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

JEFFREY E. MEISSNER[1]

CHARLES H. DOWDING[2]

ABSTRACT

The notion of blasting, even in a controlled setting such as limestone quarry, can be alarming to residents and business owners within earshot. Because humans are inherently sensitive to these 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] Undergraduate Civil Engineering Student, Northwestern University

[2] Professor of Civil and Environmental Engineering, Northwestern University

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1. INTRODUCTION

1.1 Background

This is a 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 on-going study at this house and follows Phase I's report (Kosnik 2008). It is 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 crack response to ground motion and environmental factors, Phase II includes the response of the structure, a crack out-of-plane, 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 X) has CMU exterior walls covered with stucco and wood interior construction with drywall finish. It is located adjacent to the Jones Limestone Quarry which blasted XX times in the study period (Sep 1, 2008 through Sep 1, 2009). Table X describes the blast vibration environment. Typical blasts involve 30 to 50 holes loaded with 50 to 60 lbs of ANPO and detonated with separated delays per hole. The blasts indicated by red stars in Figure X are generally 3000 to 5500 ft away from the test house. As can be seen in Figure X by the multiple excavation areas, the quarry is in its final stages of development.

Figure X - 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			
11	**Apr 1**	10:49	0.038	0.023	0.135			
12	**Jul 8**	11:08	0.053	0.040	0.003			
13	**Jul 8**	11:14	0.088	0.098	0.003			
14	**Jul 14**	10:40	0.063	0.040	0.070			
15	**Jul 14**	10:46	0.050	0.050	0.038			
16	**Jul 22**	11:15	0.088	0.088	0.063			
17	**Jul 22**	11:26	0.105	0.175	0.120			
18	**Jul 27**	10:57	0.083	0.090	0.070			
19	**Jul 27**	11:04	0.145	0.090	0.095			

Table X - Characteristics of blasts producing the vibration throughout the study period. Strength of blast can be characterized by the weight of explosive in a given hole (~60lbs) and distance (~3/4 mile)

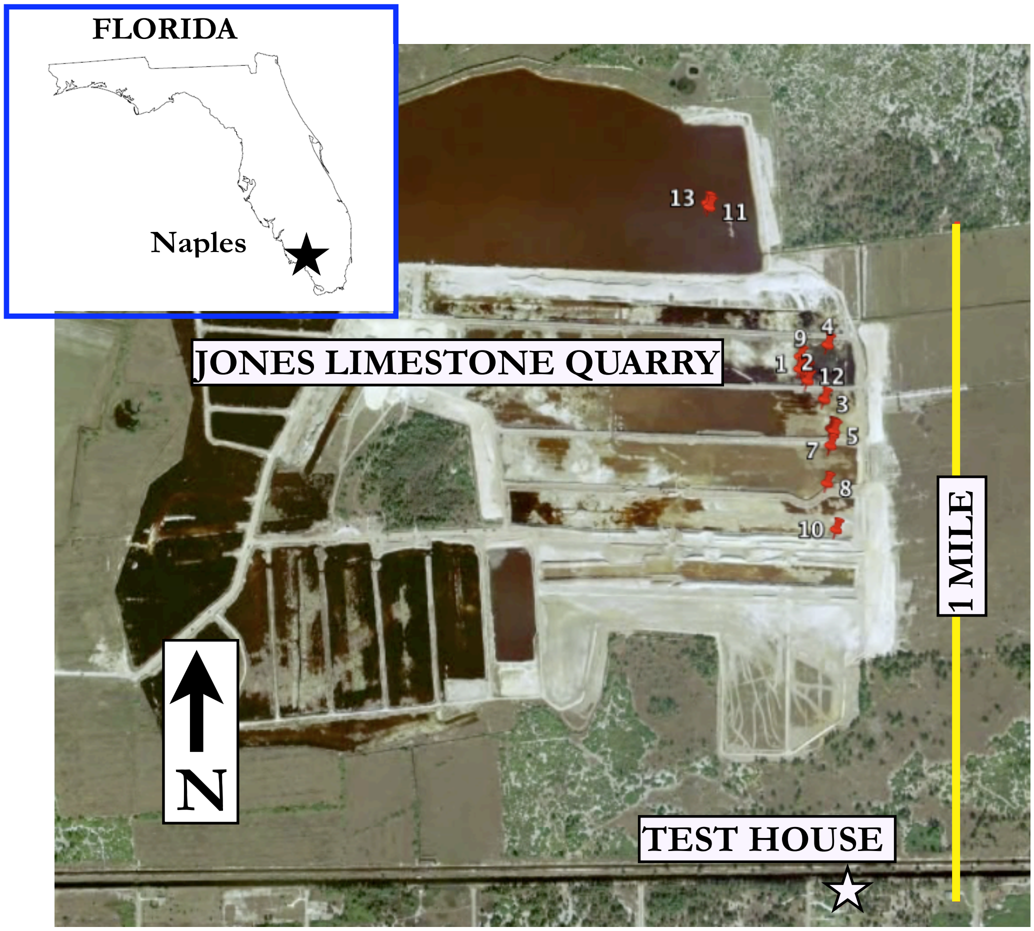


Figure X - Location of subject house in Florida south of the Jones Limestone Quarry. Red thumbtacks indicate location of blasts throughout the study period. The test house is representative of home closest to the quarry with blasts between 1/2 and 1 mile away.

1.2 Instrumentation

Plan

The house is extensively instrumented with several new crack sensors and velocity transducers to measure structural response as shown in Figure X. The system is a combination of the sensors listed in Table X; they are described in more detail in the sections below and pictured in Figures X,X, and X.

The data acquisition system is computer controlled and consists of two varieties of Somat Corporation's eDaq system: Classic and Lite which record output from [trigger transducer, A1&2, B1&2, anemometer, temperature & humidity] and [HG1-5, ceiling transducer, air overpressure,C1&2, D1&2, E1&2] respectively . Two types of data are recorded:

- **Long-term** data every hour of the crack responses, temperature, and humidity
- **Dynamic** data that are triggered by ground motion, wind, or air overpressure

Long-term data are sampled every hour for 1 second at 1000 samples per second and then averaged. Dynamic events record 1000 samples per second for 6 seconds when triggered. 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 geophones are set to trigger the whole system at thresholds indicative of blasting, thunder, or high winds.

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

- An **Out-of-Plane** 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 **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** sensor has been placed over an uncracked seam between two drywall panels in the garage ceiling

Trigger Thresholds:

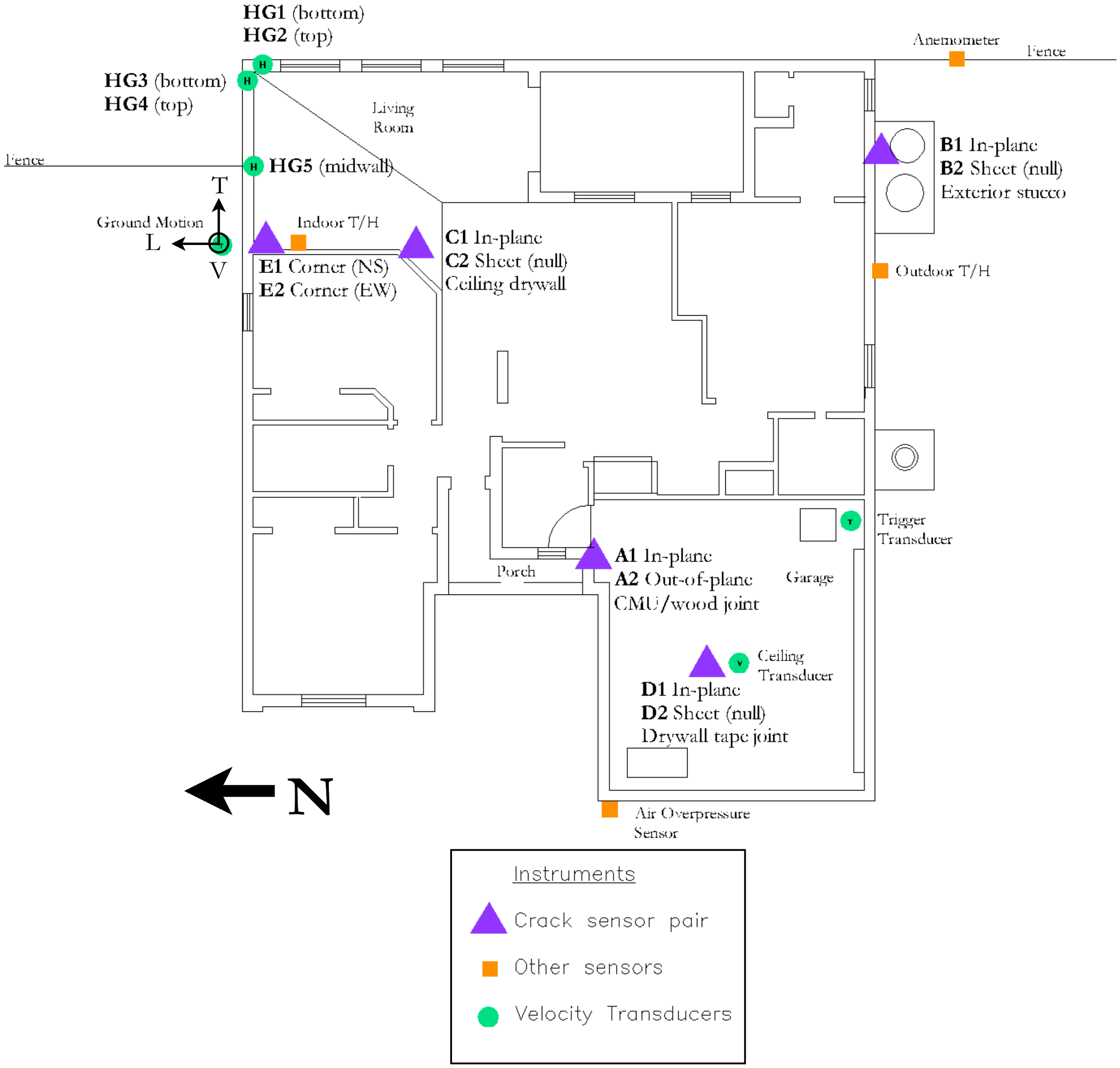


Figure X - Instrument locations that enable measurement of (1) structural response to ground motions (2) crack response in-plane, out-of-plane, and in corners (3) uncracked joint response (4) various triggering methods to capture wind response

Sensor	Model	Measures	Notes
Ground Motion	GeoSonics 3000 LC series	Ground velocity in longitudinal, transverse, and vertical directions	Define excitation motions
Structural Response Sensors	Geospace Corp. Model HS-1-LT 98449	Structural velocity in strategic locations in Living Room	5 geophones with common time base to provide detailed structural response
Crack Displacement Sensors	Kaman SMU-9000	Crack displacements both dynamically and long-term	in-plane, out-of-plane, corner joint, and uncracked joint response: A, D, E
	LVDT MacroSensors DC 750-050	Crack displacements 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		Wind velocity and direction	

Table X - 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 attached perpendicularly to an upper corner as shown below in Figure X (HG2,4) and pictured in Figure X. Wall response is measured by placing the transducer in the middle of the wall (HG5). Velocities a the bottom corners (HG1,3) are also measured as a reference. Response velocity is integrated over time to obtain displacement. All of 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 displacement 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. In other words, ground motions cause the superstructure to move at a low natural frequency (structure wobbles) while the air pulses cause the walls to bend at a high natural frequency (walls beat like a drum). These two responses are shown in Figure X. In this study, structural response is measured in blast events, thunder strike events, and occupant activity.

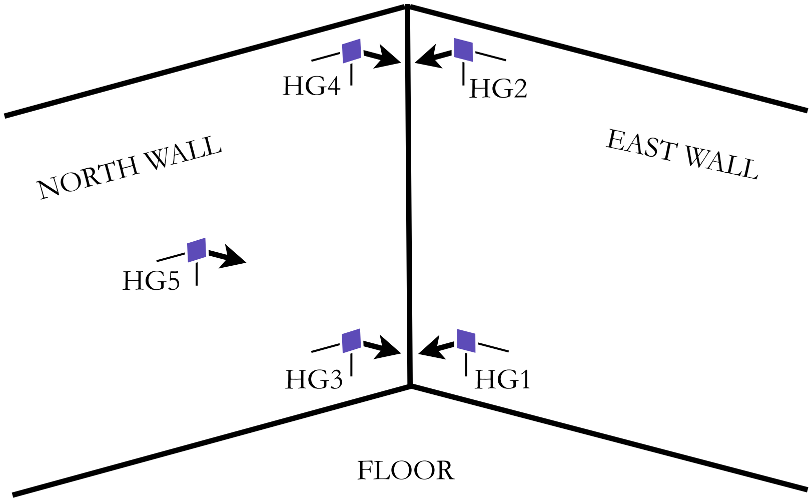


Figure X - Isometric view of the structural instrumentation of living room to measure absolute displacements of superstructure and walls

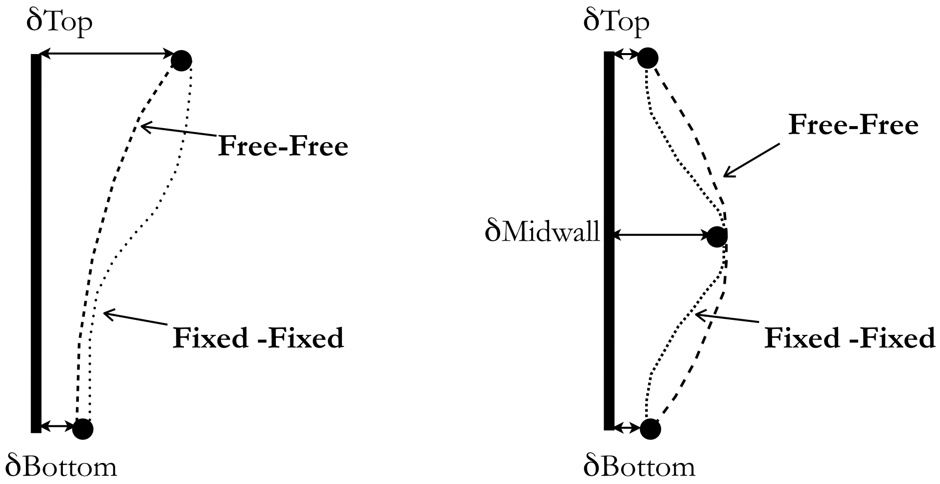


Figure X - Left: Elevation view of two possible mode shapes for superstructure response- Right: Elevation view of two possible mode shapes for wall response

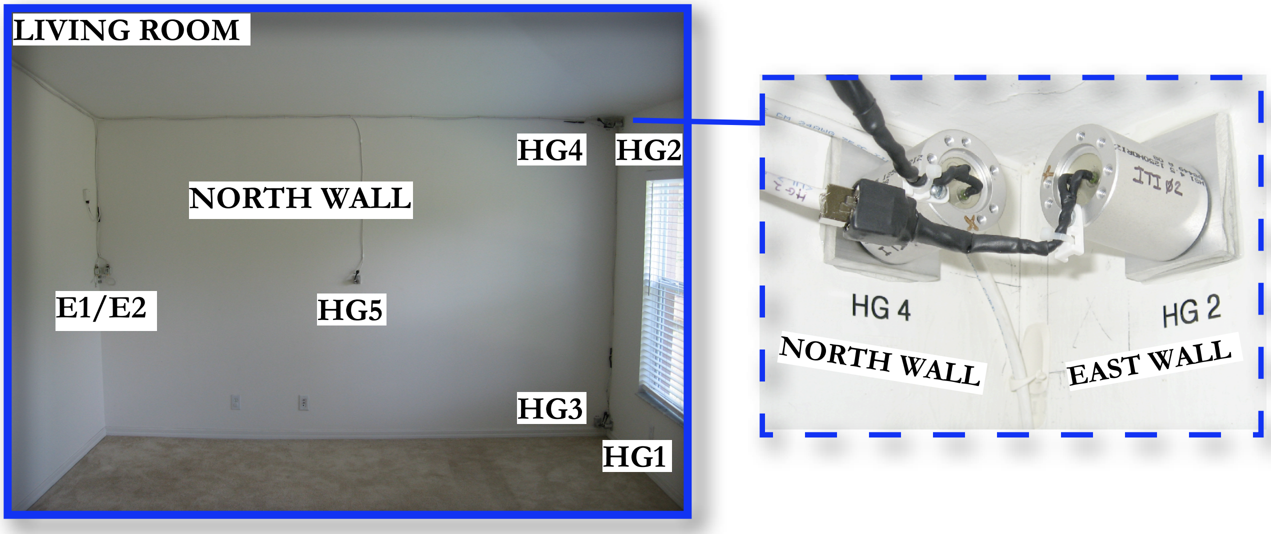


Figure X - Instrumentation of north wall of living room: 5 horizontal velocity transducers to measure velocity of the superstructure (HG3,4 North-South, HG1,2 East-West) and the wall response (HG5 North-South).

Crack Response

In addition to monitoring in-plane response of cracks, instruments have been installed to monitor out-of-plane response of a crack, response of a corner crack, as well as 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. Both out-of-plane and corner crack monitoring are unique to this project. Table X describes the transducers, locations, and purposes. Close-up images of the installation are shown in Figures X,X, and X.

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

Table X- List of cracks monitored in this study

It also important to precisely define crack response; it refers to the *change* in crack width and does not pertain to the original crack width. Figure X (Siebert 2000) helps to pictorially describe this definition. All transducers have been installed so that positive response indicated crack opening and negative indicates crack closing. These sensors across the cracks measure micro-inch resolution response. Also, null sensors are placed near the cracks to verify the crack displacements. The null sensors' displacements have been shown to be small relative to the crack displacements (Kosnik 2008)

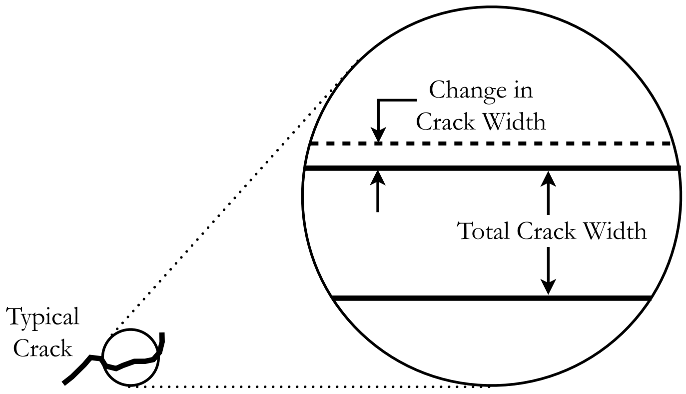


Figure X - Crack Response is change in crack width, not related to total crack width

Geometries of crack response and sensor deployment are compared in Figure X. The three special geometries (1) in-plane, (2) out-of-plane, and (3) corner are monitored by Kaman gauges as they have a lower noise level with this eDaq system and long wire runs. The context of these cracks is also shown in Figure X. The ceiling and exterior stucco cracks are monitored with LVDT displacement transducers as shown in Figure X

(1) In-Plane Response

The most often deployed - in-plane - installation is described with crack movement on the left, crack-sensor relationship in the middle, and photo of actual installation on the right of Figure X.

(2) Out-of-Plane Response

Crack movement, crack-sensor relationship, and photo are also shown for the out-of-plane case in the middle of Figure X. Since movement out of the plane of the wall must be measured, the sensor must be oriented perpendicular to the wall, which requires the glass mounting block. Glass was chosen for its low coefficient of thermal expansion (Waldron 2006). The non-crack side of the block serves as a mount for the null sensor, not included in this installation.

(3) Corner Crack Response

Crack movement, crack-sensor relationship, and photo are shown for the corner crack case in the bottom of Figure X. Since it is not known in which direction response is greatest, both must be measured, which requires two transducers as shown. As with the out-of-plane deployment, the target can be placed directly on the opposing wall of the "L" shaped bracket.

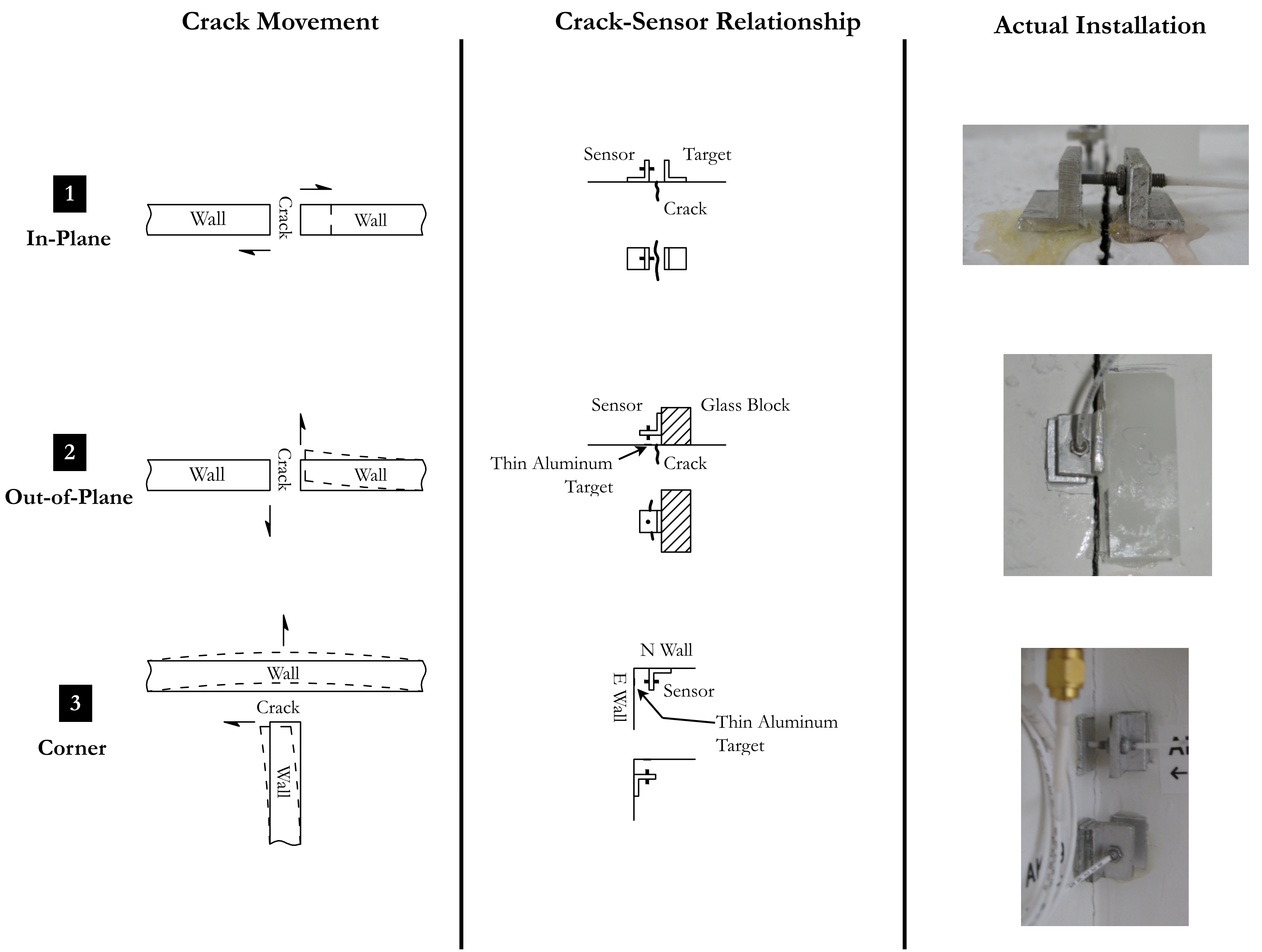


Figure X - Comparison of the differing deployment geometries for measurement of crack geometry - TOP: crack open/close in the plane of the wall - MIDDLE: crack distortion perpendicular to the plane of the wall - BOTTOM: two directions of corner crack distortion.

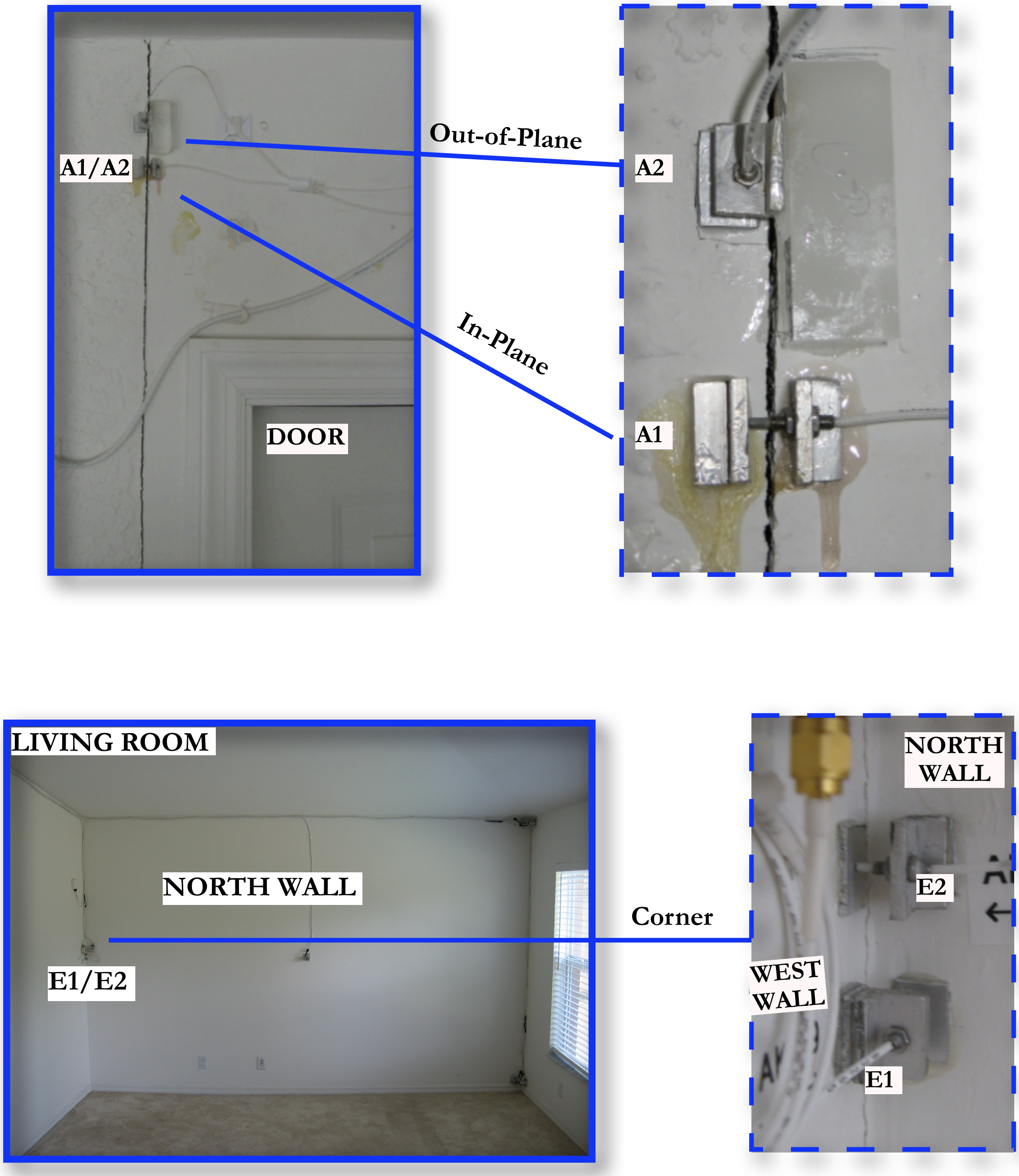


Figure X - Context of the three different sensors used and their respective closeup - TOP: Out-of-Plane MIDDLE: In-Plane BOTTOM: Corner (two directions)

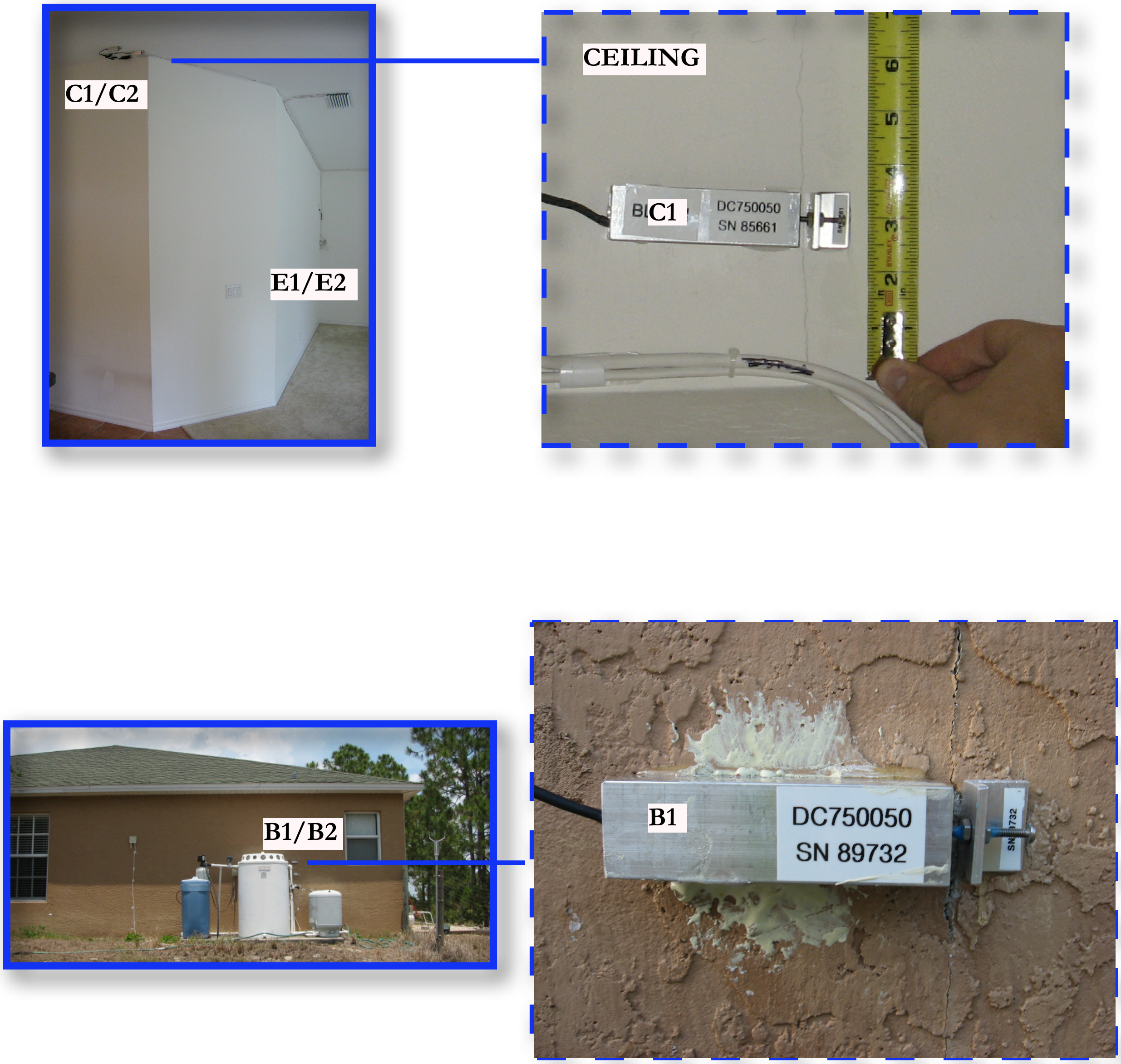


Figure X - Context of the three different sensors used and their respective closeup - TOP: Out-of-Plane MIDDLE: In-Plane BOTTOM: Corner (two directions)

Uncracked Joint Response

In addition to monitoring the structure and its cracks, this study investigates the in-plane response of an uncracked drywall joint. The response of the joint is measured in the exact same manner as a crack. The joint studied in this report is located in the garage ceiling as shown in Figure X. The purpose is to research if an uncracked region responds differently to weather and blasting than areas that are already cracked.

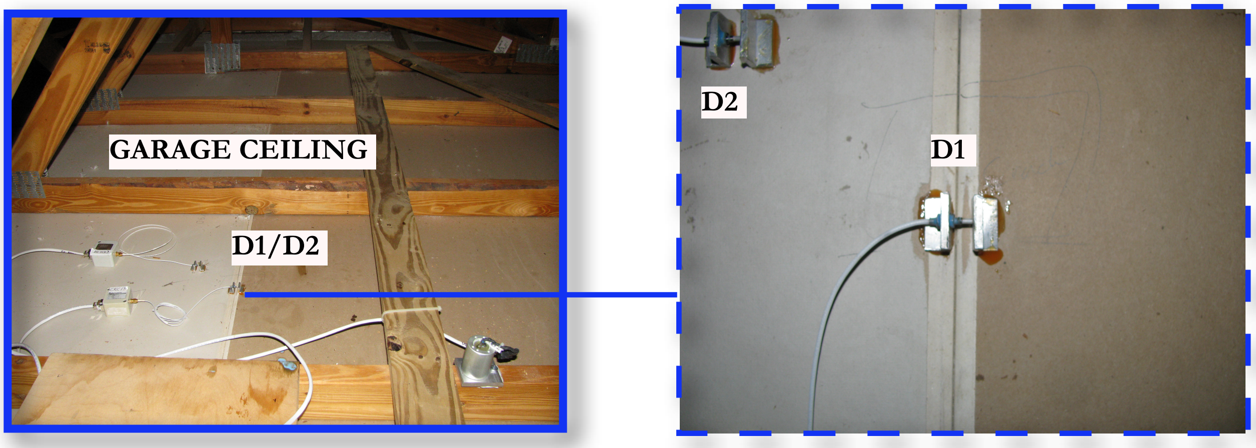


Figure X - Left: Instrumentation on uncracked drywall joint in garage ceiling Right: Close-up of gauges to measure in-plane response of joint and panel

Auxiliary Sensors

Other sensors that are important in this study are ones that describe environmental conditions or trigger the acquisition system to record dynamic events. Shown below are auxiliary sensors in Figure X. 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.

Air Overpressure Sensor

Anemometer

Temperature & Humidity Sensor

Vertical Velocity Transducer

Figure X - 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 X and X. 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. The maximums of these effects are displayed in Table X.

Response	A1	A2	B1	C1	E1	E2	D1
Max Daily	9187	7387	8097	3331	6351*	1745	
Max Frontal	4112	3109	3609	4339	7163*	1299	

Table X - Maximum crack response to frontal and daily effects in μ-in.

Response of the cracks in the living space (C1,E1,E2) is shown with the indoor temperature and humidity in Figure X. 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 greater, but the sensor went off-scale as can be seen by the truncated maximum through May 1st. Also, the large hump in November closely correlates with a large hump in the outdoor humidity that follows a long period of rainfall.

Long-term response of cracks outdoors and in the garage (A1,A2,B1,D1) are shown in Figure X. These records are less complete due to intermittent operation of the 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 displacements throughout the study period. Waldron found a similar result: long-term in-plane responses are larger than out-of-plane responses (Waldron 2006).

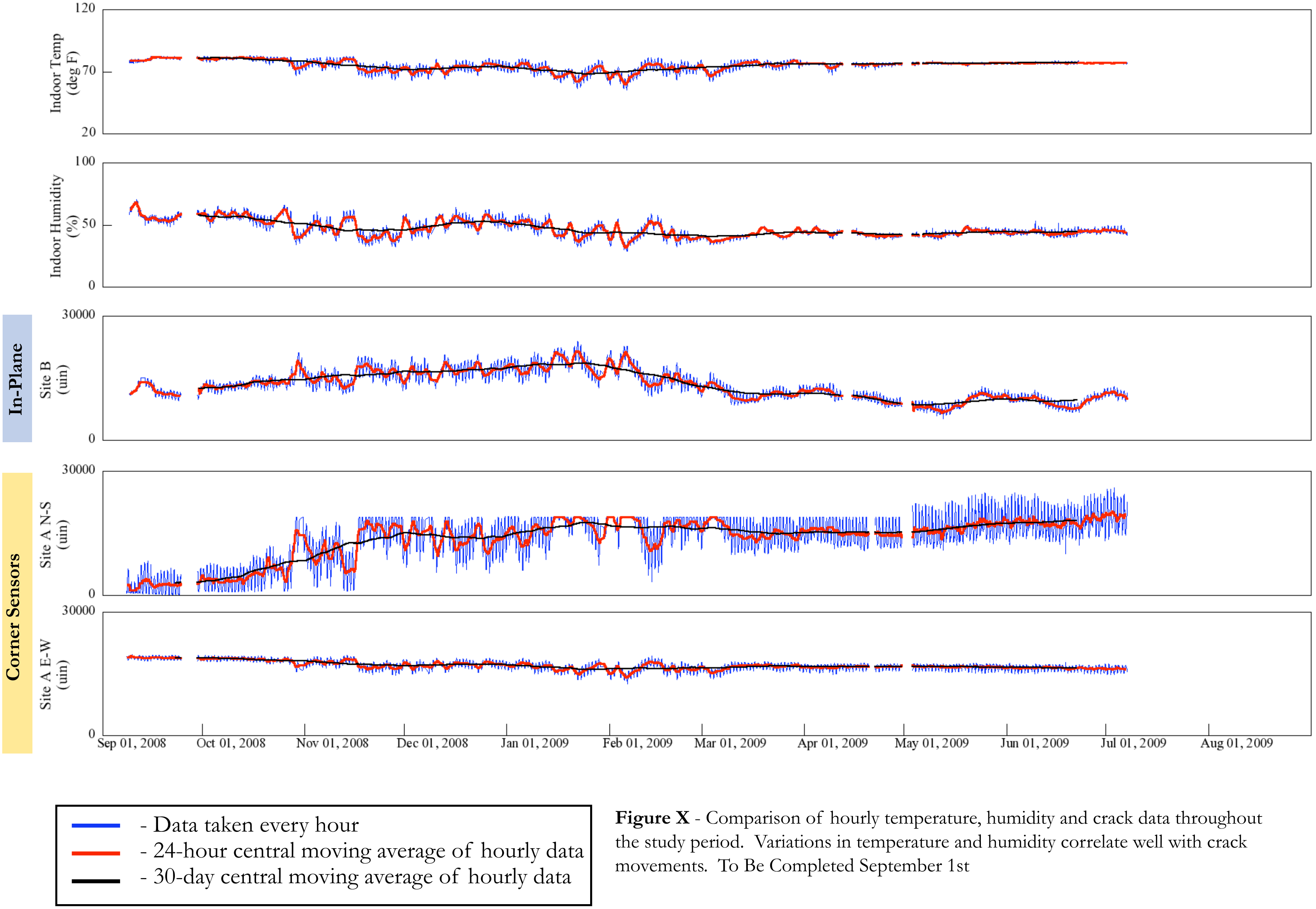


Figure X - Comparison of hourly temperature, humidity and crack data throughout the study period. Variations in temperature and humidity correlate well with crack movements. To Be Completed September 1st

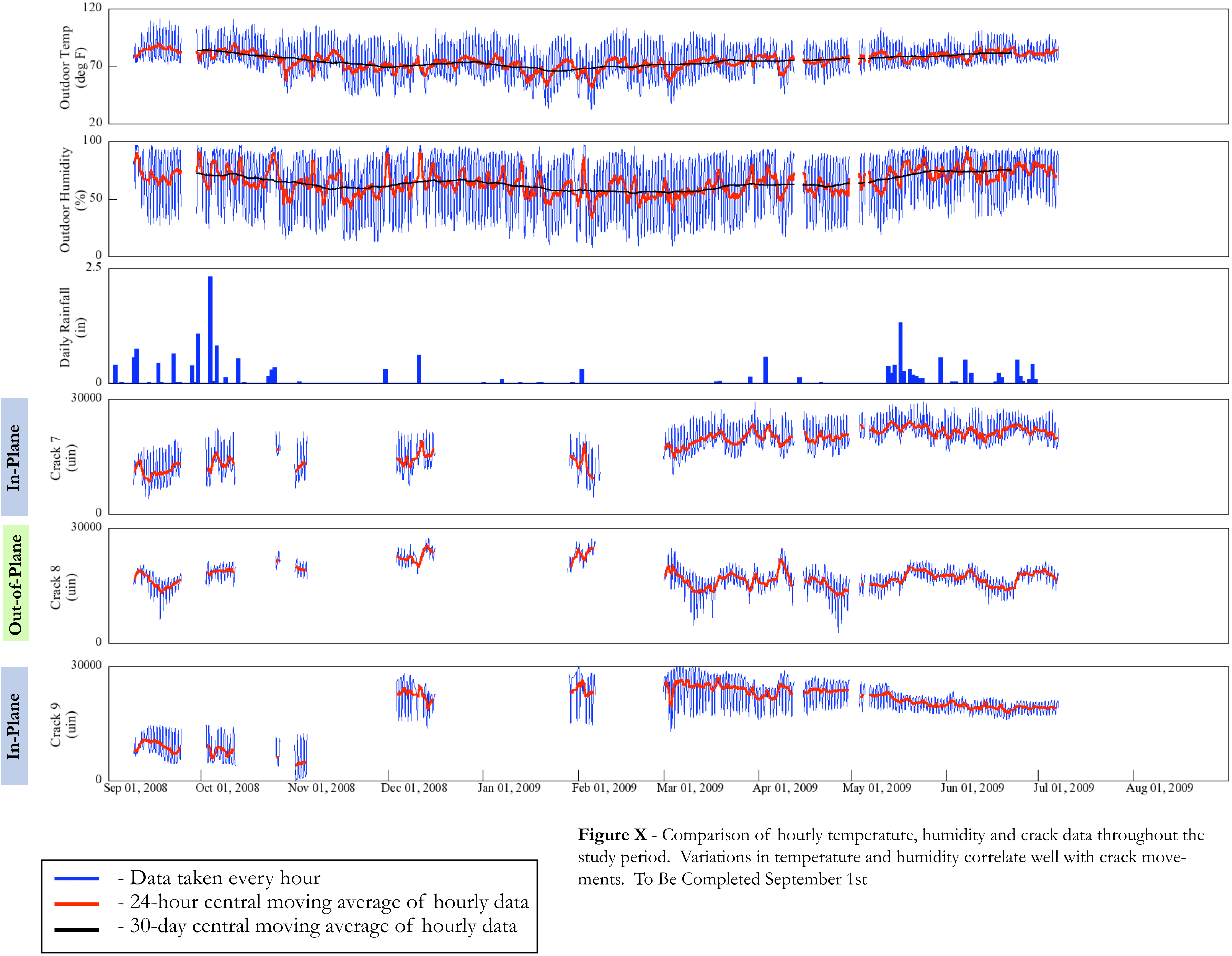


Figure X - Comparison of hourly temperature, humidity and crack data throughout the study period. Variations in temperature and humidity correlate well with crack movements. To Be Completed September 1st

2.2 Ground Motion

Structural Response

Table X 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 as shown by equation X. 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.

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

In each blast, the north superstructure (δ4-δ3) exhibits the largest response, and it is twice that of the midwall response (δ5-Avg(δ4,δ3)) in most cases. This means there is more strain from shearing than bending; this is typical for the ground motion response of this structure.

Crack Response

Table X 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 above the garage door when responding to ground motion. Also, the N-S displacements are larger than the E-W displacements in the living room corner. Both of these results are probably due to the actual construction at these areas. The corner is 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.

				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	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	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	442	172
Jul 27 (1)	0.090 [T]		5.9							
Jul 27 (2)	0.145 [L]		25.0							

Table X - 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).

Time histories in the north-south direction from the July 22nd (2) blast are shown in Figure X and the east-west direction is shown in Figure X. As evident in the time histories, the structure responds much more to the ground motions than the air blast. Also, even though the absolute displacements are larger in the east-west direction, the relative displacements are much larger in the north-south direction. This causes more strain and more crack movement; E1 (N-S) is larger than E2 (E-W)

Figure X shows a time history of the ground motion and corresponding crack responses for the interface above the garage door during the July 22nd (2) blast. The magnitude of their responses are comparable. Waldron found out-of-plane response to ground motion about half of in-plane response (Waldron 2006).

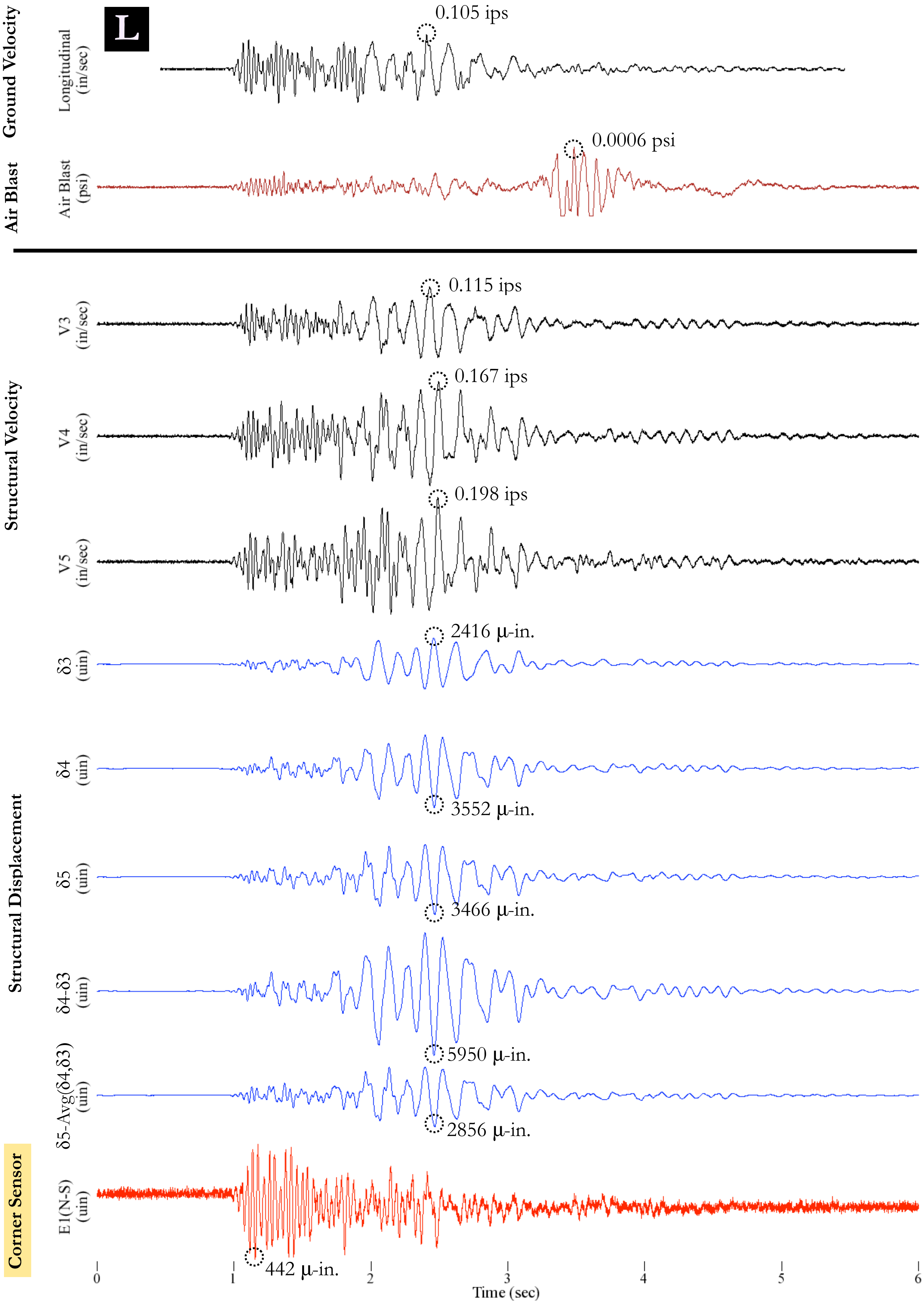


Figure X - Comparison of the **North-South** ground motion, structural response, and crack response time histories from the July 22nd (2) blast

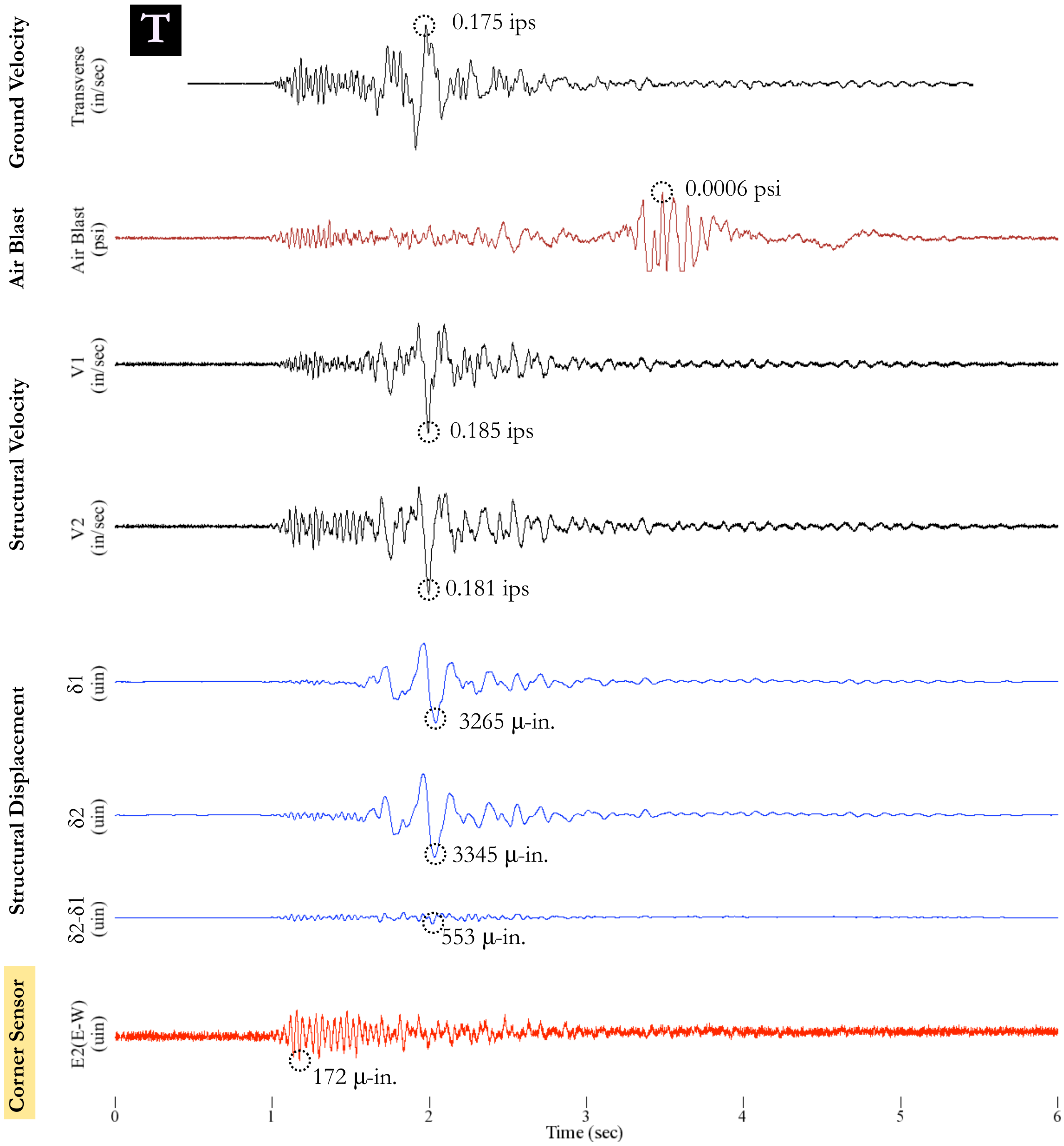


Figure X - Comparison of the **East-West** ground motion, structural response, and crack response time histories from the July 22nd (2) blast. Differential structural displacement is small compared to North-South and therefore E2's response is small

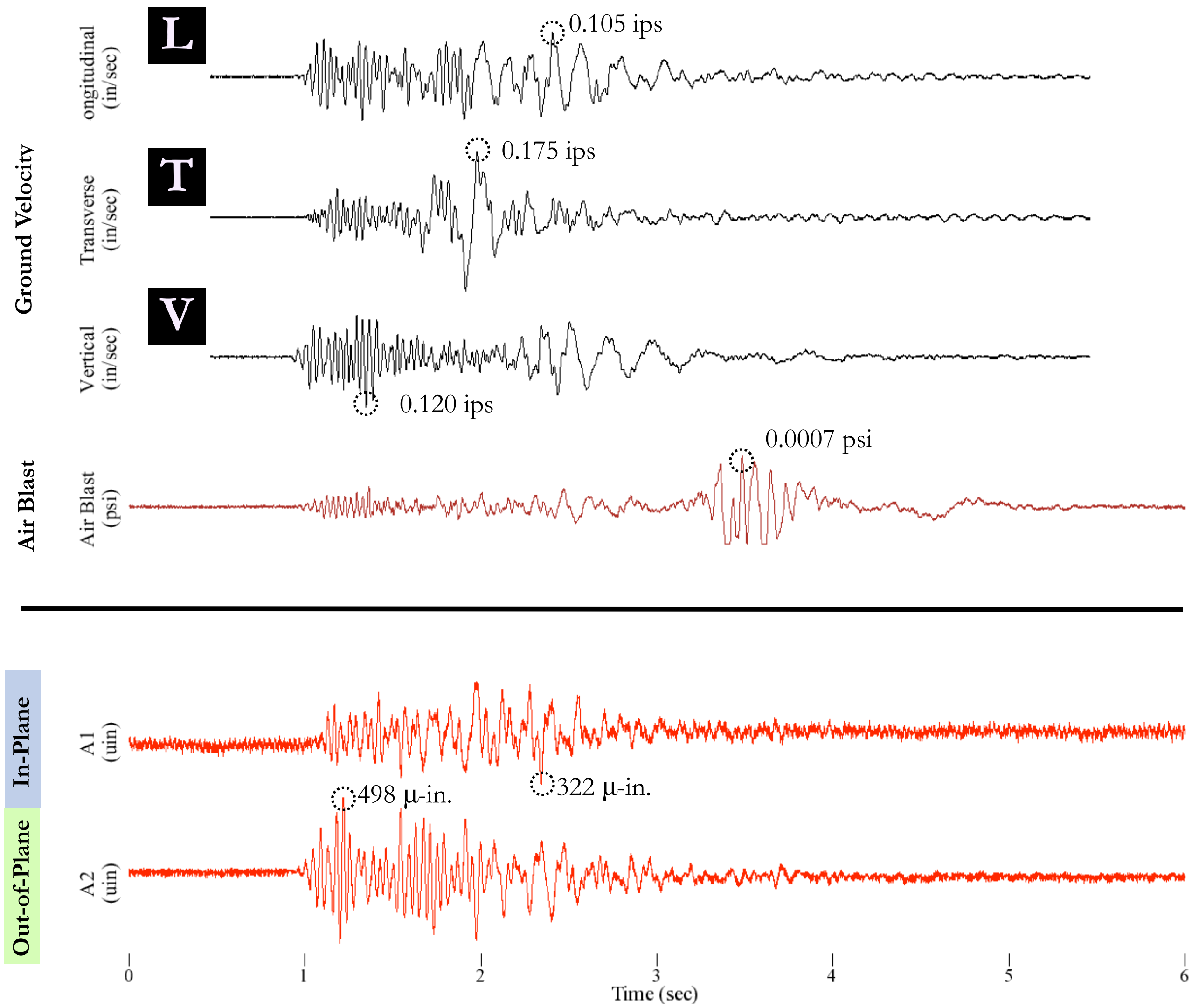


Figure X - Comparison of the ground motion, structural response, and crack response time histories from the July 22nd (2) blast. In-plane and Out-of-plane response are comparable in magnitude with out-of-plane being slightly larger.

2.3 Thunder

Table X compares lightning strikes that occurred on August 26th, 2008 and their respective structural responses. The lightning strike data were obtained from Vaisala's STRIKENet database. The potential of a strike to cause the structure to respond is directly proportional to its current and inversely proportional to its distance. Response results from the air pulse associated with the thunder clap. The midwall response is much larger than the top-bottom, therefore there is more bending in the wall than shear.

			Structural Response [μ-in.]		
Thunder	Current [kA]	Distance [mi.]	δ2-δ1 [μ-in.]	δ4-δ3 [μ-in.]	δ5 - Avg(δ4,δ3) [μ-in.]
3:58 PM	-36.8	1.1	178	220	549
4:01 PM	-23.8	0.7	266	306	942
4:08 PM	-23.8	0.6	150	94	244
4:17 PM	-17.1	0.6	151	508	508

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

Figure X shows the time histories of the 4:01 PM thunder strike on August 26th, 2008. Midwall response from this thunder clap is comparable to those induced by ground motion with PPV of approximately 0.1 ips, while the superstructure responses are much smaller.

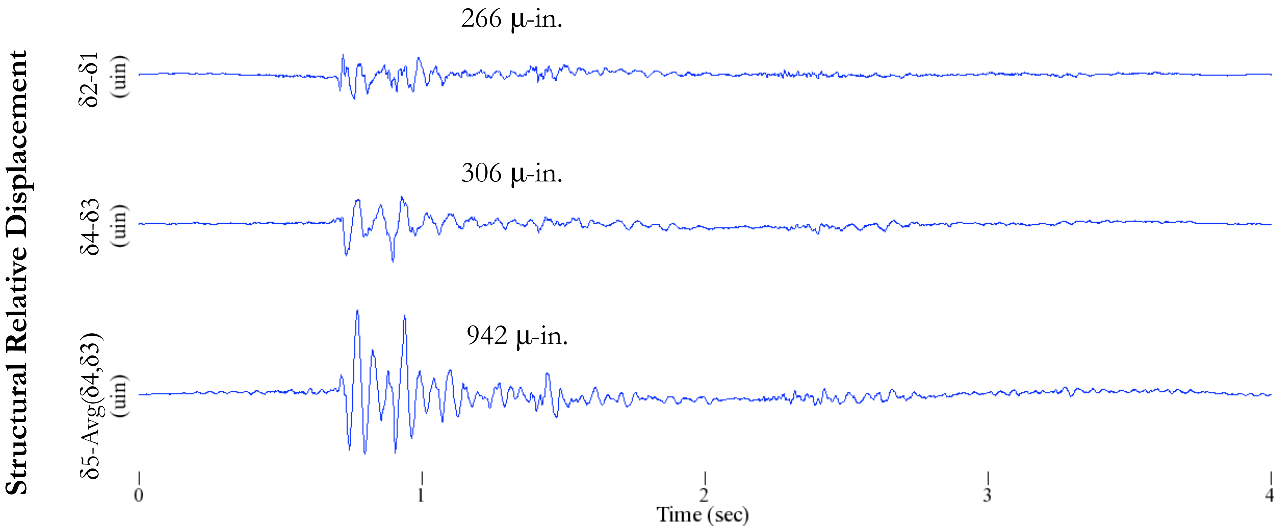


Figure X - Structural response time histories from the 4:01 PM Thunder clap on August 26th, 2008. Midwall relative displacement is similar in magnitude to that produced by ground motion with PPV of 0.1 ips.

Th thunder event on August 26th, 2008 was serendipitously captured before the crack sensors were in place. Figure X below illustrates crack data recorded during a thunderstorm on April 7th, 2008 at the same house (Phase I).

The response of A1 to this thunder strike is comparable in magnitude to those produced by ground motion with PPV approximately 0.1 ips in the current study period.

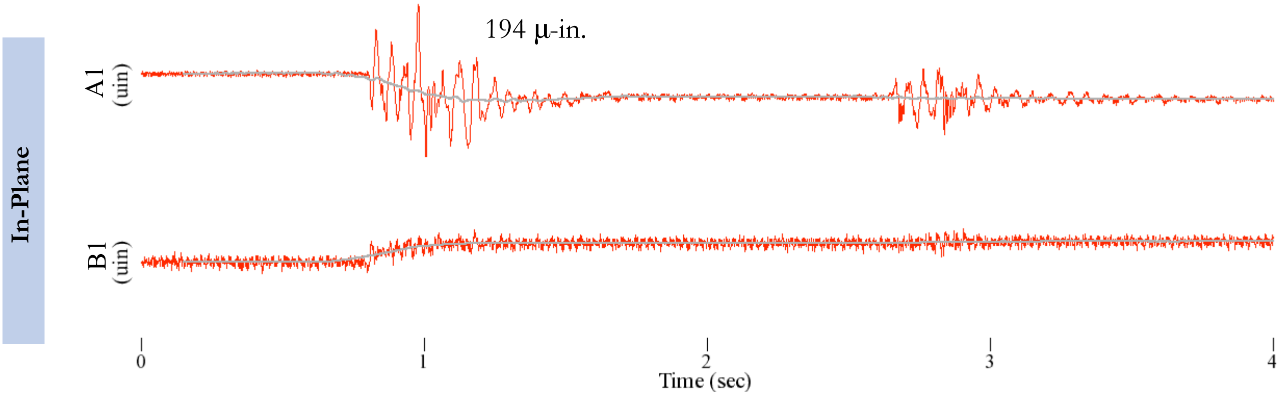


Figure X - Crack response time histories during a thunder event on April 7th, 2008. The A1 response is comparable in magnitude to those produced by ground motion with PPV 0.1 ips.

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 X summarizes the effect on the structure of closing two different doors. Figure X 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 X - 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).

Table X also summarizes the effect on the cracks of closing the two different doors. Simply opening and closing the interior garage door produces crack responses that are two orders of magnitude greater (100x) than any blast or lightning strike. Figure X below shows the crack response when the front door was opened and closed. The out-of-plane response (A2) is far greater than any from blast induced ground motion. Out-of-plane response is almost ten times greater than in-plane response. 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).

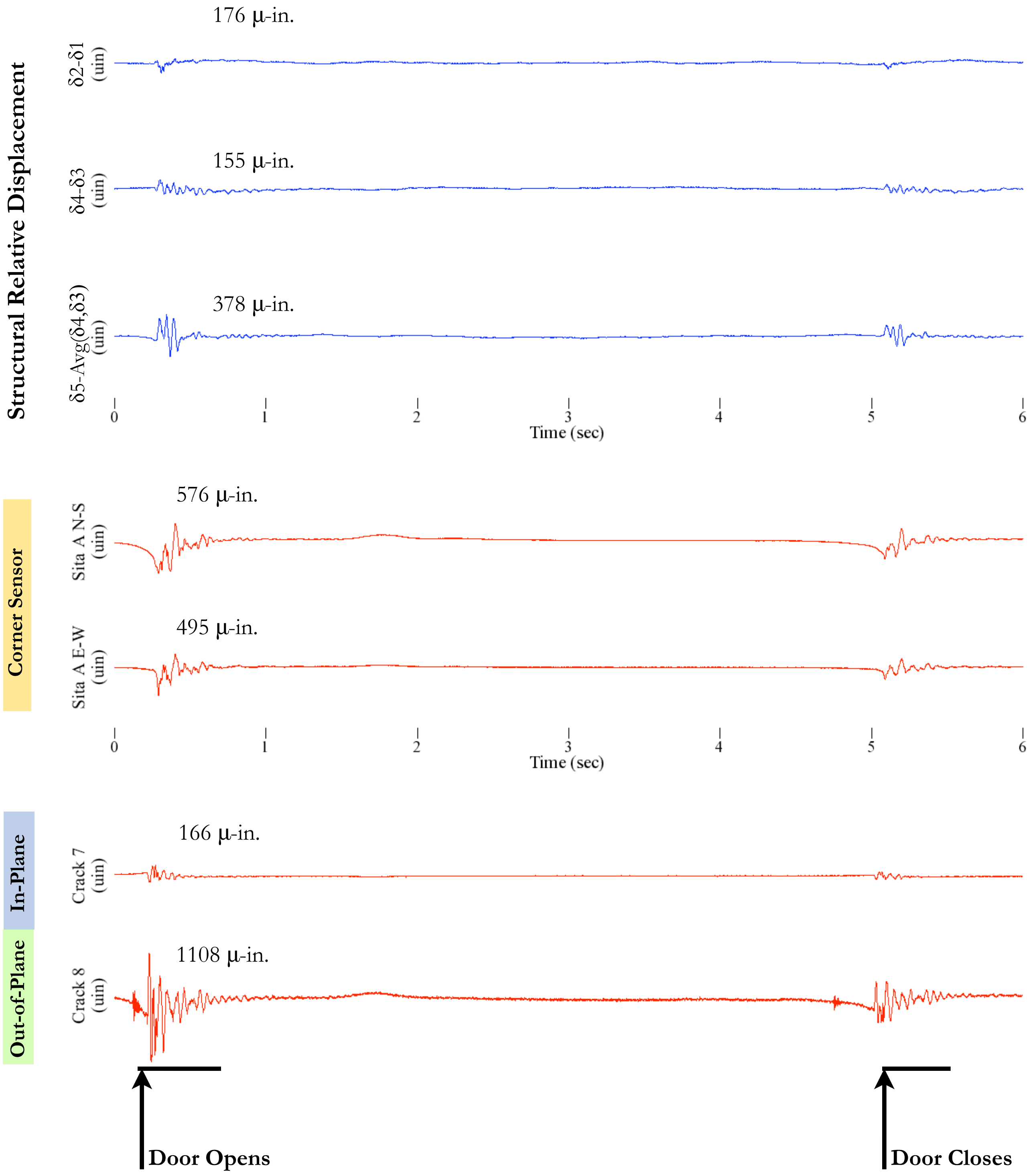


Figure X - Structural and Crack response time histories from opening/closing the front door

3. ANALYSIS

3.1 Crack Response

Comparison of Crack Response to Climatological and Vibration Effects

Figure X compares the crack response magnitudes from environmental conditions as well as dynamic events. Long-term response is generally 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.

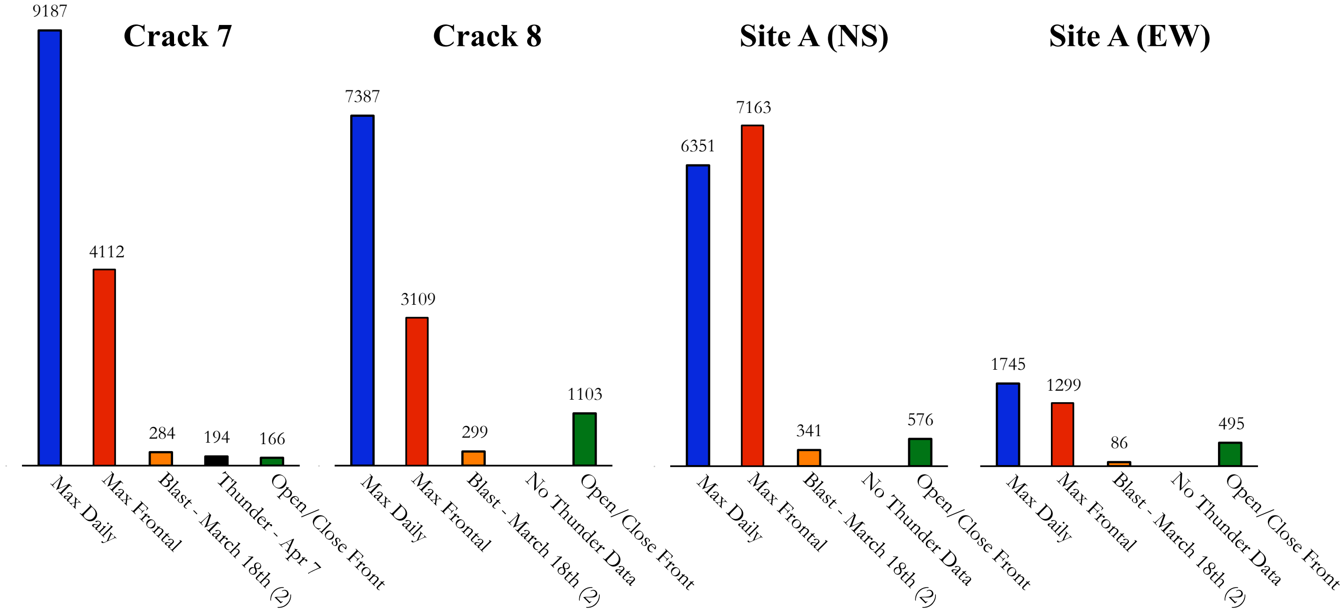


Figure X - Comparison of Crack Response magnitudes. Long term response is at least an order of magnitude greater than any dynamic event. Crack 7 responds more in-plane than Crack 8 does out-of-plane. Site A responds more north-south than east-west.

Excitation Correlation

Figure X compares crack response with excitation parameters like ground motion and structural response. The plots on the left compare PPVs parallel to the wall in which the crack is contained and the response. As expected, the correlation is positive; larger excitation yields larger response. The plots on the right compare structural responses that would cause shear strain in the plane of the walls containing the crack. Correlation of these relationships is not as strong as it has been for cracks in the plane of the wall. Response of a corner is obviously much more complex.

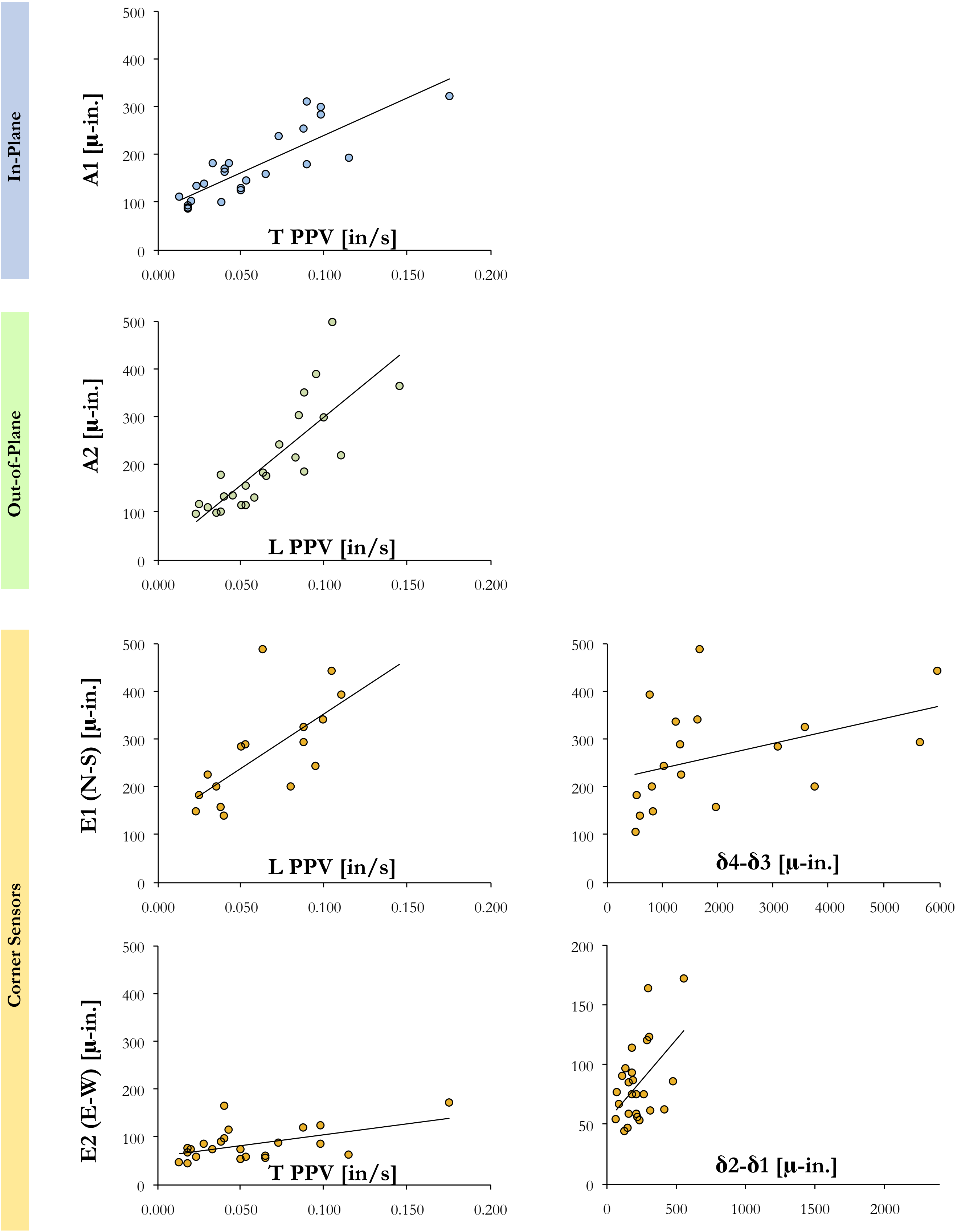


Figure X - Comparison of crack responses to two different excitations: ground motion and structural response parallel to the plane of the crack

Climatological vs. Ground Motion

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

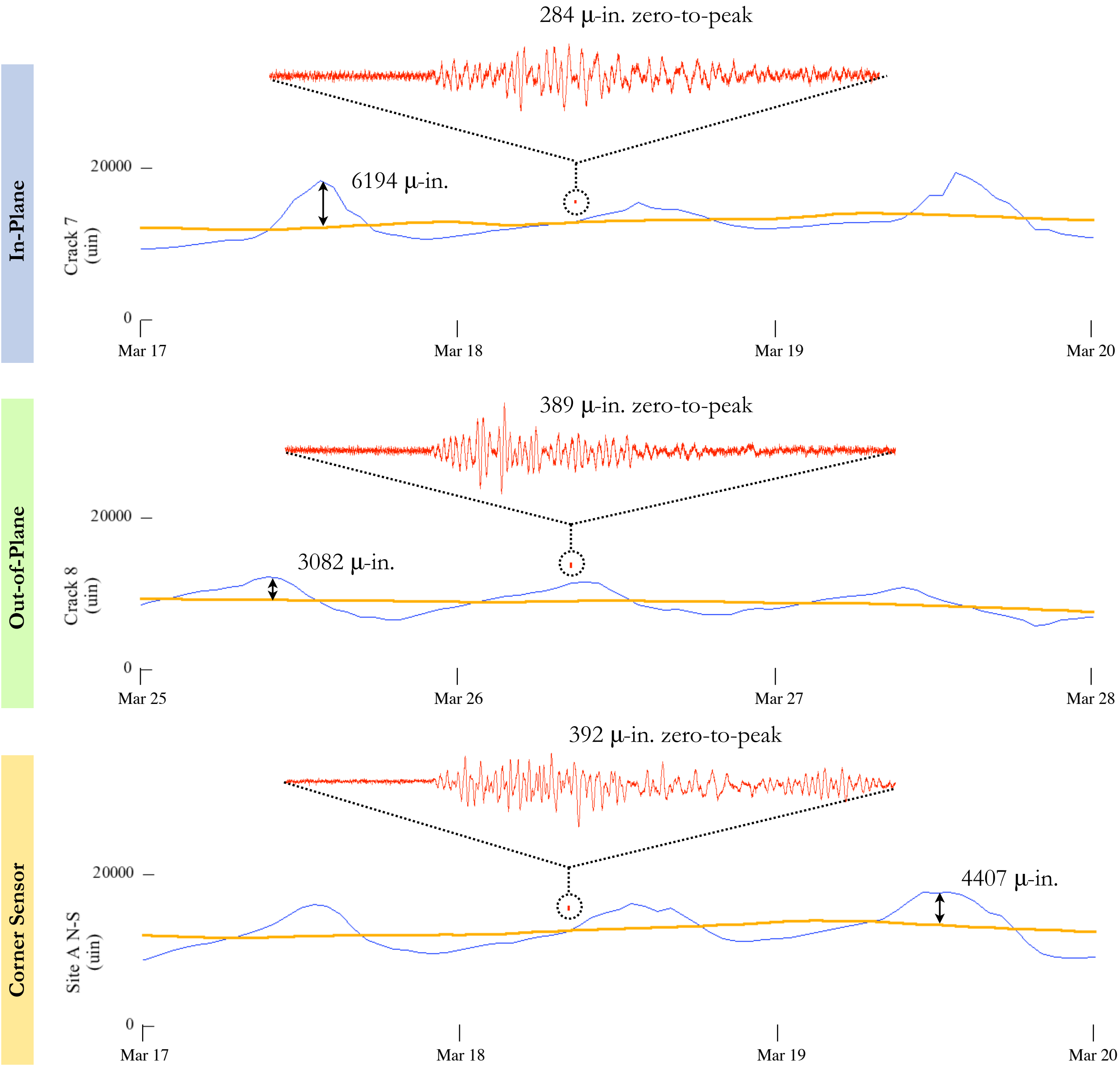


Figure X - Comparison of crack response caused by environmental effects and ground motion. The long-term response induced by weather is at least an order of magnitude greater than the ground motion response.

Movement without Blast

Figure X shows that from Nov 4, 2008 to Dec 3, 2008, Crack 9 expanded 20000 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.

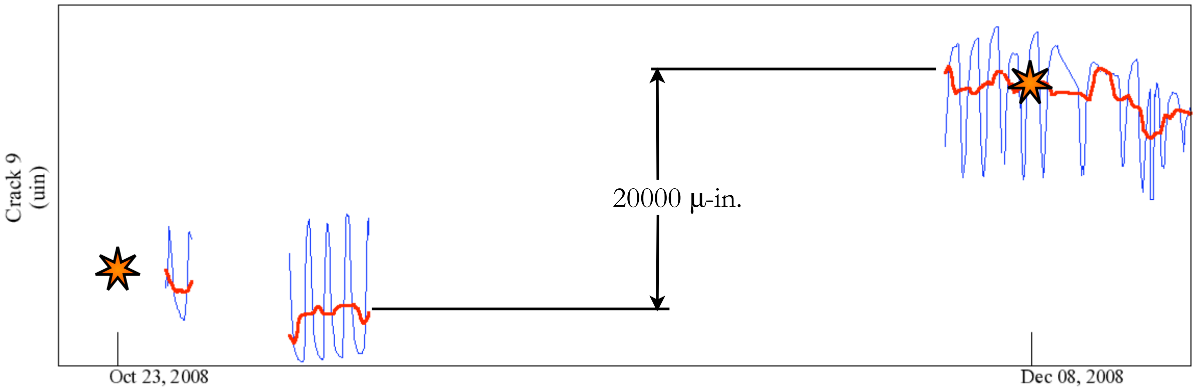


Figure X - Crack 9 expanded 19938 μ-in. in one month without a blast. Closest blasts marked with a star.

3.2 Structural Response

Comparison of Superstructure and Wall Response for Dynamic Events

Figure X 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 blast (1628 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.

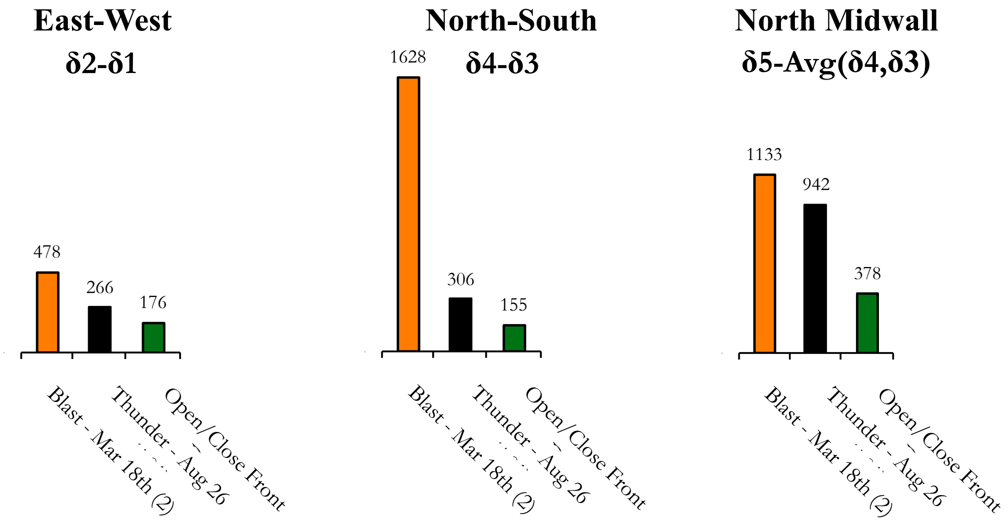


Figure X - Comparison of Structural Response magnitudes during dynamic events. The North-South direction exhibits the most top-bottom motion, while the North midwall has similar magnitude for all three dynamic events.

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 X below 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.

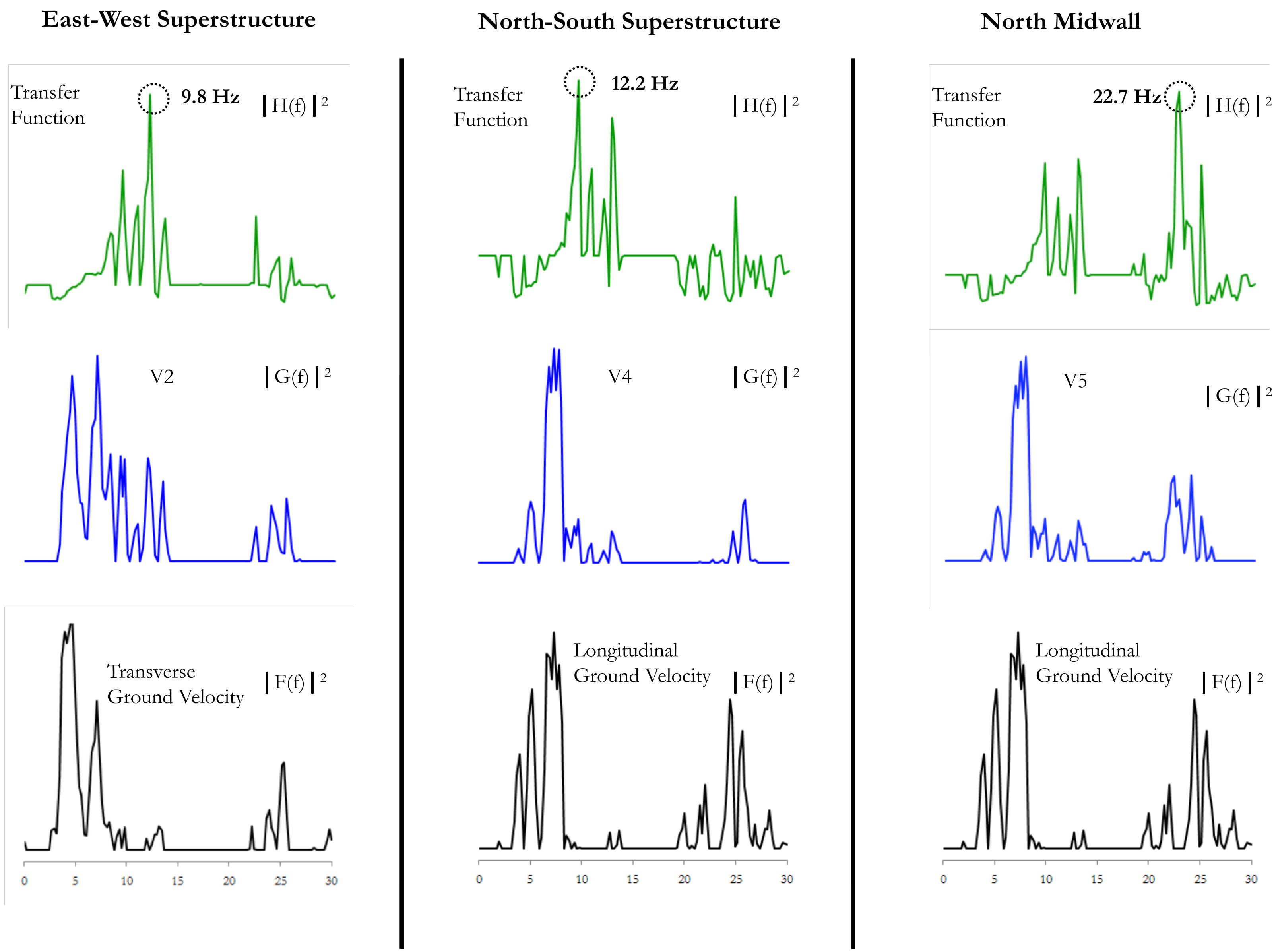
$|G(f)|$ = output of Fourier Transform Integral for structural velocity

$|F(f)|$ = 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 2007). 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. 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 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 Single Degree-of-Freedom analysis on the structure also described in (Dowding 1996). The results of this procedure are in the next section.


East-West Superstructure

North-South Superstructure

North Midwall

Figure X - 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

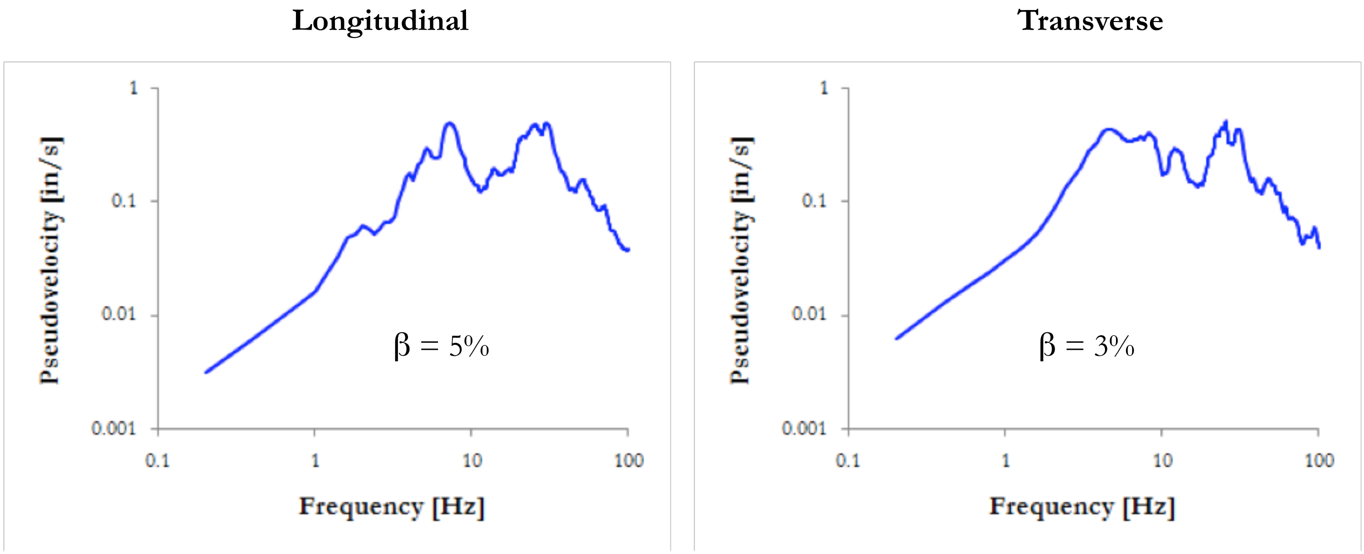


Figure X - SDOF Response spectra for both the Longitudinal and Transverse ground motions from the Jul 22nd (2) blast

4. CONCLUSION

Climatological Response is the greatest

The cracks in this structure respond an order of magnitude more to climatological effects than to any other factor. This is true for in- and out-of-plane response as well as corner joint response

In-plane vs. Out-of-plane

During dynamic events, the drywall joint in the garage responds more out-of-plane. Long-term response; however, is greater in-plane. With the exception of shutting a door, these responses are of the se order of magnitude.

Corner Joint Response

In both long-term response and dynamic events, the corner joint at Site A responds more in the north-south direction than east-west. North-South response has similar magnitude to Cracks 7 & 8.

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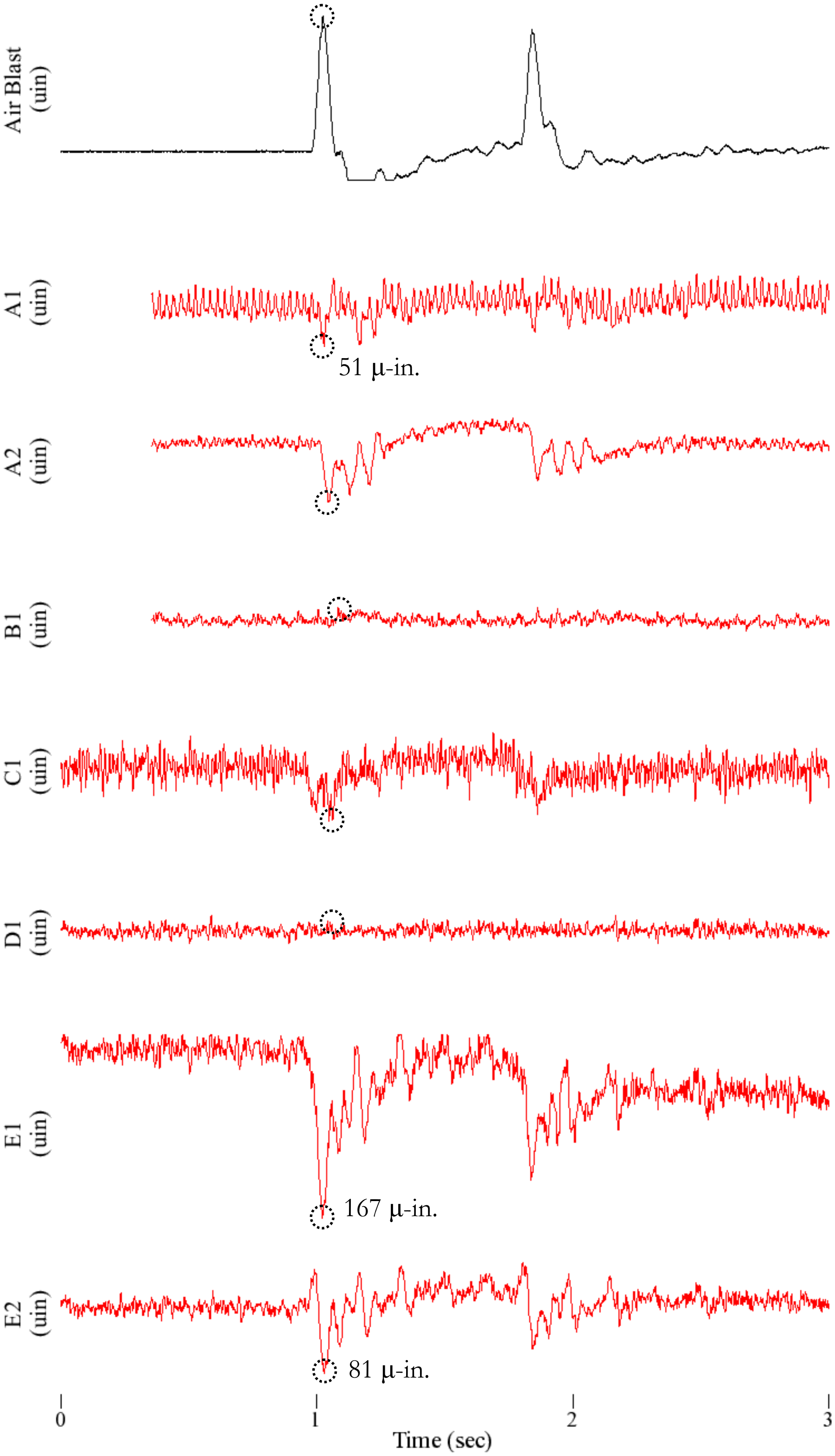
APPENDIX A

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.


Air Blast (uin)
A1 (uin)
51 μ-in.
A2 (uin)
B1 (uin)
C1 (uin)
D1 (uin)
E1 (uin)
167 μ-in.
E2 (uin)
81 μ-in.
0
1
2
3
Time (sec)