RESPONSE OF UNCRACKED DRYWALL JOINTS AND PANELS TO BLAST VIBRATION AND WEATHER

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ABSTRACT

Cracking is one of the most common concerns cited by owners of structures adjacent to construction or mining blasting. While a large database of case studies documenting the relative insignificance of ground motion induced by responsible blasting compared to weather effects on cracks in nearby structures has been established, the perception of damage to structures, particularly residences, remains common. In allegations of blast damage, litigants may downplay the utility of the database of crack response to weather and ground motion, citing that the behavior of the structure is somehow drastically altered by the existence of cosmetic cracks. In response, this study will compare the response of cracked and uncracked areas of gypsum board in two structures – one near a surface coal mine in Indiana, the other near a limestone quarry in Florida – to blast-induced ground motion and air overpressure as well as changes in temperature and humidity.

INTRODUCTION

Change in Crack width is an index of possible crack extension

Autonomous Crack Measurement (ACM) is based on measurement of micrometer changes in crack width, which is an index of the potential for the crack to extend. This logic is similar to splitting wood with a wedge. Hammering the wedge into the wood increases the width of the crack, extends the crack and eventually splits the wood. Thus comparing changes in crack width provides a comparison of the potential for crack extension. The wood splitting analogy is experimentally confirmed for fracture of cement paste as shown in Figure 1. Crack mouth opening (COD) on the vertical axis (similar to the action of the wedge to widen the penetration) is compared to fracture extension (length of the crack tip) on the horizontal axis. As the wedge width, COD, increases from 90 to 270 micro inches (2.25 to 6.75 micrometers), the crack extends from 1.4 to 2.1 inches. The graph itself displays both the opening and the extension as they increase in concert. Fracture extension by increasing crack mouth opening – crack width-- is the fracture mechanics foundation for the ACM approach.

Just as splitting wood requires the "V" from the wedge to be progressively widened by the wedge, it stands to reason that crack width must increase beyond its previous maximum for the crack to extend. Since it is unlikely that measurement would begin at the previous maximum width, the question then becomes, "what outside effects produce the largest change in crack width?" Those changes are the most likely to extend cracks. It also stands to reason that cyclic response at widths smaller than the maximum will not extend the crack. As has been measured in the more than 30 crack studies reported in Dowding (2008) climatologically induced changes in crack width (described as response) are far larger than those produced by vibratorily induced response. Thus at present vibratory limits the most likely causes of crack extension are climatological effects.

Alternate Hypotheses

Concern has been expressed about the conclusion that crack measurements show that there is a floor below which vibrations have no cracking potential. These concerns involve at least the following assertions 1) cracks are not locations of maximum strain and un-cracked locations may be more strained by vibration, 2) there are critical excitation motions that can maximize response that are not included in the data, and 3) there are maximum initial strain conditions in structures that render them vulnerable. These concerns have arisen because of several of coalescing points of view. First, there is the need to ensure that all critical factors have been included. Second there is the sensory difficulty of believing that environmental effects, which are silent, can be more influential than those that are noisy and disturbing. Finally there is the age-old issue of proximate cause: the assertion that even a small vibration can cause cracking if it occurs at the moment all of the other effects combine to maximize the strain in the wall. The three concerns will be addressed briefly first and then the first two will be explored more thoroughly with data. Exploration of the third will be addressed in another paper as this paper was already too long after exploring the first two concerns.

Consider first the concern of correct location. It has been hypothesized that once a crack is formed, the strain concentration is relieved and the large local deformations leading to cracking are reduced. Thus cracks are now positions of low strain or deformation and thus low potential for cracking. What may then be important is response of un-cracked locations. The first section of this paper will explore two case histories that involve measurement of the response of multiple, weak but un-cracked locations in gypsum drywall. These weak locations are the joints between drywall sheets.

Dry wall joints are comprised of a thin, paper tape covered with 2 to 3 mm (1/16 to 1/8 inch) of plaster. The sheets themselves are composed of 12 mm of gypsum encapsulated by by 2 to 3 mm of cardboard. All things being equal, the paper thin joints are weaker than the half inch thick sheets themselves. Response of the joints to long term, environmental effects will be compared to the response to vibratory effects. The long term and vibratory response of un-jointed locations on drywall sheets (basically the null response) will also be compared. Both or these responses will be compared to that of a cracked section where the crack was not fully extended.

Second, consider critical excitation. Critical is most often defined as high amplitude (particle velocity) excitation at the natural frequency of the structure or its components. It has been hypothesized that not enough cases of low frequency, high amplitude motions have been observed. If these low frequency events had been observed, higher amplification would have occurred which would have lead to higher dynamic crack response. Low frequency excitation would be that which would be equal to the natural frequency of the walls and the super structure, 10 to 20 Hz and 5 to 10 Hz respectively. High amplitude would be near or exceeding 12 to 25 mm/s (0.5 to 1.0 inches per second).

The second section will focus on response of un-cracked sections of wall to low frequency, 5 to 7 Hz, motions. The house instrumented with Kaman gauges in 1986 at the Universal mine in Indiana was subjected to such low frequency excitation and high amplitude motions. In several instances the amplitudes exceeded 12 mm/s at low excitation frequencies. Response of this house can be linked to crack and un-cracked drywall joint response to explore the effect of excitation motions whose frequency matches that of the super structure. Excitation motions with dominant frequencies that match those of the walls, 10 to 20 Hz, are involved in almost all cracking studies and require no special investigation.

The third concern proximate cause or "the straw that breaks the camel's back" will be briefly addressed only as there is not enough room for a suitable presentation with data. Proximate cause is one "without which the crack could not have occurred". Thus it will be instructive to consider the probabilities of effects other than blasting causing cracking and their relationship to the "natural and continuous sequence of events" in relation to all events that can occur. For the small vibration crack response to be the straw, the crack would have to be precariously on the brink of extension at the moment the ground motion reaches the house, and there can be no other straws in the air to land on the camel's back. For this brink to occur, the crack would have to be subjected simultaneously to the peak widths caused by the 1) historically largest extreme weather event (eg drought), 2) largest seasonal response (eg high seasonal heating of cooling response), 3) largest weather front response (eg long period of high humidity), 4) largest daily temperature response (a few hours in the afternoon sun), and 5) ahigh ground motion. Given the daily swings in crack response, this condition would exist only at a brief moment during one hour of the worst weather front week in the worst heating/cooling season during an extreme (drought, flood, etc) climatological condition. Another paper will address the probability of such an occurrence and other related exogenous events.

1. RESPONSE OF UN-CRACKED, WEAK SECTIONS OF WALLS

House and Crack Descriptions and Vibration Environment

Measurements described herein were obtained in two houses whose photographs and floor plans are shown in Figure 2; one in Blanford, Indiana and the other near Naples, Florida. The Indiana house contains two, instrumented, un-cracked drywall joints and a cracked drywall joint for comparison. Its multiple sections shown in the photograph were built over a period of 10's years, with the middle the oldest and the right most, two-story section the newest. Each section is built on a basement, with a full basement under the two-story section, a shallow basement beneath the middle and a crawl space beneath the left (Dowding, 1996). The walls, interior and exterior are constructed of standard wood studs and were covered in drywall for the observations. The Florida house contains an instrumented drywall joint in the garage ceiling. It is a slab on grade structure, whose exterior covered walls are built with concrete masonry units (CMU), and interior walls and ceilings were constructed of wood studs and gypsum drywall (Kosnik, 2009).

Context (top) and details (bottom) of the installations is shown in Figure 3 with those for the Indiana house on the left. The living room walls in the Indiana house contain the instrumented dry wall joints as shown in the drawing and center photograph. Horizontal and vertical un-cracked dry wall joints are C9 and C10, un-cracked locations near the centers of the drywall sheets are C2 and C. Drywall joint crack is C7, which as shown in the right most photograph, is at a doorway (to the right of C6) between the living room and the kitchen (LR and K in Figure 2). This crack is not fully extended, and did not extend during the observation period. Similar information for the instrumented garage ceiling drywall joint is shown in the bottom row in Figure 3. Sensor D1 spans the joint and D2 is nearby on the full section drywall.

Both structures are located near to surface mines (Indiana: coal and Florida: limestone), which require blasting. A typical blast, 2000 feet from the Indiana house, involved 54, 100 ft deep holes arranged in six rows (in a radial direction to the house). Each hole was loaded with 675 lbs of explosive with four decks and thus ~170 lbs of explosive per delay. This shot produced ground motion with a peak particle velocity of 0.14 ips with a dominant frequency of 9 Hz. The Florida house is located some 3000 to 5000 ft from 30 to 50 hole shots loaded with 50 to 60 lbs of explosive. These detonations produce ground motions with peak particle velocities of some 0.05 to 0.18 ips with dominant frequencies between 3 and 33 Hz.

Comparison of Climatological and Vibratory Responses

Figure 4 compares four months of responses of the 3 un-cracked (C9,C10 & D1) and one cracked (C7) drywall joints, and 3 un-cracked drywall sheets (C2,C6 & D2) to temperature and humidity-induced, climatological effects. Indiana information is on the left and Florida information is on the right. Variation in temperature and humidity inside and out is presented on the bottom. Joint, crack and sheet responses are plotted to the same scale at the top for comparison.

Responses of the drywall sheets are small, and positions such as these are regularly used as the null response. The null response describes the response of the sensor metal and un-cracked mounting material to changes in temperature and humidity. Comparison to the crack response shows that dry wall sheet response is so small as to be inconsequential compared to the crack response.

Responses to long-term climatological effects of the un-cracked, paper-thin (and thus weak) drywall joints (C9, C10) at the Indiana house are less than $1/10^{th}$ that of the cracked drywall joint (C7). The vertical and horizontal un-cracked joints are equally as responsive. The drywall joint in the Florida garage is some five times more responsive to climatological effects than are the Indiana joints. This large response is not totally unexpected as the joint is in the ceiling of an un-moderated garage over the summer in Florida. Indiana joints were on an interior of a house heated at a constant temperature during the late winter and early spring. Even though larger than that in Indiana, the Florida joint response was small compared to crack response in the garage. A crack in the garage wall at the interface between the doorframe and the CMU wall was five times more responsive than the un-cracked drywall joint (Meissner et al, 2010).

These long-term measurements, spanning some four months, show that un-cracked weaknesses in wall covering are less responsive to long term, climatological effects than other cracked locations. The same is true for vibratory response as shown next.

Vibratory response time histories of un-cracked and cracked dry wall joints for these two houses are shown in Figure 5. As before Indiana is on the left and Florida is on the right. Particle velocity and air over pressures time histories of the motions that induce the responses are shown at the top and the responses are shown at the bottom. The vertical Indiana drywall joint C10 responds the most – of all uncracked dry wall joints -- and is far more responsive than the horizontal joint. However, its response is still smaller than that for the cracked joint, C7. Response of the Florida drywall joint to ground motions is small and barely out of the noise level. The low frequency ground motions at the Indiana house are evident. Their significance will be discussed in the next section.

Cracking of a joint does not appear to diminish its dynamic response; at least not relative to other un-cracked weaknesses. The relationship between vibratory and climatological response for un-cracked wall weakness (dry wall joints) is the same as for cracks as shown by the bar chart comparisons in Figure 6. Where climatological response is small, so is vibratory response. Be it for a cracked joint or un-cracked joint. Cracked joints are seen to respond more than un-cracked joints to both vibratory and climatological drivers.

Large response of cracks is not unexpected. The cracking of wall covering provided by the drywall and its weakest element, the paper thin joints, can often be a function of the structural deformation beneath "the wall cover." Deformation of the underlying structural interface or element may not be affected much by a thin covering. Comparison of the vibration response of C7 to that of H3 and H4, velocity transducers in the second story, shows an almost harmonic congruence of the crack response and structural motion. The mass and stiffness of the lower story walls responding to the second story motion will be affected little by the appearance of a hairline crack in a piece of paper.

2. LOW FREQUENCY, HIGH AMPLITUDE EXCITATION

As shown in Table 1, a number of the events produced low frequency, high amplitude ground motions at the Indiana house. Table 1 compares ground motions, structural response and cracked (C7) and un-cracked responses for some of the highest amplitude events. As seen in the table, six of the shots produced ground motions in the 5 to 7 Hz range that either coincide or nearly match with the 5 Hz natural frequency of the superstructure demonstrated by the 5 Hz responses of H3 and H4 velocity transducers in the second story. These data are unique because they combine measurements of both structural and crack response for a case with unusually high amplitude, low frequency ground motions. These low frequency motions normally arrive later in the wave train and are thus likely to be surface waves. The earlier arriving waves are the higher frequency body waves as described in earlier presentation of these data (Dowding, 1996).

No new cracks or extensions were observed as described in the original project report. Information for the Indiana house has been exhumed from 25 year old project files for this paper. In addition to the extensive instrumentation, the house was thoroughly inspected for cracking before and after each blast in so far as possible. The house was divided into inspection grids, which were visually inspected by the same person in the same fashion in each instance. The project report has been scanned for archival purposes and is available for public inspection (Dowding and Lucole, 1988).

Table 1 allows confirmation of several important issues regarding frequency, amplitude and amplification. Figure 7 presents time histories ground motion, wall (H1 & H2) and superstructure (H3 & H4), and C10 and C7 responses responses for shots 12 and 16 that demonstrate some of the following comments. First, amplification values from low peak particle velocity motions (PPV's) cannot be assumed to be applicable for high PPV's. Second, both of the horizontal components must be considered.

Amplification values in Table 1 were calculated as the ratio of the maximum particle velocity divided by the peak of the amplitude of the excitation pulse immediately preceding it. This approach produced 3 unusually high transverse amplification values: 19,11, 10 with PPV's of 0.074, 0.200 and 0.261 ips for shots 11, 12, 13. These were not the shots that produced the greatest crack response. Shots 14 and 15 produced the maximum response with transverse amplification values of 1.8 and 6.1 with the highest PPV's in the table. Shot 15 had a low transverse PPV, but a high longitudinal PPV. Shots 14 and 15 also had high dominant frequencies of approximately 20 Hz. Higher excitation frequencies with higher PPV's are not unexpected because high PPV motions occur at small absolute distances where the lower frequency motions do not dominate.

Figure 8 graphically compares responses of the 5 measured locations with the maximum PPV in the direction parallel to the wall of interest. They are remarkably consistent and show the same trends that were measured in previous crack-structural response studies that summarized Office of Surface Mining work (Aimone-Martin et al, 2002). Cracks continue to respond more than do un-cracked weaknesses as can be seen by the comparison of C7 and C10's sensitivity to PPV (slope) as also tabulated in Table 1. Here the cracked joint sensitivity is approximately 3 times greater than that for the un-cracked joint even for low dominant frequency ground motions.

These measurements show in Figure 8 that even for high PPV (10 to 23 mm/s or 0.4 to 0.9 ips) and a mix of low (4 to 8 Hz) and higher frequency (9 to 28) excitation motions response of the cracked tape joint, C7, is the same as observed for other vibratory environments. Response follows a relatively linear trend and the sensitivity is similar to that reported by McKenna (2002). When the lowest frequency (4 to 8 Hz) motions were separated for analysis, the sensitivity of the cracked joint increased, but only slightly. There was no discernible difference in sensitivity of the un-cracked joints between low and higher frequency excitation. The ratio of vibratory response to climatological effects is still small even for low frequency excitation. This ratio is 0.18 for typical weather events and even less for the extreme event in April.

CONCLUSIONS

Measurements have been made in two structures to investigate several concerns regarding the usefulness of the observation that cracks respond more climatological than vibratory effects. Concerns addressed are that 1) cracking relieves strains and strains concentrate else where, reducing the sensitivity of cracks to excitation relative to un-cracked locations and 2) there are not enough observations of crack response in low excitation frequency - high particle velocity environments that may cause greater amplification. Measurements presented herein show that:

A cracked joint does not respond less than other un-cracked weaknesses in the wall covering to either climatological or vibratory effects.

Even in high particle velocity (10 to 23 mm/s or 0.4 to 0.9 ips) and low frequency (5 to 7 Hz) vibratory environments, cracks continue to respond more than do un-cracked weaknesses.

Responses of the weakest of wall components, the paper-thin joints between drywall sheets was measured and shown to be less than that of cracked joints.

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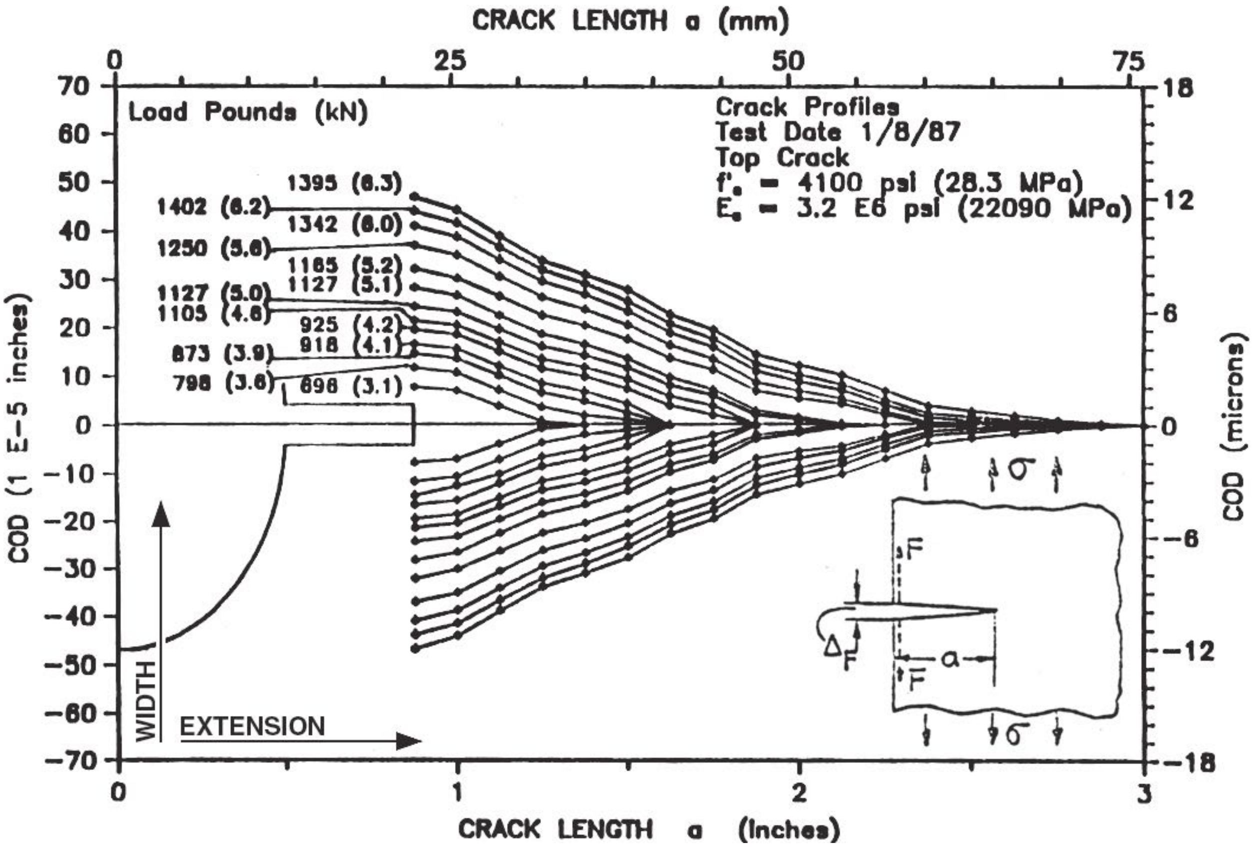

Figure 1 -Experimental observation that cracks extend as their width increases forms the foundation of fracture mechanics as well as the ACM measurement approach. Special visualization techniques were employed to measure the extension of a crack (marked by the rightward extension of the ">") as its width (COD or "crack opening displacement) increases (marked by the increasing width of the mouth of the ">" on the left. (Miller, 1989).

Figure 2 - The two houses near Blanford, Indiana (left) and Naples, Florida (right) containing the un-cracked and cracked drywall joints crack instrumented in this study; top photographs; bottom plan views showing sensor locations

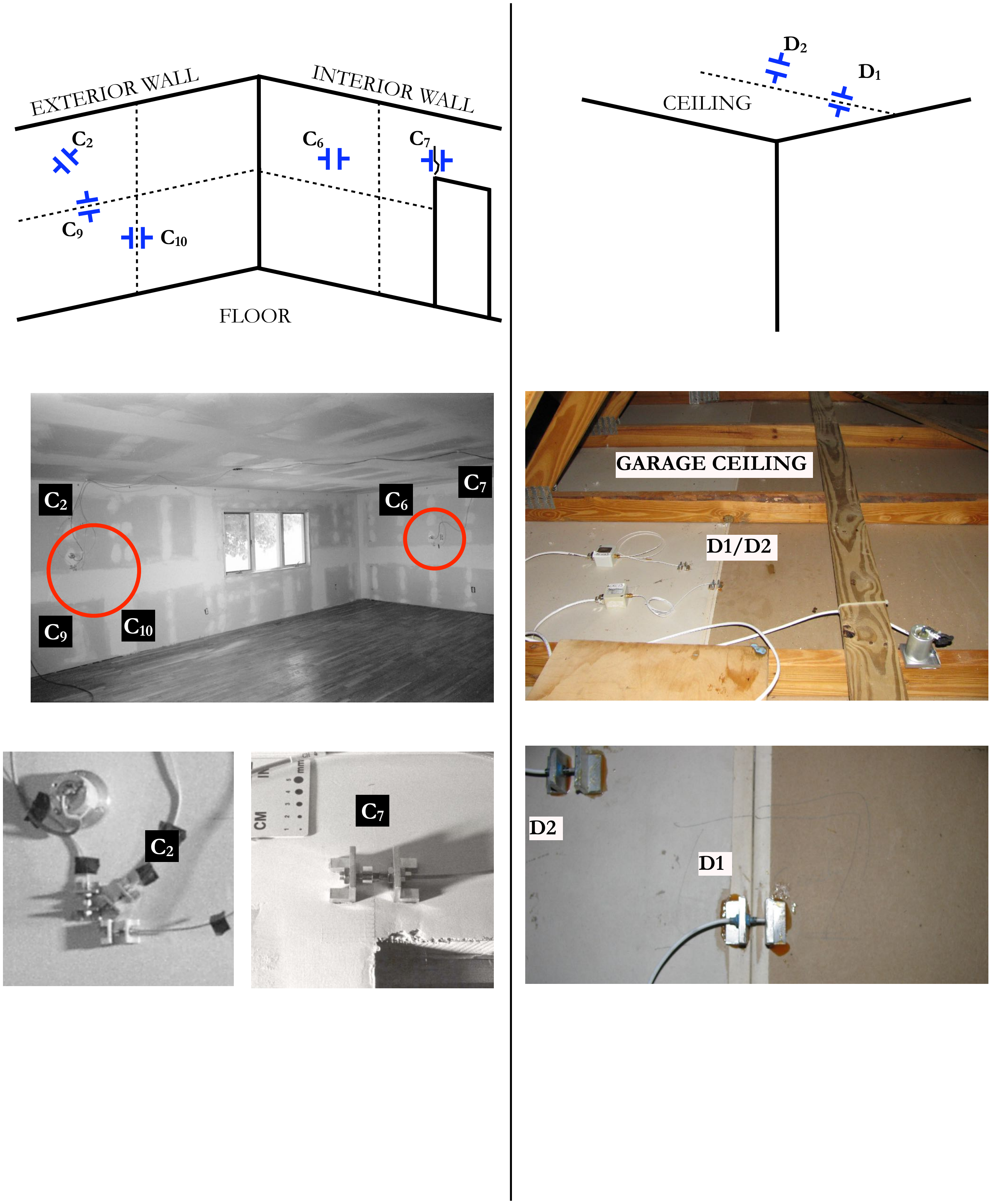

Figure 3 - Installed details of drywall joints and sensors placed in the Indiana house (left) and Florida house (right). Wall, joint and sensor orientation are illustrated on the left. Photographs showing context are in the middle column and detail with detail on the right. C9&10&D1 across uncracked drywall joints; C7 across cracked drywall joint; and C2&6&D2 on drywall sheets.

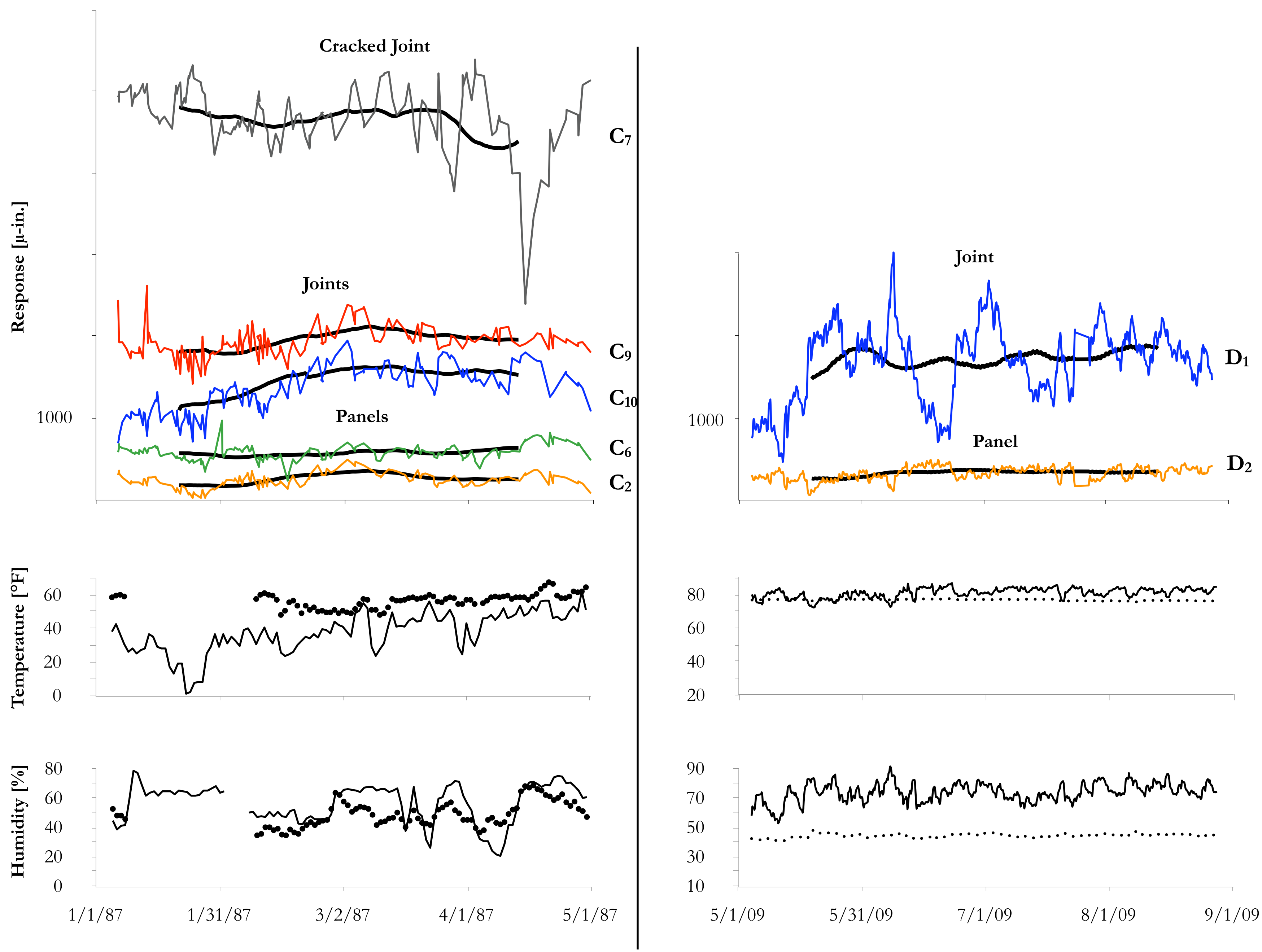

Figure 4 - Comparison of four months of climatologically induced responses of Indiana (left) and Florida (right) joints. 30-day central moving average shown with a solid line. Temperature and Humidity (bottom, dotted=inside, solid=outside), and joint responses (top) are given with common time and response scales for comparison.

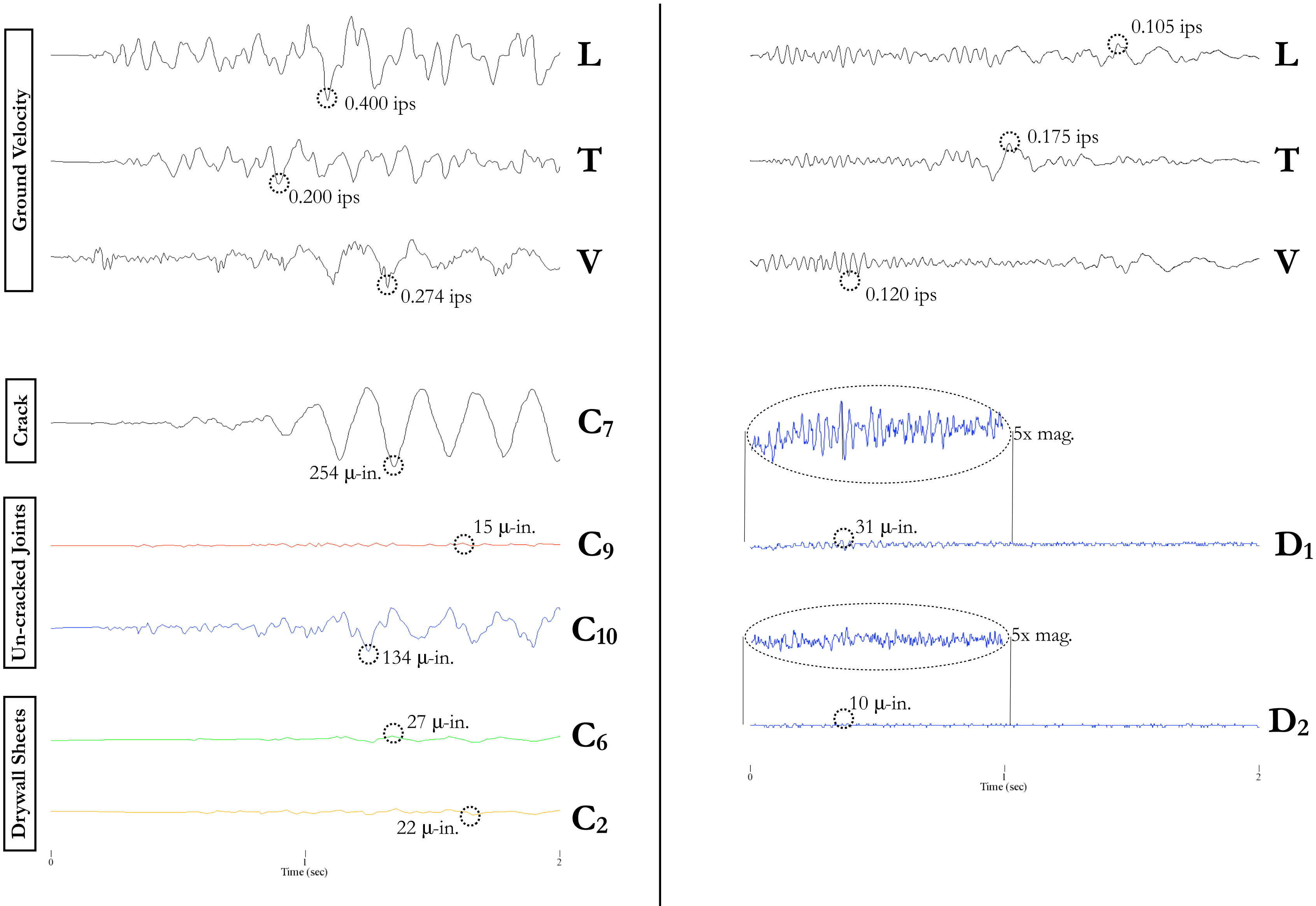

Figure 5 - Comparison of ground motions (top) with joint responses (bottom) showing unusually low excitation frequency of the Indiana ground motions (left) compared to Florida (right). Cracked joint responds more than most sensitive un-cracked joint.

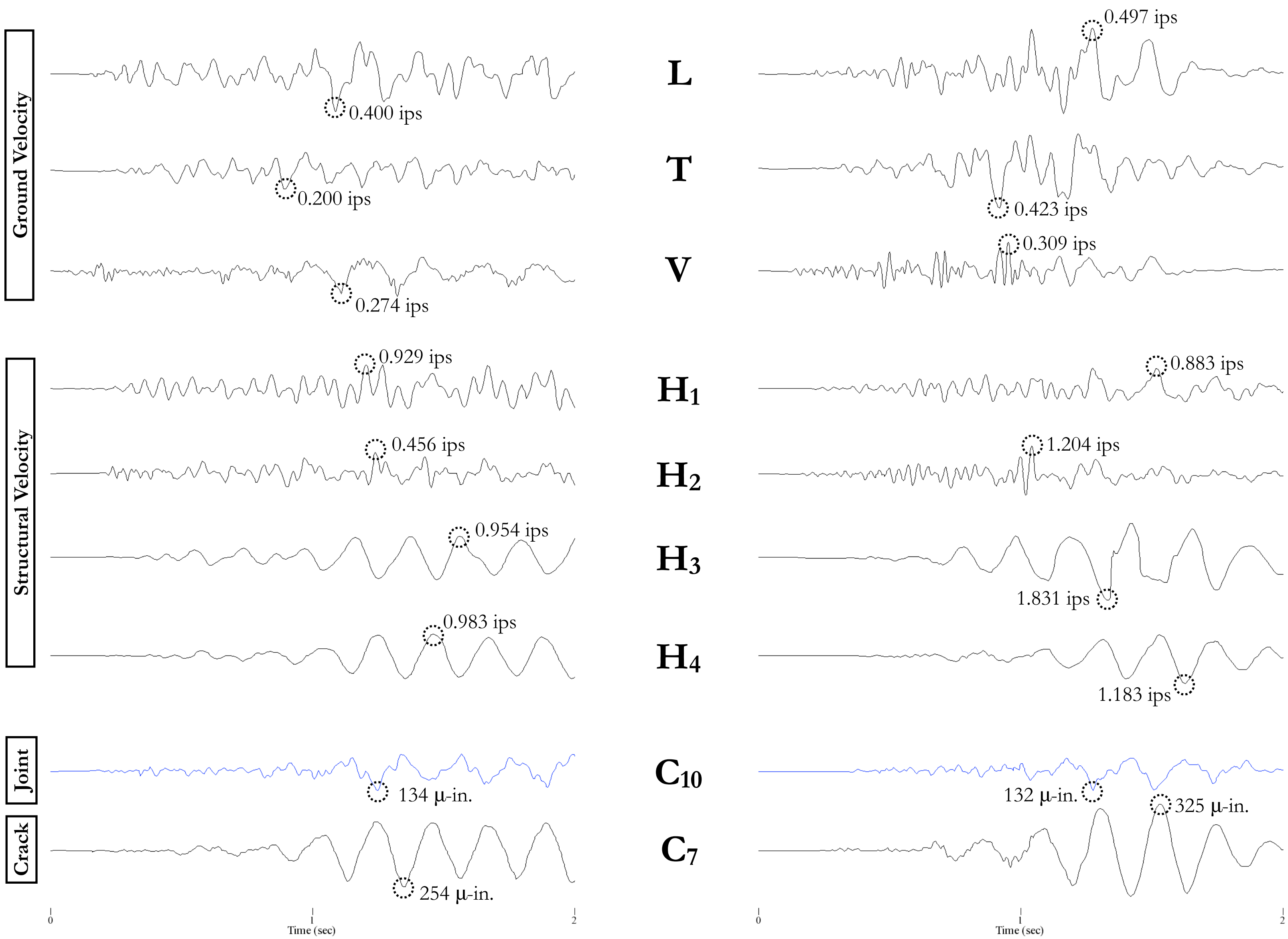

Figure 7 - Time histories of ground motion, structural response, and cracked (C7) and un-cracked drywall joint response (C10). Low frequency excitation show joint response follows the motion of the upper story. April2nd onthe left and May 1st on the right.

			Frequency [Hz]		Max PPV [in/s]		Comparative PPV [in/s]								Amplification				Response [µ-in]	
No.	Date	Time	L	T	L	T	L_1	L_4	T_2	T_3	H1	H2	H3	H4	H4/L	H3/T	H1/L	H2/T	C_7	C_{10}
1	Nov 18, 1986	1:44 PM	23	31	0.55	0.38	0.55	0.55	0.30	0.30	0.91	0.45	0.36	0.39	0.70	1.21	1.66	1.51	129	N/A
2	Nov 26, 1986	2:12 PM	18	13	0.13	0.18	0.13	0.13	0.14	0.05	0.44	0.19	0.27	0.19	1.45	5.00	3.40	1.43	39	
3*	Dec 22, 1986	9:38 AM	5	8	0.35	0.30	0.30	0.23	0.24	0.19	0.75	0.78	1.04	0.74	3.26	5.49	2.47	3.24	159	
4	Dec 27, 1986	2:58 PM	5	7	0.11	0.07	0.08	0.08	0.05	0.07	0.33	0.12	0.24	0.39	5.08	3.56	4.36	2.47	43	
5	Dec 30, 1986	5:03 PM	21	7	0.19	0.11	0.09	0.09	0.08	0.07	0.49	0.29	0.39	0.33	3.78	5.94	5.64	3.72	39	
6	Jan 1, 1987	9:03 AM	21	21	0.76	0.41	0.49	0.35	0.23	0.41	2.85	0.72	0.63	0.70	1.99	1.53	5.83	3.06	118	
7	Jan 5, 1987	10:48 AM	11	15	0.49	0.25	0.49	0.49	0.18	0.14	0.72	0.56	0.37	0.43	0.88	2.62	1.47	3.12	74	
8	Jan 5, 1987	2:13 PM	11	12	0.18	0.24	0.16	0.18	0.14	0.14	0.34	0.33	0.63	0.28	1.57	4.49	2.08	2.35	68	
9	Feb 17, 1987	2:56 PM	25	16	0.21	0.12	0.21	0.13	0.05	0.05	0.54	0.26	0.25	0.46	3.57	5.49	2.62	5.70	92	37
10	Feb 23, 1987	2:47 PM	28	9	0.41	0.26	0.24	0.15	0.16	0.16	1.00	0.61	0.41	0.33	2.21	2.49	4.22	3.73	72	71
11	Mar 23, 1987	1:57 PM	5	7	0.13	0.07	0.10	0.10	0.07	0.02	0.17	0.11	0.41	0.33	3.21	19.34	1.62	1.43	71	21
12*	Apr 2, 1987	2:40 PM	6	9	0.40	0.20	0.34	0.28	0.11	0.09	0.93	0.46	0.95	0.98	3.54	11.13	2.74	3.99	254	134
13*	Apr 4, 1987	2:55 PM	7	7	0.36	0.26	0.25	0.25	0.23	0.08	0.85	0.79	0.78	0.86	3.46	10.00	3.42	3.37	169	79
14	Apr 20, 1987	10:32 AM	21	17	0.85	0.57	0.61	0.61	0.38	0.57	3.18	0.86	1.05	0.72	1.19	1.84	5.22	2.25	463	171
15*	Apr 20, 1987	10:34 AM	19	21	0.93	0.25	0.80	0.20	0.13	0.13	2.97	0.41	0.77	0.80	4.01	6.07	3.72	3.20	438	211
16	May 1, 1987	9:12 AM	6	9	0.50	0.42	0.36	0.25	0.32	0.21	0.88	1.20	1.83	1.18	4.76	8.66	2.49	3.80	325	132

Table 1 - Tabulation of ground motion characteristics, structural response, amplification values, and associated joint and crack response that shows, high amplification values calculated from low amplitude, single pulses cannot necessarily be employed with higher particle velocities.

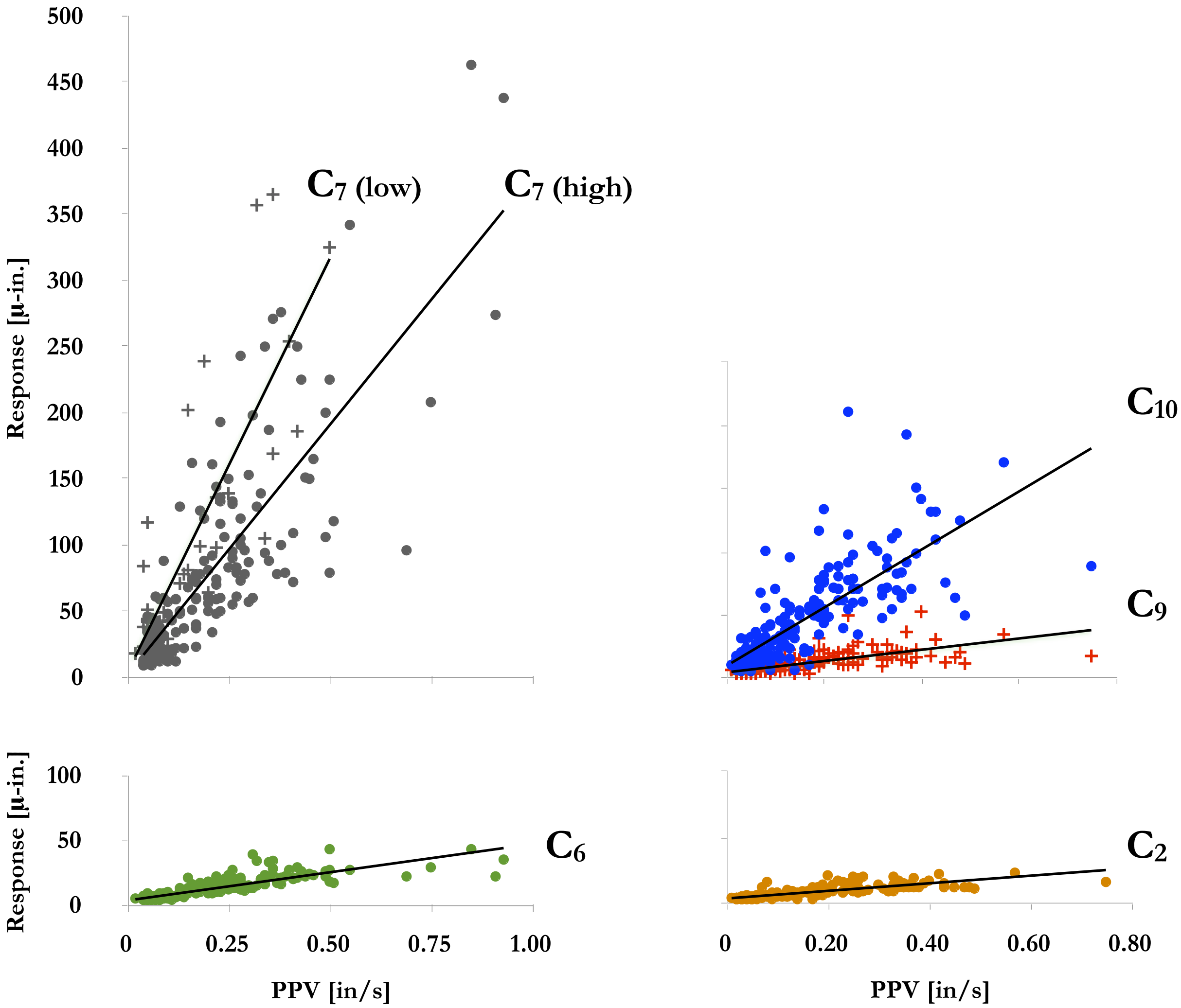

Figure 8 - Comparison of joint and crack response to increasing peak particle velocity in the direction of the wall containing the crack showing that cracks are the most responsive positions of those instrumented.

APPENDIX - Joint Response to Thunder

The uncracked joint and panel also respond to events like lightning strikes that cause a forceful air overpressure. In Figure A-1 below, the drywall joint responds 282 μ-in, much more than during any blast. Also, note that the air overpressure from the thunder clap (0.01 psi) is ten times greater than any blast in the study period.

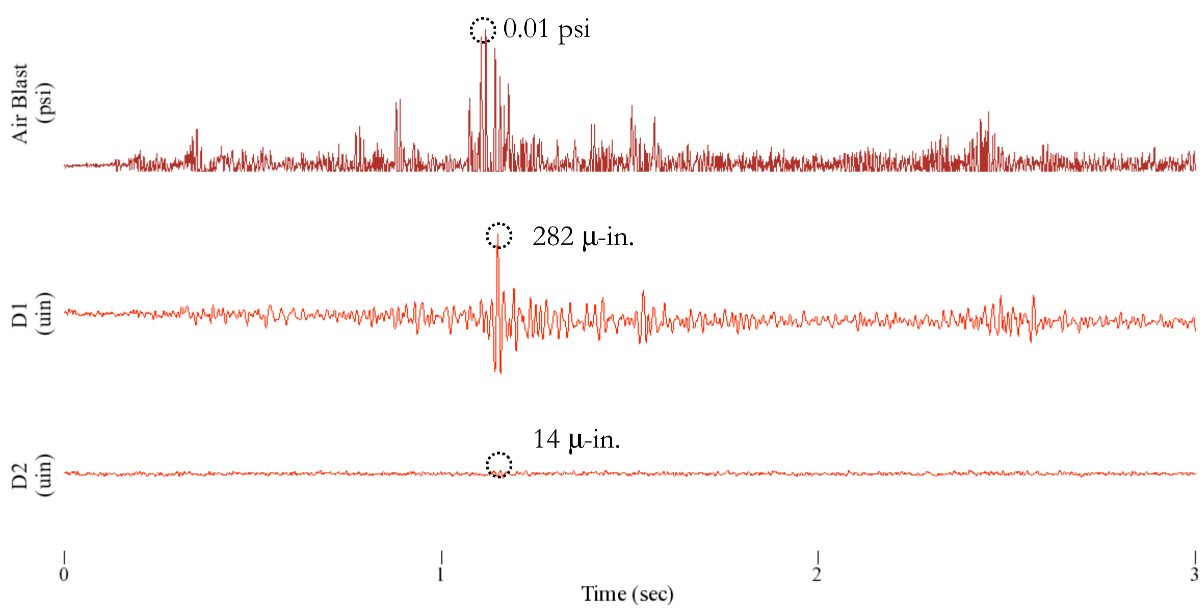

Figure A-1 - Response time histories during a thunder event on September 5th, 2009. The cracks respond directly to the very large air overpressure.