Long Term Field Measurement of Micro Inch Crack Response to Climatological and Blast Vibration Induced Effects

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ABSTRACT: This paper compares more than two years of micro inch crack displacement response and structural velocity response of a wood frame house adjacent to an operating aggregate quarry. The same transducers that monitor long term, climatologically induced micro inch crack response also measure dynamic responses induced by blast induced ground motions, occupant activities and wind gusts. The two story house has been expanded several times, is founded on an irregular basement, framed in wood and clad with wood siding and clapboard. This project is part of a larger research effort of structural health monitoring via autonomous crack monitoring [ACM]. The unusually long monitoring period allowed observation of two maximum, climatologically induced peak crack responses, and as such represents one of the longest periods of continuous observation in the literature. These once a year peak climatological responses are compared with unusually intensive ground motions in excess of that allowed by regulation. Intense ground motions were legally possible because the test house is owned by the quarry and located on the quarry property. These comparisons show that climatic and environmental variations cause greater crack response than ground motions that exceed regulatory limits.

INTRODUCTION

This paper presents structural response and the resulting crack response of a two-story residential structure situated on the property of an aggregate quarry in Sycamore, Illinois.

Focus of study

This paper compares the structural response and resulting crack response produced by:

- Ground motions from blasting
- Environmental conditions (long-term changes in temperature and humidity)
- Occupant activity
- Wind gusts

The instrumented house is a two-story wood-framed structure with a basement foundation. It is located approximately 300 feet (91m) away from the edge of the blasting zone of Vulcan Material, Co. Sycamore #397 Quarry. The house and its location are shown in Figure 1.

The ITI research engineering group installed the wired eDAQ system on June 16th and June 17th, 2010. Data collection began on July 2nd, 2010, and has continued since. The air overpressure transducer and the indoor temperature and humidity gauge were installed on July 21st, 2010. The air overpressure transducer did not begin recording properly until November of 2010.

Figure 1. Overall view of Vulcan Materials, CO. Sycamore Quarry and photograph and location of the instrumented house

During the study period (from July 1st, 2010 to October 27th, 2012), the quarry generated blasts 36 times. Table 1 describes the blast vibration environment. Blasts were initiated at varying distances from the house: between 300ft and 1400ft (90-425m) away. These distances were evaluated by triangulation using distances between the blasts and surrounding houses, provided by Vulcan Materials.

On some occurrences (indicated in Table 1 by a star), data were not recorded by the ITI system. However, Vulcan Materials compliance monitoring would have recorded ground motions where necessary.

Instrumentation

Structural and crack response is autonomously measured by the combination of sensors listed in Table 2. The crack sensors are described in more detail in the section below. All the other sensors are described in the Installation Report (Meissner, 2010).

Although the house was equipped with both a wired and a wireless monitoring system, the present report is mainly based on data gathered from the wired system. Wireless response is documented in two ITI reports by Koegel (2011) and Dowding et al. (2012).

The sensor installation plan is shown in Figure 2. Photographs of the crack sensors in their context are also shown in Figure 3. Details of the installation of the velocity transducers are documented in the Installation Report (Meissner, 2010).

Two types of data are recorded: long-term and dynamic:

- Long-term response is obtained by measuring crack response as well as temperature and humidity for comparison once every hour. These single points are the average of 1000 samples obtained in one second.
- Dynamic response is obtained by measuring crack response, ground and structural velocity, and air overpressure. These values are recorded at 1000 samples per second for 3 seconds when triggered during dynamic events, with a 0.5 second pre-trigger.

LVDT displacement sensors have been installed to monitor the in-plane responses of three cracks. Table 2 describes the locations, purposes and sensors used for each crack.

Date	Recorded PPV (in/s)			Distance to blast (ft)	Air blast		Crack response (µin)		
	[L]	[T]	[V]		[10^-4 psi]	[dB SPL]	Shear	Seam	Ceiling
09/01/10	0.108	0.134	0.239	1200	-	-	53	59	215
09/13/10	0.172	0.16	0.262	1300	-	-	82	82	427
09/20/10	0.157	0.12	0.219	1300	-	-	255	84	459
09/22/10 (*)	-	-	-	-	-	-	47	54	205
09/30/10	0.389	0.307	0.371	1300	-	-	401	242	509
10/08/10	0.452	0.34	0.636	900	-	-	274	211	444
10/19/10	0.16	0.128	0.224	1400	-	-	218	102	76
04/20/11	1.341	0.491	0.976	400	48.2	127.6	1120	532	486
04/22/11	0.817	0.792	0.646	300	50.2	128.0	2050	448	1260
05/11/11	0.197	0.189	0.201	600	27.2	122.7	154	86	201
05/19/11	0.516	0.523	0.417	400	34.4	124.7	807	439	1094
05/26/11	1.642	0.905	0.797	700	33.1	124.4	3277	1666	2162
06/03/11	0.454	0.275	0.301	1200	30.3	123.6	283	213	567
06/15/11 (*)	-	-	-	-	-	-	-	-	-
06/30/11	0.61	0.529	0.389	900	31.7	124.0	387	243	648
07/12/11 (*)	-	-	-	-	-	-	-	-	-
07/22/11	-	-	-	-	-	-	-	-	-
08/02/11	0.701	0.758	0.741	-	23.4	121.4	253	329	3032
08/10/11 (*)	-	-	-	-	-	-	-	-	-
08/18/11 (*)	-	-	-	-	-	-	-	-	-
09/07/11 (*)	-	-	-	-	-	-	-	-	-
09/14/11	1.137	0.749	0.665	400	36.6	125.3	1107	550	2363
09/22/11 (*)	-	-	-	-	-	-	-	-	-
10/03/11 (*)	-	-	-	-	-	-	-	-	-
10/10/11	0.443	0.291	0.215	-	64.3	130.1	279	170	536
06/28/12	0.847	0.452	0.662	-	65.7	130.3	918	414	2125
07/17/12	1.011	0.750	0.554	-	40.8	126.2	591	382	1630
07/23/12	1.023	0.683	0.559	-	41.5	126.3	433	314	1812
07/27/12	0.760	0.465	0.730	-	52.6	128.4	754	284	946
08/13/12	0.514	0.507	0.752	-	63.4	130.0	335	324	1203
08/17/12	0.384	0.349	0.495	-	45.1	127.1	327	200	1135
08/18/12	0.570	0.367	0.373	-	30.4	123.6	495	256	797
08/27/12	0.719	0.621	0.539	-	42.5	126.5	580	515	1059
09/05/12	0.746	0.598	0.671	-	55.5	128.9	426	483	2108
09/19/12	0.614	0.539	0.638	-	100.0	134.0	413	387	1058
09/24/12	0.468	0.319	0.233	-	37.3	125.4	512	579	1141

Table 1. Characteristics of blasts producing the vibrations throughout the study period (1in/s = 25mm/s, 1ft=0.3048m). Data were not recorded by the ITI system on instances shown by an asterisk.

Sensor	Channel Name	Description/Location
Triaxal Geophone (buried)	Geo_L_1 Geo_T_2 Geo_V_3	Buried outside the house - south-east corner
Air Overpressure	Air_Blast_4	Located on the outside wall
Temperature and Humidity	InTemp_5 InHumid_6	Indoor climatic data
Linear Variable Differential Transformer (LVDT)	LVDT_9_Shear	Shear crack, South wall, 1st floor
	LVDT_10_Null	Null sensor, uncracked area adjacent to Shear crack
	LVDT_11_Seam	Addition Seam crack, South wall, 1st floor
	LVDT_12_Ceil	Ceiling crack, Bedroom ceiling, 2nd floor
Horizontal Wall Geophone	HG_13_Bot1f HG_14_Top1f HG_15_Top2f HG_16_MidW	Wall-mounted

Table 2. Description of sensors, channel designation and location

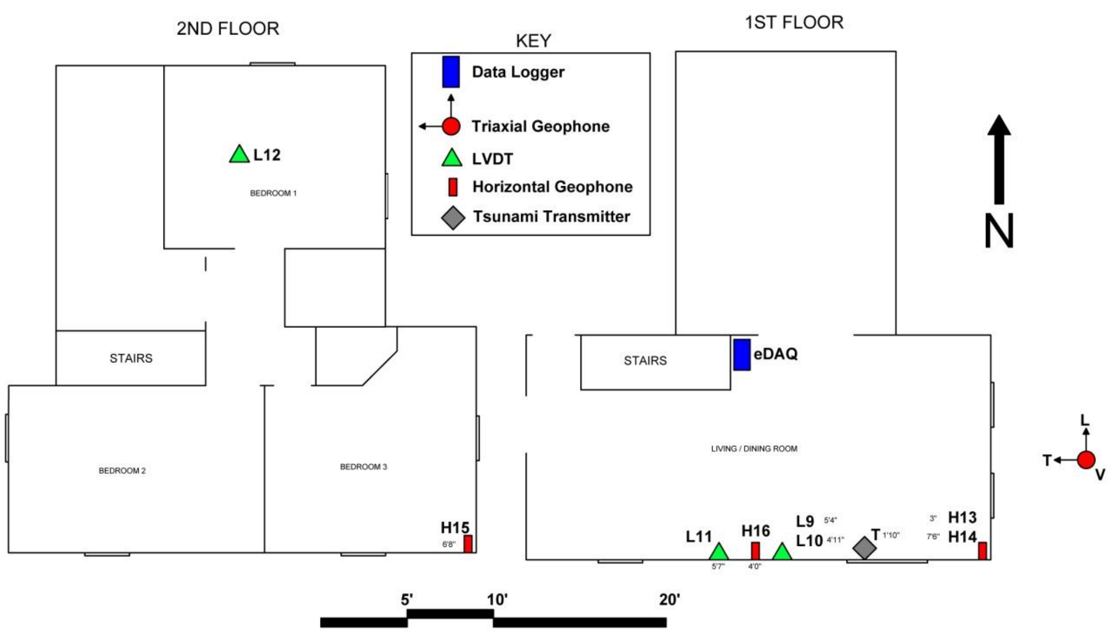
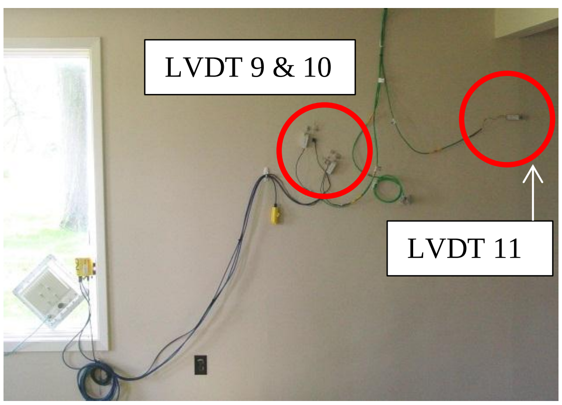
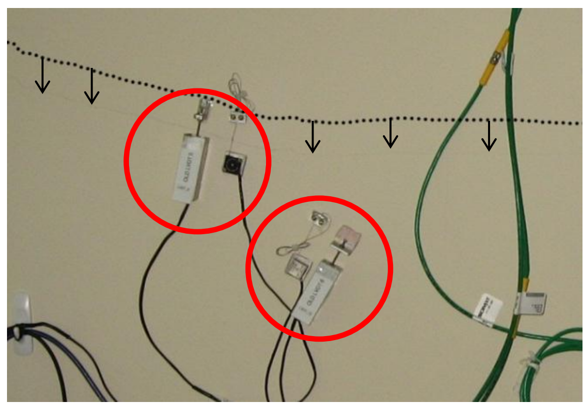


Figure 2. Exact sensor and equipment locations in the house

↑ a - Close-up of ceiling crack monitored by LVDT_12

← b – Upstairs bedroom ceiling showing the location of the crack and the transducer





↑ c - Overall view of sensor suite on south wall (first floor)

↗ d - Close-up of Shear crack monitored by LVDT_9 and Null gauge LVDT_10.

→ e - Close-up of Addition Seam Crack monitored by LVDT_11

(NB : The crack paths are indicated by the offset parallel dotted lines)

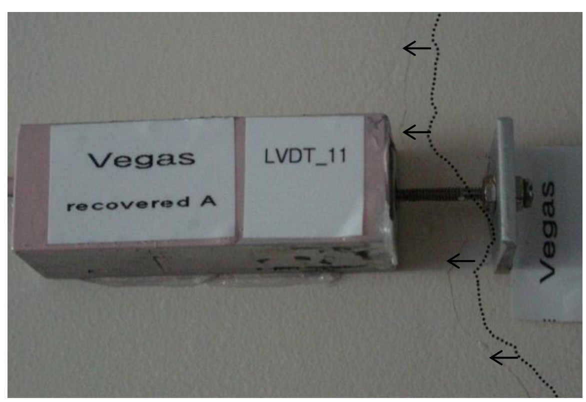


Figure 3. Overall views of the wall-mounted crack sensors

Crack response is the *change* in crack width, not total crack width, and is called *response* in this report. Figure 4 (Siebert, 2000) illustrates this definition. All transducers have been installed so that positive response indicates crack opening and negative indicates crack closing. All measurements are made in micro-inches. A null sensor, which is placed on an adjacent uncracked area, provides a record of any drift or thermal effects on sensor metal or electronics. It has been shown that the null sensors' response is small relative to the cracks' responses (Kosnik, 2008).

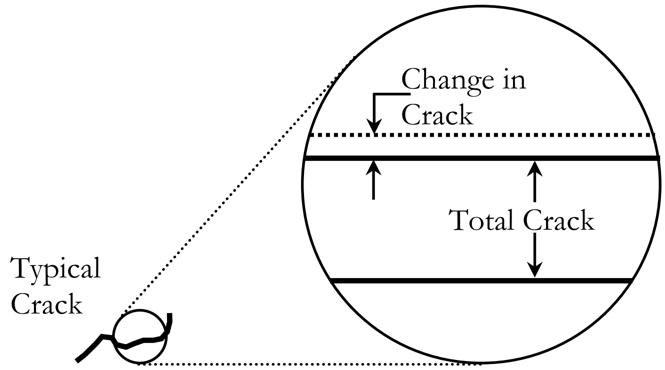


Figure 4. Crack response is the change in crack width, not total crack width (Siebert, 2000)

RESULTS – CRACK RESPONSE

Long term climatological effects

Long-term crack response is measured every hour as the average of a burst of 1000 sample in one second. Figure 5 presents a two month fragment of the whole project that will be seen again later in this paper. Long-term response to date (28 months) is compared for all three cracks in Figure 6 with indoor temperature and humidity. This hourly data is represented by the red, most highly variable line in Figures 5 and 6. The less variable blue line is a 24-hour central moving average (CMA) of the hourly data, which shows the response to weather fronts. The even less variable black line is a 30-day CMA of the hourly data, which shows the response to seasonal trends as it varies about the 2 year average green horizontal line.

Climatic responses are defined in Figure 5 to clarify the time scales of these influences. Daily response is defined as the difference between the hourly data and the 24-hour CMA (red arrow). Frontal response is defined as the difference between the 24-hour CMA and the 30-day CMA (blue arrow). Seasonal response is the difference between the black, 30-day CMA curve and the green overall average curve (green arrow). Finally, the maximal response is the sum of the daily, frontal and seasonal effects, which is the difference between the red hourly data and the overall average curve (black arrow). The maximum values from Figure 6 are listed in Table 3.

Response (μin, zero-to-peak)	Shear crack	Null	Seam	Ceiling crack
Max Daily	3276	258	2791	1849
Max Frontal	3840	122	3459	5182
Max seasonal	10485	285	2757	9157
Maximal	12064	745	4861	11726

Table 3. Maximum crack response to weather effects (1μin=0.0254μm). All measurements are zero-to-peak

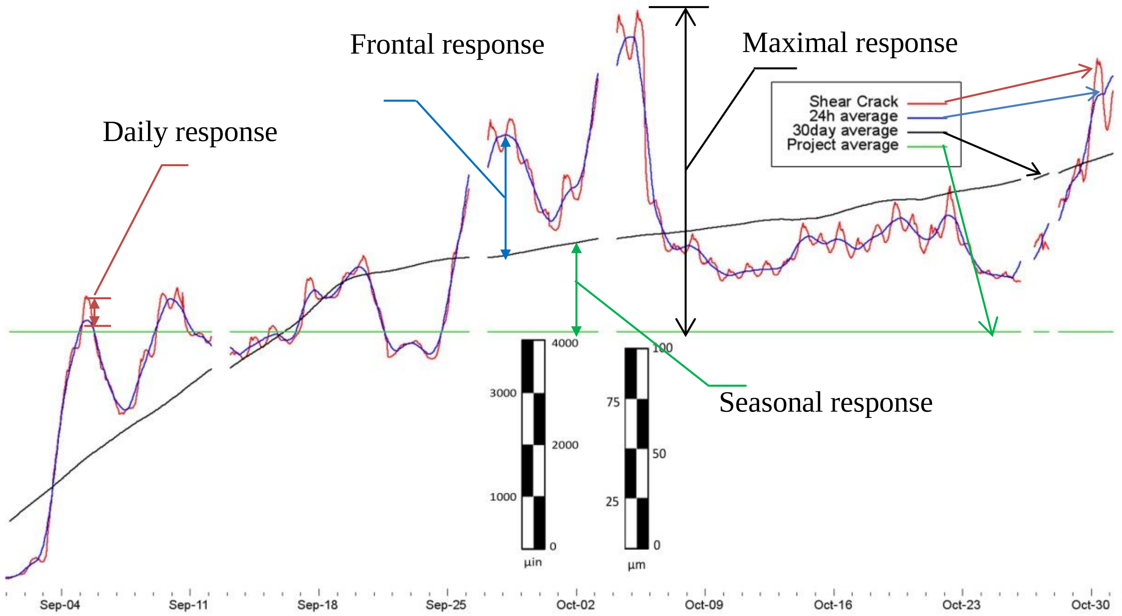


Figure 5. Crack response caused over the course of two months as shown in Figure 6

The unusual longevity of this study (28 months) allows measurement and observation of yearly responses. As described elsewhere (Dowding, 2008), such long-term obersvations show the dominance of seasonal response, which produce the largest of the responses. The yearly maximum shown by the black arrows on Figure 6 occurs once per year when all three factors (daily, frontal and seasonal) combine.

Blast-induced (dynamic) ground motion crack response

Table 1 compares the zero-to-peak crack responses with the maximum peak particle velocities and the air overpressures over the course of the 28 month study. The ceiling crack response is larger than the south wall responses (shear and seam). This difference is a function of surface orientation with respect to vertical, location of the surface, construction details such as spacing of studs or joists, and construction materials (drywall, plaster, and lath). The seam has the least response with the thinnest crack width but located across a transition between an addition and the original structure.

Time histories for both crack and structural responses are presented in Figure 7 for two blasts. The first (top graph) was recorded on September 20, 2010 with a maximum PPV of 0.219ips (5.6mm/s) in the vertical direction. The second (bottom graph) was recorded on May 19, 2011 with a maximum PPV of 0.523ips (13.3mm/s) in the transverse direction. The air blast was recorded only for the May event and is shown in the figure.

As shown in Figure 8, the air overpressure can cause crack response, especially when the ground vibrations are low. The late arrival of that air overpressure can even be responsible for a larger crack response than the ground vibrations themselves for the ceiling crack, as presented for the blast on May 11, 2011 (Max PPV = 0.201 ips = 5.1 mm/s).

High PPVs in the ground are recorded because the house is located on mine property and will eventually be dismantled as the rock is mined out underneath it. As will be discussed later, even peak particle velocities (PPVs) above 0.5ips (12mm/s) produce crack responses that are only fractions of the seasonal, frontal, or even the daily "maximum" responses.

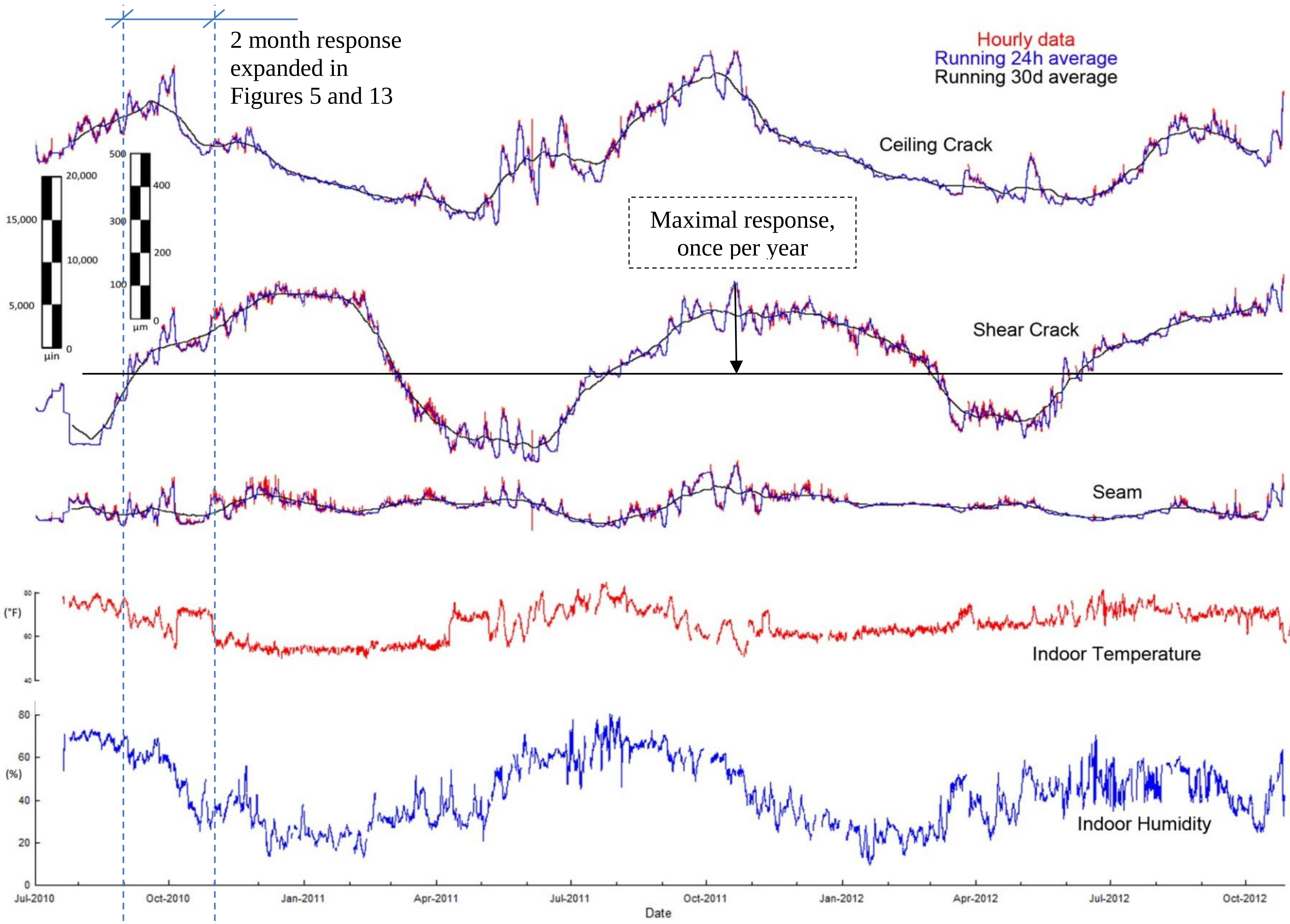


Figure 6. Comparison of the crack response with the variation in indoor temperature and humidity

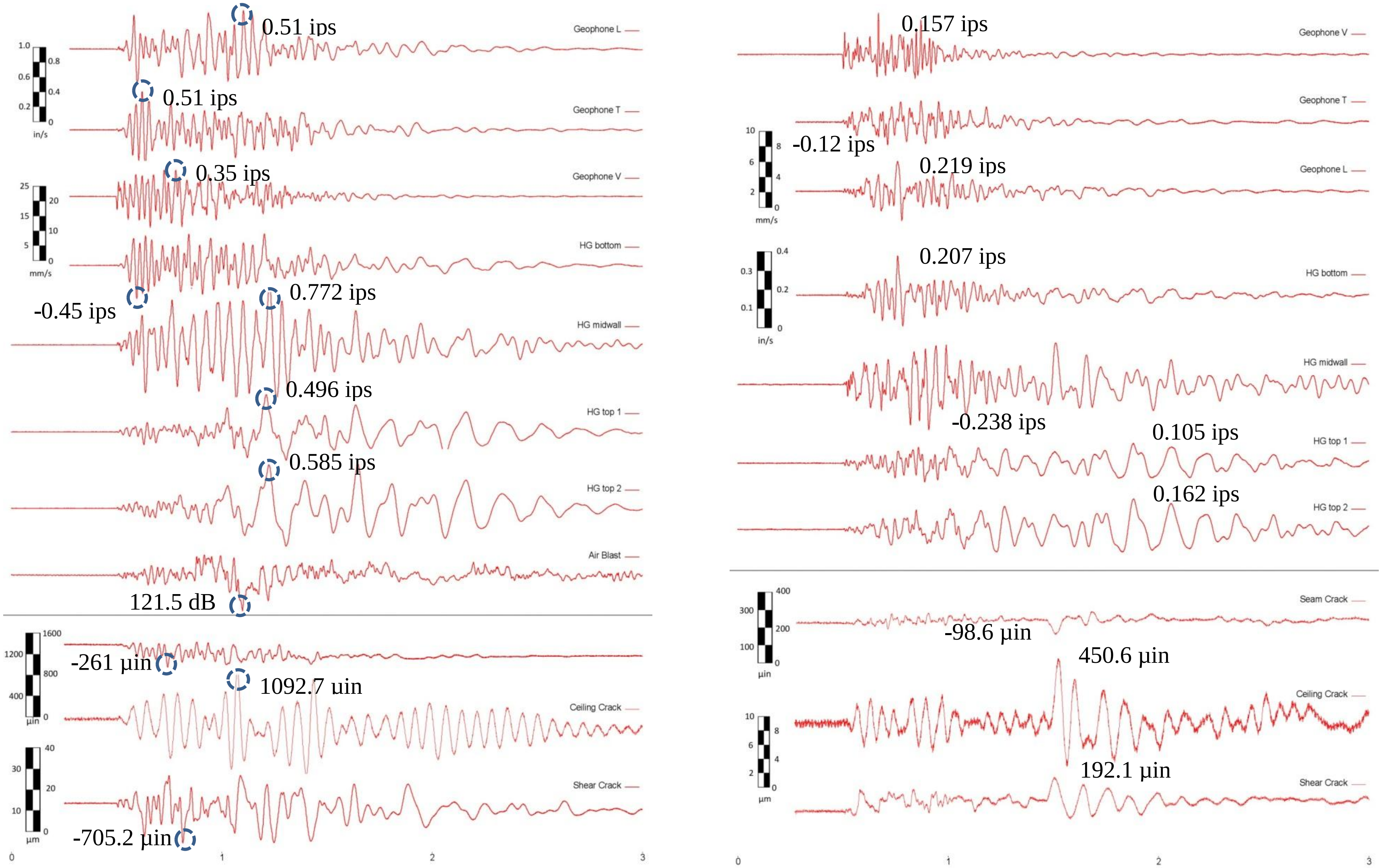


Figure 7. Structural and crack response time histories to blast events on Sep 20, 2010 (right) and May 19, 2011 (left). All measurements are zero-to-peak.

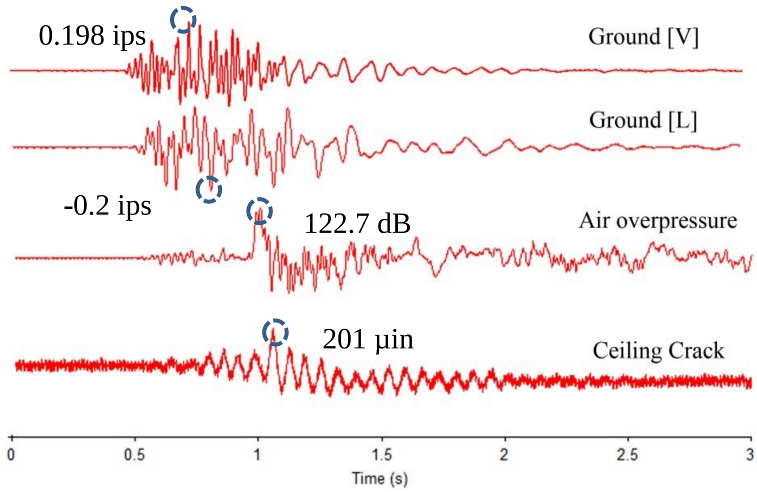


Figure 8. Influence of late arrival of air overpressure – Blast event on May 11, 2011. Measurements are zero-to-peak.

Occupant activity

Crack responses to the unplanned entrance of someone into the house are shown in Figure 9. Comparison with planned events shows that the entrance was probably by the front door. Maximum values for the crack responses to this door opening are tabulated in Table 4, along with structural and crack responses to 6 different planned occupant induced activities. Their time histories can be found in the Installation Report (Meissner, 2010). The signal to noise ratio is high for the ceiling crack because of line losses due to a greater distance between the data logger and the transducer.

One single event such as closing or slamming the bedroom door can induce an important response from the ceiling crack, located on the bedroom ceiling. Slamming the bedroom door produces a response of 2036µin (51.7µm).

Blast events must produce PPVs greater than 0.75ips (10mm/s) to produce larger ceiling crack response than the one produced when slamming the bedroom door. Moreover, the unplanned front door opening produced crack responses that are on the same order of magnitude of the responses produced by blast events such as those that occurred on Sep 01, 2010 or on May 11, 2011. These blast events produced ground motions slightly above 0.2ips.

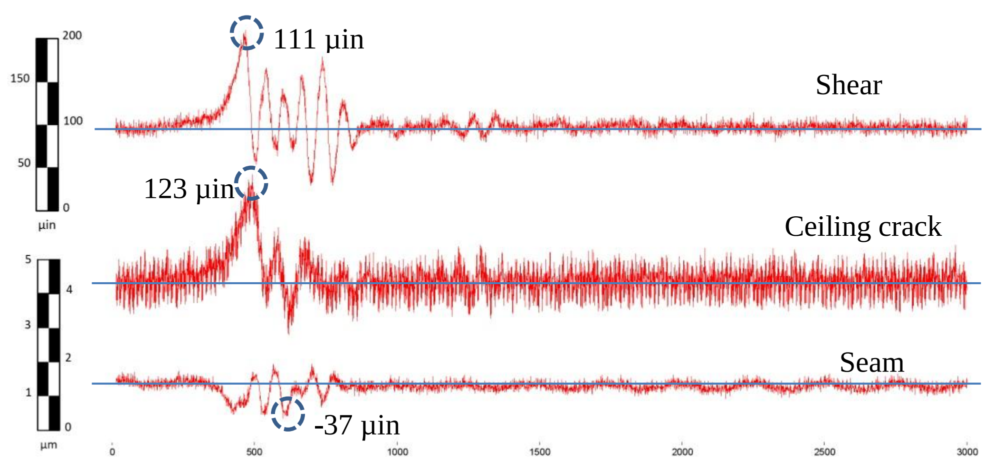


Figure 9. Crack response from opening the front door on the first floor

	Crack response (µin)				Structural response (in/s)			
Event	Shear	Null	Seam	Ceiling	HG 13 (Bottom)	HG 14 (Top 1)	HG 15 (Top 2)	HG 16 (Midwall)
Unplanned front door opening	111	18	37	123	0.008	0.02	0.03	0.12
Slam front door	18	14	39	190	0.013	0.02	0.031	0.128
Run down stairs	17	14	13	30	0.005	0.01	0.013	0.055
Close bedroom door	18	15	13	518	0.005	0.007	0.012	0.015
Slam bedroom door	13	14	13	2036	0.015	0.028	0.055	0.043
Slam garage door	15	14	23	150	0.009	0.025	0.038	0.123
Close window	17	13	12	38	0.028	0.014	0.01	0.07
Heel drop	18	20	15	39	0.003	0.003	0.004	0.025

Table 4. Crack and structural responses to 7 occupant activities (1µin = 0.0254µm)

Influence of inside temperature regulation

On October 25th, 2012, natural gas supply was terminated for future construction, which ended the temperature regulation inside the house. As shown in Figure 10, the inside temperature dropped 6°C (13°F) in one day on October 26th. After that, the temperature kept varying following a daily cycle, but at values much lower than when the heat was on.

Peak values of the crack response during large fall temperature swings are compared to average values during the 5 week period in Figure 10. They show that the absence of inside temperature regulation caused a response comparable to the largest seasonal response observed during the 30 month study, as shown in Table 5 and Figure 12.

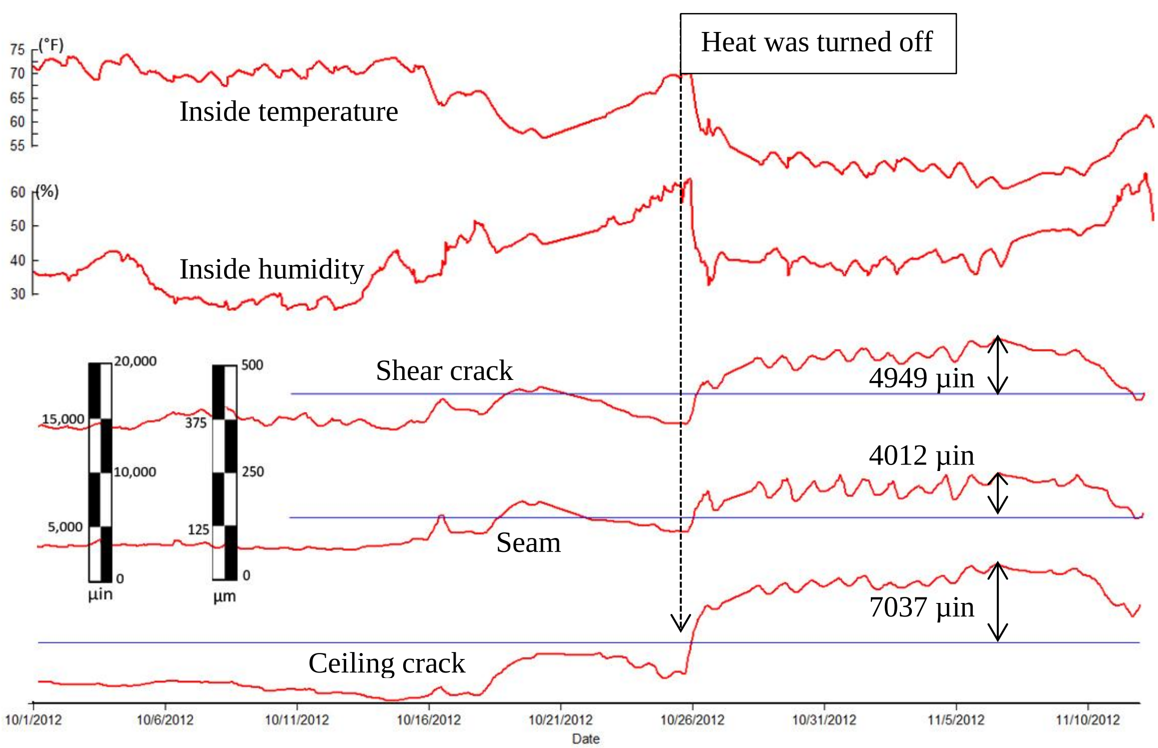


Figure 10. Influence of the inside temperature regulation during the fall of 2012

Wind response

Weather patterns, particularly involving high wind gusts, induced crack responses that could be as strong as the responses induced by blasting. Wind gusts triggered disturbances in the air overpressure sensor. Figure 11 shows an example of a response in the air overpressure sensor and the simultaneous crack displacements for all 3 cracks.

This wind gust event produced crack responses that are significant. As was observed with the occupant activity, the crack responses are on the same order of magnitude of the ones produced by blast events such as those which occurred on Sep 01, 2010 or on May 11, 2011. These blast events produced ground motions slightly above 0.2ips.

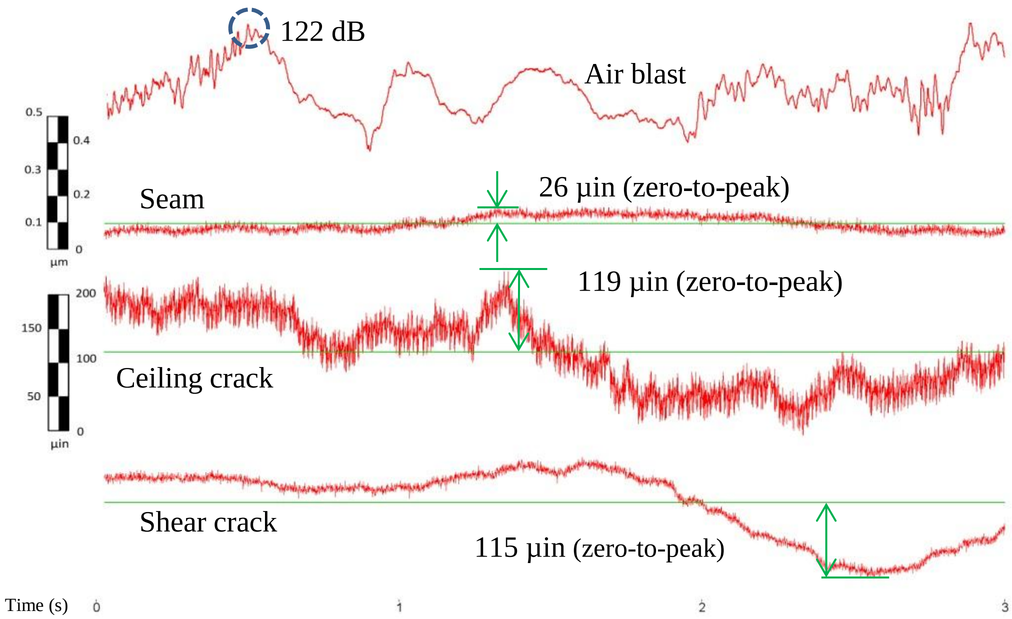


Figure 11. Example wind event on May 15, 2011 showing Air Overpressure and Crack Responses (1µin = 0.0254µm). Measurements are zero-to-peak

ANALYSIS

Comparison of crack response to climatological and vibration effects

Blast induced crack responses are compared to long-term environmental effects and occupant induced activities in Table 5.

Long-term response is at least an order of magnitude larger than any of the dynamic responses, even those produced by ground motions as high as 0.5ips (12.7mm/s). Figure 12 compares the tabulated responses in graphical form.

In general, the greater the climatologically induced long term response, the greater the dynamic response. Overall, the shear crack and the ceiling crack respond more than the seam. This difference is shown by the overall maximum response of the seam, which is less than half that of the shear or ceiling cracks. These ratios are consistent regardless of the source: occupant or blast, or the magnitude of ground motion: low (0.219ips) or high (0.523ips).

Time histories of daily climatological and blast-induced response

Time histories of crack responses to the 0.219ips blast in Figure 13 can be compared with the long-term climatic response in Figure 6. This comparison is made with the two-month timespan bounded by the vertical dashed lines in Figure 6. Two months of data illustrate the large effect of the passage of large weather systems/fronts. Blast responses are compared to the week of climatic response delimited by the dashed blue rectangle on Figure 13 (top). This week-long comparison illustrates the daily environmental fluctuations that are superimposed over the longer term effects.

Long-term and dynamic responses are plotted on the same vertical scale for both comparisons. The small black vertical bar on September 20th represents the maximum magnitude of the dynamic response, which is expanded in the rectangular box below the graph. Figure 13 shows that the environmentally induced response during the week surrounding the blast event is approximately an order of magnitude larger than the blast induced response. A similar conclusion was reached by Kosnik (2008) and Meissner and Dowding (2009).

Response (µin)	Shear crack	Null	Seam	Ceiling crack
Max Daily	3276	258	2791	1849
Max Frontal	3840	122	3459	5182
Max seasonal	10485	285	2757	9157
Maximal	12064	745	4861	11726
Ground motion (09/20/11) Max PPV = 0.219ips	192	22	99	451
Ground motion (05/19/11) Max PPV = 0.523ips	705	30	261	1093
Occupant activity (front door open)	111	18	37	123
Wind event (May 15, 2011)	115	20	27	119
Turning off the heat inside the house (on Oct. 26, 2012)	4949	117	4012	7037

Table 5. Maximum crack response to all observed sources of vibrations. All measurements are zero-to-peak (1µin = 0.0254µm)

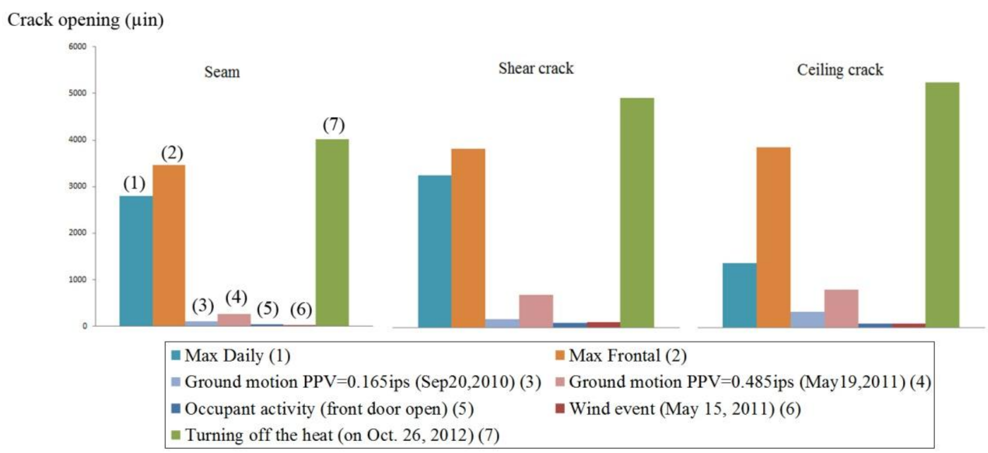


Figure 12. Comparison of crack response magnitudes as presented numerically in Table 5

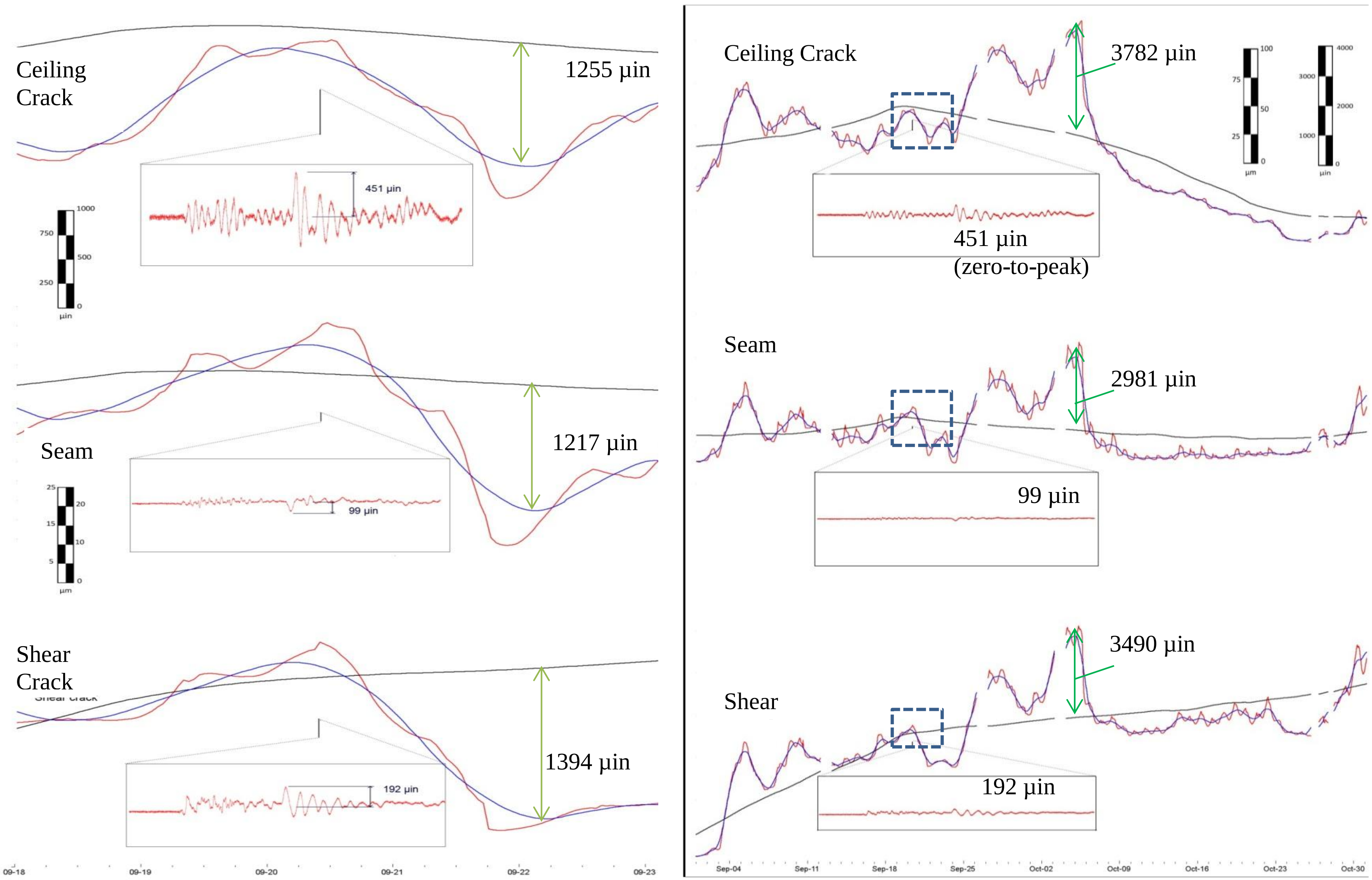


Figure 13. Comparison of zero-to-peak crack response to environmental effects over the course of two months (top) and one week (bottom, delimited in dashed boxes) with that produced by the PPV=0.219in/s event. (1µin=0.0254µm, 1in/s=25.4mm/s)

CONCLUSIONS

Data provided herein are a compilation of one of the longest continuously recorded crack responses to date. More than 28 months of continuous crack response have been recorded, including several periods of many months without blasting, thus showing that large crack response occurs without blasting. The unusually long period of observation provided the opportunity to observe response to two seasonal variations.

As has been observed before, crack response to environmental variations is overwhelmingly larger than that produced by blast induced ground motion and associated air overpressure pulses. Seasonal variations and even the passing of weather fronts can produce crack response that is larger by at least an order of magnitude. Turning off the heat inside the house in the fall can cause crack response of that order of magnitude as well, but over periods of time as short as a week.

Observation of occupant activity and wind gust events shows that both can produce crack response as large as that produced by blast induced ground motions.

ACKNOWLEDGEMENTS

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