RESPONSE OF A CONCRETE BLOCK STRUCTURE TO QUARRY INDUCED GROUND MOTION AND WEATHER

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ABSTRACT

The notion of blasting, even in a controlled setting such as a limestone quarry, can be alarming to residents and business owners within earshot. Because humans are inherently sensitive to blast-induced vibrations, they perceive that the structures in which they live in are equally sensitive. The goal of this project is to compare effects caused by ground motions with those caused by everyday events. By so doing, it is hoped to provide a rational basis for judging the sensitivity of a structure to vibration. This project reports the effects of ground motion caused by blast vibrations on the structural response and crack displacements in a one-story house. More importantly, these effects are compared with those caused by thunder, occupant activity, and long-term climatic factors. These comparisons show that hourly, daily, and seasonal variations in temperature and humidity cause cracks to displace orders of magnitude more than the dynamic events by which people are very concerned.

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1. INTRODUCTION

1.1 Background

This is the second report on the **structural response** and resulting **crack movements** of a one-story residential structure in Naples, Florida. It presents data from Phase II of an ongoing study at this house and follows the Phase I report (Kosnik 2008). It is also part of a larger research project: Autonomous Crack Monitoring (ACM) at the Infrastructure Technology Institute (ITI) at Northwestern University.

Focus of Phase II

In addition to being a continuation of Phase I's measurement of crack response to ground motion and environmental factors, Phase II includes the response of the structure, a crack in- the out-of-plane direction, a cracked corner joint, and an uncracked drywall joint. This report compares the **structural response** and resulting **crack movements** caused by:

- ✦ Ground motions from blasting
- ✦ Thunder
- ✦ Occupant activity (door slamming)
- ✦ Environmental conditions (long term changes in temperature and humidity)

This slab-on-grade, one-story house (shown in Figure 1-1) has CMU exterior walls covered with stucco and wood interior construction with drywall finish. It is located adjacent to the Jones Limestone Quarry which generated blasts 25 times in the study period (Sep 1, 2008 through Sep 1, 2009). Table 1-1 describes the blast vibration environment. Typical blasts involve 30 to 50 holes loaded with 50 to 60 lbs of ANFO each and detonated with separate delays in each hole. The blasts, in the red areas Figure 1-2, are generally 3000 to 5500 ft away from the test house (shown as a white star at the bottom). As can be seen in Figure 1-2 by the multiple excavation areas, the quarry is in its initial stages of development.

Figure 1-1 - Photograph of west face of house in Naples, FL

Blast	Date	Time (AM)	Geophone PPV [in/s]			Distance [ft]	Weight [lbs]	No. Holes
			L	T	V			
1	**Oct 23**	10:29	0.080	0.065	0.060	4320	60	48
2	**Dec 8**	10:33	0.073	0.065	0.060	3660	64	27
3	**Dec 8**	10:40	0.085	0.115	0.078	3530	64	35
4	**Mar 6**	11:41	0.045	0.050	0.048	3220	60	20
5	**Mar 18**	10:42	0.110	0.043	0.088	4220	60	43
6	**Mar 18**	10:58	0.100	0.098	0.100	2880	60	47
7	**Mar 23**	10:57	0.053	0.013	0.028	5450	60	40
8	**Mar 23**	11:08	0.065	0.053	0.090	4200	50	48
9	**Mar 26**	10:32	0.095	0.073	0.133	4080	50	48
10	**Apr 1**	10:38	0.058	0.033	0.055	3830	50	42
11	**Apr 1**	10:49	0.038	0.023	0.135	5570	60	44
12	**Jul 8**	11:08	0.053	0.040	0.003	3890	50	49
13	**Jul 8**	11:14	0.088	0.098	0.003	3970	50	43
14	**Jul 14**	10:40	0.063	0.040	0.070	3890	50	49
15	**Jul 14**	10:46	0.050	0.050	0.038	3370	50	49
16	**Jul 22**	11:15	0.088	0.088	0.063	3180	40	49
17	**Jul 22**	11:26	0.105	0.175	0.120	3110	80	46
18	**Jul 27**	10:57	0.083	0.090	0.070	3170	80	49
19	**Jul 27**	11:04	0.145	0.090	0.095	3120	80	50
20	**Aug 17**	10:51	0.090	0.070	0.075	2890	80	53
21	**Aug 17**	10:59	0.098	0.080	0.113	2860	80	50
22	**Aug 20**	11:08	0.123	0.085	0.098	3270	80	47
23	**Aug 20**	11:19	0.093	0.073	0.088	2940	80	48
24	**Aug 20**	11:27	0.080	0.080	0.088	2880	80	48
25	**Aug 27**	10:15	0.068	0.058	0.075	3070	80	48
Avg.			0.081	0.070	0.075	3623	64	45

Table 1-1 - Characteristics of blasts producing the vibrations throughout the study period. Strength of blast can be characterized by the weight of explosive per delay (hole in this case, ~60lbs) and distance (~3/4 mile). These PPV's were supplied by GeoSonics from the compliance instrument, labeled "Ground Motion" in Figure 1-3.

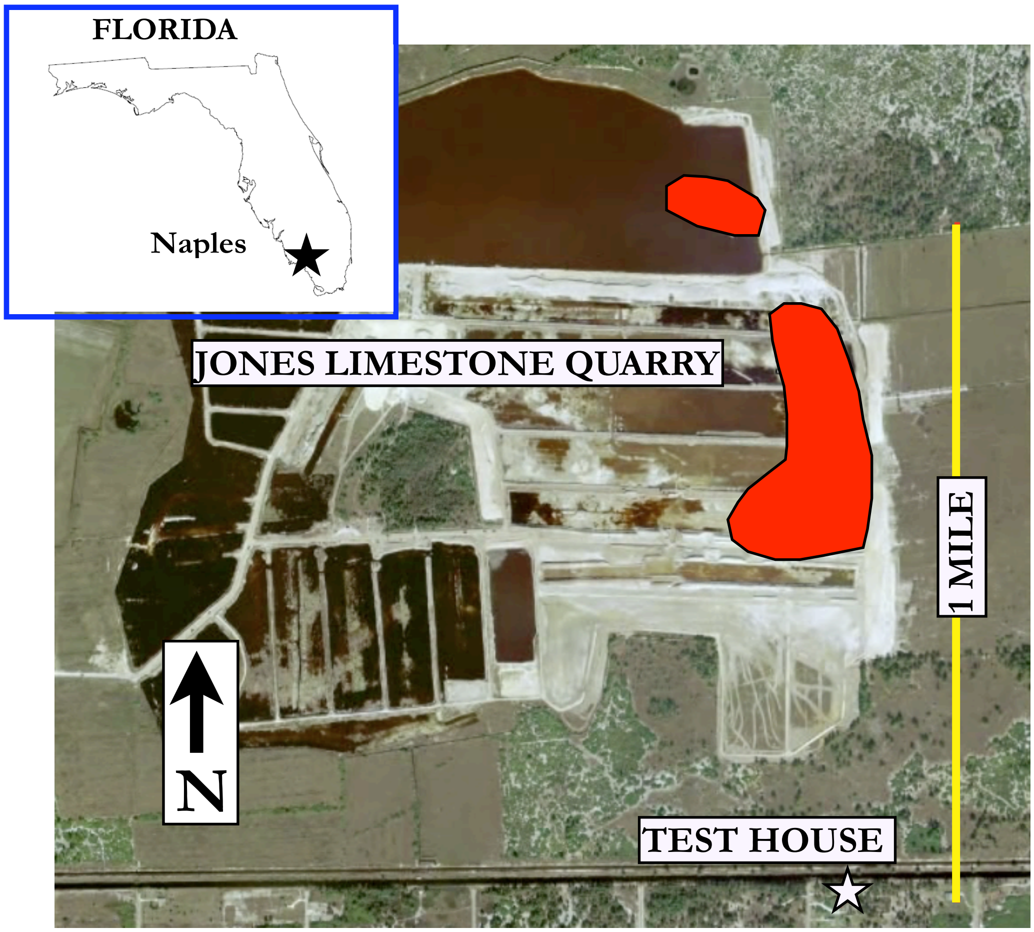

Figure 1-2 - Location of subject house in Florida south of the Jones Limestone Quarry. The red regions indicate location of blasts throughout the study period. The test house is representative of home closest to the quarry with blasts between 1/2 and 1 mile away.

1.2 Instrumentation

Plan

Phase II features an expanded instrumentation program, with several new crack sensors and velocity transducers to measure structural response as shown in Figure 1-3. The system is a combination of the sensors listed in Table 1-2; they are described in more detail in the sections below and pictured in Figures 1-9 through 1-11.

Two computer-controlled data acquisition systems are employed; both are from SoMat Corporation's eDaq product line. the eDaq Classic records triaxial ground motion, wind speed and direction, temperature and humidity, and crack displacements A1&2 and B1&2. The eDaq Lite records velocity transducers HG1-HG5, the ceiling velocity transducer, air overpressure, and crack displacements C1&2, D1&2, and E1&2.

Two types of data are recorded: **long-term** and **dynamic**. Crack responses, temperature, and humidity are recorded every hour for long-term data as an average of 1000 samples in one second. Crack responses, ground & structural velocity, and air overpressure are recorded at 1000 samples per second for 6 seconds when triggered during dynamic events. Both dynamic events and long-term data are recorded by the on-site eDaq computer and are downloadable from the internet via a password-protected site. The triaxial, horizontal and vertical velocity transducers, and air overpressure sensor are set to trigger the whole system at thresholds indicative of blasting , thunder, high winds, or occupant activity.

Though this configuration is quite similar to previous ACM studies and Phase I at this house, there are four new sensors and trigger mechanisms:

- An **Out-of-Plane** crack response sensor (A2) has been placed at the CMU interface crack at the entrance to the kitchen from the garage
- Two **Corner** sensors (E1, E2) have been placed at the northwest living room crack to measure both North-South and East-West movements
- Five **Horizontal Velocity Transducers** (HG1-HG5) have been placed at the top and bottom of the north and east walls as well as in the middle of the north wall to measure structural response
- A **Tape Joint** response sensor has been placed over an uncracked seam between two drywall panels in the garage ceiling

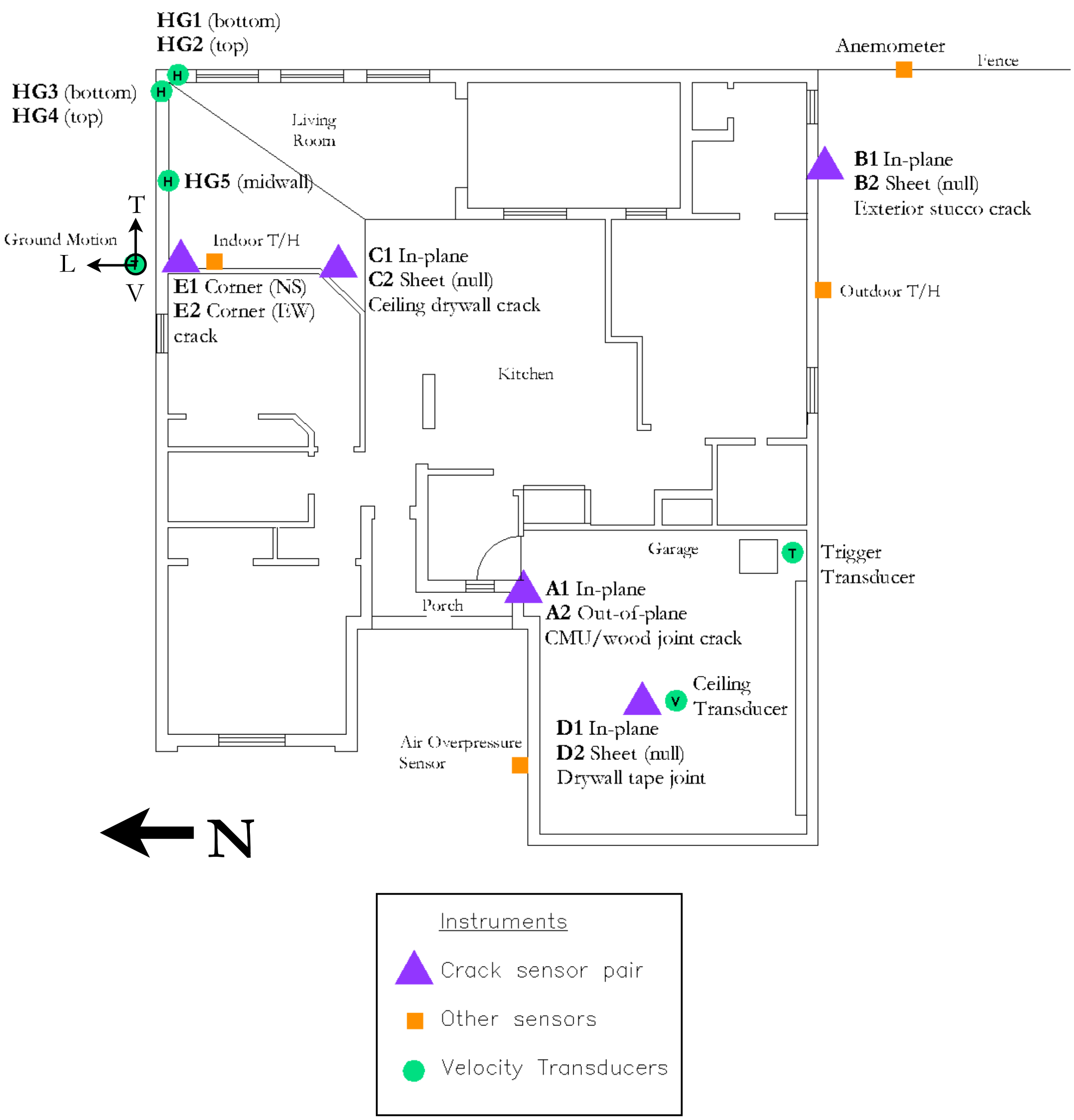

Figure 1-3 - Instrument locations that enable measurement of (1) structural response to ground motions (2) crack response in-plane, out-of-plane, and in corners (3) uncracked joint response (4) various triggering methods to capture wind response

Sensor	Model	Measures	Notes
Ground Motion	GeoSonics 3000 LC series	Ground velocity in longitudinal, transverse, and vertical directions	Defines excitation motions
Structural Response Sensors	Geospace Corp. Model HS-1-LT 98449	Structural velocity in strategic locations in Living Room	5 transducers with common time base to calculate relative structural displacements
Crack Displacement Sensors	Kaman SMU-9000	Crack width, both dynamically and long-term	In-plane, out-of-plane [A], corner joint [D], and uncracked joint response [E]
	LVDT MacroSensors DC 750-050	Crack width, both dynamically and long-term	In-plane response [B, C]
Temperature/Humidity Gauge	Vaisala HMT-50 & 100	Indoor & Outdoor temperature & humidity	Model 50 is used inside, Model 100 outside
Air Overpressure Sensor	GeoSonics 3000 series microphone	Air pulses from blasting and weather events	Compare air pressure with wind velocity
Anemometer	Vaisala WS425	Wind velocity and direction	

Table 1-2 - Detailed description of each sensor and its purpose

Structure Response

Though structures consist of many components, two of the most important are walls and superstructure. Superstructure response is measured by horizontal velocity transducers (HG2,4) attached perpendicularly to an upper corner as shown below in Figure 1-4 and pictured in Figure 1-6. Out-of-plane wall response is measured by the transducer (HG5) in the middle of the wall. Transducers at the bottom corners (HG1,3) are used as a reference. Response velocity is integrated over time to obtain displacement. All these transducers measure absolute motion, so differences in time correlated displacements of selected pairs can be employed to estimate relative motion and therefore strain from shearing/bending in the walls. These strains can then be compared to crack response magnitude and timing to assess correlation and causality (Dowding 1996).

In residential structures, ground motions generally displace the top transducers relative to the those on the bottom, while air pulses displace the midwall transducer more relative to the top and bottom. As a result, ground motions cause the superstructure to respond at their lower natural frequency (structure wobbles) while the air pulses cause the walls to bend at their higher natural frequency (walls flex like a drum membrane). Mode shapes of these two responses are shown in Figure 1-5. In this study, structural response has been measured from blast events, thunder, passage of the Space Shuttle (Appendix A), and occupant activity.

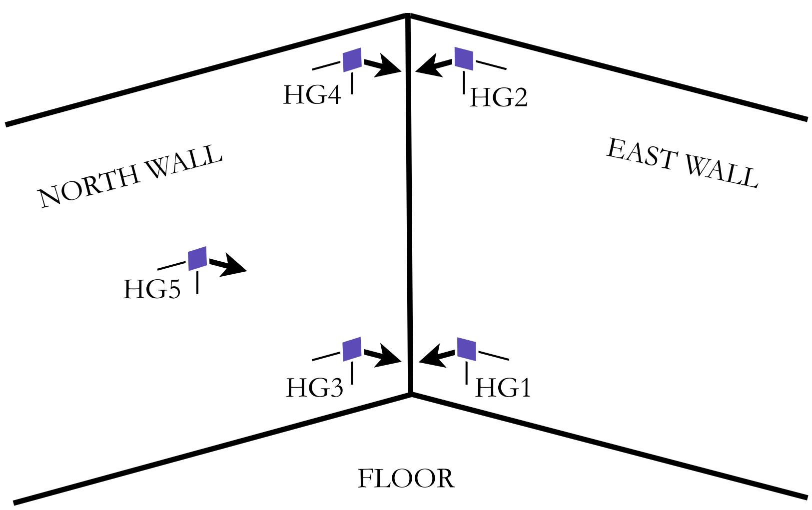

Figure 1-4 - Isometric view of the structural instrumentation of living room to measure absolute displacements of superstructure and walls

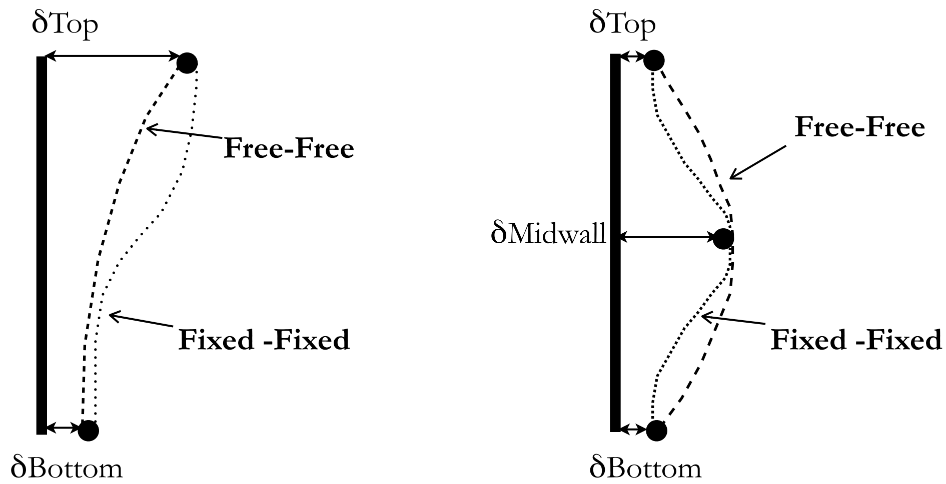

Figure 1-5 - Left: Elevation view of two possible mode shapes for superstructure response- Right: Elevation view of two possible mode shapes for wall response

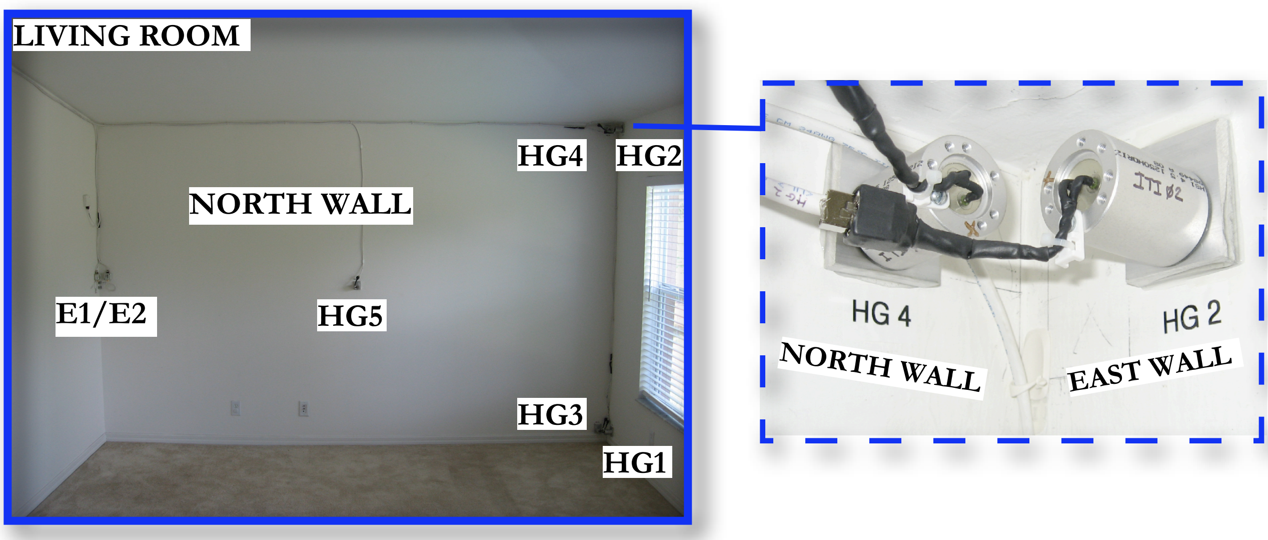

Figure 1-6 - Instrumentation of north wall of living room: 5 horizontal velocity transducers to measure velocity of the superstructure (HG3,4 North-South, HG1,2 East-West) and the wall response (HG5 North-South).

Crack Response

Additional instruments have been installed to monitor out-of-plane response of a crack, response of a corner crack, and in-plane response of an uncracked drywall joint. Traditionally, ACM has been employed to monitor crack responses in the plane of the wall containing the crack. Long-term monitoring of out-of-plane and corner crack response are unique to this project. See Waldron (2006) for development of the out-of-plane sensing system. Table 1-3 describes the transducers, locations, and purposes. Close-up images of the installation are shown in Figures 1-9,10, and 11.

Crack Type	Transducer Pairs	Description	Location	Sensor Type
In-plane	A1	Junction between CMU & door frame	Above entrance to kitchen from garage	Kaman
Out-of-plane	A2			
In-plane	B1	Exterior stucco over CMU	South exterior wall	LVDT
Adjacent uncracked	B2			
In-plane	C1	Interior drywall crack	Ceiling in living room	LVDT
Adjacent uncracked	C2			
In-plane of joint	D1	Interior drywall tape joint	Attic above garage	Kaman
Adjacent uncracked	D2			
Corner (North-South)	E1	Interior drywall crack at corner junction between CMU & wood frame	Interior living room corner	Kaman
Corner (East-West)	E2			

Table 1-3- List of cracks monitored in this study

Crack response is the *change* in crack width, not total crack width, and is called *response* herein after. Figure 1-7 (Siebert 2000) describes this definition. All transducers have been installed so that positive response indicates crack opening and negative indicates crack closing in micro-inches. Also, null sensors (on uncracked areas) are placed near the cracks to provide a record of any drift or thermal effects on sensor electronics. The null sensors' responses have been shown to be small relative to the cracks' (Kosnik 2008).

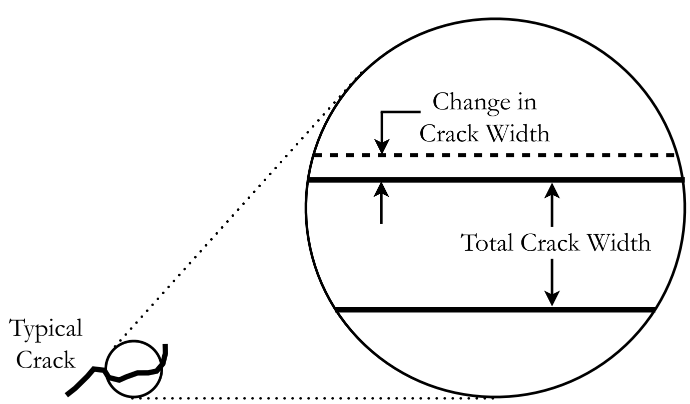

Figure 1-7 - Crack Response is change in crack width, not related to total crack width

Geometries of crack response and sensor deployment are compared in Figure 1-8. Crack movement is shown on the left, crack-sensor geometrical relationship in the middle, and the photo of actual installation on the right. The three special geometries: in-plane, out-of-plane, and corner are monitored by the smaller eddy current transducers for geometrical reasons. The context of each of these cracks is shown in Figure 1-9. The ceiling and exterior stucco cracks are monitored with LVDT displacement transducers as shown in Figure 1-10.

Typical crack response is measured in the plane of the wall. The in-plane ceiling drywall and exterior stucco cracks are monitored with LVDT displacement transducers as shown in Figure 1-10. In-plane response of the cracked door-frame/CMU interface in the garage was measured as well as an uncracked drywall joint in the garage ceiling to compare with crack responses.

To measure movement out of the plane of the wall, the sensor must be oriented perpendicular to the wall, which requires a glass mounting block. Glass was chosen for the block material due to its low coefficient of thermal expansion (Waldron 2006). The non-crack side of the block may serve as a mount for a null sensor but was not included in this installation.

Measurement of corner crack behavior requires a special mounting similar to that for out-of-plane measurements, as shown in Figure 1-9. Since it is not known in which direction response is greatest, both must be measured, requiring two transducers as shown. As with the out-of-plane deployment, the target, a thin aluminum plate, is placed directly on the wall opposing the "L" shaped bracket.

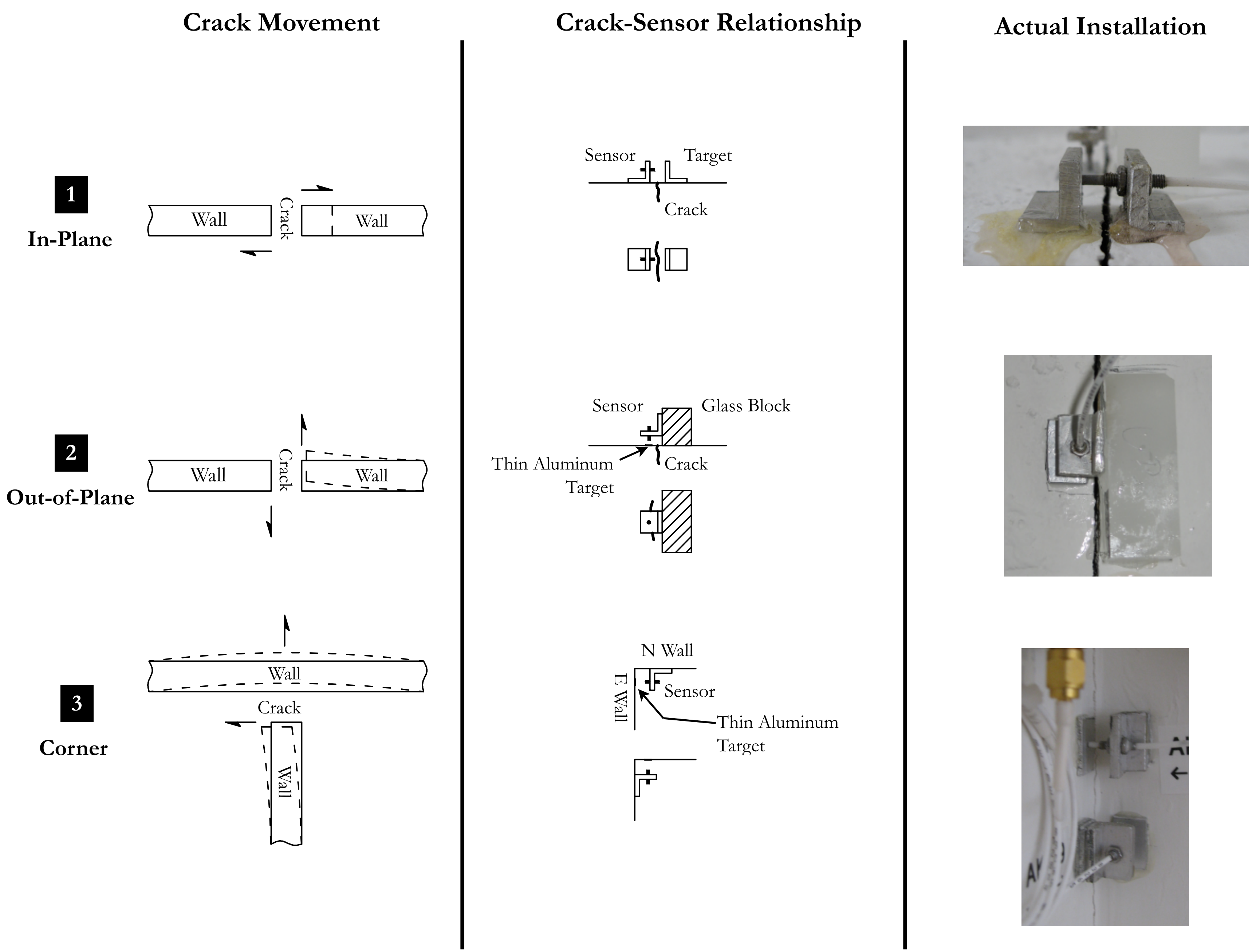

Figure 1-8 - Comparison of the differing deployment geometries for measurement of crack geometry - TOP: crack open/close in the plane of the wall - MIDDLE: crack distortion perpendicular to the plane of the wall - BOTTOM: two directions of corner crack response.

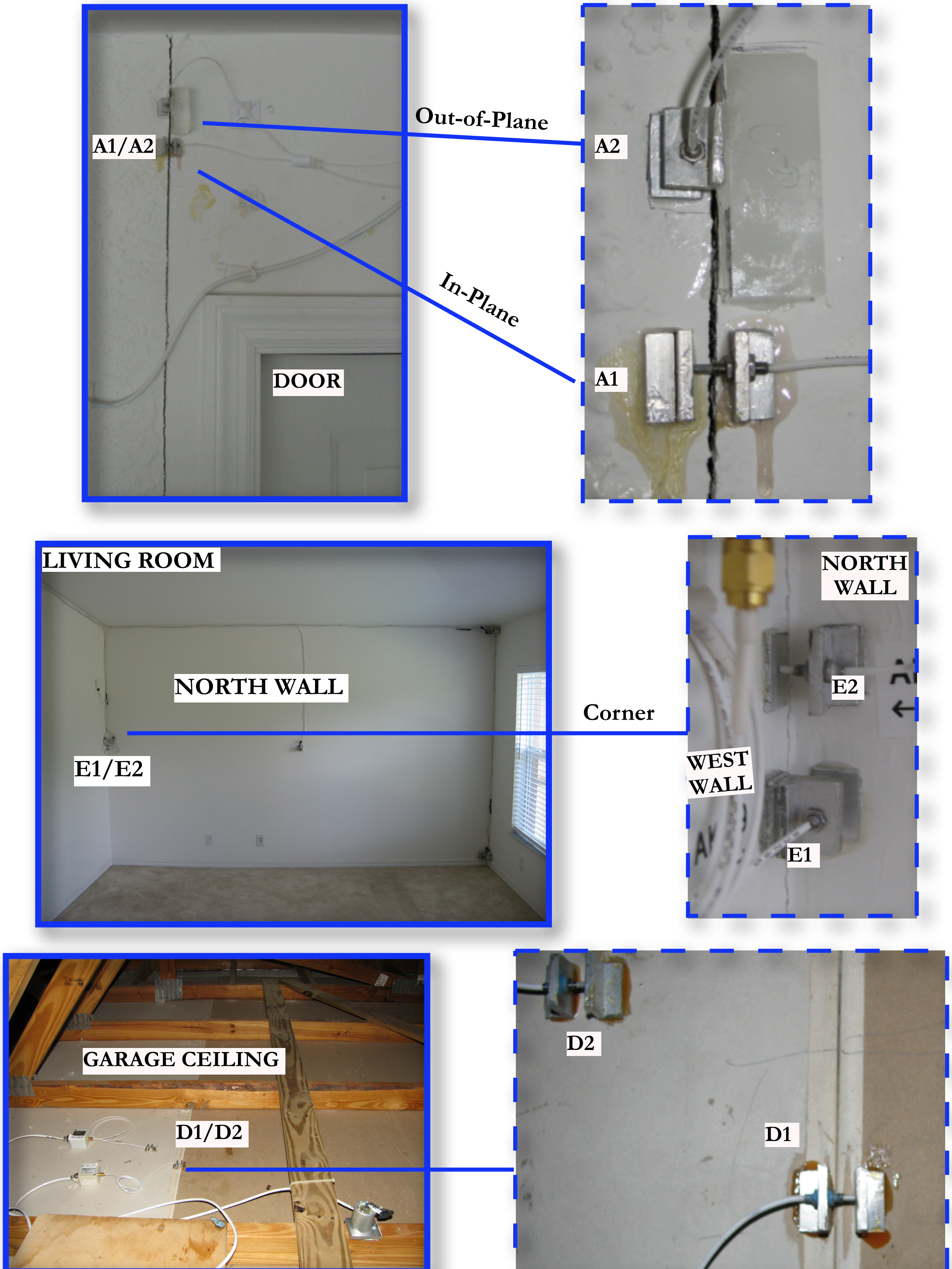

Figure 1-9 - Context of the sensors (left) used and their respective close-up (right) - TOP: In- and Out-of-Plane MIDDLE: Corner (two directions) BOTTOM: In-plane of uncracked drywall joint (near the vertical velocity transducer)

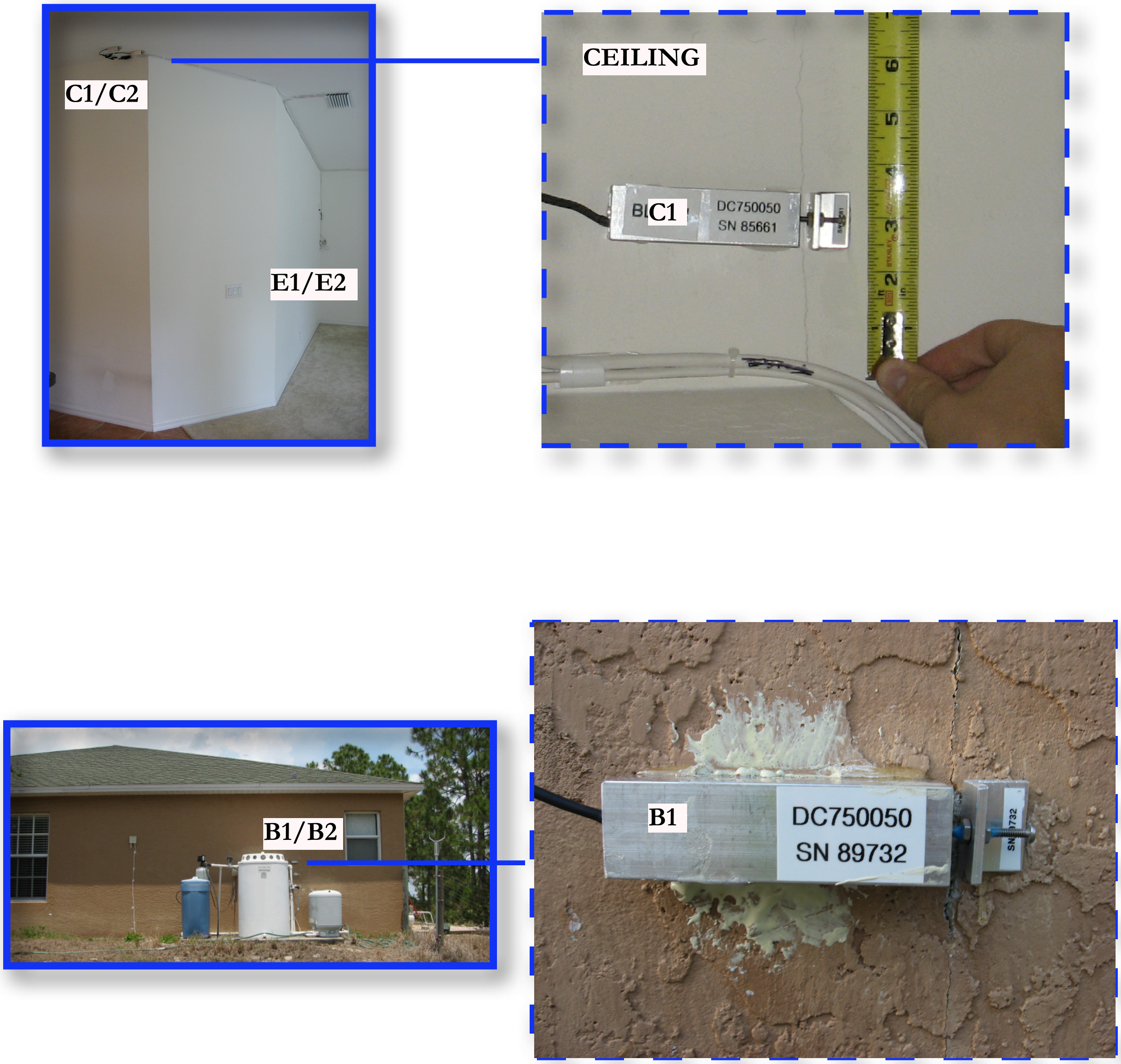

Figure 1-10 - Context of the sensors used and their respective close-up - TOP: In-plane crack in kitchen ceiling BOTTOM: In-plane crack in exterior stucco

Auxiliary Sensors

Other important sensors in this study, shown in Figure 1-11, describe environmental conditions or trigger the acquisition system to record dynamic events. Air overpressure is recorded by a sensor on the front of the house during a blast or wind event, wind direction and speed are recorded by the anemometer, the temperature and humidity are recorded both indoor and outdoors, and triggering transducers are placed in both the garage ceiling and on the garage floor. Ground motion data are recorded by a triaxial geophone buried in the yard, adjacent to the north wall and closest to the quarry.

Air Overpressure Sensor

Anemometer

Temperature & Humidity Sensor

Vertical Velocity Transducer

Figure 1-11 - Images of sensors that aid in determining environmental conditions, structural response, and air overpressure intensity

2. RESULTS

2.1 Long-Term Climatological Effects

Long-term crack response is measured by accumulating crack data every hour as the average of a burst of 1000 samples in one second. These data are assembled as the highly variable **blue** line in Figures 2-1 and 2-2. The thick, less variable **red** line is a 24-hour central moving average (CMA) of the hourly points which develops the passage of weather fronts. The **black**, even less variable line is a 30-day CMA of the hourly points which will display seasonal trends.

The **Daily response** is defined as the time correlated difference between the hourly data and the 24-hour CMA, and the **Frontal response** is defined as the time correlated difference between the 24-hour CMA and the 30-day CMA. **Seasonal Response** is the overall range of the 24 hour curve (**red**), and **Max Response** is the overall range of the hourly curve (**blue**). Maxima of these effects are displayed in Table 2-1 and visually described in Figures 2-1 and 2-2.

	CMU/door-frame interface		Exterior Stucco	Ceiling Drywall	Drywall Joint	Drywall Panel	Corner N-S	E-W
Response	A1	A2	B1	C1	D1	D2	E1	E2
Max Daily	8685	10064	9090	3331	1856	719	8021	1873
Max Frontal	6404	5501	5735	4593	1403	272	7536	2173
Max Seasonal	15878	13272	22921	14901	3135	709	20954	5205
Max	25490	24531	30275	18768	4761	1251	26542	7087

Table 2-1 - Maximum crack response to weather effects in μ-in. Daily and Frontal are zero-to-peak measurements, while Seasonal and Max are peak-to-peak measurements.

Response of the cracks in the living space (C1,E1,E2) is shown with the indoor temperature and humidity in Figure 2-1. The ceiling crack's (C1) frontal response closely follows the variations in the 24-hour CMA of indoor humidity. Response of the corner crack in the N-S direction (E1) responded to the movement of the interface between the exterior CMU wall and the interior wood-framed wall much more than the E-W direction. This seasonal response would have been larger, but the sensor went off-scale as can be seen by the truncated maximum through May 1st.

Long-term response of cracks outdoors and in the garage (A1,A2,B1,D1) are shown in Figure 2-2. These records are less complete due to intermittent operation of the sensor power supply. Nonetheless, environmental factors similarly affect both in- and out-of-plane crack response with in-plane response being slightly larger. This is evident from A1 and A2 exhibiting comparable responses throughout the study period. Waldron found a similar result in his case: long-term in-plane responses are larger than out-of-plane responses (Waldron 2006).

The longevity of this study presented the opportunity to measure seasonal (or yearly) responses. The frontal responses build upon the seasonal trends, and the daily responses build upon the frontal responses (24 hr CMA). Together these time correlated responses produce the maximum responses.

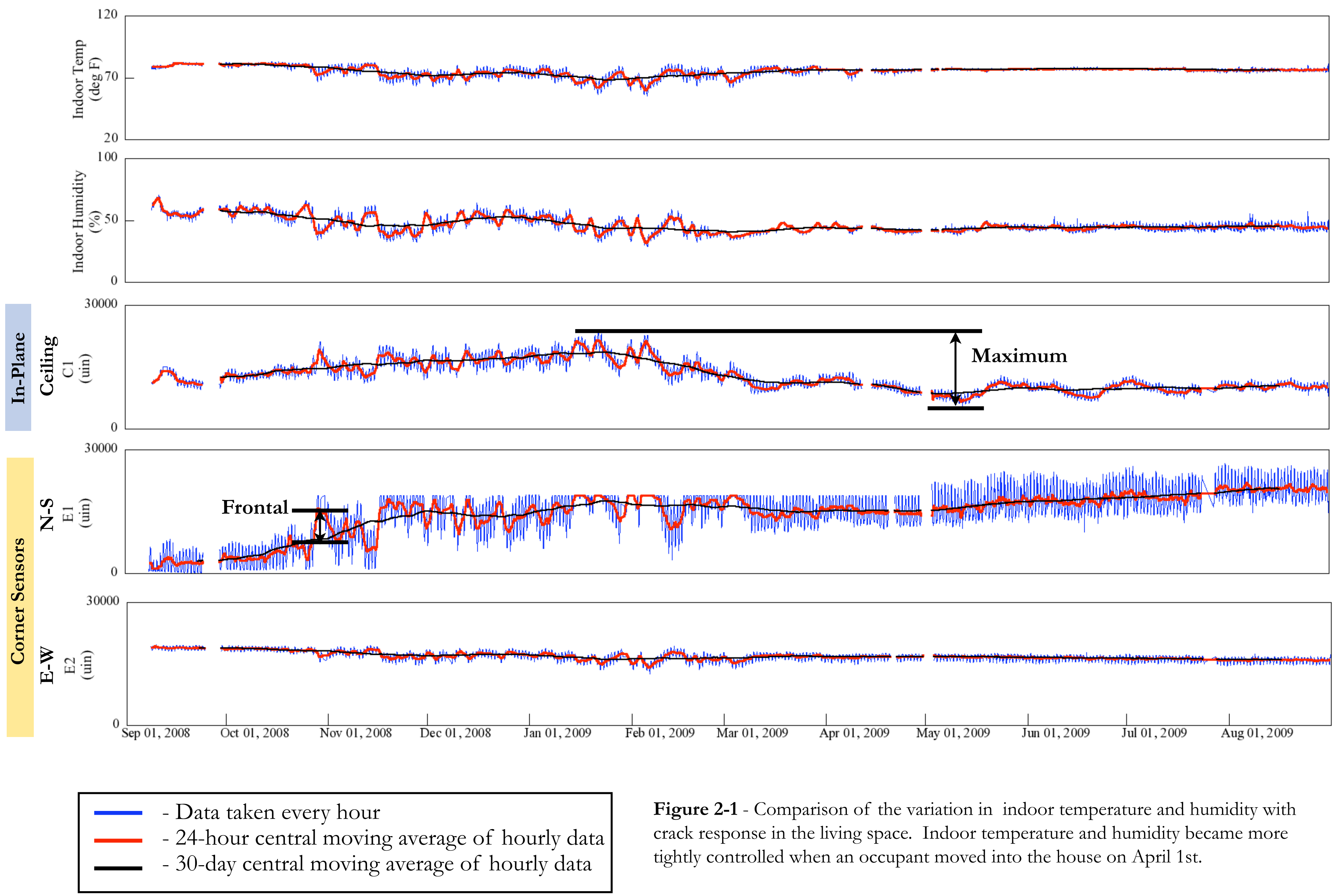

Figure 2-1 - Comparison of the variation in indoor temperature and humidity with crack response in the living space. Indoor temperature and humidity became more tightly controlled when an occupant moved into the house on April 1st.

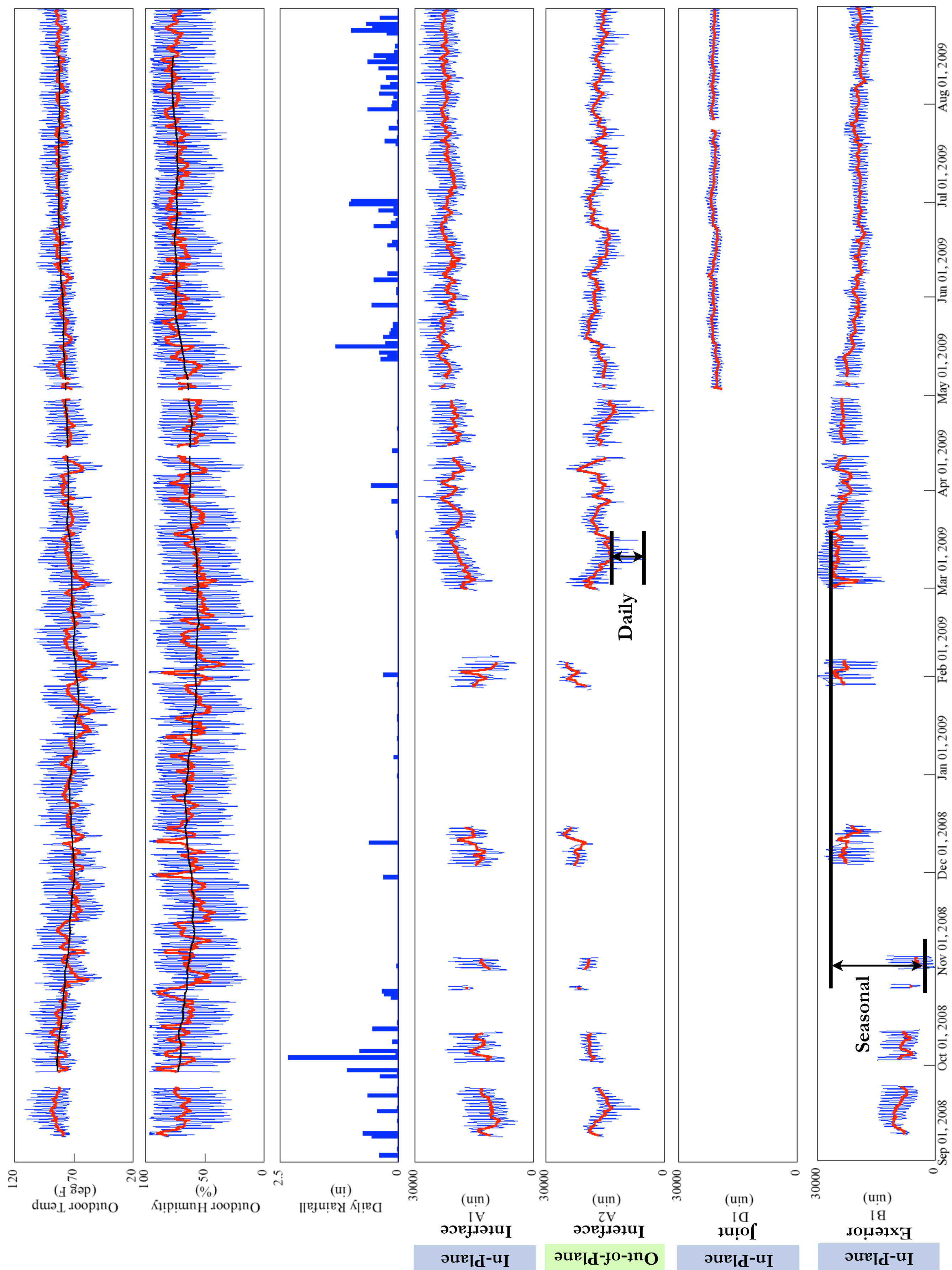

Figure 2-2 - Comparison of outdoor temperature and humidity with crack response outside the living space.

2.2 Ground Motion

Structural Response

Table 2-2 compares the peak particle velocities and air overpressures with the zero-peak structural blasts throughout the study period. The "δ" indicates the displacement of the structure at that location calculated by integrating the velocity time history (V_{HGX}) as shown by Equation 2.2.1.

$$\int_0^{t_f} V_{HGX}\,dt = \delta X \qquad \textbf{Eq. (2.2.1)}$$

The δ2-δ1 and δ4-δ3 columns indicate the maximum time correlated differential displacement between the top and bottom of the east and north walls respectively. The δ5-Avg(δ4,δ3) column indicates the maximum differential displacement of the midwall relative to the top and bottom. These relative displacements cause strains in the wall that inevitably induce crack response.

In each blast, the north superstructure (δ4-δ3) exhibits the largest response, approximately twice that of the midwall response (δ5-Avg(δ4,δ3)) in most cases.

Crack Response

Table 2-2 also compares the peak particle velocities and air overpressures with the zero-to-peak crack responses throughout the study period. The out-of-plane response (A2) is larger in than the in-plane response (A1) of the crack at the kitchen-garage entrance when responding to ground motion. The N-S responses are larger than the E-W responses in the living room corner. Both of these results are probably due to the actual construction at these areas. The corner is most likely a perpendicular junction between an interior wood-framed wall and an exterior CMU wall, and the garage door crack is an interface between CMU and wood-frame. The difference in the responses can be explained by the difference in the relative stiffness of the two materials, and lack of constraint out of the plane of the wall at the kitchen-garage entrance.

Time histories in the north-south direction from the July 22nd (2) blast are shown in Figure 2-3 and the east-west direction is shown in Figure 2-4. This event produced the largest overall structural and crack responses as indicated by the yellow entries in the Jul 22nd (2) row. As evident in the time histories, the structure responds much more to the ground motions than the air blast. Relative displacements are much larger in the north-south direction for both the superstructure and the wall response. This potential for larger N-S response may be a major contributor to the larger N-S corner crack response (E1). The cracks responded more to the higher frequency portion of the excitation than the trailing low frequency, high amplitude excitation.

				Structural Response [μ-in.]			Crack Response [μ-in.]							
Date	PPV [in/s]	Air Blast [10^{-4} psi]	freq [Hz]	δ2-δ1	δ4-δ3	δ5 - Avg(δ4,δ3)	A1	A2	B1	C1	D1	D2	E1	E2
				E-W	N-S									
Oct 23	0.080 [L]	3.93	8.9	314	3735	1349	-	-	-	-	-	-	200	61
Dec 8 (1)	0.073 [L]	4.48	23.8	220	1329	655	159	242	-	-	-	-	-	56
Dec 8 (2)	0.115 [T]	7.65	2.9	415	2288	1059	192	303	-	-	-	-	-	62
Mar 18 (1)	0.110 [L]	4.77	33.3	180	763	891	181	219	-	-	-	-	392	114
Mar 18 (2)	0.100 [L]	7.10	33.3	478	1628	1133	284	299	-	-	-	-	341	86
Mar 23 (1)	0.053 [L]	2.67	25.0	151	585	400	112	155	-	-	-	-	-	47
Mar 23 (2)	0.090 [V]	5.56	25.0	215	1549	735	144	176	-	-	-	-	-	59
Mar 26	0.095 [L]	4.43	31.3	192	1025	722	238	389	-	-	-	-	244	87
Apr 1 (1)	0.058 [L]	3.69	29.4	271	1950	905	182	131	-	-	-	-	-	75
Apr 1 (2)	0.135 [V]	1.68	1.6	159	499	449	134	178	-	-	-	-	-	59
Jul 8 (1)	0.053 [L]	4.90	31.3	139	1328	701	171	115	-	-	-	-	289	97
Jul 8 (2)	0.098 [T]	4.50	6.4	309	5634	2954	300	351	31	60	30	12	293	123
Jul 14 (1)	0.070 [V]	4.42	29.4	300	1665	816	162	182	-	-	-	-	488	164
Jul 14 (2)	0.050 [L]	4.50	9.6	180	3080	1521	125	114	-	-	-	-	284	75
Jul 22 (1)	0.088 [T]	6.02	6.1	296	3568	1746	254	185	-	-	-	-	324	120
Jul 22 (2)	0.175 [T]	6.02	5.4	554	5950	2856	322	498	56	98	41	12	442	172
Jul 27 (1)	0.090 [T]		5.9	-	-	-	178	214	-	-	-	-	-	-
Jul 27 (2)	0.145 [L]		25.0	-	-	-	310	364	-	-	-	-	-	-
Aug 17 (1)	0.090 [L]	4.50	7.8	293	4543	2232	221	261	39	78	30	12	540	174
Aug 17 (2)	0.098 [L]	4.62	29.4	360	3161	1474	321	478	38	102	27	14	546	175
Aug 20 (1)	0.123 [L]	6.91	27.8	311	3309	1704	254	358	23	78	37	13	354	114
Aug 20 (2)	0.093 [L]	4.90	26.3	288	3496	1726	206	276	-	-	-	-	404	131
Aug 20 (3)	0.088 [V]	4.50	27.8	213	2974	1512	187	233	-	-	-	-	394	123
Aug 27	0.075 [V]	5.26	31.3	334	2072	969	280	188	-	-	-	-	369	99
Average	0.080	4.86	20.2	281	2551	1296	214	257	37	83	33	13	369	103

Table 2-2 - Comparison of peak excitation particle velocity and air blast characteristics to structural and crack response for the blasts during the study period. **Structural Response:** Relative displacements are larger in the north-south direction (4-3), and larger in the superstructure than the walls. **Crack Response:** A2 (out-of-plane) responds more than A1 (in-plane) above the garage door, and E1 (N-S) responds more than E2 (E-W). Maximums are indicated by yellow highlighting.

Figure 2-5 shows a time history of the ground motion and corresponding crack responses for the interface above the garage door, the ceiling, and drywall joint during the July 22nd (2) blast. In-plane response is comparable to out-of-plane. Both respond the most to the lower frequency portion of the excitation at 2.0 seconds and later, although out-of-plane response is still high for the initial high frequency portion of the excitation. Waldron found out-of-plane response to ground motion about half of in-plane response (Waldron 2006).

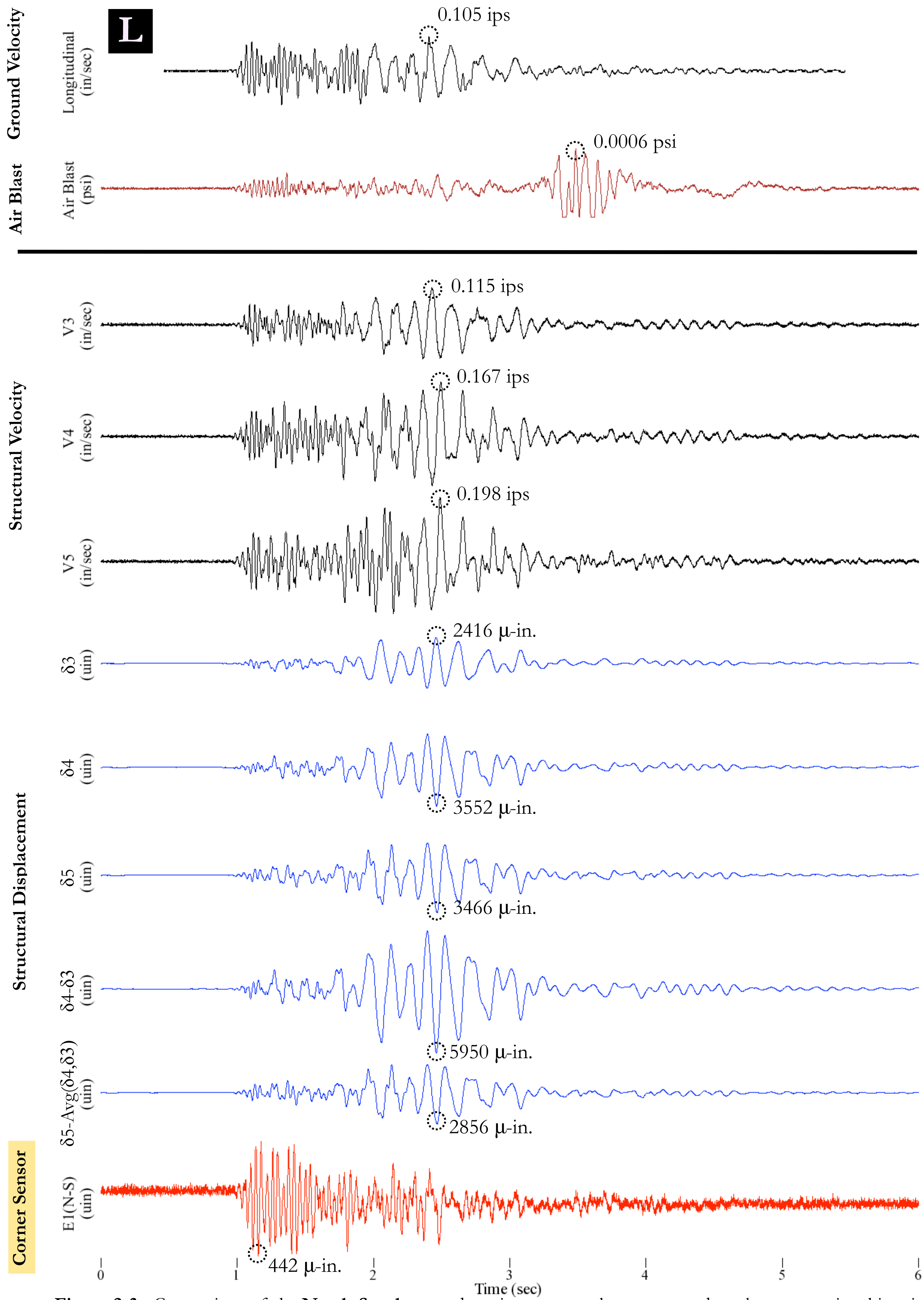

Figure 2-3 - Comparison of the **North-South** ground motion, structural response, and crack response time histories from the July 22nd (2) blast

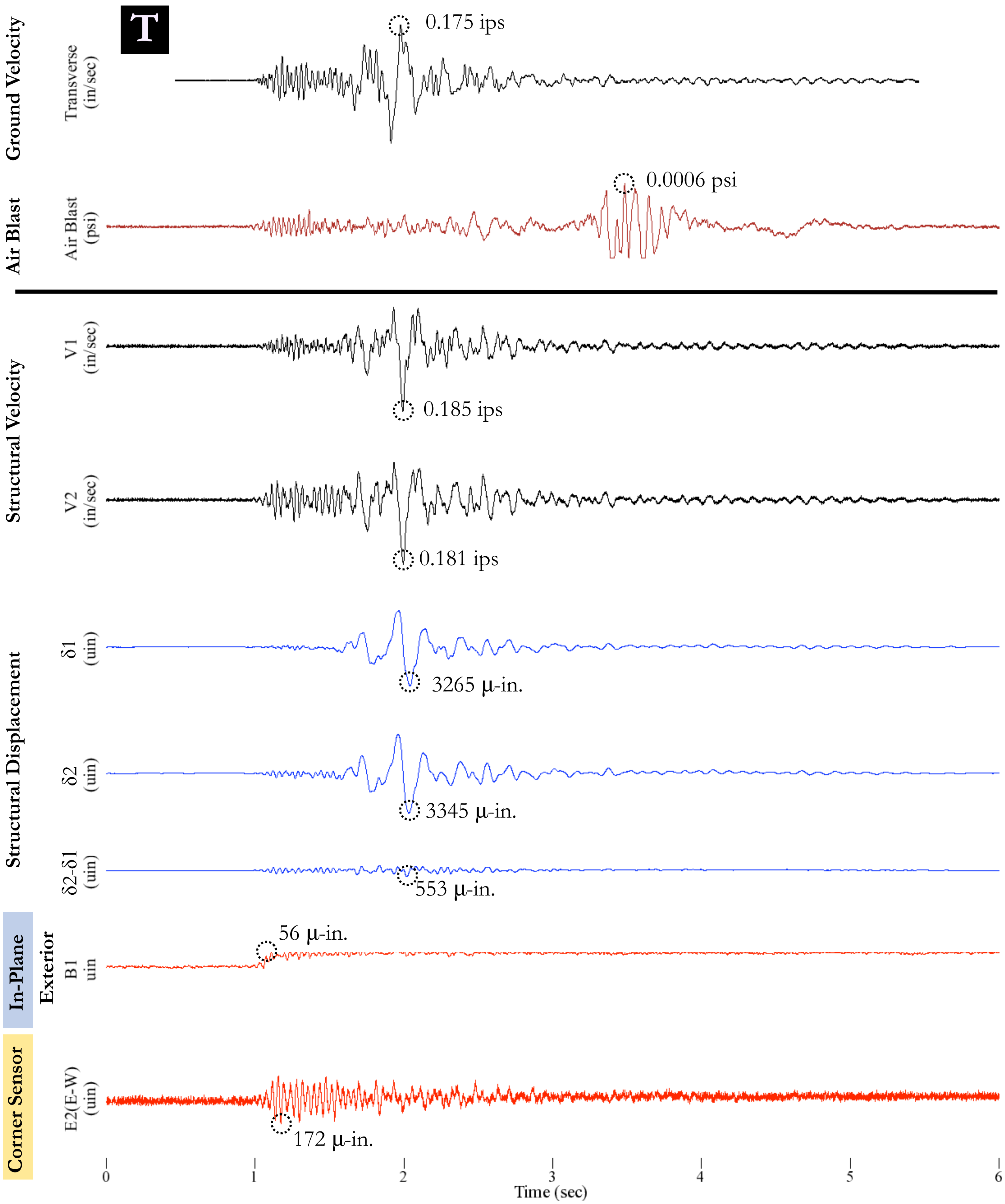

Figure 2-4 - Comparison of the **East-West** ground motion, structural response, and crack response time histories from the July 22nd (2) blast. Differential structural displacement is small compared to North-South and therefore E2's response is small

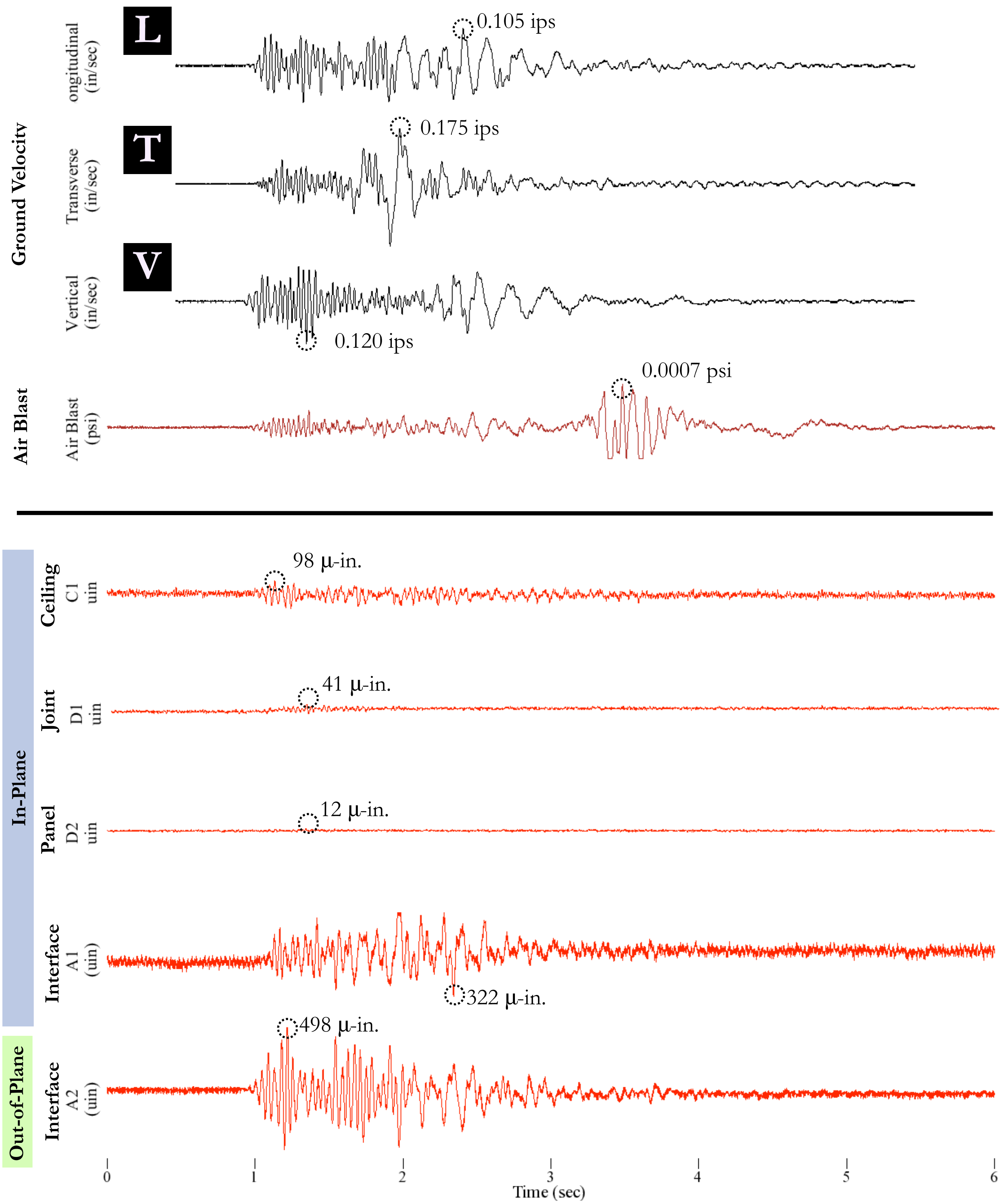

Figure 2-5 - Comparison of the ground motion, structural response, and crack response time histories from the July 22nd (2) blast. In-plane and out-of-plane response are comparable in magnitude with out-of-plane being slightly larger.

2.3 Thunder

Table 2-3 compares air overpressures from lightning strikes that occurred in the beginning of September, 2009 and their respective structural and crack responses. The lightning strike data were obtained from Vaisala's STRIKENet database. The potential of a strike to cause the structure to respond is the result of the air pressure wave accompanying the thunder clap. The wall response is much larger than the superstructure, therefore there may be more bending than shear distortion.

			Structural Response [μ-in.]			**Crack Response [μ-in.]**							
Date	Time	Air Over-pressure [psi] (x 10^{-2})	δ2-δ1 [μ-in.]	δ4-δ3 [μ-in.]	δ5 - Avg(δ4,δ3) [μ-in.]	A1	A2	B1	C1	D1	D2	E1	E2
Sep 2	3:28 PM	0.969	237	279	566	73	161	26	86	39	11	382	104
Sep 5	1:59 PM	1.07	139	108	54	47	94	17	45	95	10	142	71
Sep 5	2:03 PM	0.137	69	92	217	33	90	20	44	62	11	195	73
Sep 5	2:07 PM	1.01	170	131	477	174	260	20	93	282	14	519	107

Table 2-3 - Comparison of thunder clap characteristics to structure response for the 4 events that occurred on August 26, 2008. These strikes and the accompanying thunder (less than a mile away) cause more wall response than superstructure response.

Figure 2-6 shows the structural response and corner crack time histories of the 2:07 PM lightning strike and accompanying air overpressure on September 5th, 2009. Midwall response from this induced air overpressure is comparable to those induced by ground motion with PPV of approximately 0.1 ips, while the superstructure responses are much smaller. Also, the air overpressure (0.01 psi) is ten times greater than during any blast. Figure 2-7 shows the remaining crack response time histories. These crack response are comparable to those induced by blasting.

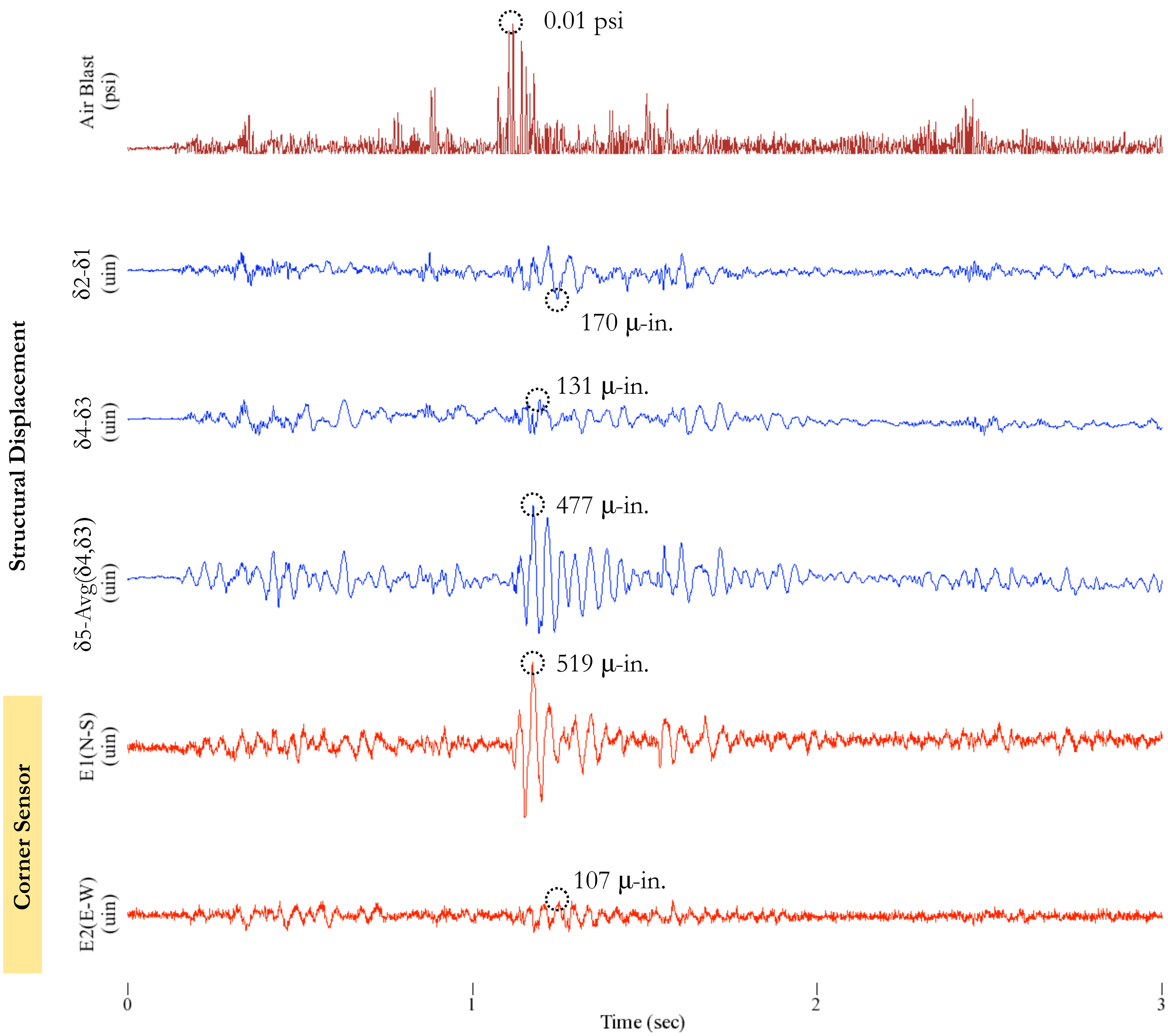

Figure 2-6 - Living room structural and crack response time histories during a thunder event on September 5th, 2009. Both the structure and the cracks respond directly to the very large air overpressure.

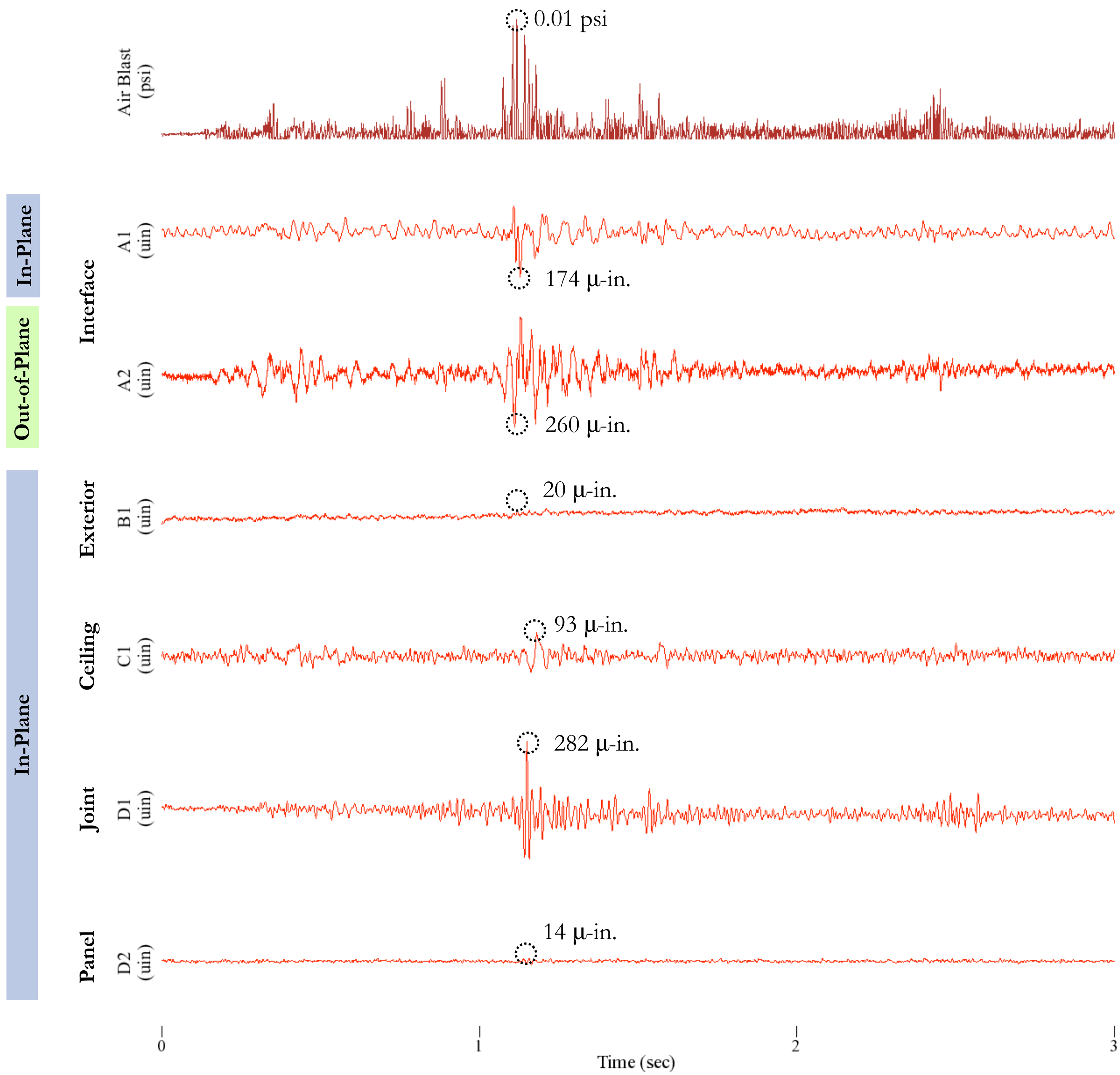

Figure 2-7 - Crack response time histories during a thunder event on September 5th, 2009. The cracks respond directly to the very large air overpressure.

2.4 Occupant Activity

Occupant activity often induces surprisingly high responses in the structure. Slamming a door, jumping up and down, or pounding a nail into a wall produces larger than expected results. Table 2-4 summarizes the effect on the structure of closing two different doors. Figure 2-8 shows the structural response when the front door was opened and closed.

	Structural Response [μ-in.]			Crack Response [μ-in.]			
Activity	δ2-δ1	δ4-δ3	δ5 - Avg(δ4,δ3)	A1	A2	E1	E2
Open/Close Front Door	176	155	378	166	1103	576	495
Open/Close Interior Garage Door	86	209	471	2076	28000	653	322

Table 2-4 - Summary of occupant activities and their respective structural and crack responses. Midwall response is larger than that of the superstructure. Out-of-plane response (A2) is much greater than in-plane (A1).

Simply opening and closing the interior garage door produces crack responses that are two orders of magnitude greater (100x) at the door than any blast or thunder event. Figure 2-8 also shows the crack response when the front door was opened and closed. The out-of-plane response (A2) and N-S corner crack responses are far greater than any from blast induced ground motion. This is especially remarkable since the corner crack that is tens of feet away from either door. Out-of-plane response is almost ten times greater than in-plane response at the door seam. Waldron found out-of-plane response to be less than in-plane response induced by closing a door, but he was focusing on a crack in a ceiling, while this study focuses on a joint between the door frame and CMU wall that was obviously not well attached (Waldron 2006).

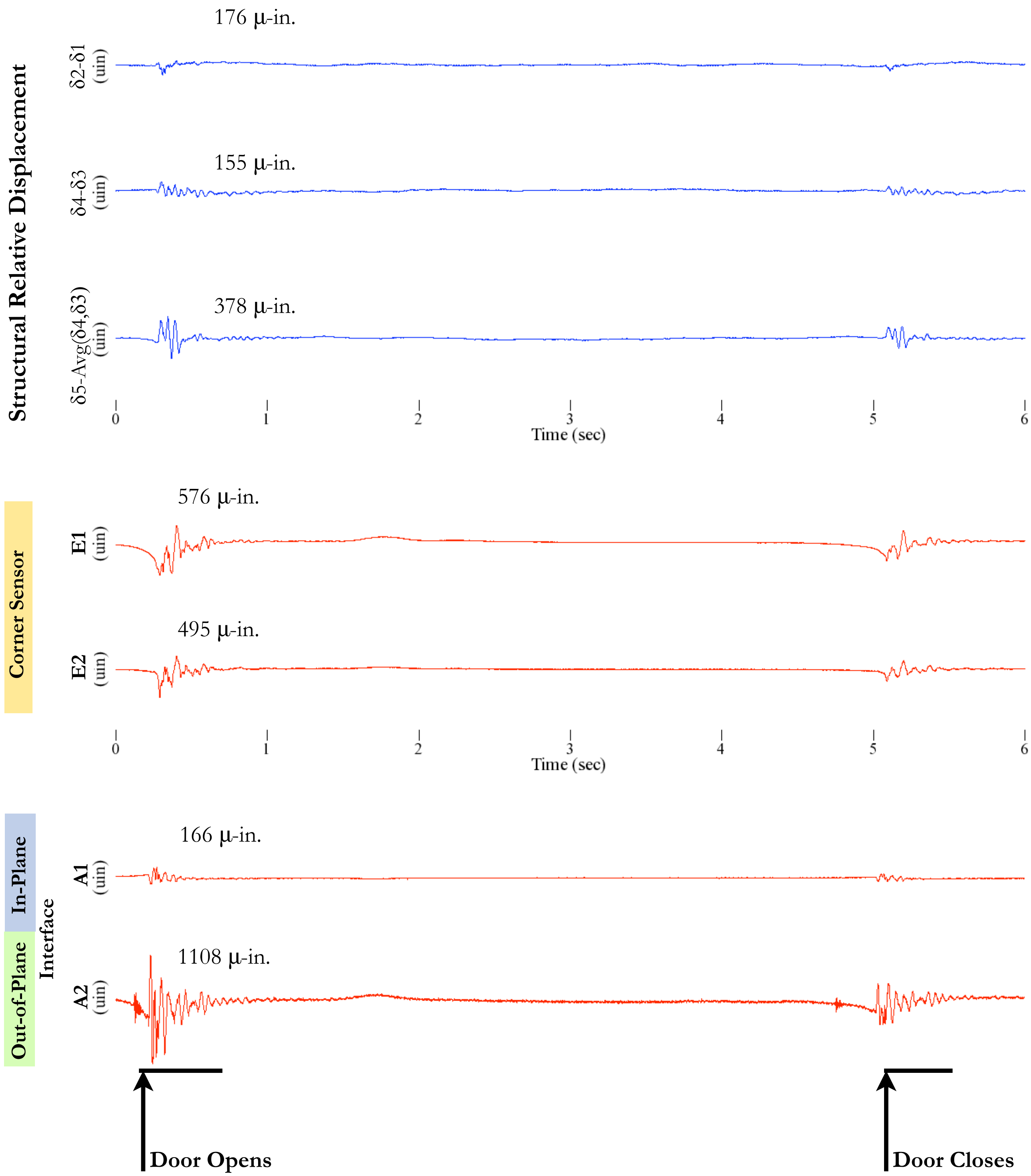

Figure 2-8 - Structural and crack response time histories from opening/closing the front door. The corner crack and interface crack are tens of feet away from the front door and in different rooms.

3. ANALYSIS

3.1 Crack Response

Comparison of Crack Response to Climatological and Vibration Effects

Figure 3-1 compares the crack response magnitudes from environmental conditions as well as dynamic events. Long-term response is at least an order of magnitude larger than any of the dynamic responses. The garage door crack responds more in-plane (A1) than out-of-plane (A2). Also, the corner crack responds more in the north-south direction than east-west.

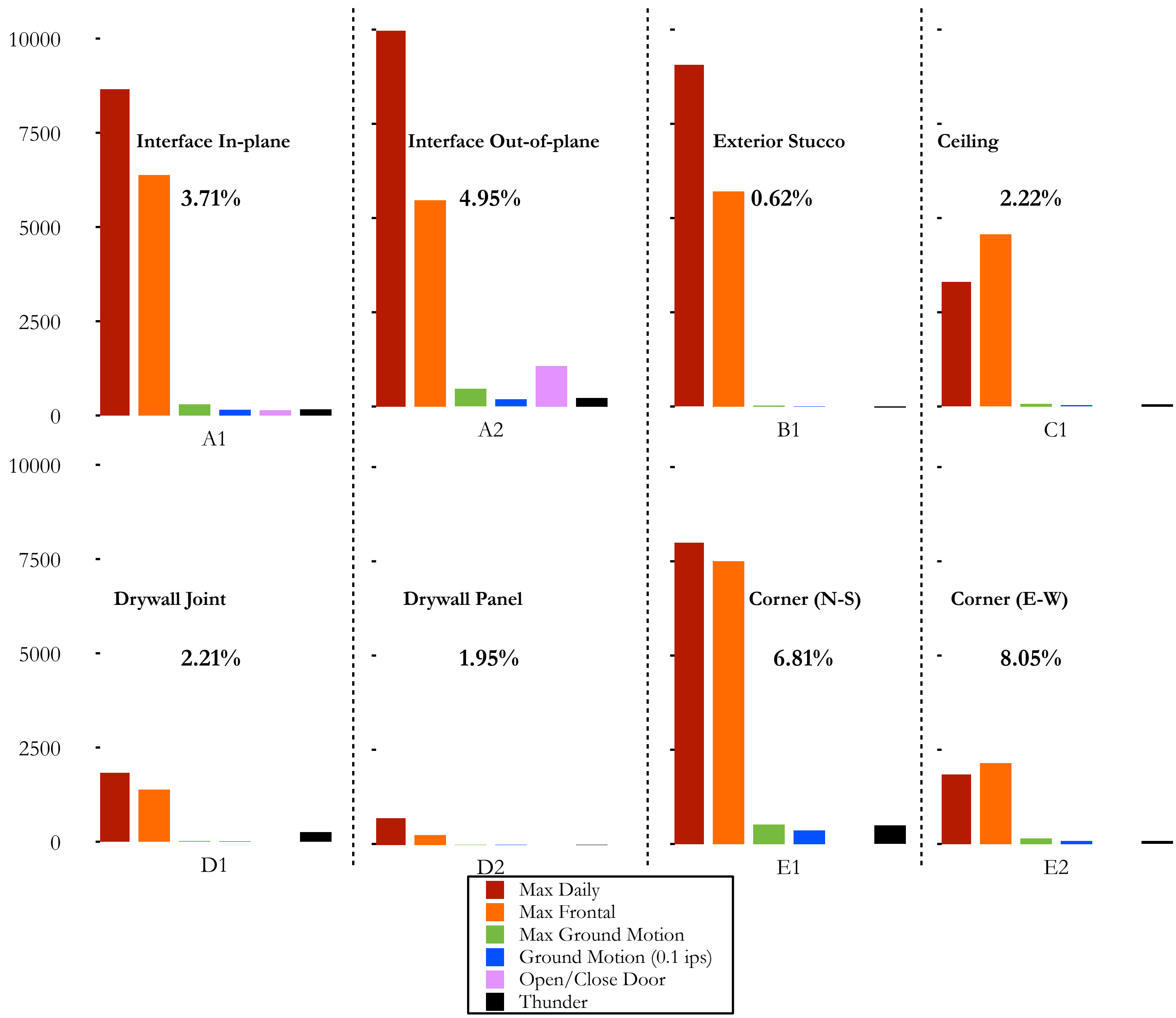

Figure 3-1 - Comparison of crack response magnitudes. Long term response is at least an order of magnitude greater than any dynamic event. The interface crack responds more in-plane than out-of-plane. The corner crack responds more north-south than east-west. The percentage is the ratio of max ground motion to max frontal response.

Comparison of Crack Response to Dynamic events only

Vibratory responses in the comparison of crack responses to climatological and vibratory events are so small that they need to be separated and enlarged as shown in Figure 3-2. Three of the cracks respond as much or more to operating the front door and nearby thunder than to the maximum blast event. The three cracks are the out of plane interface and N-S corner crack as well as the un cracked drywall joint. All of the cracks except the exterior CMU crack respond more to opening and closing a remote door and thunder than to typical blast events producing maximum ground motions of 0.1 ips.

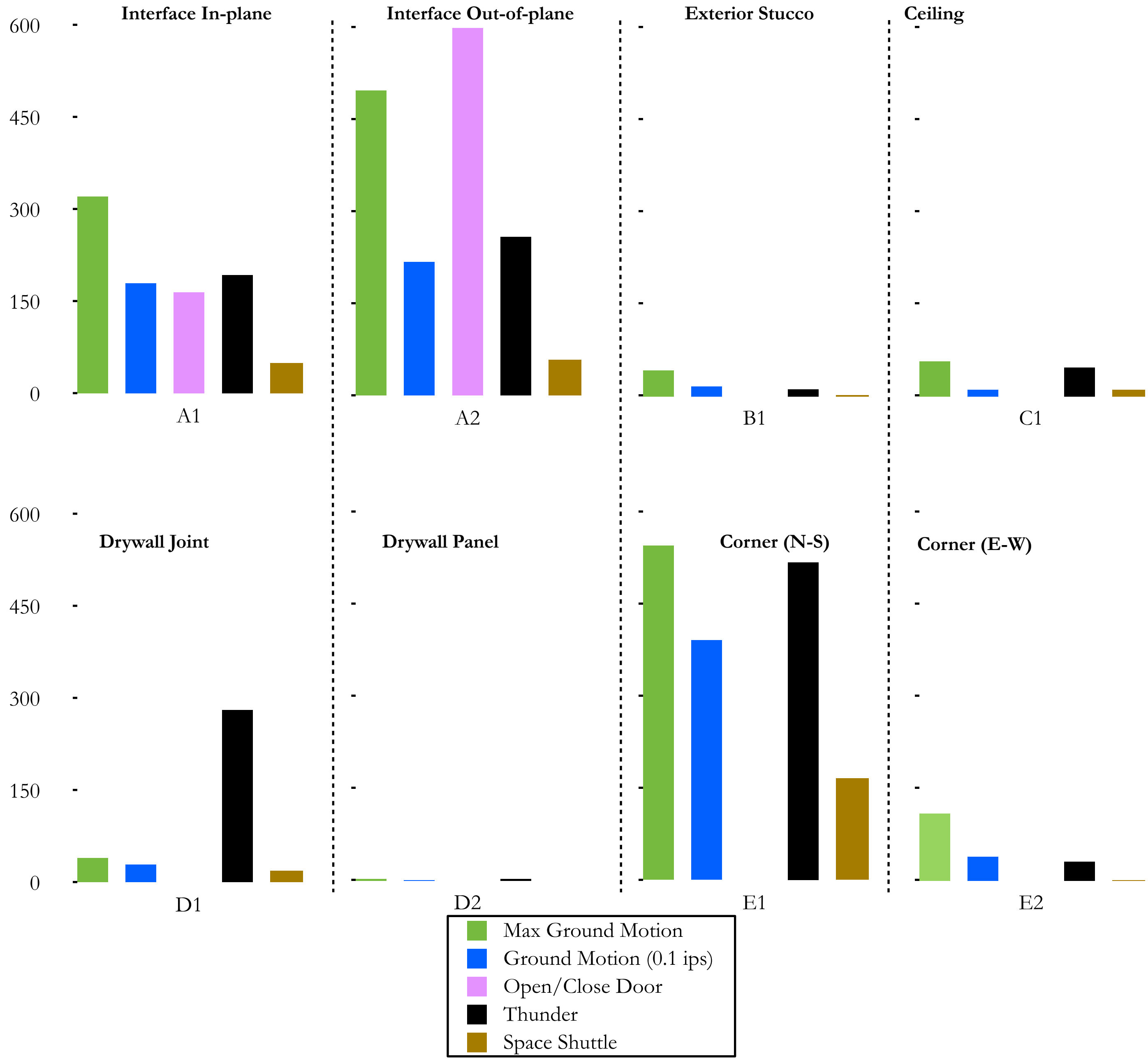

Figure 3-2 - Enlargement of the dynamic event induced crack response portions of Figure 3-1 with the addition of response of the space shuttle

Excitation Correlation

Figure 3-3 compares crack response for the corner and interface with excitation parameters like ground motion and structural response. The plots on the top compare PPVs parallel to the wall in which the crack is contained and the response at the interface crack in the garage. The plots on the bottom compare the corner crack response to both PPV parallel to the wall and relative structural displacement. As expected, all correlations are direct relationships; larger excitation yields larger response. A2 (out-of-plane) is more sensitive to ground motion than A1 (in-plane); there was not a significant correlation with any structural response because this crack is on the other side of the house from the structural sensors. E1 (N-S) is much more sensitive than E2 (E-W) to ground motion, while E2 is actually more sensitive to structural displacement, but E-W motions were much smaller in general, therefore E2 response is always smaller.

The plot in Figure 3-3 on the right compare structural responses that would cause shear strain in the plane of the wall containing the corner crack. Correlation of this relationship is not as strong as it has been for cracks in the plane of the wall. As described in Section 2, structural response is the difference in displacement between the top and bottom of the adjacent corner in the direction of the plane of the wall containing the crack. Time histories of the corner response displacements in Figure 2-4 and 2-4 show that interior corner crack sensors E1 & 2 respond more to the initial, high frequency body wave portion of the ground motion than to the later arriving surface wave. Since the corner crack is in an interior corner located in the mid third of the E-W tending north wall, its response may be more a function of interior wall rattle.

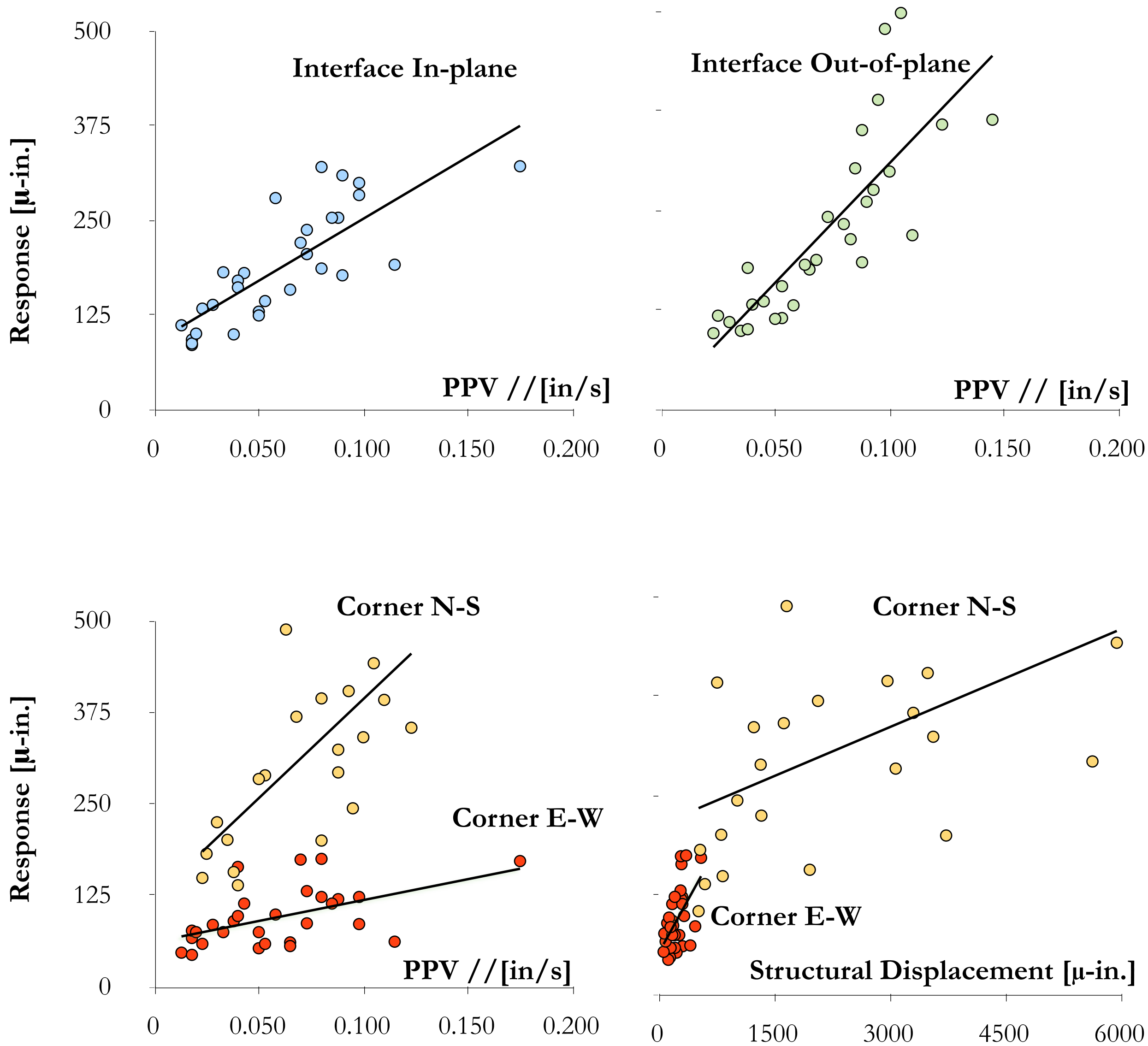

Figure 3-3 - Comparison of bi-directional crack responses; in- and out-of-plane response of the interface crack (top) and N-S and E-W response of the corner crack

Climatological vs. Ground Motion

Figure 3-4 compares the dynamic crack responses from blasting to the long-term climatic response. Plotted on the same scale, the tiny red dot (circled) represents the response of the crack induced by ground motion, while the continuous blue line represents the data taken every hour. The red, expanded vibration response time history is magnified 10x to make visible. The environmental response is approximately an order of magnitude (10x) larger than the dynamic responses in all three cases. (Kosnik 2008) came to the same conclusion.

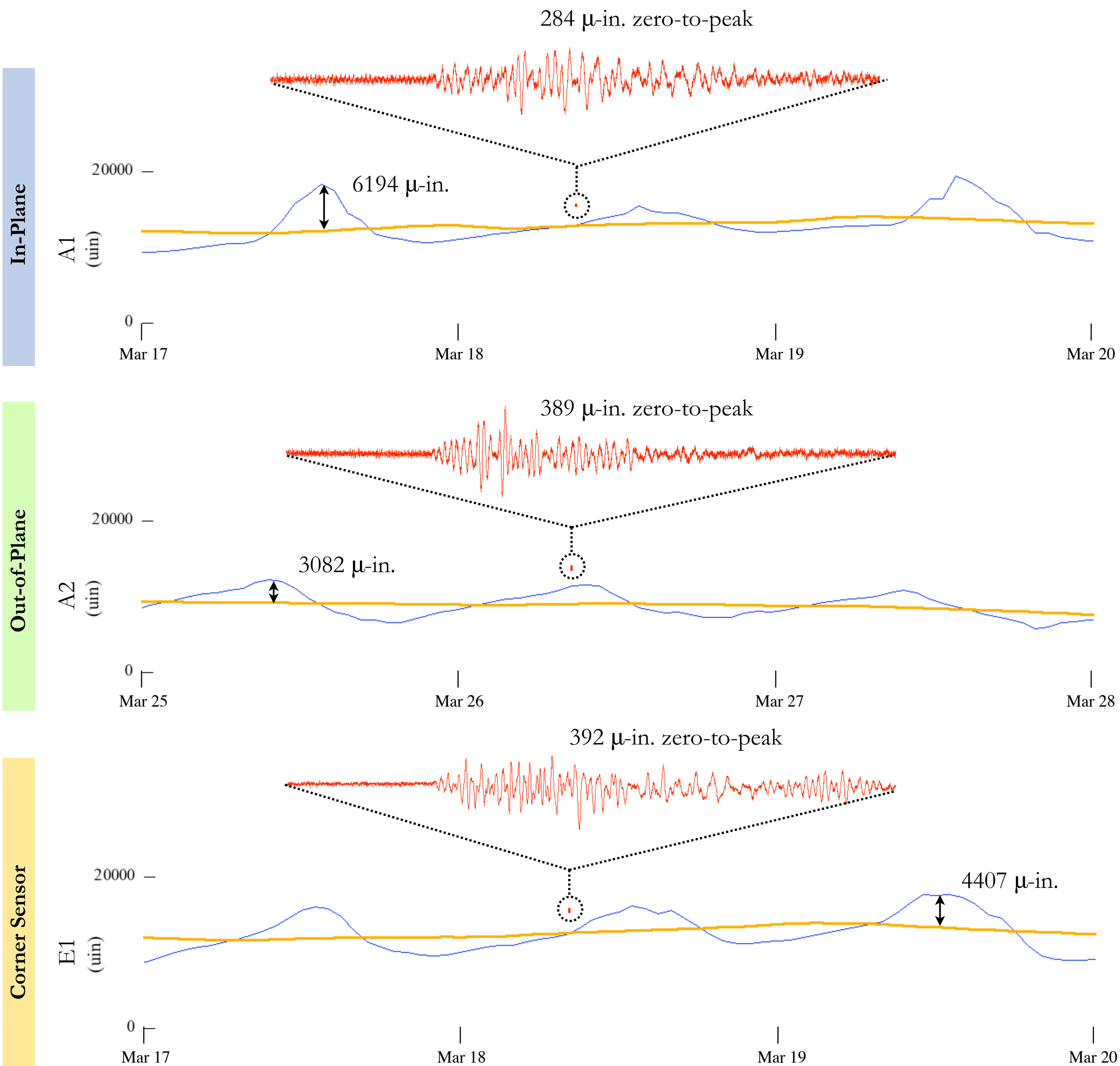

Figure 3-4 - Comparison of crack response caused by environmental effects and ground motion. The long-term response induced by weather is at least an order of magnitude greater than the ground motion response.

Movement without Blast

Figure 3-4 shows that from Nov 4, 2008 to Dec 3, 2008, Crack 9 expanded 20,000 μ-in. There was no blast during this period, as the only blasts occurred on Oct 23 and Dec 8, so this expansion resulted from something other than blasting.

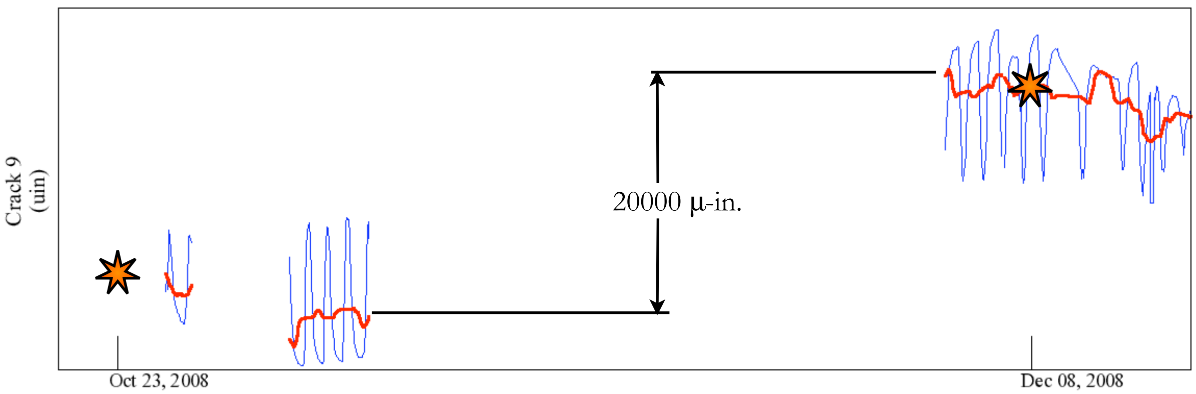

Figure 3-5 - Crack 9 expanded 20,000 μ-in. in one month without a blast. Closest blasts marked with a star.

3.2 Structural Response

Comparison of Superstructure and Wall Response for Dynamic Events

Figure 3-5 compares the magnitude of structural responses in the form of relative displacements for ground motion, thunder, and occupant activity. Relative displacement was employed rather than absolute velocity response because it is proportional to strain in the wall.

The north "top-minus-bottom" relative displacement is dominated by the max ground motion (5950 μ-in.). This is expected, because ground motion causes a much larger superstructure response than the other two dynamic excitations. It also contains the largest response to blasting of the three structural responses.

The north midwall response for these dynamic events is relatively comparable. The air pulse from the thunder and the door opening/closing create responses in the north wall that are comparable to the ground motion induced response.

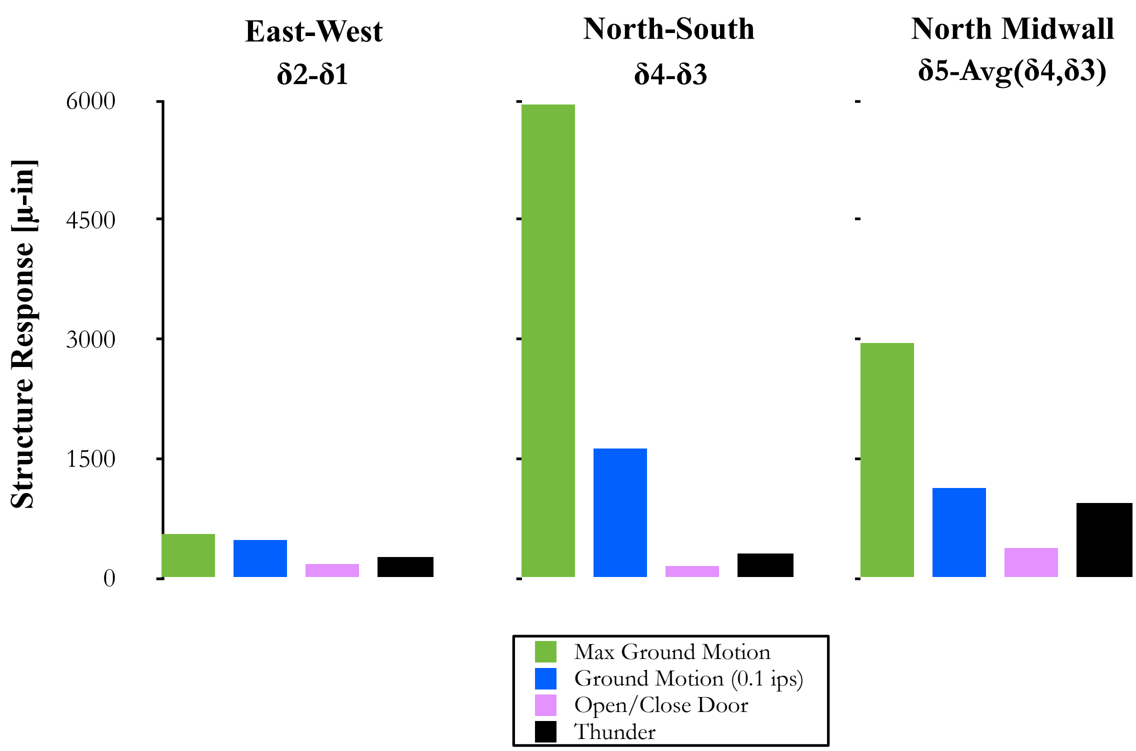

Figure 3-6 - Comparison of structural response magnitudes during dynamic events. The North-South direction exhibits the most top-bottom motion, while the North midwall has similar magnitude for all three dynamic events.

Fourier Frequency Analysis

Fourier Analysis can be used to determine the frequency content of a signal like the ground and structural velocity time histories during a blast event. Figure 3-7 shows the power spectral density functions of relative structural velocity ($|G(f)|^2$), ground velocity ($|F(f)|^2$), and a transfer function ($|H(f)|^2$) for the superstructure in the north-south and east west directions, and the midwall in the north-south direction.

$|G(f)|$ = output of Fourier Transform Integral for structural velocity

$|F(f)|$ = output of Fourier Transform Integral for ground velocity

$|H(f)|^2$ = Fourier Transfer Function = $|G(f)|^2 / |F(f)|^2$

Transfer function analysis can be employed to calculate natural frequency when there is no free response. Natural frequencies of one-story block superstructures are typically between 8 and 10 Hz (Dowding 1996). Both the north-south and east-west superstructure movements have natural frequencies of 9.8 Hz and 12.2 Hz respectively as depicted by their transfer functions. This seems reasonable as the north midwall natural frequency of 22.7 Hz is much higher than the superstructure's, and still higher than expected. Typical natural frequencies for one-story wood-framed structure walls range from 10 to 15 Hz (McKenna 2002). These higher than average natural frequencies can probably be explained by the structure's stiffness; the CMU walls vibrate at a higher frequency than typical wood-frame walls.

The transfer function can also be employed to calculate structural damping as described in (Dowding 1996.). Damping is used in pseudo-velocity response analysis of the ground motion as described in (Dowding 1996). The results of this procedure are in the next section.

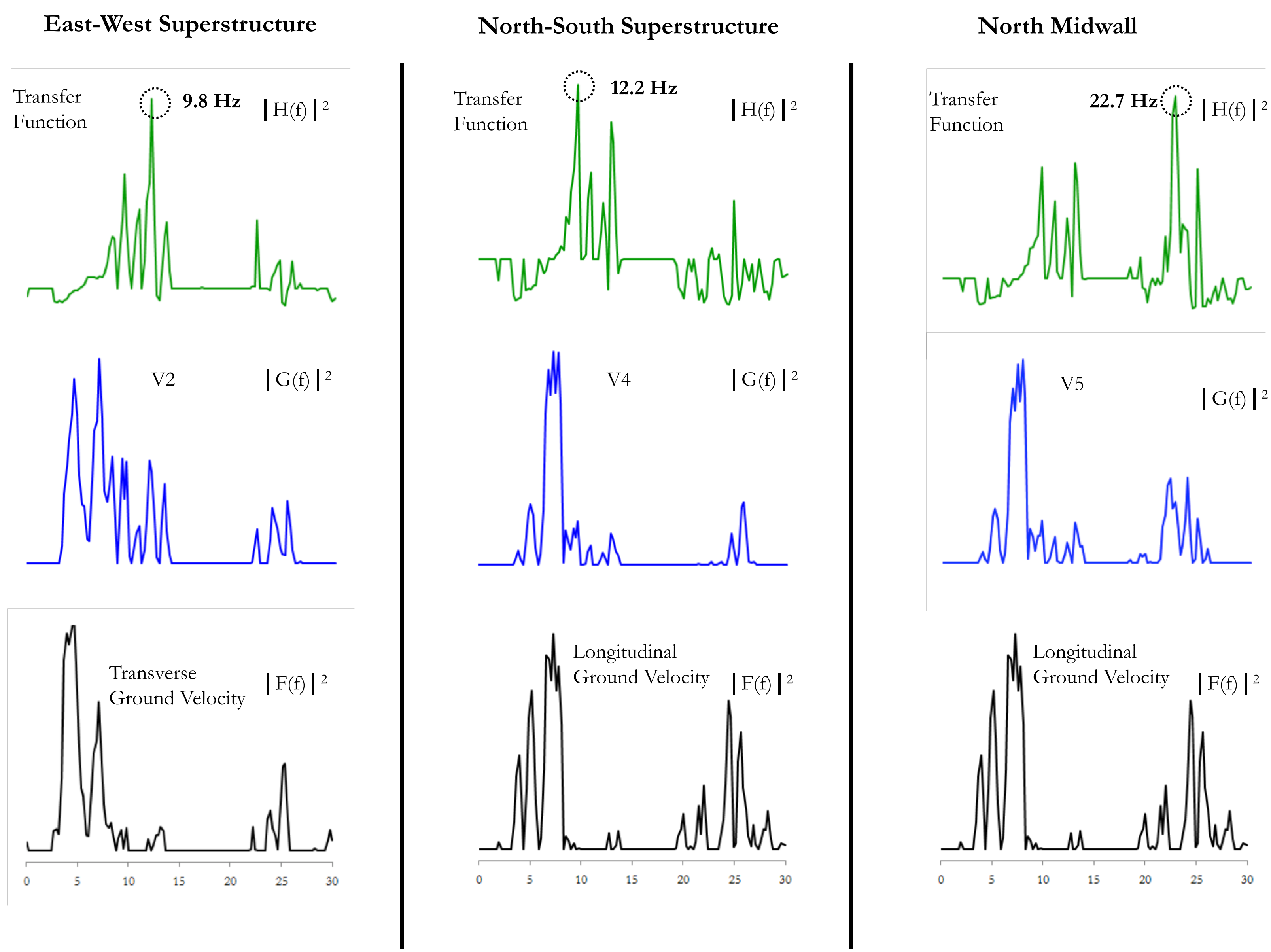

Figure 3-7 - Fourier frequency analysis of structure velocity, ground velocity, and transfer function for East-West superstructure, North-South superstructure and North Midwall for the Jul 22 (2) blast. Natural frequencies are indicated by a dotted circle.

Response Spectra

Pseudo velocity response spectra of the horizontal components of the ground motions produced by the July 22 (2) event are shown in Figure 3-8. The Fourier frequency transfer function - defined in the previous section showed that the damping would be between 3 to 5%, and that was employed in response spectrum analysis. There are two peaks, one between 5 and 10 Hz and another at 20 to 30 Hz, which is similar to the fourier frequency spectrum of the ground motions. This is to be expected, as described in Dowding (1996). This dual peak response spectrum shows that elements with natural frequencies in the 20 to 30 Hz range will respond as much as those with natural frequencies of 5 to 10 Hz. As observed earlier, many of the highly responsive cracks responded most to the earlier arriving, high frequency portion of the excitation ground motions.

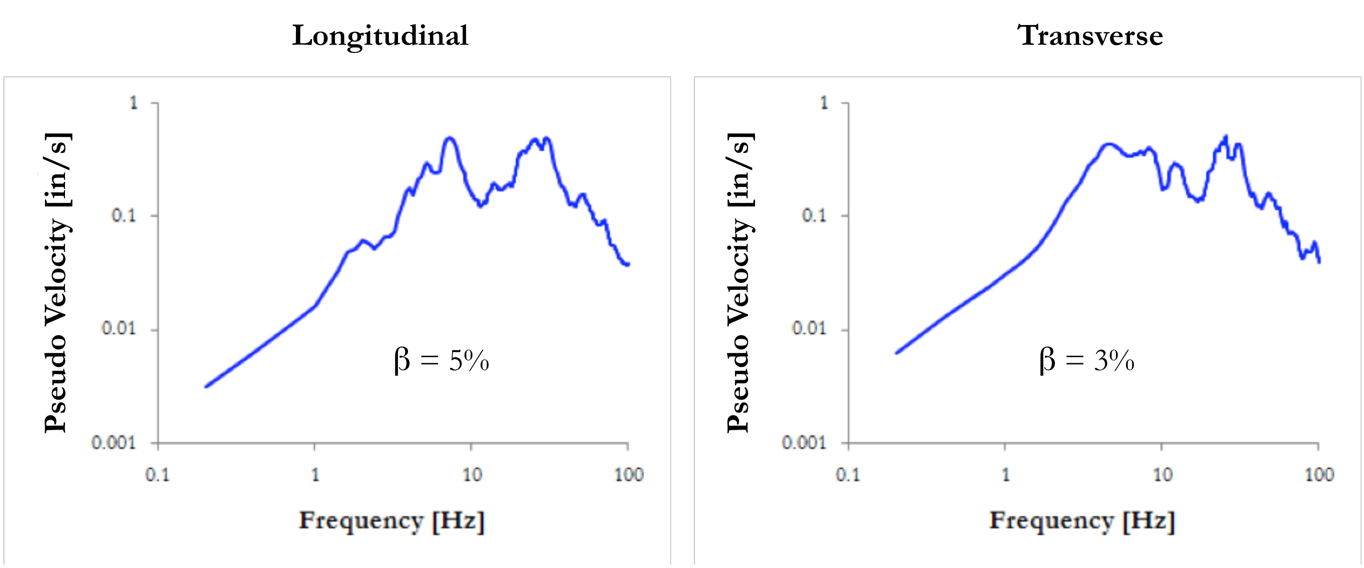

Figure 3-8 - SDOF Response spectra for both the longitudinal and transverse ground motions from the July 22nd (2) event

4. CONCLUSIONS

This second phase of response measurement lasted slightly over a year and spanned several periods of more than a month without blasting. It also involved measuring structural response as well as a number of unique measurement devices or crack locations.

The long period of observation provided the opportunity to observe response to thunder as well as the sonic boom produced by the Space Shuttle. Of these two highly energetic air pressure phenomena, the thunder was the most intense. Thunder produced air overpressures that were over ten times greater than the greatest produced by blasting.

As has been observed before, climatologically induced crack response overwhelms that produced by blast induced ground motion. Changes in temperature and humidity produce crack response that is ten to fifty times larger. Seasonal variations can be even greater. Between October 23 and December 8 there was no blasting. However, several of the cracks continued to respond. Response of the exterior crack and the N-S direction of the living room corner crack were particularly large.

Occupant and thunder induced crack response can be as large and sometimes larger than that produced by blast induced ground motions of 0.1 ips. Occupant activity was closure of a remote door, one that was not in the same room as the crack. Thunder was that produced by lightning strikes that were on the order of 1000 ft from the house, as estimated by the one-second interval between the system electrical strike and the arrival of the air overpressure pulse.

Special crack sensor fixtures allowed measurements normal to walls. These sensors were affixed across cracks at the garage-kitchen door and a corner crack in the junction of an interior and exterior wall in the living room. The ratio of responses varies. The perpendicular crack response at the doorway was always larger than the in plane crack response. The normal direction was always the most responsive in the living room corner crack.

Corner and doorway cracks responded more to the earlier arriving high (20-30Hz) frequency waves than to the later arriving, lower (5-10 Hz) frequency surface waves

This long period of observation also allows the measurement of seasonal crack response to long-term climate and home heating/air-conditioning. This seasonal response, when combined with response to frontal and daily changes in the weather, combine to produce long-term response which can be six times larger than the response to the largest blast-induced ground motions.

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APPENDIX A

Figure A-1- NASA's Space Shuttle *Endeavour* landing at Cape Canaveral, FL (nasa.gov)

On July 31, 2009, the Space Shuttle flew over Naples while on approach to Cape Canaveral. The sonic boom produced larger air overpressure excitation than the largest blast event. The double pulse air overpressure wave and the crack responses are shown in Figure A-2. The largest blast induced air overpressure pulse was some 0.0007 psi and the shuttle's sonic boom was 0.002 psi, some three times greater. Interestingly the air overpressure pulse produced by nearby lightning strikes was on the order of 0.01 psi, five times greater than the sonic boom produced by the Shuttle.

Crack response from the Shuttle's sonic boom was greatest for the corner cracks, with the NS direction the greatest. This NS direction (perpendicular to the long dimension of the exterior wall) is the most sensitive for blast induced events as well. Crack responses were not as large as those produced by blast induced ground motions.

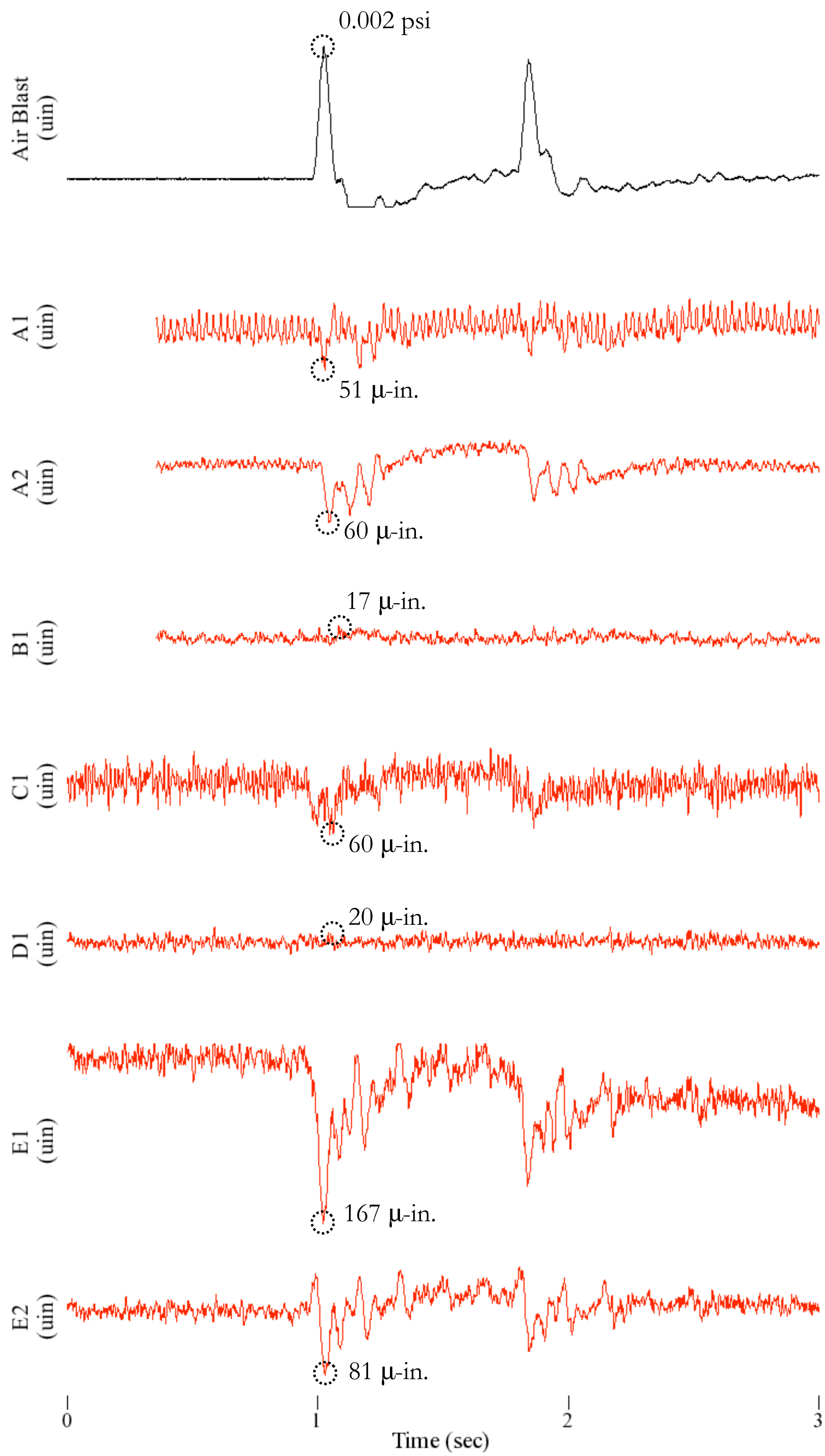

Figure A-2- Time histories for air overpressure and corresponding crack responses when *Endeavour* passed overhead at supersonic speed.