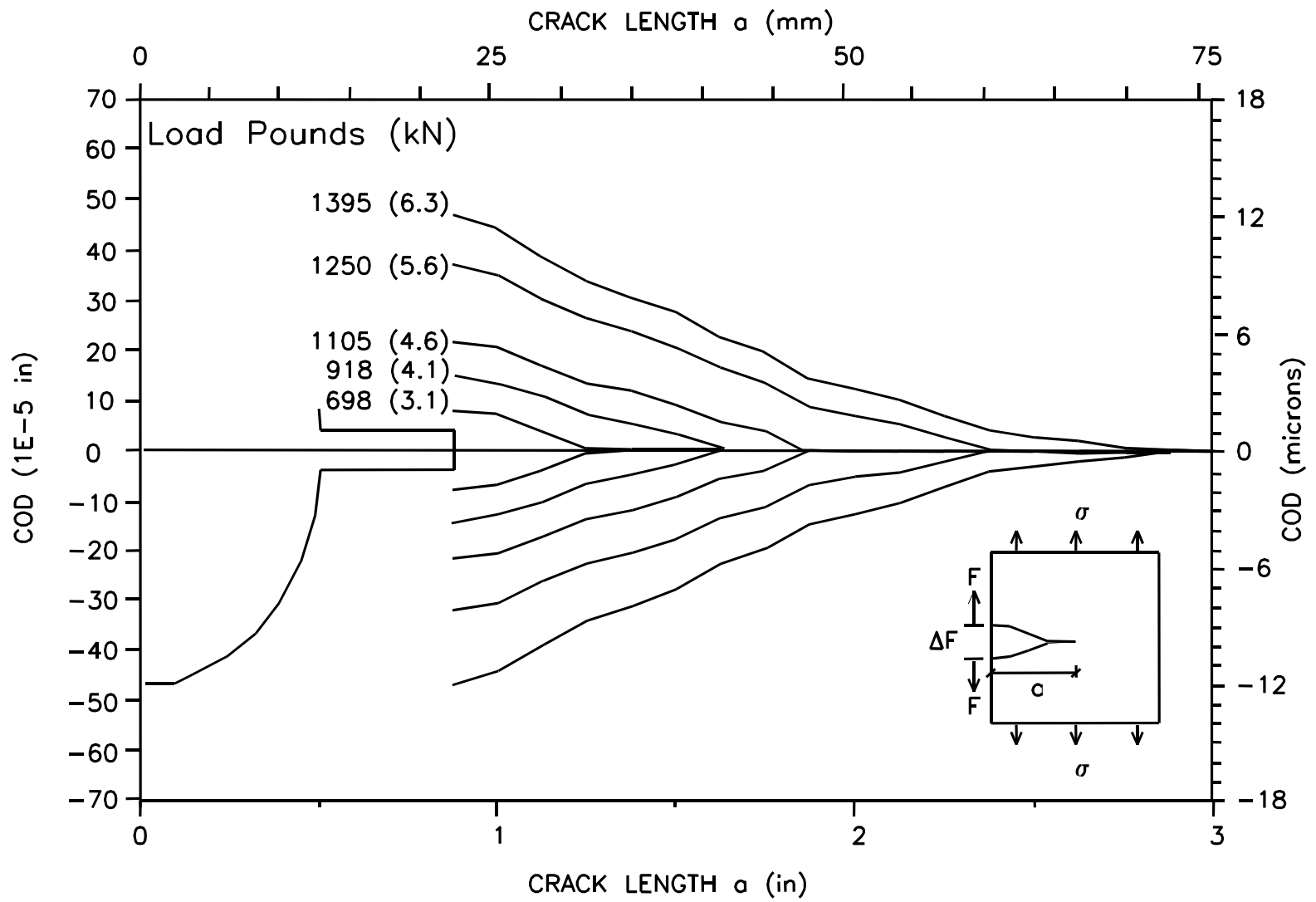


Figure 2 Experimental verification of proportionality of crack width and length

The Data Acquisition System (DAS), used to collect crack response was a Somat 2000/2100 Field Computer System (Somat, 1999 & 2001). For transient crack response, the sampling rate of the system was 1000 samples per second. System resolution of the DAS was governed by either A/D resolution or sensor resolution; however, in these cases the two were similar: between 0.65 and 0.083 micrometers per A/D division (unit). Long-term crack measurement was accomplished by measuring crack displacement once every hour. The time series of these “hourly” readings provides the long-term crack displacement time history. This “long term sampling” feature is not available on standard vibration monitors at this time, although its development is underway at most manufacturers.

## Homes and Cracks Studied

The four structures wherein crack response was directly measured are photographed in Figure 3, and diagramed in Figure 4. These four structures were instrumented with crack sensors in addition to the motion sensors that were implemented for the study. The houses were located in Pennsylvania, New Mexico, and southern Indiana. Both structure type and location varied widely, and included a double-wide trailer (TD-PA), an adobe brick ranch house (E1S-NMB), a bungalow with a concrete block basement (W1S-IN), and a highly distressed wood-framed house (W2S-IN). All structures were one story, and all but E1S-NMB were founded on a basement.

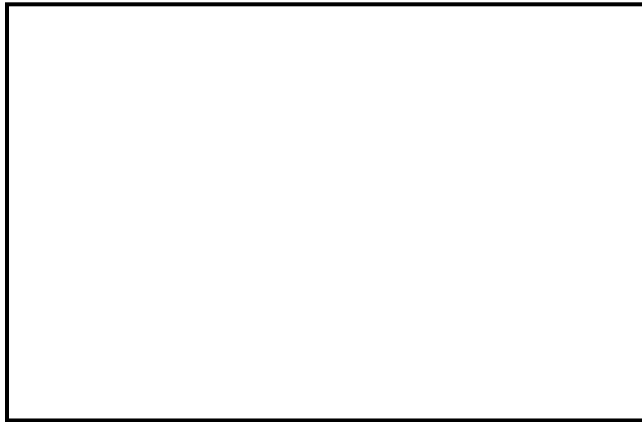
All four structures were subjected to ground motions generated by surface coal mining. Maximum peak ground motions (parallel to the walls containing the cracks) ranged from 0.1 to 0.3 ips (2.5 mm/s to 8 mm/s), and generated responses that lasted between 1 to 4 seconds. Occupant induced crack response was recorded in TD-PA and W2S-IN. The blast vibration environment for all 4 structures is summarized in Table 1. See the “Velocity Transducer” section for details of the location of the velocity transducers. As shown in the table these ground motions generated structural response velocities (S2 in Table 1) of 0.17 to 0.42 ips and S2/S1 structural amplification between 1.3 and 1.6 during maximum crack response. Values of S2/g at the moment of maximum S2 would not be the same as S2/S1.

Long-term response of cracks was monitored at all 4 of the structures for varying lengths of time that were in general shorter than normal. Structures TD-PA, W1S-IN and W2S-IN were observed for one week or less, while E1S-NMB was monitored for approximately 1 month. As will be discussed at the end of the appendix, observation periods of less than a week are too short to observe maximum weather events and thus the long term measurements reported here are in a sense not as long a term as have recorded and reported elsewhere (Dowding, 1996; Louis, 2000; Siebert, 2000; McKenna, 2002).

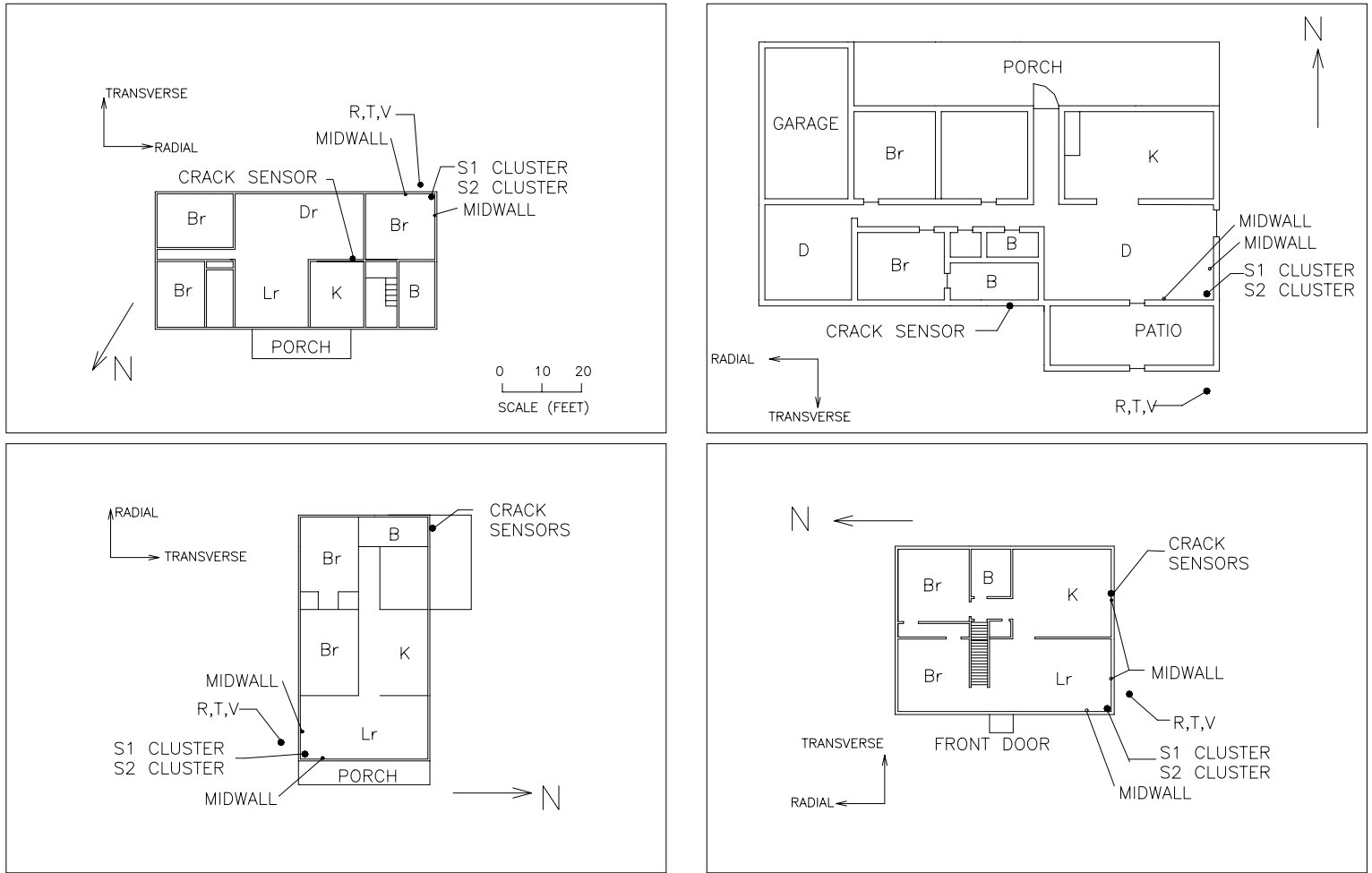
Even though all of the cracks that were monitored were cosmetic in nature, their locations varied widely and involved a wide variety of material types. These cracks were chosen as the largest and most visible in the structure. As shown at the bottom of Table 2, the width of these cracks varied from 0.019 to 0.047 in. (19,000 to 47,000 micro-inches or  $\mu$ -inches). Their locations in plan view are denoted as “crack sensor” in Figure 4. They were located on 1) interior drywall above an entryway (TD-PA), 2) interior plaster and lath above a window (W2S-IN), 3) exterior concrete block on the bottom (W1S-IN), and 4) exterior stucco over adobe bricks at the lower corner of a window (E1S-NMB).

**Table 1 Summary of maximum crack response to blasting**

Structure	Response				Maximum Ground Motion			Blast			
	Maximum peak velocity parallel to cracked wall for shot causing greatest crack response (ips)				Maximum crack response ( $\mu$ in)		Peak Frequency (Hz)	Peak Particle Velocity (ips)	Length of significant excitation (sec)	Distance from crack (ft)	Charge/Delay (lb)
g	S1	S2	S2/S1	Dynamic	Weather						
<i>Structure Identification</i>											
<i>Location</i>											
<i>Wall type</i>											
<i>Wall thickness (in)</i>											
<b>Trailer, TD-PA</b> Kittanning, PN Drywall 4	0.24	0.31	0.42	1.35	36	945	16.5	0.24	1.2	1440	612
<b>Adobe ranch, E1S-NMB</b> Farmington, NM Adobe 12	0.13	0.11	0.17	1.54	168	984	6.2	0.14	7.1	4940	9590
<b>Bungalow, WIS-IN</b> Francisco, IN Concrete Block 9	0.18	0.13	0.21	1.53	11	472	28.4	0.23	5.8	1500	451
<b>Wood frame house, W2S-IN</b> Francisco, IN Plaster/Lath 6	0.28	0.18	0.25	1.38	535	2047	14	0.3	3.2	2100	1051



**Figure 3 Four structures monitored for crack response to long-term and transient effects (clockwise from top left: TD-PA, E1S-NMB, W2S-IN, and W1S-IN)**



**Figure 4 Plan views of four structures monitored for crack response to long-term and transient effects (clockwise from top left: TD-PA, E1S-NMB, W2S-IN, and W1S-IN)**

## Velocity Transducers

Placement of velocity transducers has already been described in the main body of the report. Excitation motions were measured with standard seismographs and particle velocity transducers in the horizontally radial (R), horizontally transverse (T), and vertical (V) directions. In this study R is parallel to the long dimension of the structure. These triaxial geophones were typically located within three to ten feet of the structure and buried approximately 4 to 6 inches in the ground. An air blast (over pressure) transducer, which responded linearly between 2 and 30 Hz was installed on a 3-foot high dowel.

Response motions for the four structures were measured at the interior corner of the house nearest the buried excitation geophone block. As shown in Figure 5, two indoor seismographs, each with four separate, single-axis velocity transducers, were employed. Seismograph, S1, serviced three single-axis velocity transducers (R, T, & V) installed at the **bottom** corner of the structure, and one on the middle of an adjacent wall. The second interior seismograph, S2, was also connected to four single-axis velocity transducers. The first three were installed in the **upper** corner, and the fourth on the middle of the remaining adjacent midwall. The indoor seismographs were linked to the outdoor seismograph and thus all three were triggered simultaneously at a ground excitation threshold of 0.02 ips at the ground geophones. Data files from each of the three seismographs contained 4 channels of time histories for each triggered event. Each set of time histories was at least 7 seconds long, which was long enough to capture the entire event.

## Measured Response and Example

Figures 6 and 7 compare crack displacement with velocity time histories of excitation ground motions and structure response to two coal mining blasts at the distressed, wood-framed structure, W2S-IN. The first blast consisted of 1051 lbs of ANFO per delay and was initiated 2100 feet from the structure on 22 August 2001 at 17:30. The second blast consisted of 301 lbs of ANFO per delay and was initiated 3730 feet from the structure on 23 August 2001 at 13:00. The two blasts produced peak crack displacements of 535  $\mu$ -inches (13.6  $\mu$ m) and 101  $\mu$ -inches (2.6  $\mu$ m), respectively, with peak ground motions, parallel to the cracked wall (transverse by study convention), of 0.28 ips (6.4 mm/sec) and 0.06 ips (1.5 mm/sec), respectively. The time histories for the lower corner transverse velocity, S1(T), and the upper corner transverse velocity, S2(T), as well as their difference, S1-S2 (T), are shown. The air blast response is also included in this figure for comparison. While space restrictions prevent inclusion of all 11 time histories, they have been archived electronically and summarized in (McKenna, 2002).

The dominant frequency of each structure was estimated with at least one of two different methods: 1) the zero-point-crossing frequency determination method and 2) Fourier Frequency Spectra method (Dowding, 1996). The zero-crossing method (calculating the frequency of the structure motion from the inverse of twice the time between two successive zero-crossings) was employed when free response of the upper structure was observed after excitation ground motions. For the distressed wood-framed house, W2S-IN, values calculated from free response of the S2 (R and T) motions were averaged, for a dominant frequency of 8 Hz. The Fourier frequency approach is most useful when there is little or no free response observed. In this

method, the ratio of the FFT spectra of the structure response divided by the ground motion provides a means to determine the dominant frequency of the cracked wall. Dominant response frequencies estimated from these ratios of FFT spectra were also approximately 8 Hz.

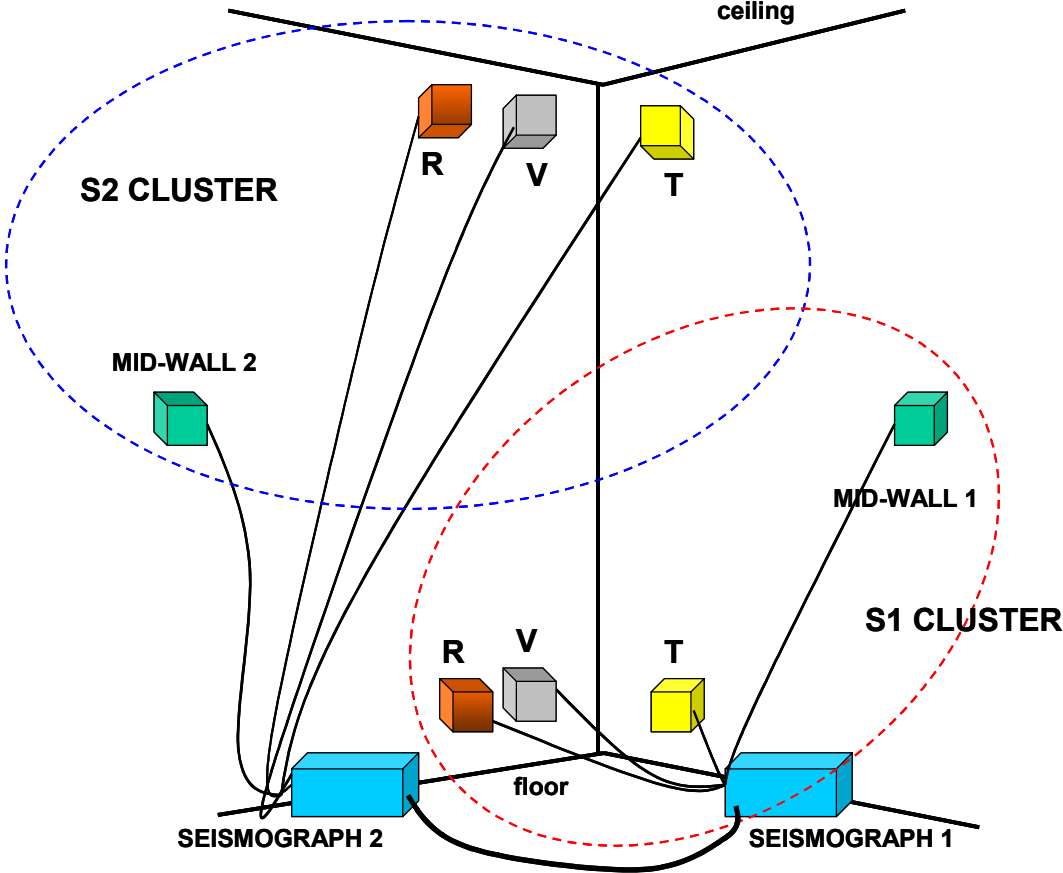
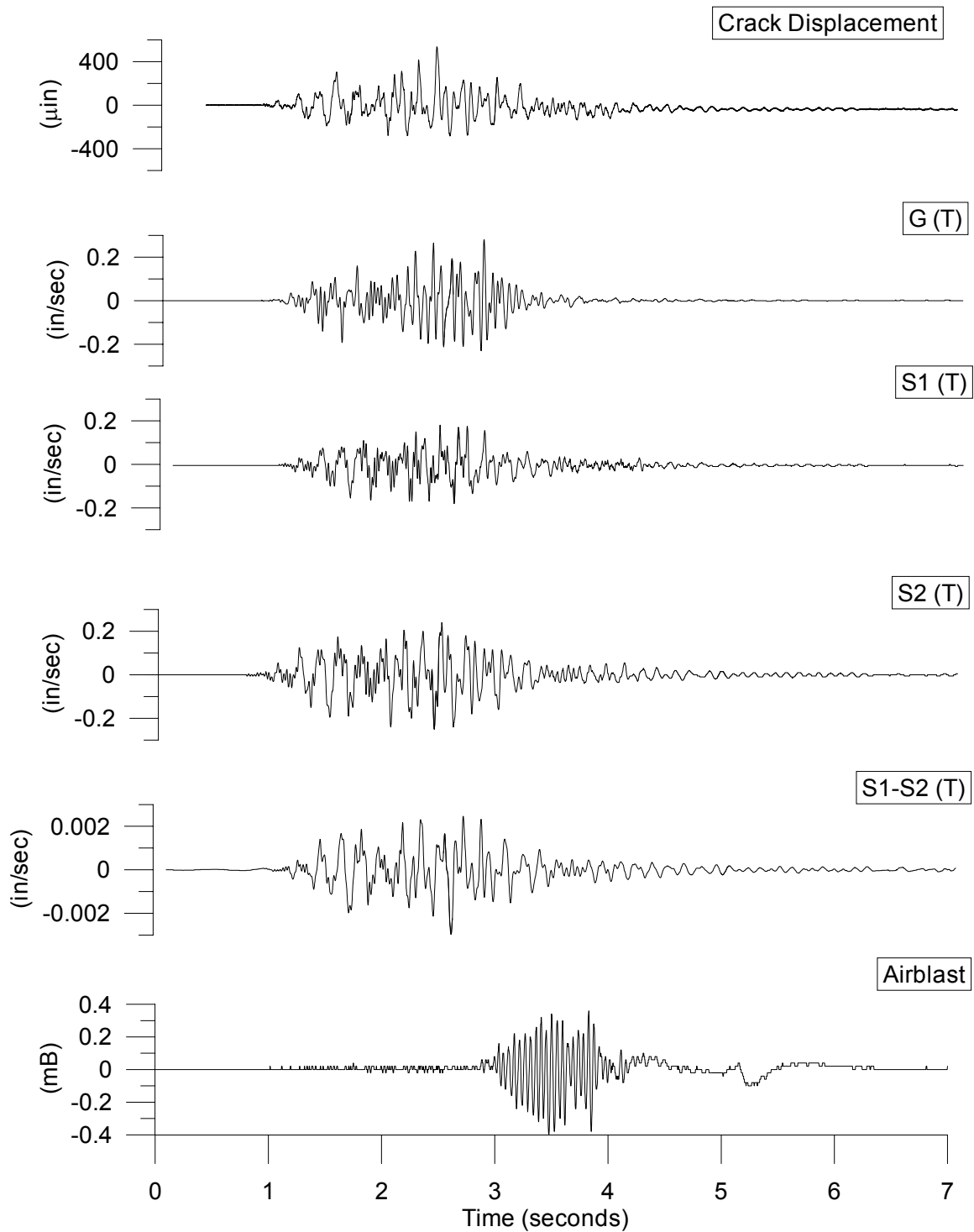
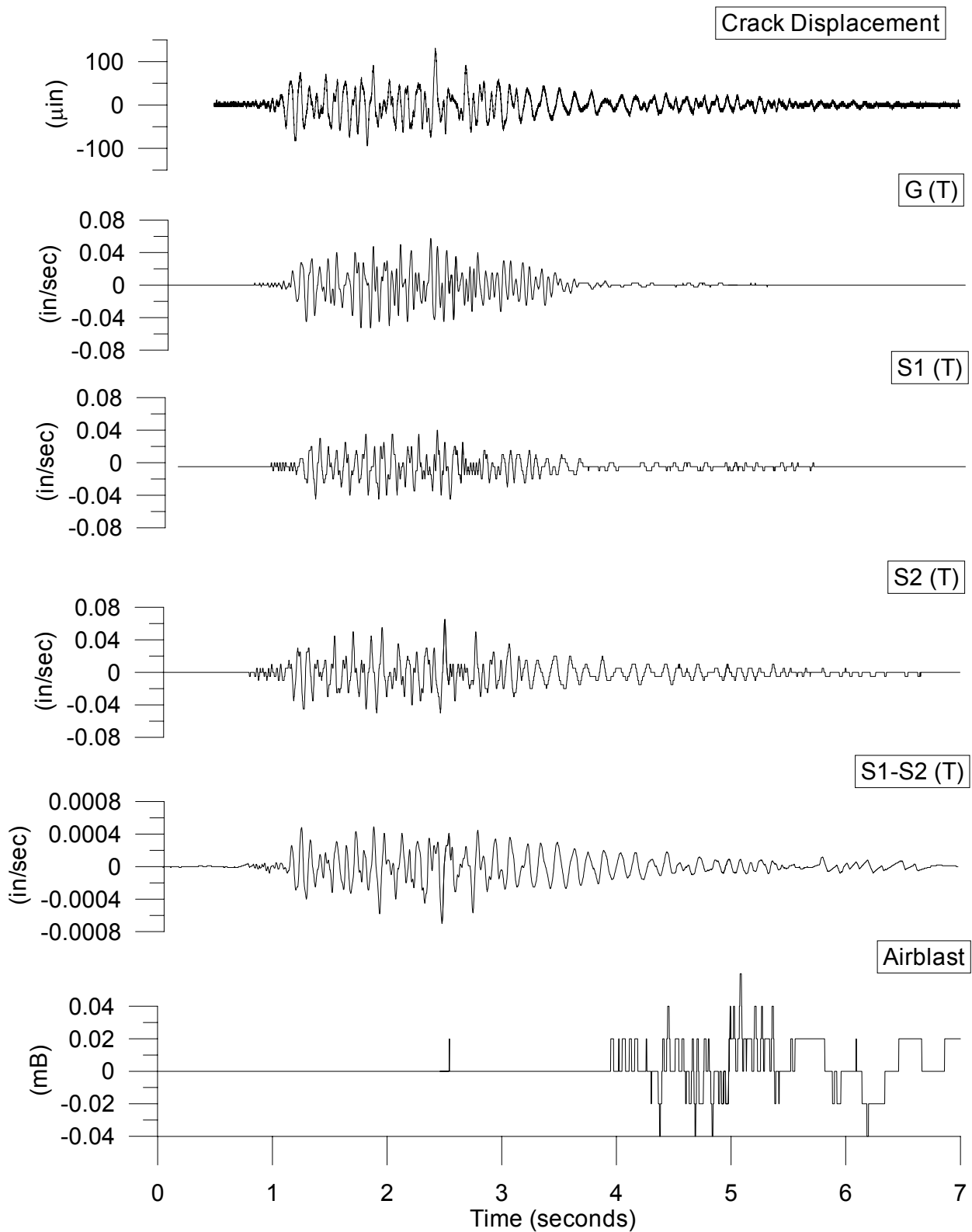


Figure 5 Typical indoor velocity transducer and seismograph set-up (Martell, 2002)



**Figure 6 Time histories of crack displacement on 22 August 2001 at 17:30 compared to transverse ground, S1, and S2 structure motions, calculated displacement of the structure (S1-S2 )T, and air blast response**



**Figure 7 Time histories of crack displacement on 23 August 2001 at 13:00 compared to transverse ground, S1, and S2 structure motions, calculated displacement of the structure (S1-S2 )T, and air blast response**

The response spectra of transverse ground motions, from the 22 August blast, as well as the one on 23 August, are displayed in Figure 8. This is a pseudo velocity spectrum wherein the response velocity is estimated as  $2\pi f$  times the relative displacement which is calculated from the ground vibration time history (Dowding, 1996). The spectrum gives the relative displacements of a family of structures with differing natural frequencies,  $f$ , with a common assumed damping of 5%. Since the approximate dominant frequency of W2S-IN was 8 Hz, the estimated displacements of the structure relative to the blast-induced ground motion were 0.0059 in or 5900  $\mu$ -in (150  $\mu$ m) and 0.0024 or 2400  $\mu$ -in (61  $\mu$ m), respectively, as shown by the intersection of the vertical 8-Hertz line with the response spectrum. These relative displacements are normally assumed to take place completely within the structure and its walls.

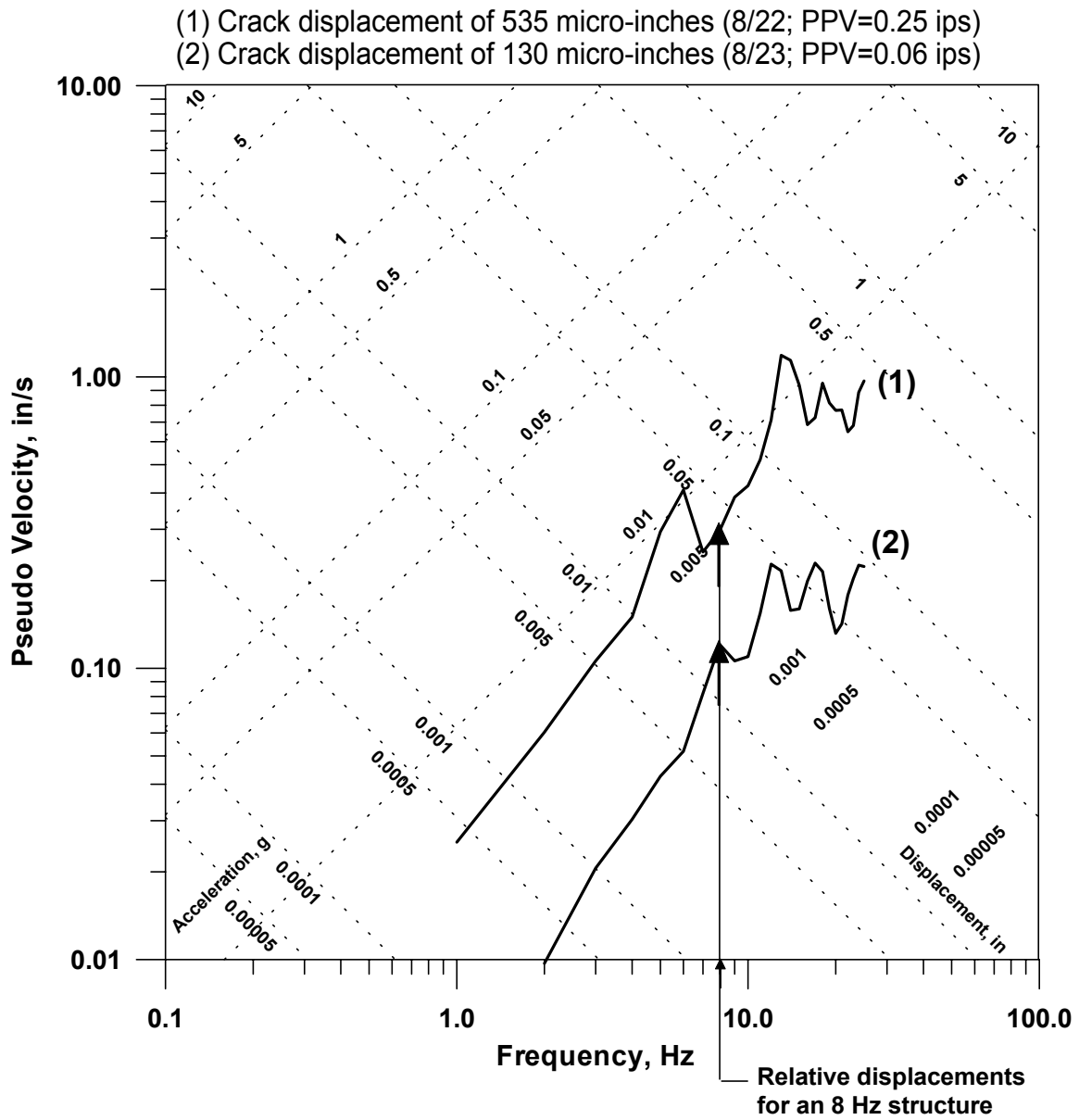
## **Crack Response to Long-Term Environmental Effects**

Crack displacement response for structure W2S-IN, is compared to the variation of weather indicators (temperature and humidity) in Figure 9 to illustrate interrelationships for the house during its three days of observation. Complete sets of these observations, for all structures, are contained in (McKenna, 2002). Long-term crack displacement was measured hourly during the monitoring period, while temperature and humidity were measured every 10 minutes. A Supco Data Logger was employed to measure Temperature and Humidity for these structures. This sensor operated separately from the DAS, but recorded readings every 10 minutes that were integrated later with the structure and crack response data

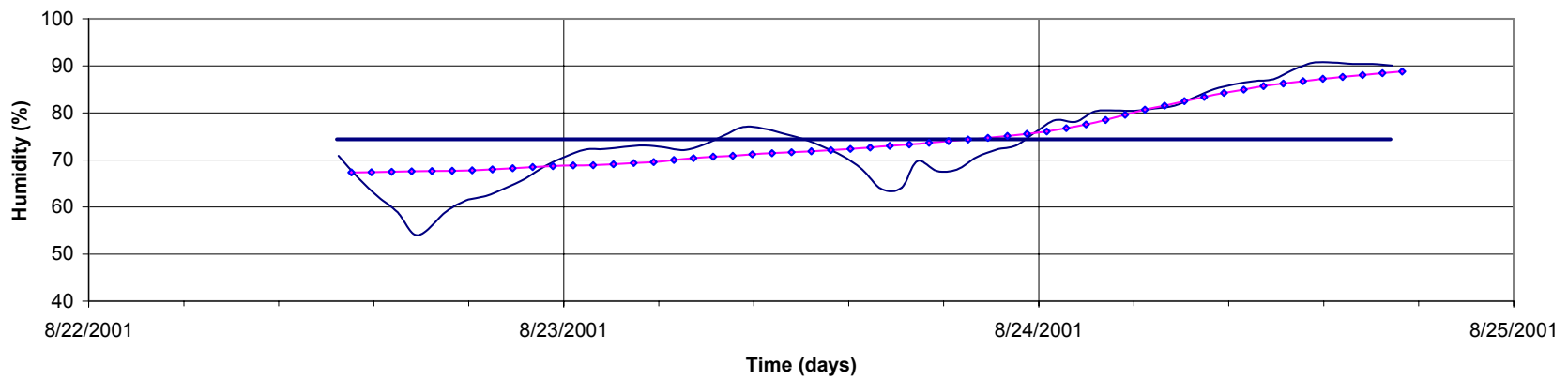
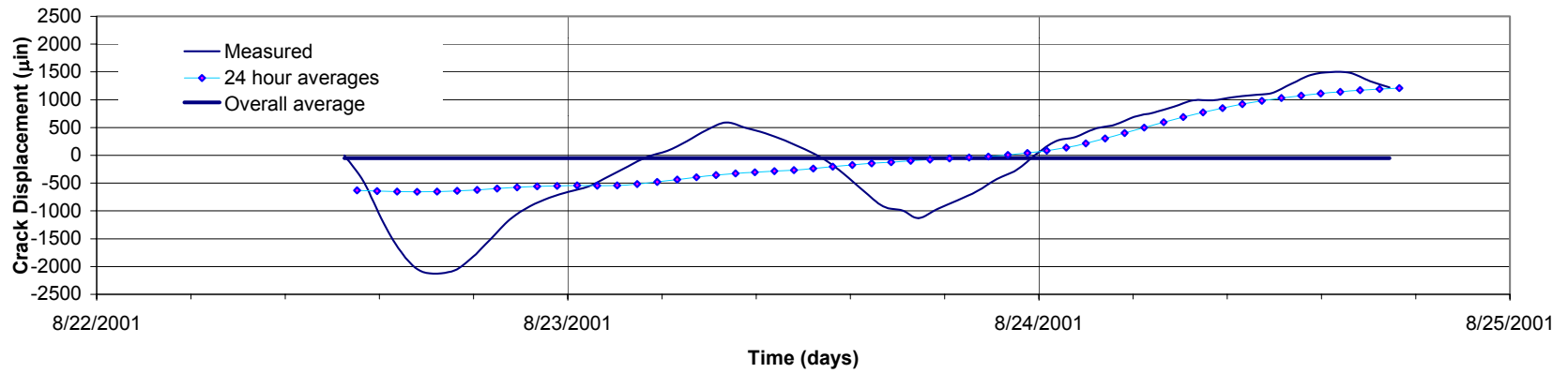
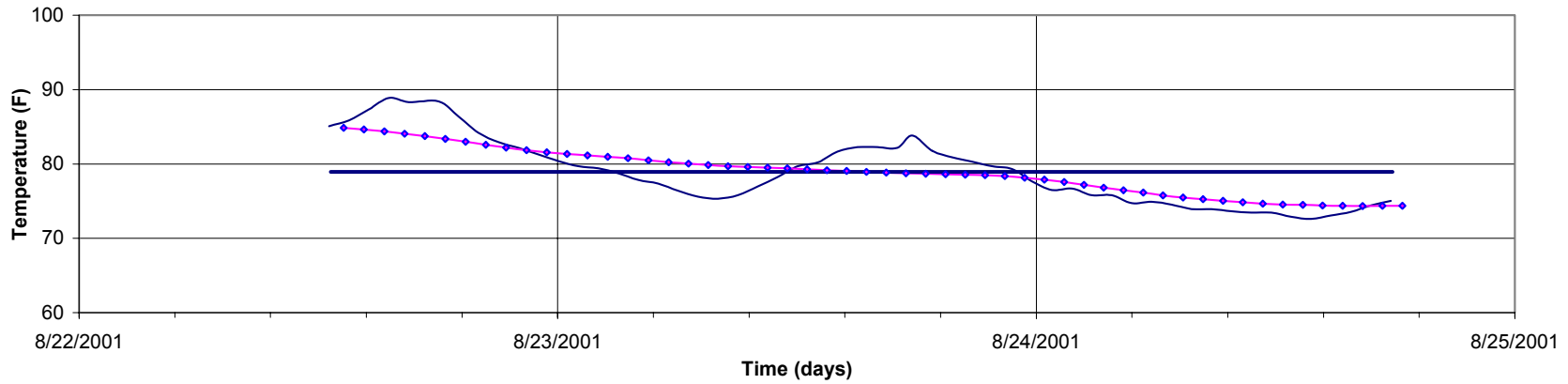
Average values of crack displacement (and temperature and humidity) were systemically calculated at every hourly measurement taken (and are shown in Figure 9 with diamond-constructed lines). These 24-hour “rolling” averages consisted of the measurements from 12 hours before and 12 hours after each hourly measurement. For example, at 12:00 p.m. on 22 August 2001, a 24-hour average crack displacement was calculated from the 24 measurements recorded between 12:00 a.m. on 23 August to 12:00 on 24 August. 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.

Overall averages, shown with the thick solid lines in Figure 9, 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.

Long-term crack response is enlarged in Figure 10 to define the specific long-term trends employed in this study, to facilitate the comparison of long-term response of all structures. 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.



**Figure 8 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 displacements of an 8 Hz structure**



**Figure 9 Long-term crack response and weather versus time for structure W2S-IN**

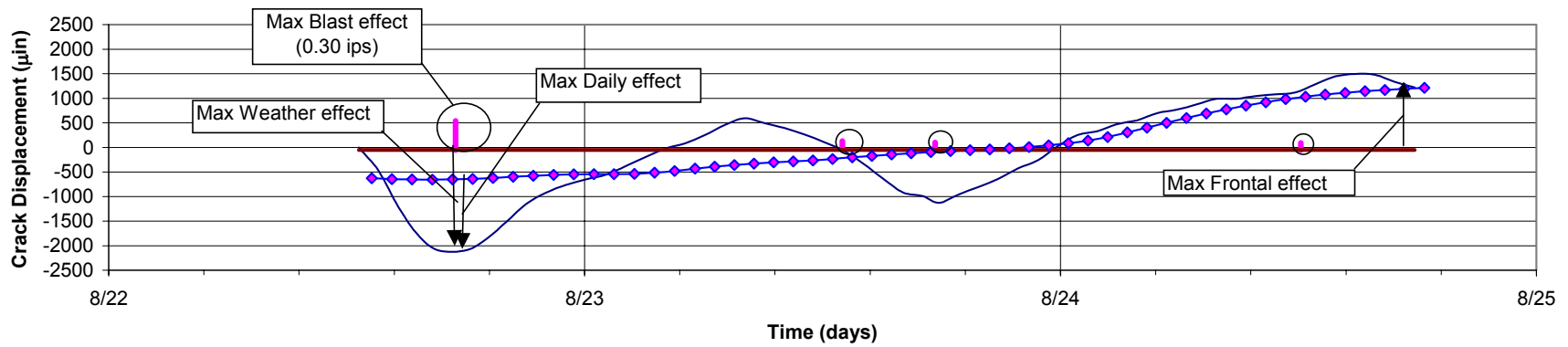
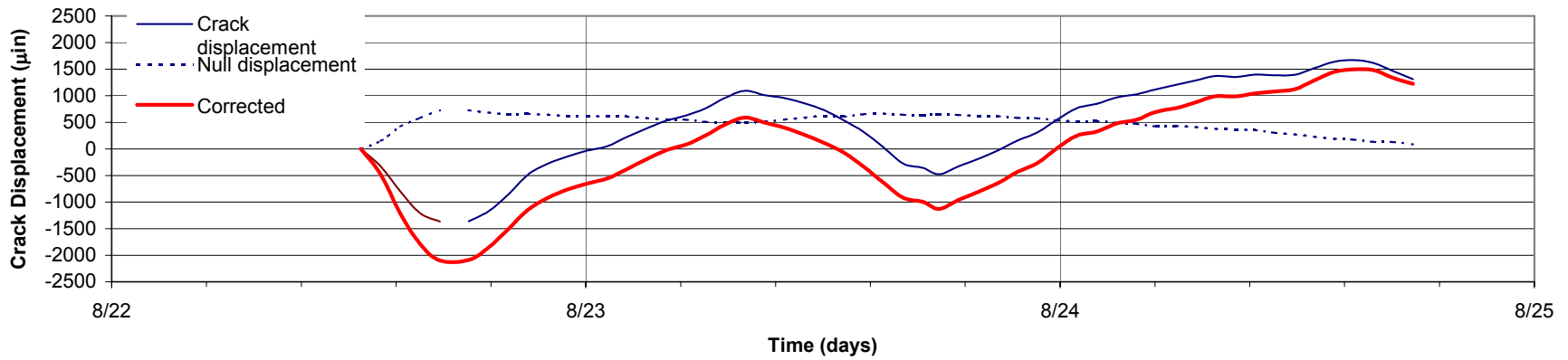


Figure 10 Typical crack response due to long-term phenomena and maximum zero to peak dynamic blast events

As shown on Figure 10, 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 maximum frontal effect on crack displacement during the three-day monitoring period of structure W2S-IN occurred at the end and was some 1300  $\mu$ -in (32  $\mu$ m). The daily effect, is defined as the difference between the peak actual measurement and 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 maximum daily effect on crack displacement during the three-day monitoring period occurred at the beginning and is some 1500  $\mu$ -in (38  $\mu$ m). The weather effect is defined as the difference between the peak actual measurement and 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 maximum weather effect on crack displacement during the three-day monitoring period also occurred at the beginning and was 2024  $\mu$ -in (52  $\mu$ m).

### **Comparison of Long-term, and Vibratory Crack Displacement**

These specific observations at the distressed house, shown in Figure 10, illustrate how small blast-induced responses are compared to those produced by weather. It also should be noted how small the weather response of the crack is compared to the actual width of the crack, which was determined to be 47,400  $\mu$ -in (1200  $\mu$ m). As discussed earlier, it was observed that cracks extended when the maximum total crack width is exceeded. In order to display the relatively, small responses associated with the blasts, the four resulting peak displacements are encircled. The maximum, dynamic crack displacement response of 535  $\mu$ -in or 13.6  $\mu$ m (0.28 ips at 15 Hz) is approximately 1/4 of the 2024- $\mu$ -in maximum weather effect response during only 3 days of observation. The dynamic crack response for the 23 August blast (in Figure 6) of 101  $\mu$ -inches (2.6  $\mu$ m) (0.06 ips at 14 Hz) was less than 1/20<sup>th</sup> of the maximum weather displacement. Had this structure been monitored for a longer period, the maximum weather response would have been larger.

Both dynamic and long-term crack displacements are small compared to the width of the crack, 47,200  $\mu$ -in. The magnitude of each dynamic measurement corresponds to the absolute, maximum zero-to-peak displacement of the crack during the significant portion of vibratory motion. This zero to peak measure is similar to the peak particle velocity measure employed in past research. Figure 11 shows long-term weather and blast-induced responses from a previous structure studied during a much longer monitoring period some 9 months (Dowding, 1996). Blast-induced responses depicted in this figure result from blasting vibration levels reaching as high as 0.75 ips. This case history (Dowding, 1996) involved large distances from large coal mining blasts where the dominant frequency of the surface wave induced ground motions was similar to the natural frequency of the structure, some 7 Hz. Structural amplification defined by the velocity response ratio  $S_2/g$ , the traditional approach, was as high as 2.8.

This figure further emphasizes the large difference in magnitude between weather response and blast-induced response of cracks when large weather events and seasonal effects are included in the observations.

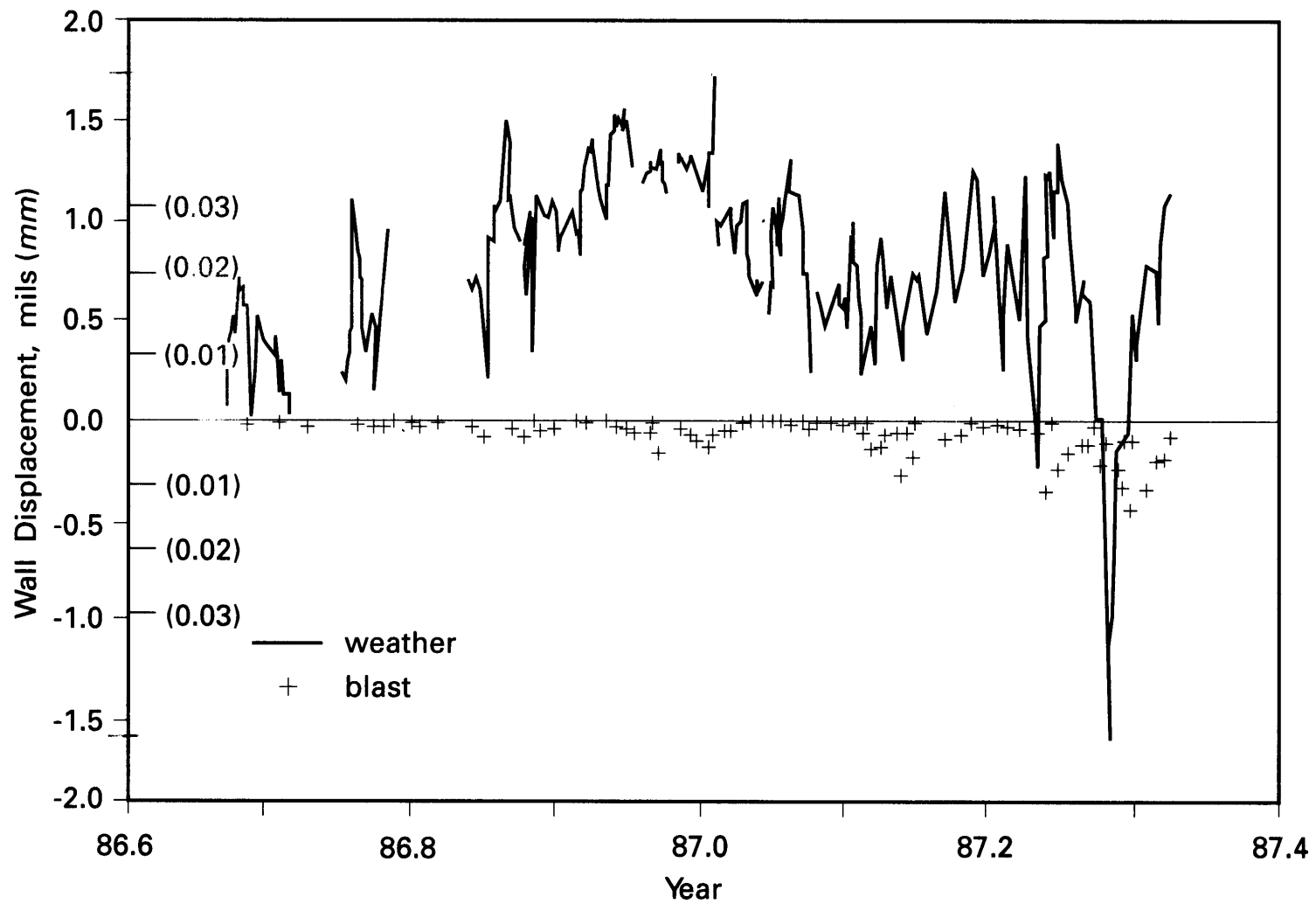


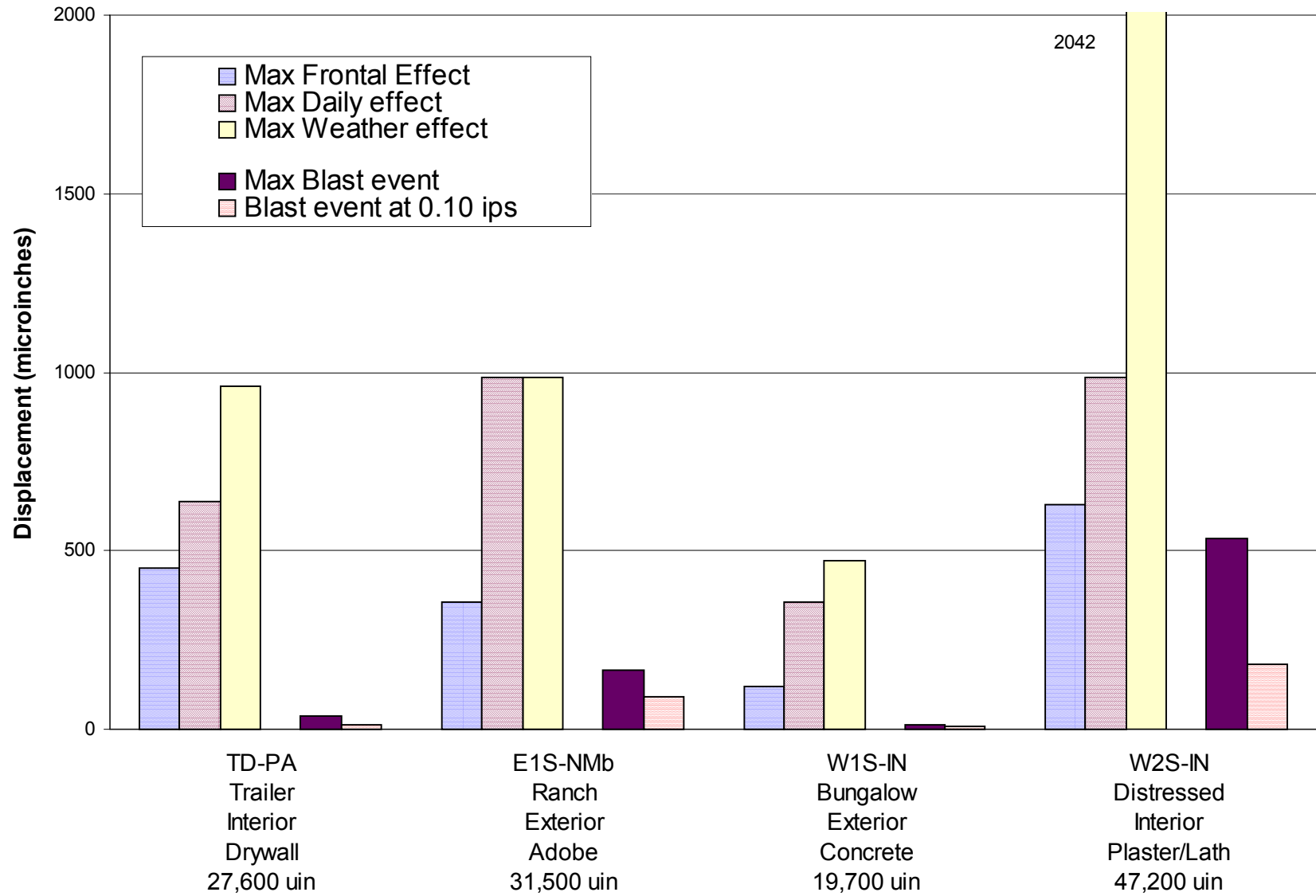
Figure 11 Comparison of weather and blast-induced crack displacements from a previous study (Dowding, 1996)

**Table 2 Comparison of crack displacement response from environmental and vibration effects**

	(TD-PA) Trailer Interior Drywall	(E1S-NMb) Ranch Exterior Adobe	(W1S-IN) Bugalow Exterior Concrete Block	(W2S-IN) Distressed Frame Interior Plaster/Lath
Event	Displacement (micro-inches)			
Max Frontal Effect	451	354	118	630
Max Daily effect	639	984	354	984
Max Weather effect	962	984	472	2,042
Max Blast event (ppv in ips)	35 (0.32)	165 (0.13)	12(0.23)	535 (0.30)
Blast event at 0.10 ips	12	79	8	197
Slamming door	98 (6) <sup>1</sup>	-	-	63 (14) <sup>1</sup>
Jumping	59 (10) <sup>1</sup>	-	-	75 (16) <sup>1</sup>
Hammering	8 (11) <sup>1</sup>	-	-	87 (1) <sup>1</sup>
Shutting window	-	-	-	161 (3) <sup>1</sup>
Walking on Stairs	-	-	-	-
Foundation Response (Permenant)	-	630	-	-
Width of crack (micro-inches)	27,559	31,496	19,685	47,244
Days of observation ( $\Delta T$ in deg F)	5 (13)	35 (51)	4 (30)	3 (17)

Notes:

(1) Distance to crack in feet



**Figure 12 Comparison of measured crack displacements due to static and dynamic events**

Environmental and vibratory responses of cracks in all 4 structures are compared in Table 2 and in Figure 12. In addition to weather and vibratory crack responses, responses to occupant activities in structures TD-PA and W2S-IN are also included in Table 2. The length of monitoring of each structure (in days) is also included in the table. The implications of these measurements will be discussed further in the end of the appendix.

For all four structures, maximum weather effects are at least 10 times greater than the vibratory effects produced by ground motions of 0.1 ips. The 0.1 ips level is that at which the vibration is noticeable. As described earlier, the maximum weather effect is defined as the maximum difference in the peak actual measurements from the overall computed averages of crack displacement during the study period. The vibratory response is the maximum, zero to peak crack displacement during the vibratory response. Both long-term, weather, and transient, vibratory, responses are measured by the same sensor, and thus are directly comparable.

As shown in Table 2, response to occupant activity can be as large as that produced by vibratory excitation. Activities presented are a common subset of the tests conducted at two of the four structures. These tests were not undertaken at the other two structures. Distances from the crack to the location of the activity are shown along with the crack responses produced. Those activities closest to the crack produced the greatest response. The greatest response, 161  $\mu$ -in (4.1  $\mu$ m), was produced by shutting a window three feet away from the crack in structure W2S-IN.

Seasonal events, such as the rainstorm that occurred in New Mexico (during monitoring of structure E1S-NMB), create large and relatively permanent crack responses, as was seen in the measured long-term response of the structure. A half of an inch rainfall at the adobe home, E1S-NMB, which did not have a basement, produced a 630  $\mu$ in (16  $\mu$ m) change that remained for the duration of the monitoring period (McKenna, 2002). This permanent deformation is 8 times greater than the response of the crack to 0.1 ips blast-induced ground motions. These types of extreme events typically are expected to be observed only within periods of six months or longer. The large magnitude and permanence of the crack response implies that seasonally extreme events produce even larger crack displacement than other events reported for most of the structures in this study.

## **Comparison of Vibratory Crack Displacement with Structural Response from Velocity Measurements**

Measured crack response is compared in Figures 13 and 14 with the more traditional estimates of relative wall displacement or cracking potential in order to determine the similarity of the approaches. This appendix focuses on direct measurement of crack response. Traditionally ground particle velocity or structural velocity response is measured to deduce or estimate relative wall displacement or gross strain as an index of crack response and/or cracking potential. Structural velocity responses are manipulated to calculate relative displacements (or strain) in the plane of the wall, which are then compared to critical levels. Computed relative displacements can be estimated by 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. Also included is a comparison with the peak parallel ground motions, since it is the method by which vibratory activities are regulated. All of these comparisons are presented in Figures 13 and 14. Since crack displacements are measured in the plane of the wall,

comparisons with structural and wall responses are made in the plane of the wall. Thus, the important velocities are always in the direction parallel to the wall with the crack.

Relative wall displacements can be most directly calculated from pairs of measured structural velocity responses. These calculations are compared in Figures 13 (a) and (b) with the directly measured crack displacement. Subtraction of perfectly time correlated ( $\pm 0.001$  sec) pairs of integrated velocity time histories to create a relative displacement time history is the most direct method of computing peak relative wall displacement. In these cases the pairs are: 1) upper corner, S2, minus lower corner, S1 (S2-S1), and 2) S2 minus ground (S2-G). From the resulting time history, the peak relative displacement is determined for comparison with the measured crack displacement.

If measured structure response is not available, but ground motions are, a third, less precise index is sometimes calculated from the integrated ground particle velocity alone. Figure 13 (c) shows the comparison between peak measured crack displacements and these peak integrated values of the particle velocity.

Relative wall displacements can be estimated by calculating Single Degree of Freedom (SDOF) relative displacement responses from the ground velocity time histories as described in (Dowding, 1996). Two such comparisons are made with the directly measured crack displacements in Figures 13 (d) and (e). A standard damping ratio of 5% is used for all calculations. Estimated relative displacements are found from either: (d) SDOF relative displacement response at the dominant frequency of the super structure or (e) the average of responses between 10 and 15 Hz. Average values of natural frequencies for typical residential structure walls typically range between 10 and 15 Hz. Since the monitored cracks were located on walls that can respond to both superstructure and wall motions, depending on the design of the walls and the ground motions, both approaches were taken to estimate a relative displacement associated with the ground motion. Figure 13 (d) shows the comparison of measured displacement with the estimated displacement for the dominant frequency of the structure, while Figure 13 (e) shows that with the average of estimated displacements in the 10 to 15 Hz range.

The traditional method of estimating cracking potential is measuring the peak particle velocity (PPV). PPV in the direction parallel to the plane of the wall is compared with measured crack displacements in Figure 13 (f).

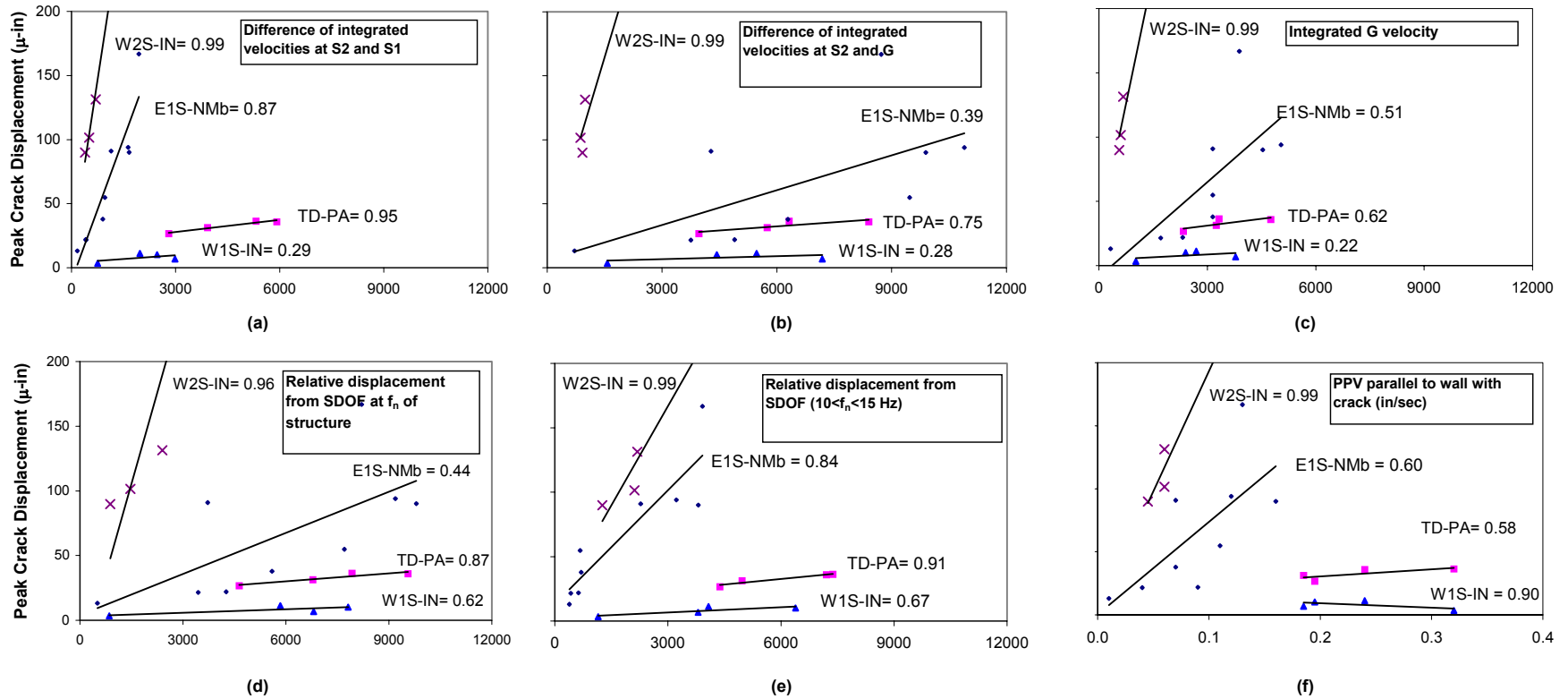


Figure 13 Comparison of  $R^2$  correlations between measured crack displacements and estimated displacements and peak parallel ground motions

Relative wall displacements can be approximated visually from time histories by assuming that velocity time histories approximate sinusoidal waveforms. Wall displacement,  $\delta$ , can be estimated with the following equation:

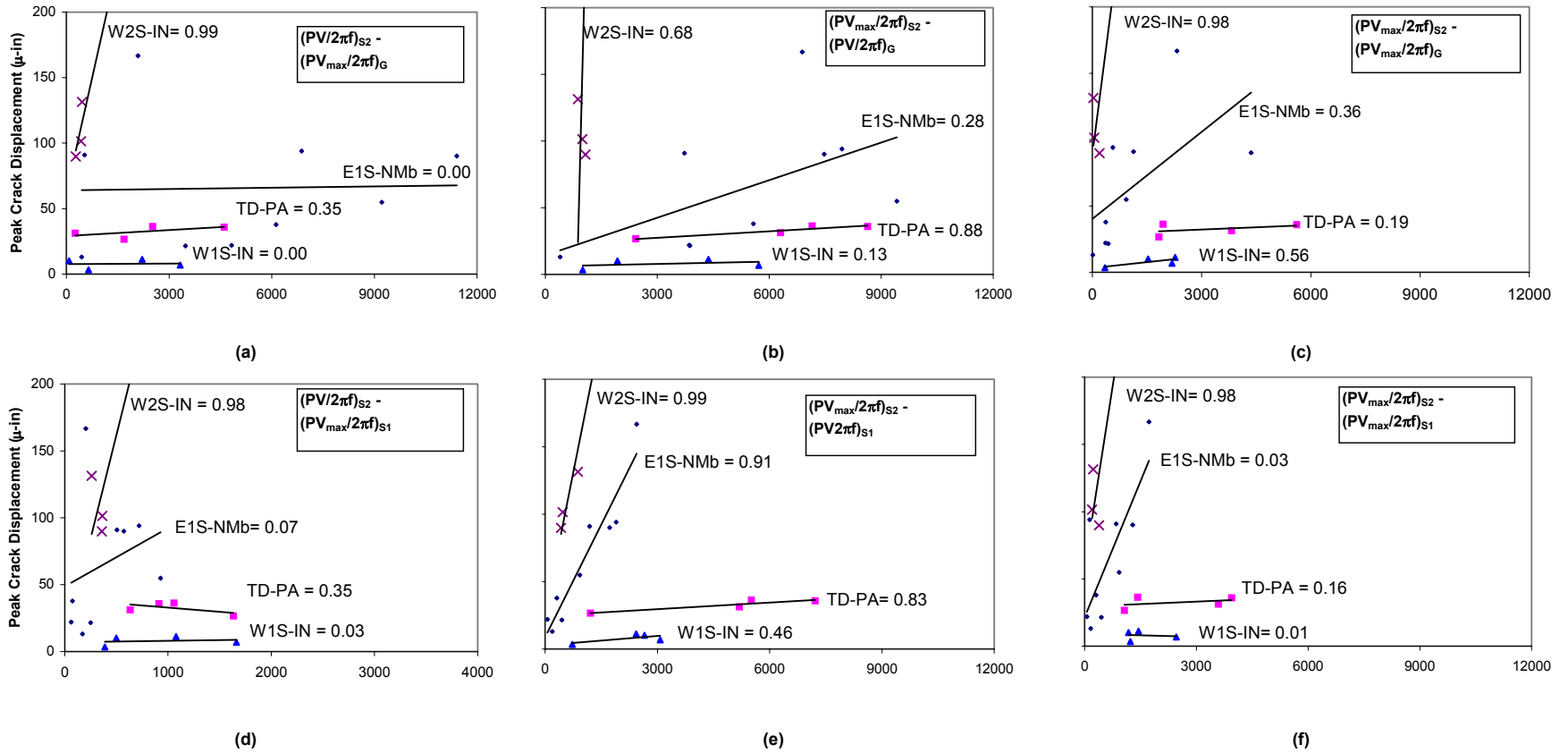
$$\delta = V/2\pi f,$$

where  $V$  is a given PPV in a time history and  $f$  is the 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 PPV. Displacements approximated in this manner can be determined for both upper and lower elevations of the wall of a structure and subtracted in order to obtain various measures of relative displacement.

Figure 14 compares directly measured crack displacement with six methods of approximating relative wall displacements. Approximated relative displacements have been produced from the following pairs of velocity time histories: (a) ground motion,  $G$ , and upper corner,  $S2$ , at the time of peak  $G$ , (b)  $G$  and  $S2$  at the time of peak  $S2$ , and (c) peak  $G$  and peak  $S2$ , regardless of the time at which each occurs. For the two time-correlated pairs, (a) and (b), displacement is still computed at the same time, regardless of the magnitude of velocity at that point in time, for either of the time histories. In other words, if the velocity of one of the time histories is 0.0 ips and the velocity of 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. The resulting values from  $\delta(S2)-\delta(G_{max})$ ,  $\delta(S2_{max})-\delta(G)$ , and  $\delta(S2_{max})-\delta(G_{max})$ , were all used as representative values of estimated displacements. Comparisons between measured crack displacements and these approximated displacements are presented graphically as Figure 14 (a), (b), and (c), respectively.

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  $\delta(S1)-\delta(G_{max})$ ,  $\delta(S1_{max})-\delta(G)$ , and  $\delta(S1_{max})-\delta(G_{max})$ , were also used as representative values of estimated displacements. Comparisons between measured crack displacements and these computed displacements are presented graphically as Figure 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 an estimated 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.



**Figure 14 Comparison of  $R^2$  correlations between measured crack displacements and estimated relative displacements**

## Discussion

Dual-purpose sensors described herein could be placed across a crack to simultaneously measure long-term and vibratory changes in crack width to augment the traditional approach of measuring particle velocity. This augmentation might be helpful where blasting or construction vibrations occur for sustained periods of time, as many complainants who believe that construction vibrations disturb their homes or buildings tend to focus their discussion on cosmetic cracks like that in Figure 1. Because people interpret the response of buildings through their senses they tend to believe that if the vibrations can be felt and associated noise heard, there could be a negative effect on the structure. Additional measurement of crack response would allow comparison between the effects of the "silent crackers" – temperature, humidity, long term distortion, material changes, etc - to the phenomena that is felt and heard – blasting.

This appendix presents measured crack responses associated with this study of atypical response in order to 1) introduce the concept of crack measurement and 2) to demonstrate that a single transducer and computer system can be employed to detect both long term and vibratory response of cracks. It was and is not meant to set forth an argument for any set of conclusions, except that such measurement could augment the traditional means of assessing the potential for cracking from blasting vibrations. Thus this appendix is not meant to be a definitive treatise on crack measurement and structural response. That discussion would take far more space than possible because of the myriad of considerations that would need to be considered. The detailed discussion of the measurements was included to demonstrate the manner in which this new type of data could be employed.

Data presented in this appendix is limited by the time that was allotted for the measurement of long term response. Because of this short time of observation, long term crack response of the four structures studied does not include significant changes in weather, seasonal weather changes, or other seasonal environmental effects. "Long-term" relative to the age and environmental stress history of a structure must of necessity be described in terms of no less than months. Only one of the four structures was monitored for more than 5 days. Observation of only a handful of days is too short to observe the effects of a significant change in the weather.

Thus the reader is cautioned not to extrapolate from these data to draw general conclusions. For instance, one might be tempted to conclude from the detailed example presented that vibratory response is significant compared to long term response. It is for these three days, but these measurements do not include any weather extremes or seasonal effects.

Differences in relations between measured crack and structural response are small compared to the large impact of weather related response, as demonstrated above. Changes in crack width produced by noticeable ground motions of 0.1 ips were less than 200  $\mu$ -in; whereas, the maximum weather responses during one week (or less) periods of observation were 500 to 2000 micrometers. The crack in structure W2S-IN that showed the largest motion response (197  $\mu$ -in) also showed the largest weather response (2045 $\mu$ -in ). More measurements are needed to draw general conclusions about the implications of these observations.

Of all of the responses calculated by traditional means, measured crack displacement correlated best with those resulting from the difference in integrated velocity time histories of the upper and lower corners, (S2-S1). This correlation is shown in Figure 13 (a). This high correlation was expected, as (S2-S1) is the relative displacement of the wall, which is proportional to the gross, in-plane, shear strain in the wall. In a sense, this calculated difference

also could be considered as a direct measurement of the wall strain when measured at the upper and lower elevations of a single story wall of constant cross section.

The second best correlation with the measured crack displacement is obtained from the pseudo velocity response spectrum (PVRS), with the average of responses 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 (Siskind et al 1980, Dowding, 1985, and 1996). These correlations, shown in Figure 13 (e), are almost identical to that between the two direct measures of wall strain. This frequency range lies between the natural frequency of super structures and walls. Correlations are lower with PVRS displacements for the estimated dominant frequency associated with each superstructure.

A number of factors affect the relationship between directly measured crack displacement and structural response (or estimated relative wall displacements), one of which is crack location. The crack in structure W1S-IN was located at the top of the basement wall, only 3 feet from the ground surface. Magnitudes of crack response for this structure were smaller than all other observed crack response in this study, even though it sustained peak parallel ground motions as high as 0.2 ips, as shown in Figure 13. However, this low response was expected, as the basement wall moves with the ground and thus is not free to respond as is the superstructure. Vibratory displacements of this crack would not be expected to correlate well with estimated measures, which presume free response of the structure. Crack displacement of this basement wall best correlates to peak parallel ground motion, because it is most directly related to ground strains. The worst correlation with this crack response occurs with calculated displacement (between S2 and S1), as these responses are for the above ground, freely responding portion of the structure.

Another factor that may affect the relationship between crack displacement and structure response is the actual magnitude of crack width. The most responsive of the cracks in wall covering of the superstructure, also tended to be the widest. Consider the crack in structure W2S-IN, which was uniformly wide, like that in Figure 1, and extended the entire distance between the window top and the ceiling. The correlations for this structure are uniformly the highest; however, these high correlations may have resulted from the large range of measured crack displacements. Graphs in Figures 13 and 14 have been truncated at measured peak crack displacements of 200  $\mu$ -in in order to include the lower ranges of response. The one missing point for W2S-IN is located at 535  $\mu$ -in, which corresponds to a peak particle velocity of 0.28 ips (7 mm/s) parallel to the wall containing the crack.

## Conclusions

This appendix presents measurements of the response of cosmetic cracks to long term environmental effects as well as blast-induced ground motions in four structures. Crack sensors employed in this study allowed simultaneous measurement of both long-term (environmental or weather induced) and vibration (blast induced) changes in crack width in a variety of wall materials. Cosmetic cracks monitored in this study occurred in 1) exterior stucco over adobe bricks as well as concrete masonry units, and 2) interior plaster and lath, as well as dry wall. Structures were framed with wood, concrete masonry units, and adobe, and included a trailer, an adobe ranch house, a concrete block basement, and a wood framed house.

Direct measurements of vibratory cosmetic crack response of the four structures subjected to blast-induced peak particle velocities between 0.1 and 0.3 ips were compared with a wide range of estimates of the wall distortion. Twelve of these methods were compared to the measured crack response in order to determine the best correlations. Through these comparisons, it was possible to estimate crack responses at 0.1ips, which is assumed to be noticeable to a wide range of individuals.

Long-term cosmetic crack response to weather induced changes was measured in all four of the structures over periods of 3 to 36 days. Three of the four structures were monitored for 5 days or less and most likely did not capture the effects of significant changes in weather. The long-term response was subdivided into effects caused by 1) daily changes, 2) passage of weather fronts occurring over a period of days, and 3) extremes of unusual weather or other environmental effects.

Synthesis of these measurements and calculations leads to the following conclusions with regard to this set of observations. More work and measurements are needed to generalize these conclusions.

- Long-term response of the monitored cosmetic cracks in these four cases with short observation periods is at least 4 to 5 times larger than the vibratory response of cracks at maximum measured peak particle velocities and more than 7 to 10 times greater at low but noticeable levels.
- Extreme events such as rain storms in dry climates can cause offsets and or extreme crack displacements that are much larger than those induced by typical weather changes.
- Vibratory crack response induced by household activities can approach or exceed the vibratory response to low but noticeable peak particle velocities. The response varies as a function of distance from the crack in which the activity occurs.
- Crack displacements induced by typical changes in weather and noticeable vibrations are far smaller than the width of the cracks.
- Measured crack displacements correlate best with the difference in calculated displacement of the top and bottom corners of the structure. These displacements are calculated by integrating time correlated velocity time histories of structure motion measured in the plane of the wall containing the crack.
- Measured crack displacements also correlated well with estimates made from ground motions that take into account the time history of the excitation and response characteristics of the structure using the single degree of freedom response method.
- Responses of the same type of sensor, one across the crack and the other on adjacent, un-cracked material (a null sensor), shows crack displacements to be large compared to the combination wall material and sensor response measured by the null sensor. Therefore, a null sensor may not be necessary in many cases.

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