

RESPONSE OF UN-CRACKED DRYWALL JOINTS AND SHEETS TO BLAST VIBRATION AND WEATHER

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ABSTRACT

Cracking is one of the concerns cited by owners of structures adjacent to construction or mine blasting. During the past decade a large number of measurements have documented the low level of crack response produced by typical, ground motions compared to those produced by climatological effects. These data support the observation that there is a level below which ground motions do not cause even cosmetic cracking. As with all new findings, these crack response measurements need to be thoroughly investigated for all possible alternative interpretations. Among these alternatives is that uncracked locations are more affected than cracked locations. This paper presents measurements to shed light on the influence of existing cracks and the response of uncracked, but weak locations. Blast and weather induced responses of cracked and uncracked areas of gypsum wall board are compared in two structures: one near a surface coal mine in Indiana, the other near a limestone quarry in Florida. The ground motions that excited one of the structures were unusual in that the dominant excitation frequencies of 5 Hz were near the structure's natural frequency and amplitudes exceeded 0.7 ips (18mm/s).

INTRODUCTION

Concerns about crack response measurements

Concern has been expressed about the evidence provided by crack measurements that support the observation that there is a level below which vibrations have no potential to induce cosmetic cracks. Two of these concerns will be addressed herein: 1) cracks are not locations of current maximum sensitivity and uncracked locations may be more sensitive to vibration, and 2) there are critical excitation motions that can maximize response that are not included in the data.

These concerns have arisen because of several coalescing points of view. First there is the need to ensure that all critical factors have been included in the crack response measurements. 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.

Consider first the concern of most sensitive 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 uncracked locations. This paper will explore two case histories that involve measurement of the response of multiple, weak but uncracked 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 (1/2 in) of gypsum encapsulated 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 unjointed locations on drywall sheets (basically the null response) will also be compared. Both of 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 led 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 Indiana house, was subjected to such low frequency, 5 Hz, 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 cracked and uncracked 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.

1. RESPONSE OF UNCRACKED, WEAK SECTIONS OF WALLS

Change in distance across a weakness is an index of possible crack development

Response of uncracked sections was obtained with localized measurement of micrometer changes in distances between a sensor and its target (hereinafter called displacement) when mounted across weaknesses in walls. Displacement across weaknesses is proportional to strains in the weakness. These displacements were measured with the same sensors as employed with the Autonomous Crack Measurement [ACM] system (Dowding, 2008). When placed across a crack they measure change in crack width as discussed below, and when placed across an uncracked weakness, they measure displacements and thus strains across that weakness or material. Thus the same sensor can be employed to study on comparable basis localized displacements or responses across both uncracked weakness and cracks.

ACM systems measure the displacement perpendicular to the crack, or in this case a weakness, which is an index for the potential for crack extension, or in this case crack development. The logic of ACM system 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. If the wedge is backed out, the crack would decline in width, but still respond to small movements of the wedge. Only when the wedge is advanced beyond its farthest penetration (or the split widened beyond maximum past width) will the wood split advance. Thus comparing changes in crack width (or distance between sensor and target- i.e. displacement) provides a comparison of the potential for crack extension (or in this case crack appearance).

Choice of uncracked wall sections for measurement

Joints between gypsum dry wall sheets were chosen for measurement because they are the weakest sections of dry wall installations. Gypsum dry wall is the dominant interior wall covering in the United States, and is affixed to the structure by nailing/screwing $\frac{1}{2}$ to $\frac{3}{4}$ inch thick, 4 ft by 8 (or 12) ft sheets to the frame wall. Joints between these sheets are connected with a paper tape, which is in turn covered with a thin coating of plaster. These joints are the vertical and horizontal white stripes in the photograph in the middle left in **Figure 2**.

The plaster coated – paper tape joints are by construction weaker than the gypsum wall board. The joints are constructed – in place -- of thin craft paper covered with about $\frac{1}{8}$ inch (3 mm) of plaster. The manufactured sheets are a three layer sandwich of ~ 2mm of paper – 8 to 12 mm of gypsum – and ~ 2 mm of paper. They have to be strong enough and flexible enough to withstand large vibrations during transport as well as distortion caused by irregular lifting.

In addition to measuring response of the uncracked tape joints, response of the drywall sheets themselves was measured to provide a baseline comparison. This baseline response is that of the paper-gypsum-paper sandwich and the metallic gauge. It is similar to the null gauge response that is reported in many of the cases included in the 2008 compilation of crack response measurements (Dowding, 2008).

House and Crack Descriptions and Vibration Environment

Measurements described herein were obtained in two houses whose photographs and floor plans are shown in **Figure 1**; one in Blanford, Indiana and the other near Naples, Florida. Two uncracked drywall joints and a cracked drywall joint in the living room of the Indiana house were instrumented for comparison. Multiple sections of the house shown in the photograph were built over a period of 10's of 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. One drywall joint in the garage ceiling of the Florida house was instrumented for this study. The Florida house 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).

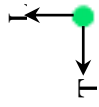
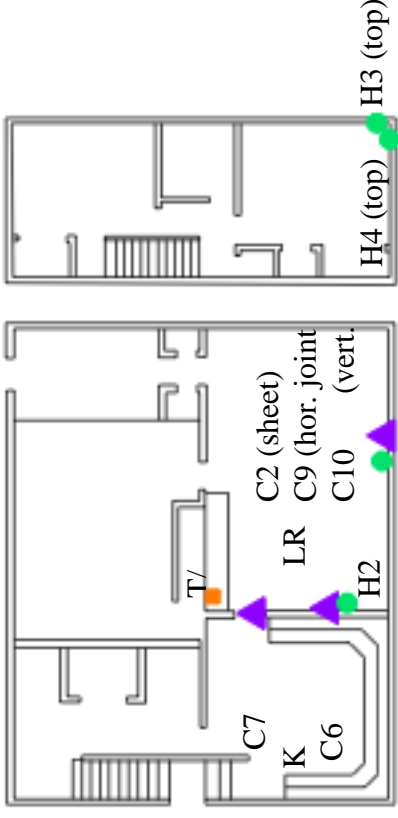
Context (top) and details (bottom) of the instrument installations are shown in **Figure 2** with those for the Indiana house on the left; Florida house on the right. The living room walls in the Indiana house contain the instrumented dry wall joints as shown in the drawing and center photograph. Horizontal and vertical un-cracked dry wall joints are C9 and C10. Uncracked locations near the centers of the drywall sheets are C2 and C6. Drywall joint crack, C7, shown in the bottom right most photograph, is at the doorway (adjacent to C6) between the living room and the kitchen. This crack is not fully extended, and did not extend during the observation period. Out-of-plane, mid-wall motions were measured with velocity transducers as shown in the bottom left photograph.

Similar information for the instrumented garage ceiling drywall joint in the Florida house is shown on the right of **Figure 2**. Sensor D1 spans the joint and D2 is nearby on the full section drywall. They are installed on the attic, upper, or uninhabited side of the garage ceiling as can be seen in the center photograph. As with the wall measurements, out-of-plane ceiling responses were measured with a velocity gauge as shown in the middle photograph.

Both structures are located near surface mines (Indiana: coal and Florida: limestone), which require blasting. A typical blast, 2000 feet (610 meters) from the Indiana house, involved 54, 100 ft (30 m) deep holes arranged in six rows (in a direction radial to the house). Each hole was loaded with 675 lbs (306 kg) of explosive with four decks and thus ~170 lbs of explosive per delay. Such a shot would produce ground motions with a peak particle velocity of 0.14 ips to 0.9 ips (3.5 mm/s to 23 mm/s) and a dominant frequency of 6 to 30 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 (1.27 mm/s to 4.6 mm/s) with dominant frequencies between 5 and 33 Hz.

Comparison of Climatological and Vibratory Responses

Figure 3 compares four months of responses of the 3 uncracked (C9,C10 & D1) and one cracked (C7) drywall joints, and 3 uncracked drywall sheets (C2,C6 & D2) to temperature and humidity-induced, climatological effects. Time histories of Indiana responses [C] are graphed on the left and Florida time histories [D] are 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



- ▲ Displacement
- Other
- Velocity

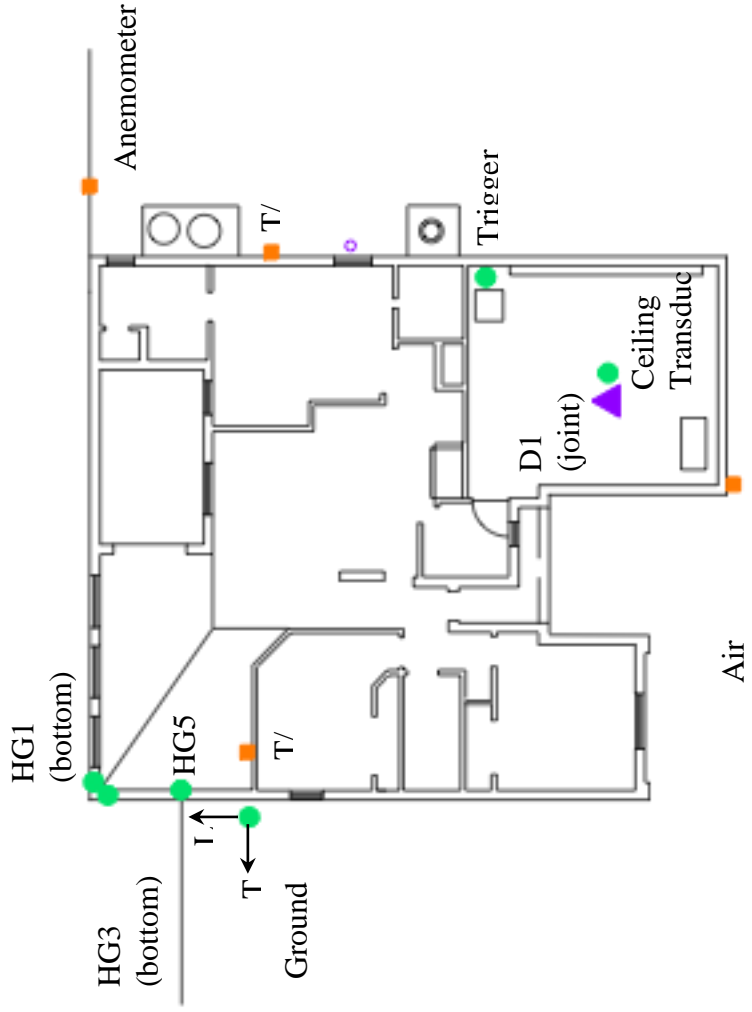


Figure 1 - Photographs and plan views of test structures. Top: Blanford, IN Bottom: Naples, FL

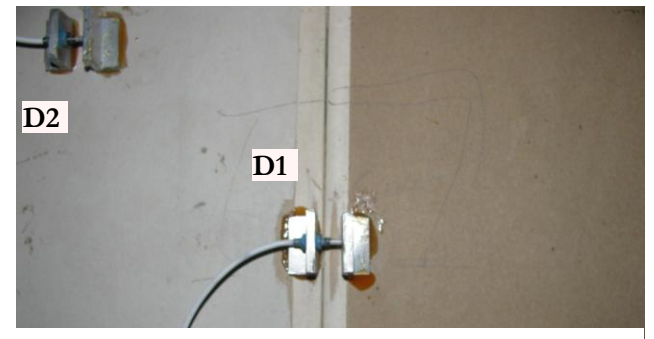
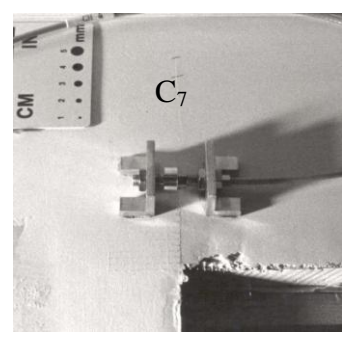
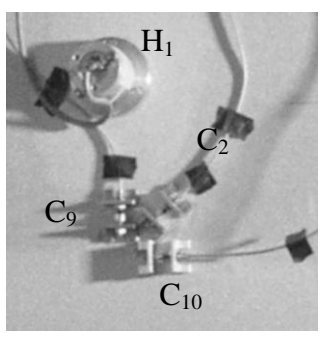
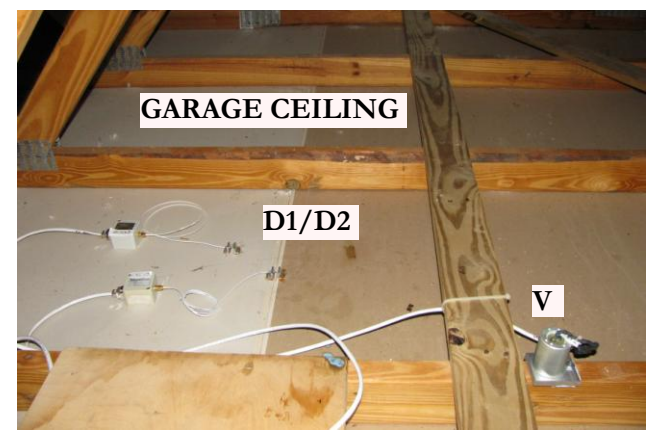
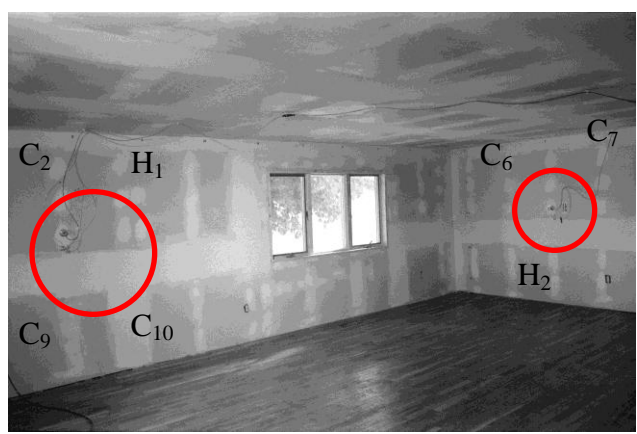
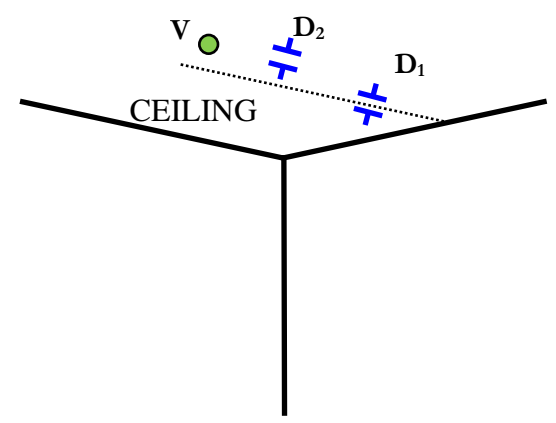
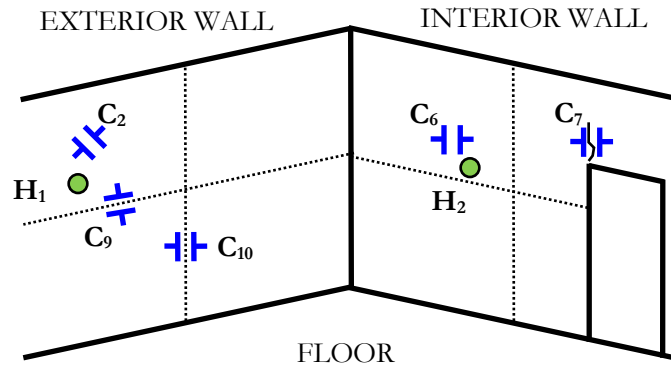


Figure 2 - Installation details for the Indiana (left) and Florida houses (right). Wall, joint and sensor orientation are illustrated on the top row. Photographs showing context are in the middle row and with detail on the bottom. C9&10&D1 cross un-cracked drywall joints; C7 crosses a cracked drywall joint; and C2&6&D2 are located on drywall sheets.

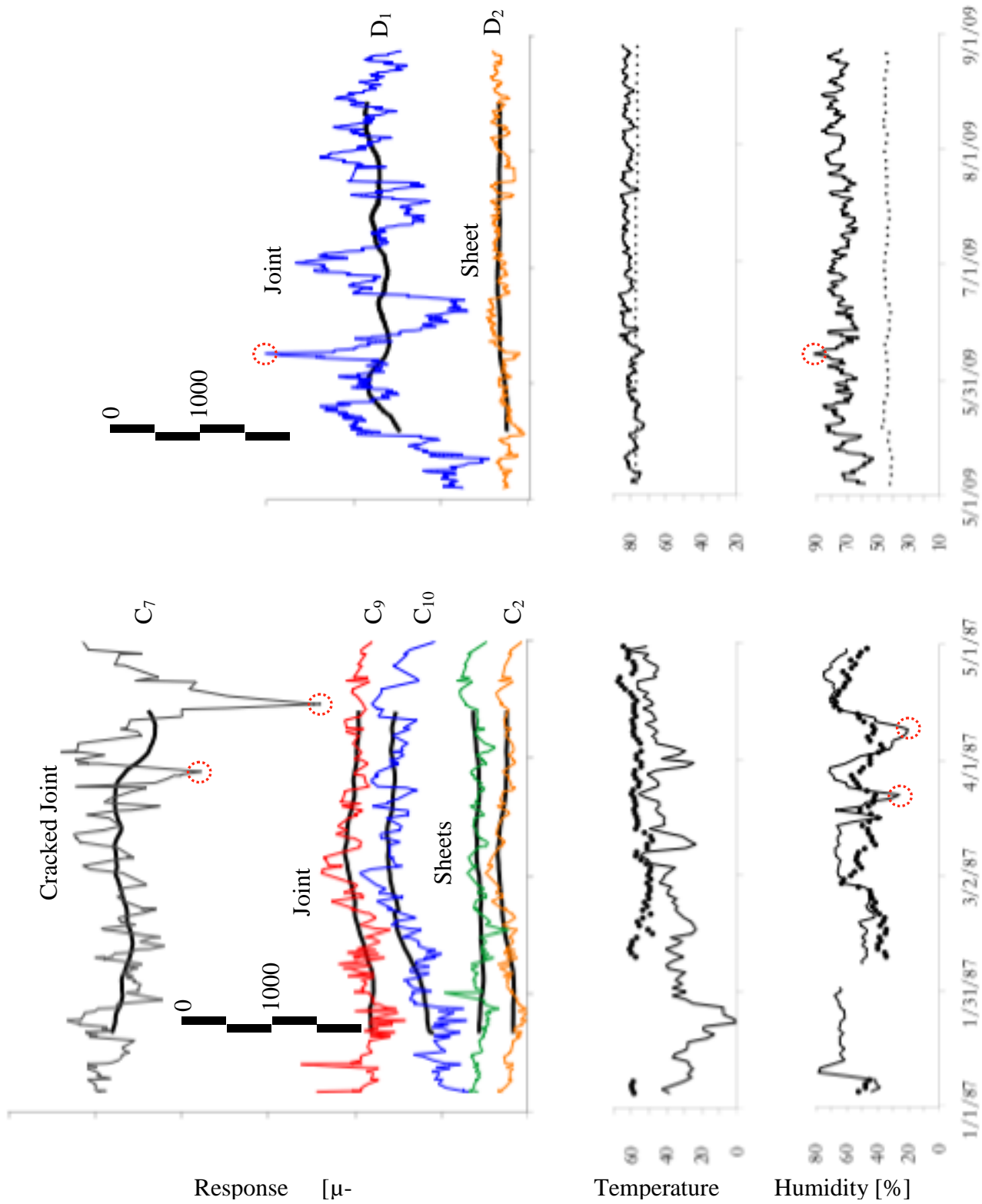


Figure 3 - Comparison of four months of climatologically induced responses of Indiana (left) and Florida (right) joints. 30-day central moving average shown with the thick line. Temperature and Humidity are plotted on the bottom (dotted=inside, solid=outside), and joint responses are plotted on the top with common time and response scales for comparison.

the top for comparison.

Responses of the drywall sheets (C2,C6) 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 uncracked mounting material to changes in temperature and humidity. Comparison to the crack response (C7) shows that dry wall sheet response is so small as to be inconsequential compared to the crack response. It is also small compared to the response of the paper tape joints.

Responses to long-term climatological effects of the uncracked, paper-thin (and thus weak) drywall joints (C9, C10) at the Indiana house are less than $1/10^{\text{th}}$ that of the cracked drywall joint (C7). The drywall joint in the Florida garage (D1) is some five times more responsive to climatological effects than are the Indiana joints. This larger response is not totally unexpected as the Florida joint is in the ceiling of an un-moderated garage during the summer. Indiana joints were on an interior wall of a house heated at a constant temperature during the late winter and early spring. Even though larger than that in Indiana, the Florida uncracked joint response was small compared to crack response in the garage. While there was no cracked joint in the garage ceiling of the Florida house for comparison there was a crack in the garage wall at the interface between the door frame and the CMU wall. This cracked interface was five times more responsive than the uncracked Indiana drywall joints (C9&C10) (Meissner et al, 2010). In both cases, significant changes in exterior humidity, marked with circles, seem to drive the largest long-term crack response. It is reasonable for changes in humidity to produce crack and joint response because of the response to changes in humidity of wooden wall frames to which the sheets are attached.

These long-term measurements, spanning some four months, show that uncracked 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 uncracked and cracked dry wall joints for these two houses are shown in **Figure 4**. As before Indiana responses are on the left and Florida's are on the right. Particle velocity time histories of the ground motions that induce the responses are shown at the top and the joint 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 (D1) 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

The relationship between vibratory and climatological response for uncracked wall weakness (dry wall joints) is the same as for cracks as shown by the bar chart comparisons in **Figure 5**. Where climatological response is small, so is vibratory response for both cracked and uncracked joints. Cracking of a joint does not appear to diminish its dynamic response; at least not relative to other uncracked weaknesses such as the joints. Cracked joints are seen to respond more than uncracked 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 is unlikely to be affected significantly by a thin covering.

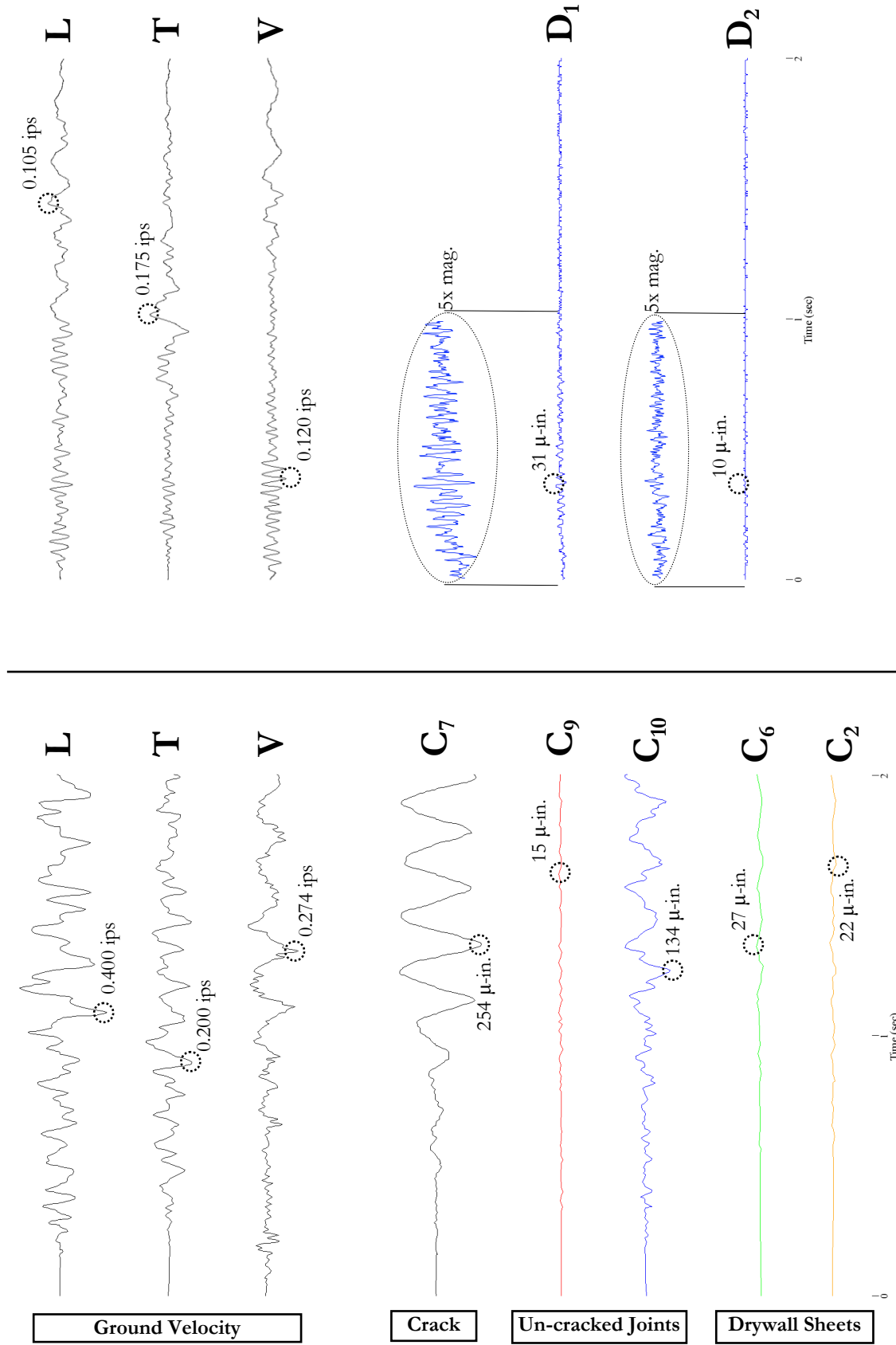


Figure 4 - Comparison of ground motions (top) with joint responses (bottom) showing unusually low excitation frequency of the Indiana ground motions (left) compared to Florida (right). Cracked joint. (1 ips = 25.4 mm/s, 1 μ-in = 0.025 μm)

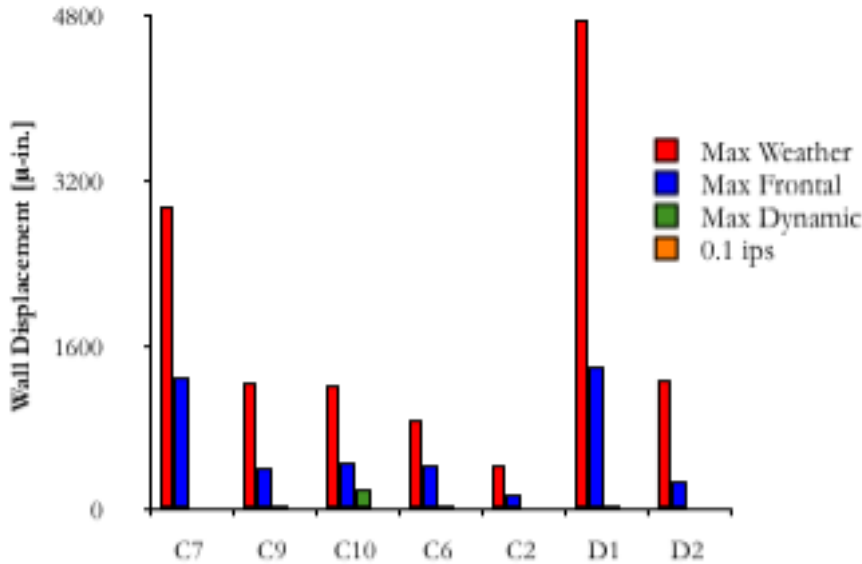


Figure 5 - Bar chart comparison of crack/joint/sheet response induced by weather

cracked (C7) and uncracked (C9,C10) responses for the lowest excitation frequency, 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 with or nearly match the 5 Hz natural frequency of the superstructure demonstrated by the 5 Hz responses of H3 and H4 velocity transducers in the second story as shown in **Figures 4 & 6**. 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. 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. Amplification values in **Table 1** were calculated in two ways: **1)** the OSM Method (Aimone-Martin, et al 2002): as the ratio of the maximum structural velocity divided by the amplitude of the immediately preceding largest particle velocity excitation pulse and **2)** by the response spectrum or structural dynamics method, which employs the entire wave train of the excitation pulse. See Appendices A & B in the web version of this paper at www.itn.northwestern.edu/acm for a detailed explanation. **Figure 6** presents time histories of ground motion, first-story wall out-of-plane (H1 & H2) and top second story superstructure (H3 & H4) velocity responses. These wall and superstructure motions are compared with un-cracked (C10) and cracked (C7) joint responses for shots 10 and 12 that demonstrate some of the following observations. First, amplification values from low peak particle

Figure 6 comparison of the vibration response of C7 to that of H3 and H4, structural velocity response at 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 spanning a drywall joint.

2. LOW FREQUENCY, HIGH AMPLITUDE EXCITATION

Table 1 compares ground motions, structural response and

velocity motions (PPV's) cannot be assumed to be applicable for high PPV's. Second, both of the horizontal components must be considered.

Figure 7 graphically compares responses of the 5 drywall joint locations with the maximum PPV in the direction parallel to the wall of interest. These plots contain more data than **Table 1**, because only 16 events had recorded time histories from which the table was developed. The other responses are tabulated in the 1988 Dowding & Lucole report. They are remarkably consistent and show the same trends that were measured in previous crack-structural response studies that are summarized in Office of Surface Mining reports (Aimone-Martin et al, 2002). Cracks continue to respond more than do uncracked weaknesses as can be seen by the comparison of C7 and C10's sensitivity to PPV as also tabulated in **Table 1**. A steeper slope for C7 implies greater sensitivity. Here the cracked joint sensitivity is approximately 3 times greater than that for the uncracked joint even for low dominant frequency ground motions. These comparisons show in **Figure 7** that even for high PPV (0.4 to 0.9 ips or 10 to 23 mm/s or) and a mix of low (4 to 8 Hz) and higher frequency (9 to 28 Hz) excitation motions, response of the cracked tape joint (C7) is the same as observed for other vibratory environments. Response of C7 follows a relatively linear trend and the sensitivity is similar to that reported by McKenna & Dowding (2004) where they reported slopes of 50 to 1900 compared with approximately 380 and 630 for the two slopes corresponding to C7. When the lowest frequency (4 to 8 Hz) motions were separated for analysis, the sensitivity of the cracked joint increased 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 as shown in the bar charts in **Figure 5**.

The largest crack (C7) response did not occur with the lowest frequency excitation, because the low frequencies were associated with particle velocities below 0.5 ips (12 mm/s). Higher PPV's were generated by shots detonated closer to the test house with the associated higher excitation frequencies, and thus elicited lower structural response.

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: 1) sensitivity of uncracked locations and 2) crack response in low excitation frequency - high particle velocity environments. Responses of the weakest of wall components, the paper-thin joints between drywall sheets were measured and shown to be less than that of cracked joints. Specifically, measurements presented herein show that a cracked joint does not respond less than other uncracked weaknesses in the wall covering to either climatological or vibratory effects. Even in high particle velocity (0.4 to 0.9 ips or 10 to 23 mm/s) and low excitation frequency (5 to 7 Hz) environments cracks continue to respond more than do uncracked weaknesses.

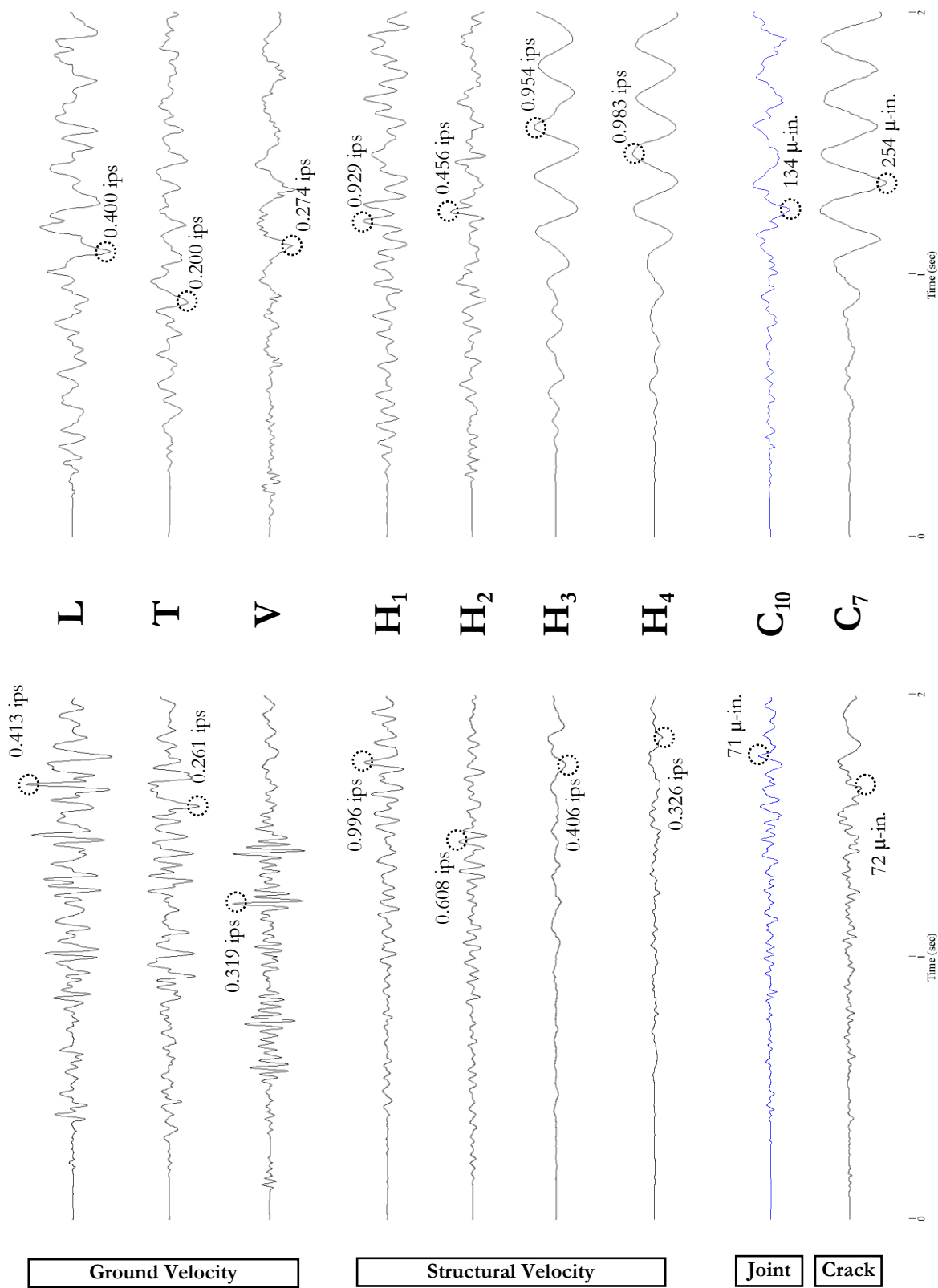


Figure 6 - Time histories of ground motion, structural response, and cracked (C7) and un-cracked drywall joint response (C10). Low frequency excitation show joint response follows the motion of the upper story. 2/23/87 on the left and 4/2/87 on the right. (1 ips = 25.4 mm/s, 1 μ-in = 0.025 μm)

No.	Date	Time	Amplification																				Response [μ -in]			
			Frequency			Peak Velocity [in/s]				Comparative Velocity/Freq [in/s \				Traditional				Dynamics		C ₇	C ₉	C ₁₀				
			L	T	V	L	T	V	H1	H2	H3	H4	L ₁ *	L ₄ *	T ₂ *	T ₃ *	H1	H2	H3				H4	H3	H4	
1	11/18/86	1:44 PM	23	31	42	0.550	0.380	0.398	0.909	0.449	0.361	0.387	0.549\18	0.549\18	0.308\19	0.308\19	1.66	1.46	1.17	0.70				129		
2	11/26/86	2:12 PM	18	13	11	0.130	0.180	0.086	0.438	0.194	0.271	0.187	0.129\19	0.107\13	0.132\15	0.176\12	3.40	1.47	1.54	1.75				39		
3	12/22/86	9:38 AM	5	8	31	0.350	0.300	0.233	0.745	0.777	1.041	0.738	0.352\10	0.352\10	0.251\17	0.298\8	2.12	3.09	3.49	2.10				159		
4	12/27/86	2:58 PM	5	7	6	0.110	0.070	0.079	0.332	0.120	0.242	0.387	0.085\20	0.110\8	0.052\18	0.068\7	3.93	2.32	3.56	3.52				43		
5	12/30/86	5:03 PM	21	7	16	0.187	0.110	0.058	0.487	0.293	0.390	0.326	0.187\19	0.187\19	0.105\17	0.092\20	2.60	2.79	4.24	1.74				39		
6	1/1/87	9:03 AM	21	21	25	0.760	0.410	0.432	2.847	0.717	0.629	0.703	0.759\20	0.759\20	0.410\19	0.410\19	3.75	1.75	1.53	0.93				118		
7	1/5/87	10:48 AM	11	15	25	0.490	0.250	0.206	0.722	0.558	0.374	0.432	0.491\10	0.491\10	0.313\23	0.243\14	1.47	1.78	1.54	0.88				74		
8	1/5/87	2:13 PM	11	12	23	0.180	0.240	0.082	0.339	0.328	0.626	0.284	0.172\11	0.181\10	0.244\12	0.244\12	1.97	1.34	2.57	1.57				68		
9	2/17/87	2:56 PM	25	16	5	0.210	0.120	0.069	0.542	0.261	0.251	0.455	0.207\9	0.121\5	0.122\15	0.122\15	2.62	2.14	2.06	3.77				92	10	37
10	2/23/87	2:47 PM	28	9	36	0.410	0.260	0.319	0.996	0.608	0.406	0.326	0.413\26	0.413\26	0.225\18	0.261\13	2.41	2.70	1.56	0.79	4.23	2.78		72	26	71
11	3/23/87	1:57 PM	5	7	7	0.130	0.070	0.048	0.168	0.106	0.409	0.332	0.118\10	0.120\5	0.058\7	0.074\6	1.42	1.84	5.53	2.77				71	7	21
12	4/2/87	2:40 PM	6	9	5	0.400	0.200	0.274	0.929	0.456	0.954	0.980	0.400\6	0.400\6	0.200\7	0.200\7	2.32	2.28	4.77	2.46	3.56	2.84		254	15	134
13	4/4/87	2:55 PM	7	7	28	0.360	0.260	0.326	0.848	0.791	0.783	0.858	0.230\12	0.358\8	0.261\13	0.261\13	3.69	3.03	3.00	2.40				169	13	79
14	4/20/87	10:32 AM	21	17	31	0.850	0.570	0.408	3.176	0.858	1.051	0.722	0.852\23	0.852\23	0.329\10	0.572\14	3.73	2.61	1.84	0.85	2.86	4.02		463	35	171
15	4/20/87	10:34 AM	19	21	12	0.930	0.250	0.274	2.966	0.406	0.771	0.800	0.930\19	0.930\19	0.254\20	0.254\20	3.19	1.60	3.04	0.86	3.57	3.25		438	50	211
16	5/1/87	9:12 AM	6	9	31	0.500	0.420	0.309	0.883	1.204	1.831	1.183	0.497\6	0.497\6	0.423\8	0.423\8	1.78	2.85	4.33	2.38	3.33	3.34		325	18	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.

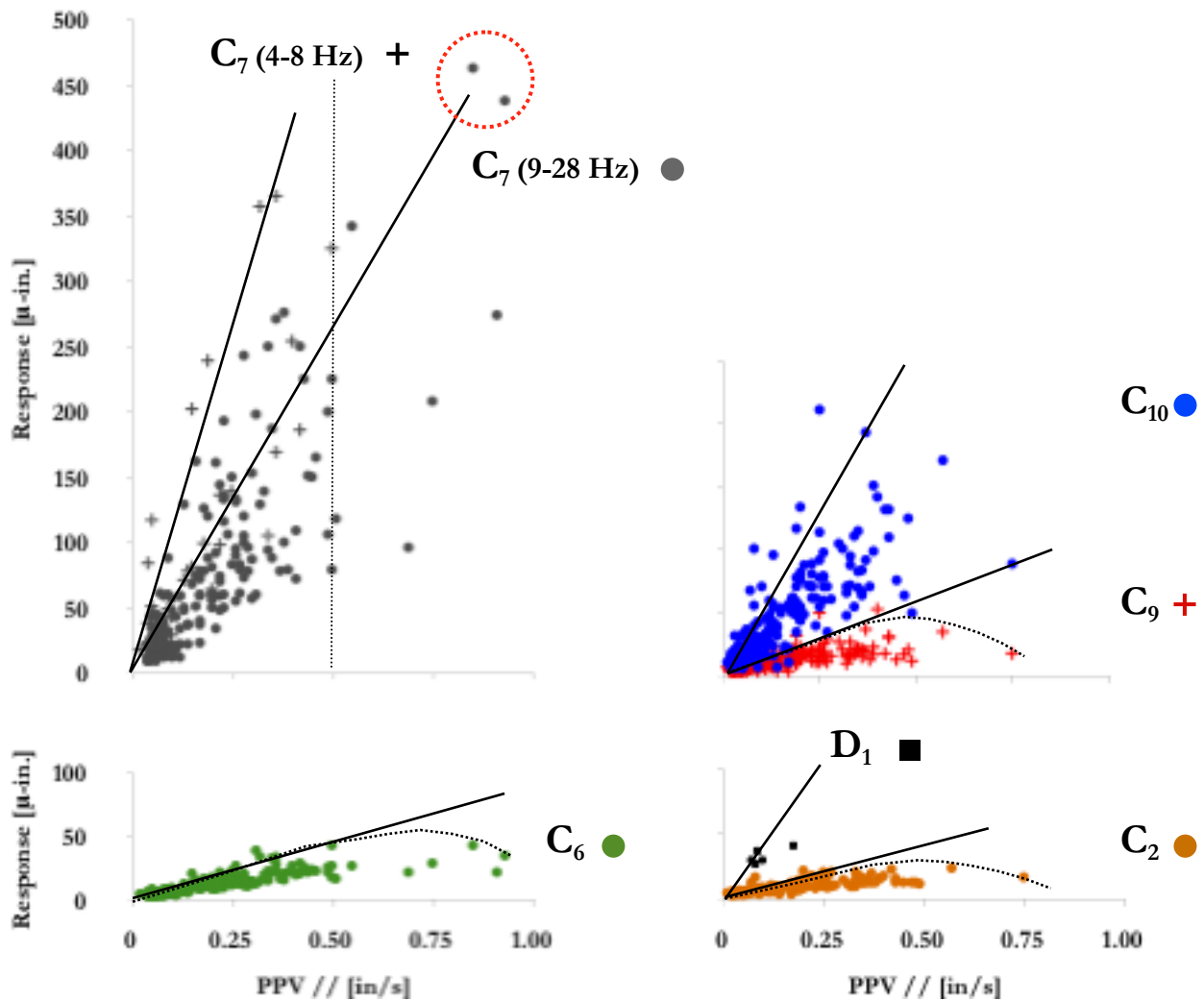


Figure 7 - Comparison of uncracked joint (C10,C9) on the right with crack (C7) response on the left to increasing peak particle velocity in the direction of the wall containing the joint/crack. Crack C7 is the most responsive or sensitive (has the steepest slope) of those instrumented. Sensitivity of drywall sheet (C2,C6) is the smallest as expected. Sensitivity of the Florida uncracked joint (D1) is similar to that of C10 for Indiana. (1 ips = 25.4 mm/s, 1 μ-in = 0.025 μm)

ACKNOWLEDGEMENTS

The authors are indebted to all those who have contributed to this synthesis of two separate projects, one which occurred several decades ago. The structures were/are owned by two resource companies, Peabody Coal Co. and Jones Mining and without their cooperation this project would not have been possible. Instruments were installed by Digital Vibration Incorporated and field engineers of the Infrastructure Technology Institute [ITI] of Northwestern University: Dave Kosnik, Mat Kotowsky, and Dan Marron. We are also grateful for the financial support of ITI for this project through its block grant from the U.S. Department of Transportation to develop and deploy new instrumentation to construct and maintain the transportation infrastructure.

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