Vibratory and climatologically induced crack response: effects of uncracked weaknesses, low frequency excitation, & period of vulnerability

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ABSTRACT: Cracking is a concern in structures adjacent to construction or blasting sites. Studies over the past decade show the insignificance of compliant-level ground motions relative to climatological effects, suggesting that there is a floor below which ground motions do not cause cracking. There are three alternative interpretations to these findings that are often raised. First, uncracked locations are more affected than cracked locations. Second, not enough cases of low-frequency, high-amplitude motions are documented. Third, a structure can become vulnerable to cosmetic cracking from small dynamic events. This paper sheds light on responses of uncracked weaknesses, high-amplitude, low-frequency motions and probabilities of small events during periods of vulnerability. Crack responses are compared in two structures. Uncracked weaknesses in drywall coverings did not respond differently to climatological or vibratory ground motions. Field measurements demonstrate that occupant-induced events are more likely than blast events to occur during the period of vulnerability or exposure.

INTRODUCTION

Concerns about crack response measurements

Concern has been expressed about the conclusion that crack measurements provide further evidence that there is a level below which vibrations have no potential to induce cosmetic cracks. These concerns involve at least the following assertions 1) cracks are not locations of current maximum strain and uncracked 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 strain conditions in structures that render them vulnerable. 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. These concerns will be addressed briefly and then they will be explored more thoroughly with data.

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 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 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.

The third concern is that of the proximate cause or "the straw that breaks the camel's back. 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 effects caused by the 1) historically largest extreme weather event (e.g. a drought that occurs in seven to ten year cycles), 2) largest seasonal response (e.g. high seasonal heating, cooling, or groundwater induced response), 3) largest weather front response (e.g. long period of high humidity), 4) largest daily temperature response (e.g. a few hours in the afternoon sun), and 5) high 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. And of course, there could be no other effect that could have occurred at this brief moment of vulnerability. Blast induced crack response will be compared with occupant induced response to show that occupant induced crack response is more probable.

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 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). The ACM transducers are capable of measuring micrometer changes in the distance between the sensor and a target. When placed across a crack they measure change in crack width as discussed below. However when placed across an uncracked weakness, they measure displacements across that weakness or material. Whether placed across a weakness or an existing crack, changes in displacement between the sensor and target can be compared directly. Thus the same system can be employed to study on comparable basis localized displacements (or strain) 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 as shown in Figure 1. 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).

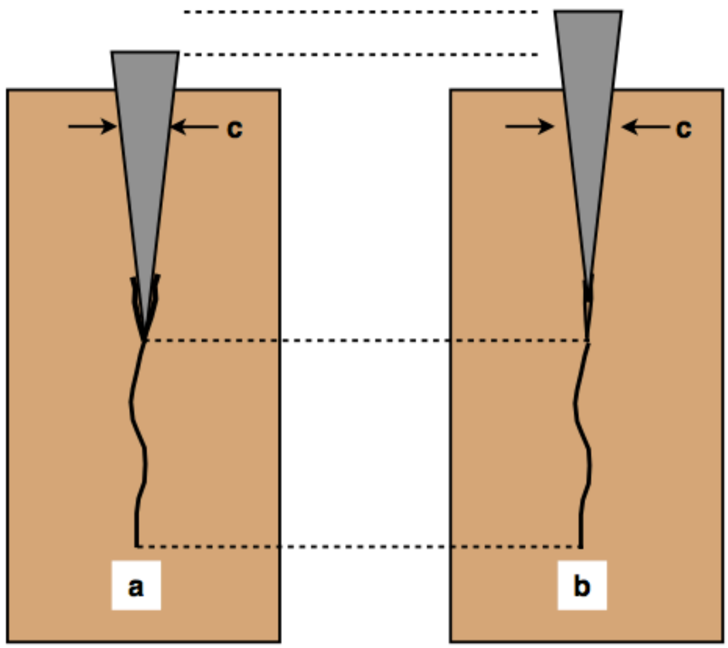

Figure 1. Wedge splitting wood analogy with "a" the deepest penetration (widest opening at c) and "b" with wedge backed out (narrower opening at c).

The wood splitting analogy is experimentally confirmed for fracture of cement paste as shown in Figure 2. Crack mouth opening (COD in the figure) 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 micro-meters), the crack extends from 1.4 to 2.1 inches (36 to 53 millimeters). 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, crack width (or in this case displacement between sensor and target across a weakness) must increase beyond its previous maximum for the crack to extend (or initiate). It is unlikely that measurement in a structure under observation would begin at the previous maximum width. Thus the question then becomes, "what outside effects produce the largest change in crack width (or in this case displacement across a weakness)?" Those changes are the most likely to extend cracks (or in this case initiate a crack). It also stands to reason that cyclic response at widths smaller than the maximum will not extend the crack (or in this case initiate a crack).

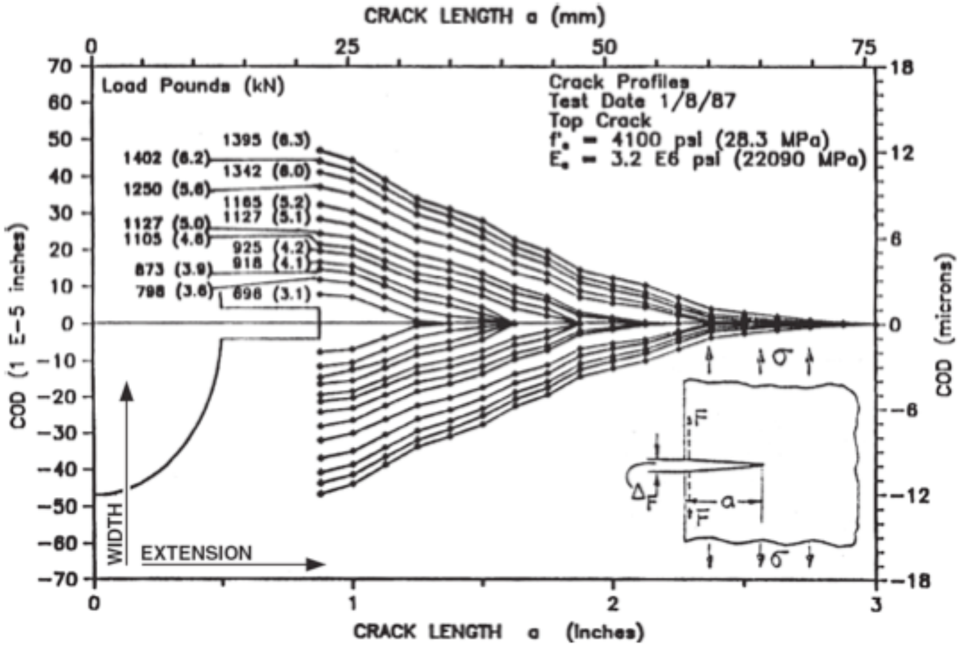

Figure 2. Experimental observation that cracks extend as their width increases forms the foundation of fracture mechanics as well as the ACM measurement approach. Special visualization techniques were employed to measure the extension of a crack (marked by the rightward extension of the “>”) as its width (COD or “crack opening displacement) increases (marked by the increasing width of the mouth of the “>”) on the left. (Miller, 1989).

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 ½ to ¾ 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 3.

The plaster coated – paper tape joints are by construction weaker than the gypsum wallboard. The joints are constructed – in place -- of thin craft paper covered with about 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).

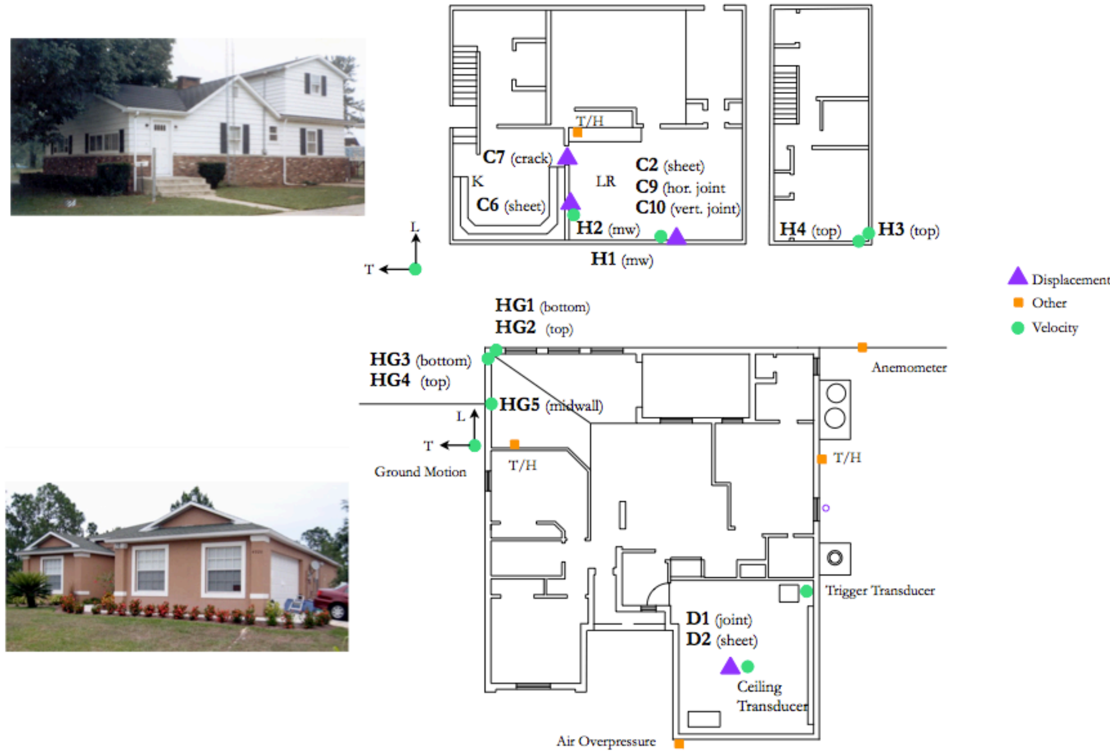

Figure 3. Photographs and plan views of test structures. Top: Blanford, IN. Bottom: Naples, FL.

House and Crack Descriptions and Vibration Environment

Measurements described herein were obtained in two houses whose photographs and floor plans are shown in Figure 3; one in Blanford, Indiana and the other near Naples, Florida. The Indiana house contains two, instrumented, uncracked drywall joints and a cracked drywall joint 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.

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 instrument installations are shown in Figure 4 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 uncracked 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 4. 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 (306 kg) lbs 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.

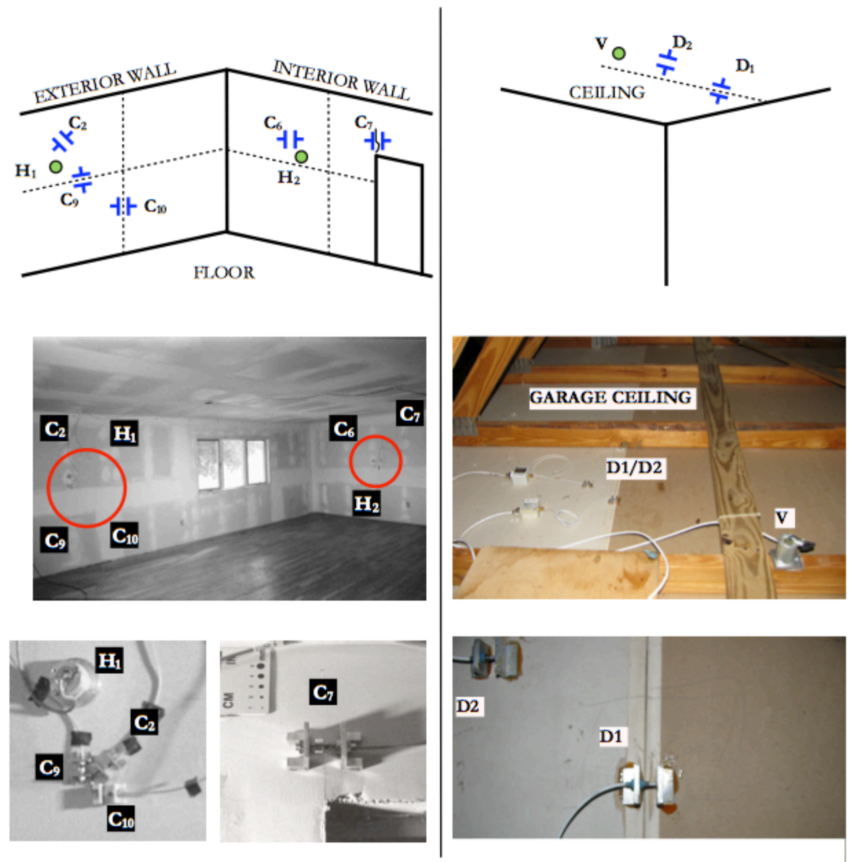

Figure 4. Installation details for the Indiana (left) and Florida houses (right). Wall, joint and sensor orientation are illustrated on the top row. Photographs showing context are in the middle row and with detail on the bottom. C9&10&D1 cross uncracked drywall joints; C7 crosses a cracked drywall joint; and C2&6&D2 are located on drywall sheets.

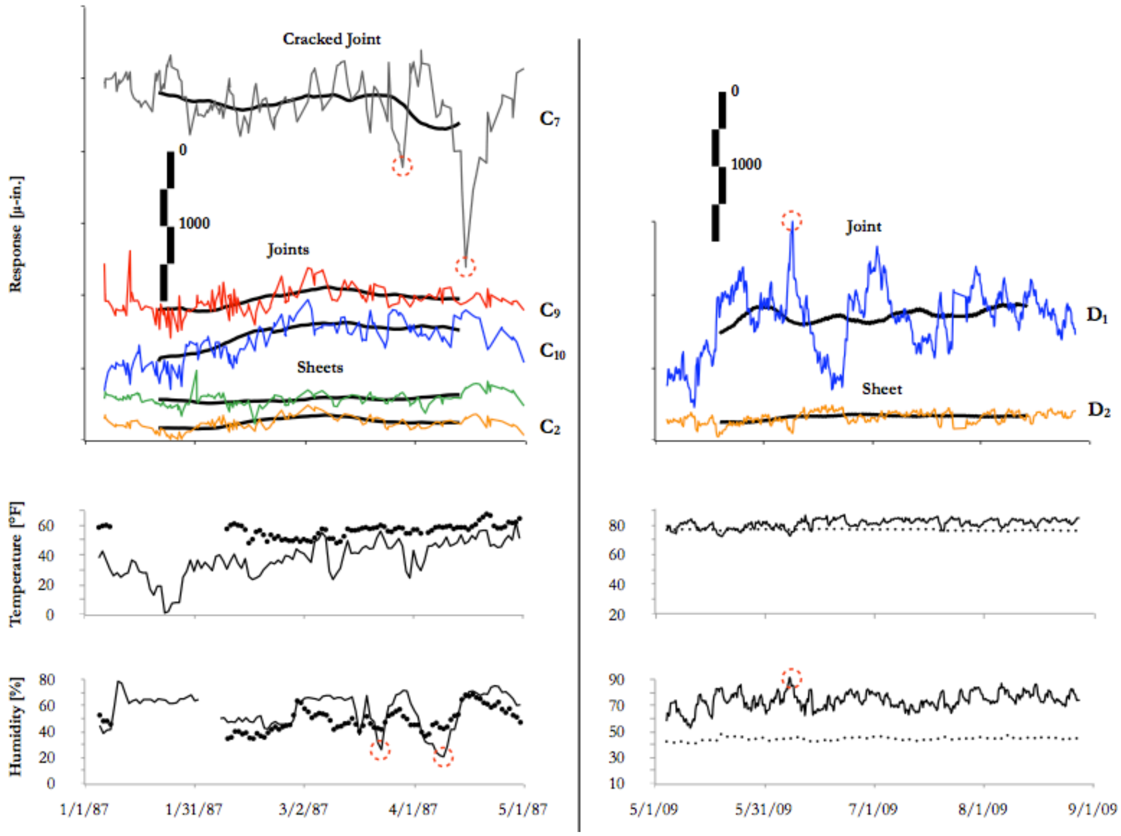

Figure 5. Comparison of four months of climatologically induced responses of Indiana (left) and Florida (right) joints. 30-day central moving average shown with the thick line. Temperature and Humidity are plotted on the bottom (dotted=inside, solid=outside), and joint responses are plotted on the top with common time and response scales for comparison.

Comparison of Climatological and Vibratory Responses

Figure 5 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 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 1/10th 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 joint is in the ceiling of an un-moderated garage during the summer in Florida. 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 6. 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 (see Appendix A for thunder response). The low frequency ground motions at the Indiana house are evident. Their significance will be discussed in the next section.

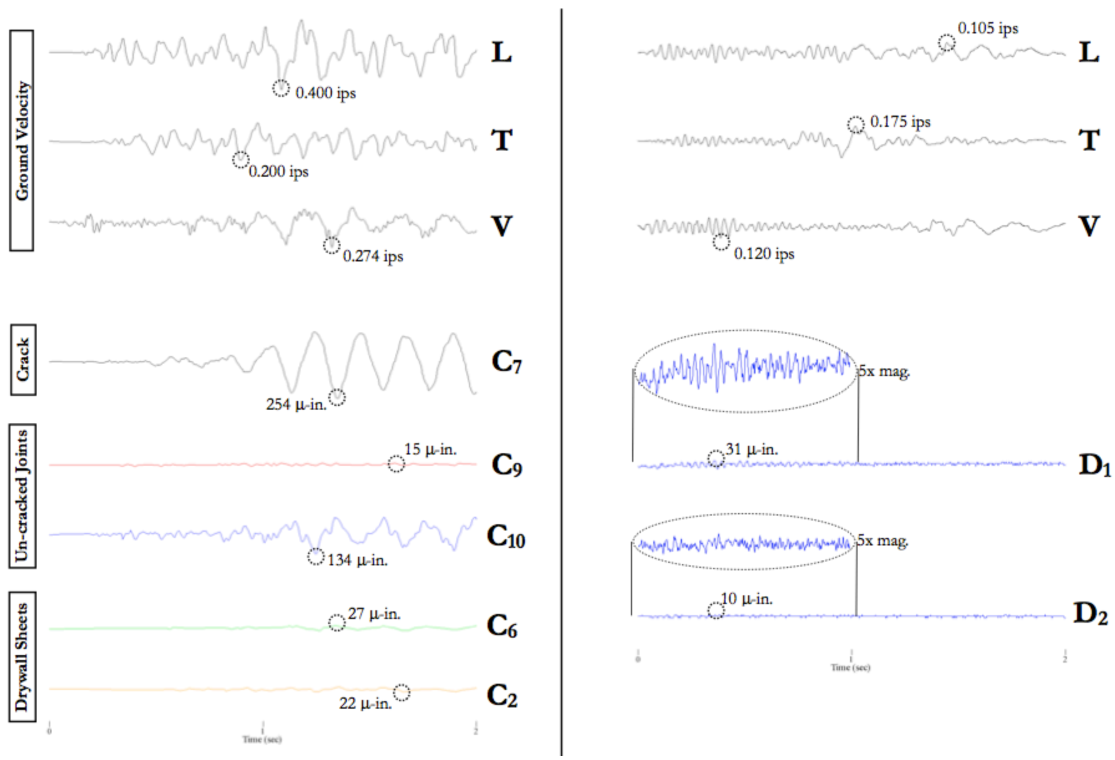

Figure 6. Comparison of ground motions (top) with joint responses (bottom) showing unusually low excitation frequency of the Indiana ground motions (left) compared to Florida (right). Cracked joint responds more than most sensitive uncracked joint.

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 7. 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.

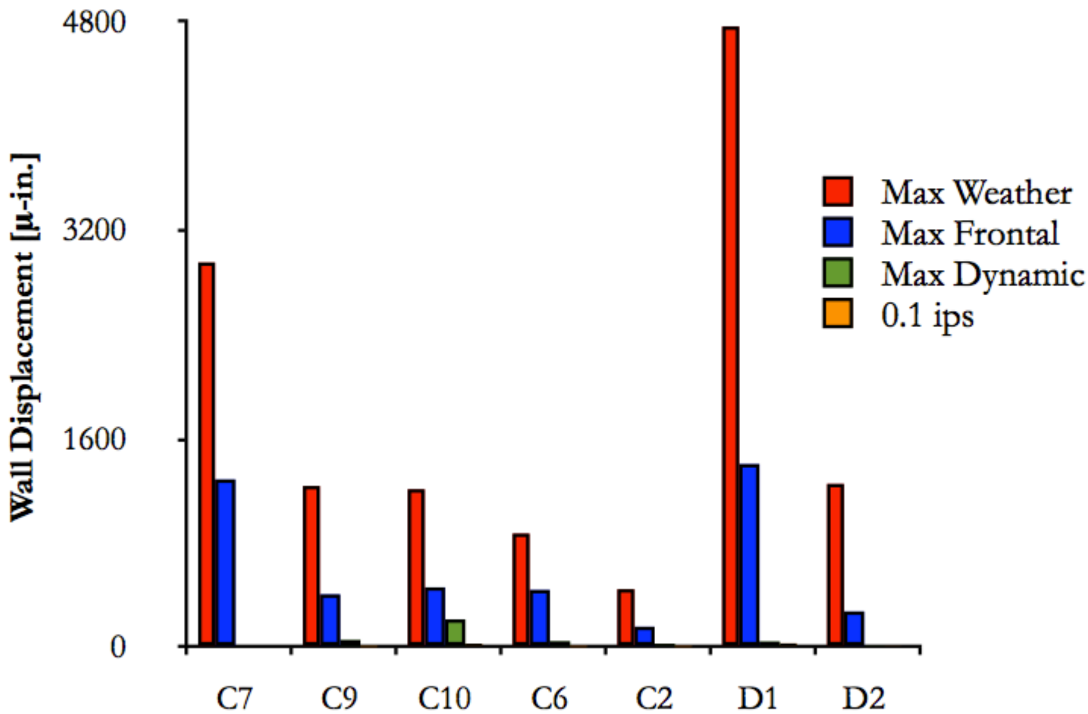

Figure 7. Bar chart comparison of crack/joint/sheet response induced by weather and blast events. Weather response is at least an order of magnitude greater than dynamic response.

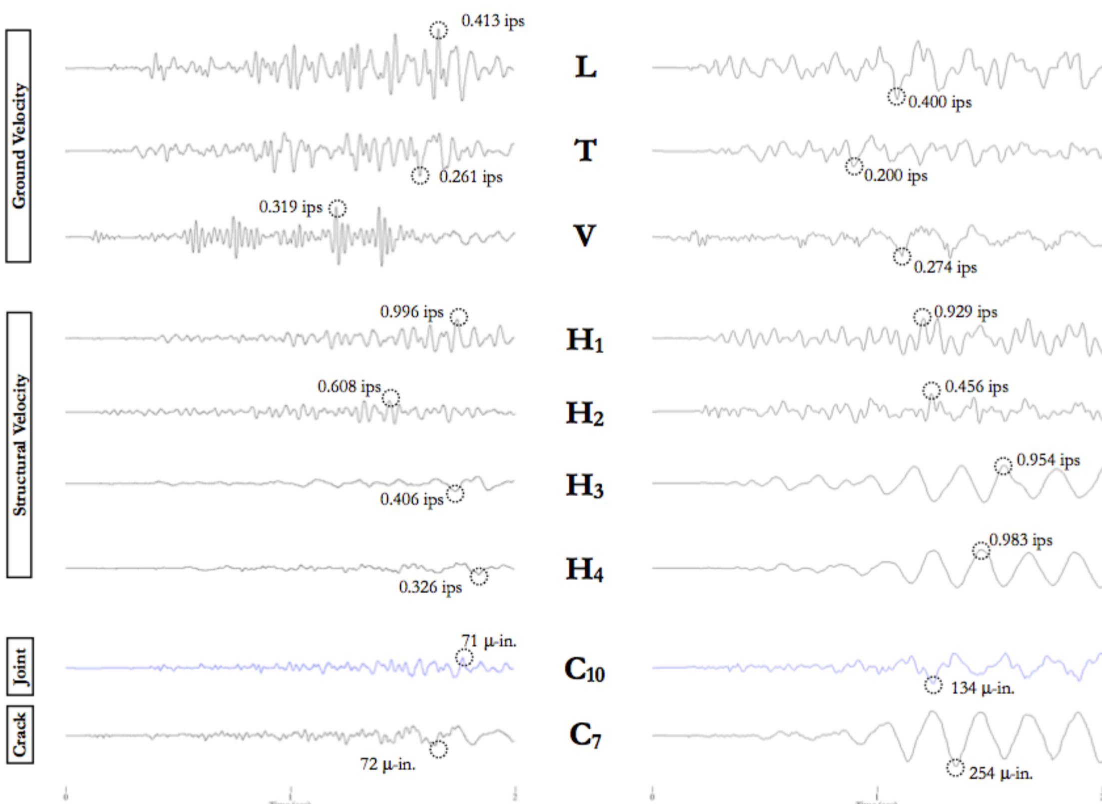

Figure 8. Time histories of ground motion, structural response, and cracked (C7) and uncracked drywall joint response (C10). Low frequency excitation show joint response follows the motion of the upper story. 2/23/87 on the left and 4/2/87 on the right.

Comparison of the vibration response of C7 to that of H3 and H4, structural velocity response at the second story (shown in Figure 8), 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 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 7 & 8. 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.iti.northwestern.edu/acm for a detailed explanation. Figure 8 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 uncracked (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 velocity motions (PPV's) cannot be assumed to be applicable for high PPV's. Second, both of the horizontal components must be considered.

Figure 9 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 9 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 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 Dowding & McKenna (2005) 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 cracked joint sensitivity increased slightly. There was no discernible difference in sensitivity of the uncracked joints between low and higher frequency excitation.

			Frequency			Peak Velocity [in/s]							Comparative Velocity/Freq [in/s \				Amplification: Traditional				Amplification: Dynamics		Response [μ-in]		
No.	Date	Time	L	T	V	L	T	V	H1	H2	H3	H4	L_1*	L_4*	T_2*	T_3*	H1	H2	H3	H4	H3	H4	C_7	C_9	C_{10}
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 join and crack response that shows, high amplification values calculated from low amplitude, single pulses cannot necessarily be employed with higher particle velocities.

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 6.

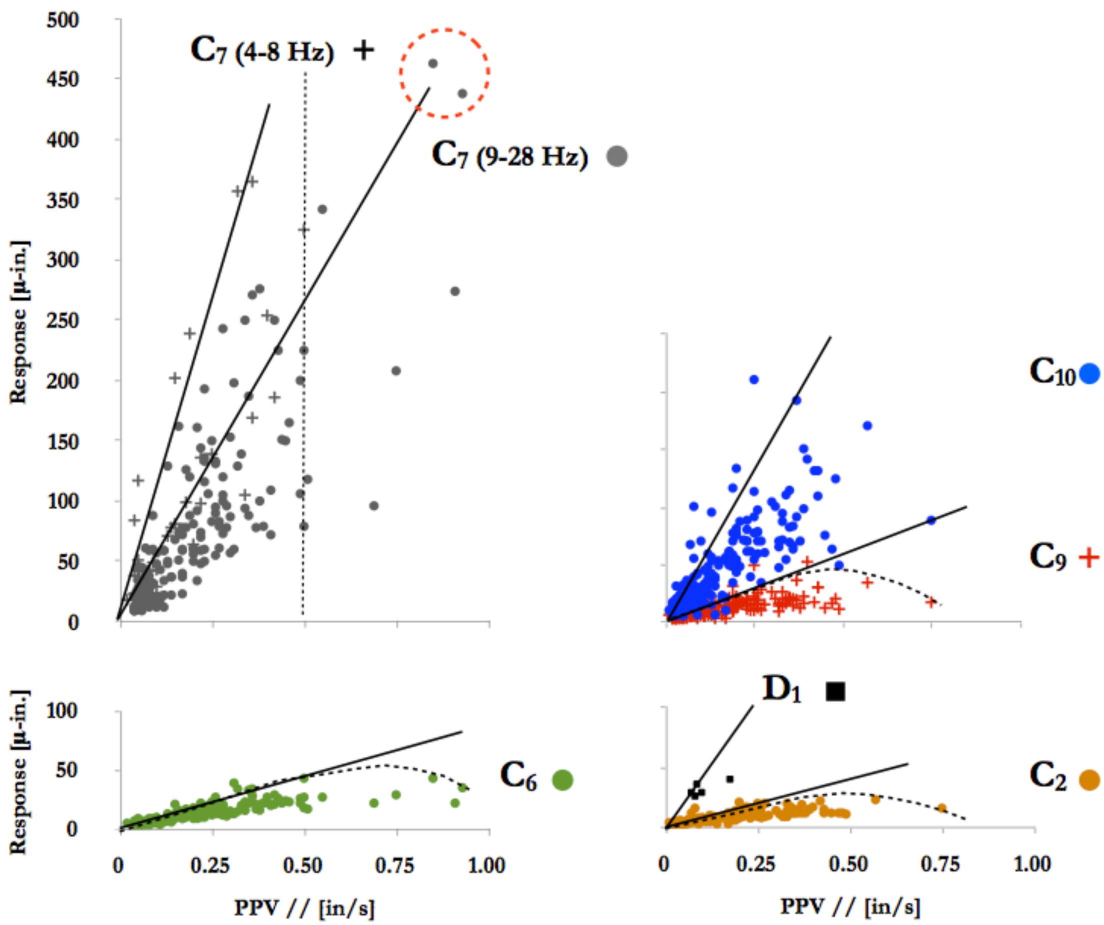

Figure 9. Comparison of uncracked joint (C10,C9) on the right with crack (C7) response on the left to increasing peak particle velocity in the direction of the wall containing the joint/crack. Crack C7 is the most responsive or sensitive (has the steepest slope) of those instrumented. Sensitivity of drywall sheet (C2,C6) is the smallest as expected. Sensitivity of the Florida uncracked joint (D1) is similar to that of C10 for Indiana.

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). In order to generate higher PPV's, the shots had to be detonated closer to the test house; smaller absolute distances are generally associated with higher PPV's and higher excitation frequencies.

3. PROBABILITY OF A SMALL EVENT CAUSING A CRACK

Crack response during critical period of extreme event year

For a comparatively small dynamic crack response to be the "straw" that extends the cosmetic crack , the cosmetic crack would have to be precariously on the brink of occurrence/extension at the moment the dynamic event occurs. For this brink to occur, the wall/crack would have to be subjected simultaneously to the same sign peaks of the 1) an historical extreme event 2) the largest seasonal response, 3) the largest weather front response, 4) the largest daily temperature response, and 5) a sufficiently intense (high) dynamic event. Given the daily swings in crack response, this condition would exist only during one hour of the worst weather front week, that occurs during the yearly peak seasonal response, all of which occur during an historical extreme event such as a drought, flood, structural overload etc.

Figure 10 illustrates the occurrence of such maximum cracking potential, A. This maximum occurs during the half year with the annual or seasonal peak crack width, which in turn occurs during a once in a decade extreme event year. The upper time line shows the portion of the crack response during the half-year of the seasonal maximum. Variation in response produced by the once in ten year, extreme event is not shown.

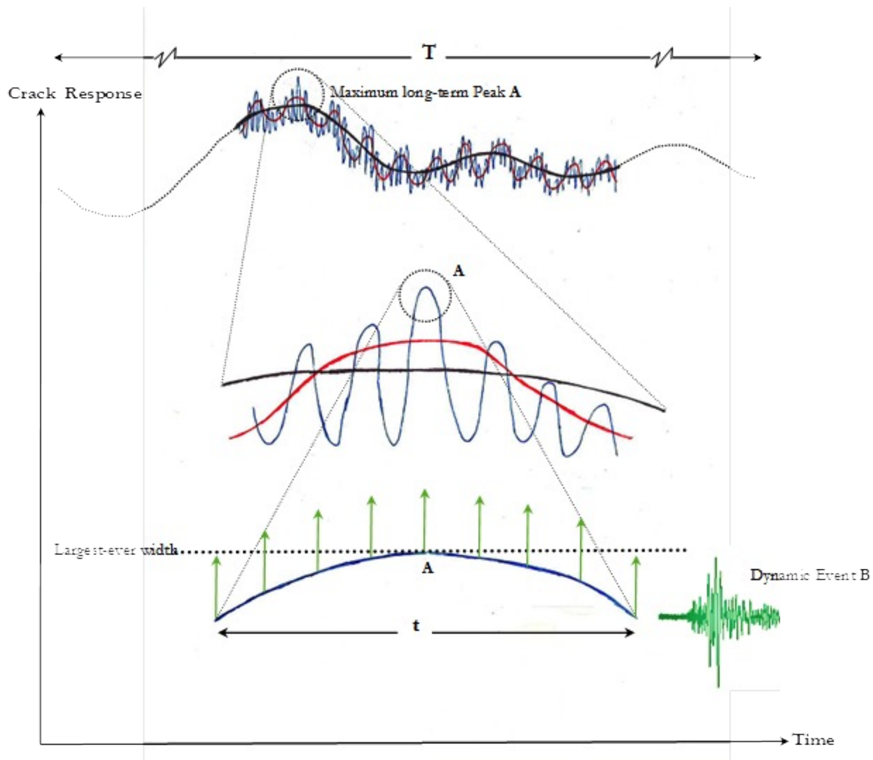

Figure 10. Illustration of the cyclicity of crack response that shows the peak portion of the yearly or seasonal response (black), the weekly, weather front induced response (red) and the daily climatological response (blue)

Variation in the seasonal response is illustrated by the oscillating black line, which peaks on the left. Crack response to changing weather fronts is denoted with the red line that oscillates about the black, seasonal response with a return period of approximately a week. The blue daily variation then oscillates about the red, weather front- induced variation to produce the, one and only, peak, A. The resulting, singular peak response at A is enlarged in the middle time line.

Peak response at A is further enlarged at the bottom of Figure 10 to illustrate how the period of vulnerability or critical exposure time, “t”, is related to the amplitude of dynamic crack response, B, shown in green at the bottom right. Exposure time, “t”, is defined to be the time during which the zero to peak amplitude of the dynamic response “could” be added to the daily peak response to widen the crack more than it had ever been in the past (dotted line labeled largest-ever).

Probability of a sufficiently intense dynamic event occurring during the maxim crack opening (period of vulnerability or exposure time, t)

Cracking can only occur if a sufficiently intense dynamic event occurs during the peak of the one daily cycle of crack response during the period of observation/calculation, T. The period of observation must include the extreme event with a return period of some 10 years as well as the yearly seasonal maximum. Calculation of the probability that a dynamic event occurs during this single peak requires the definitions and assumptions below as illustrated in Figure 10.

- Overall time period of observation/calculation is T, which is a half-year in this example
- Dynamic event (B) occurs randomly (unpredictably) in time
- Dynamic event peaks (B) are assumed to occur instantaneously (A single dynamic peak would occur in 0.025 sec and as will be seen later the exposure time, "t" is around 80 minutes)
- There are "n" number of dynamic events with similar "t's" in the overall time period T
- Only the highest long-term peak (A) is of significance, and it occurs only once and randomly during time period, T (Dowding 2008).
- The period of vulnerability or exposure time, "t", is determined with the amplitude of the dynamic crack response in relation to the curvature of the maximum daily response, A, as shown in Figure 10.
- Both the long term peak response, A, and the dynamic event, B, are independently random.

Calculating the probability that a dynamic event, B, occurs during the long-term peak crack response, A, can be illustrated with a dice analogy shown in Figure 6. Imagine the edges of surface A to represent "t" of the sides on a T-sided die. Imagine B to be a roll of one of these dice. Say, for example, one dynamic event B is expected to occur in T. Thus if the die lands so that one of the sides of surface A is touching the ground surface, the position symbolizes a coincidence of B given A. The probability of rolling the die so that a side would touch the ground is approximately t/T. In the figure there are 6 possibilities of landing with a side of A touching the ground. Relative to the time line of crack response, if "t" were 60 minutes and T were 6 months, t/T would be 60/(0.5*365*24*60) or 0.0044 or 4 chances in a 1000.

Figure 11. The "T" edged die with side A encompassed within the "t" percentage of exposure time: left, one roll. Right: multiple rolls.

Now, say that 20 dynamic events (with a similar intensity and thus similar "t") are expected to occur in T. The die is rolled 20 times and the probability is now 20 times t/T (t/T + t/T +t/T ….. for 20 rolls) that one of the roles will show A or a dynamic event B coincides with the long-term peak A. Therefore, given that A and B are independent and derived from a uniform distribution, the probability of coincidence is nt/T, where n is the number of dynamic events in T. The conditional probability that describes this situation is given in Equation 1. This simple expression for calculating the probability was validated with a Monte Carlo simulation (Meissner, 2009).

$$(1) \quad P(A \cap B) = \frac{nt}{T}$$

This conditional formulation of the probability of crack extension contains components for the consideration of the number of occurrences of dynamic events, n, differing amplitudes of dynamic event crack response, "t", and the period of observation, T. It is relatively easy to grasp the relation of n and T to the issue of crack extension; however, the relationship of "t" requires further discussion. The parameter "t" is the exposure time at the peak of the long-term crack response when a dynamic perturbation of a defined amplitude can cause the crack to widen beyond its greatest historical width. Thus it is the period of time the crack/material/location is vulnerable to cracking for an event associated with amplitude "t". During all other time intervals it is not vulnerable.

Typical long-term and dynamic crack responses will be employed to demonstrate the determination of exposure time, “t” as already illustrated in Figure 10 above. Figure 12 compares a typical ground motion induced crack response with typical long term, climatologically-induced crack responses. The amplitude of the encircled dot of a dynamic event on that day is magnified by more than 10 times in the expansion to allow its details to be observable. Figure 13 further enlarges the March 18, daily response to illustrate determination of “t” (Meissner 2009). Consider an event that produces 10 micrometer (400 micro-inch) zero to peak crack response. The relative amplitude of this dynamic contribution is shown by the two horizontal black lines in Figure 13 at the peak of the 100 micrometer (4000 micro-inch) daily climatologically induced crack response. Limits of the intersection of the lower horizontal black line with the blue daily response time history are shown by the vertical red lines. The distance between these red lines show that the exposure time for a 10 micro-meter (400 micro-inch) event would be some 80 minutes. Red lines are shown only for the left portion and the exposure time. The secondary peak on the right was included in the calculation but not in the illustration. This exposure time was verified by analyzing several other daily response time histories in a similar fashion.

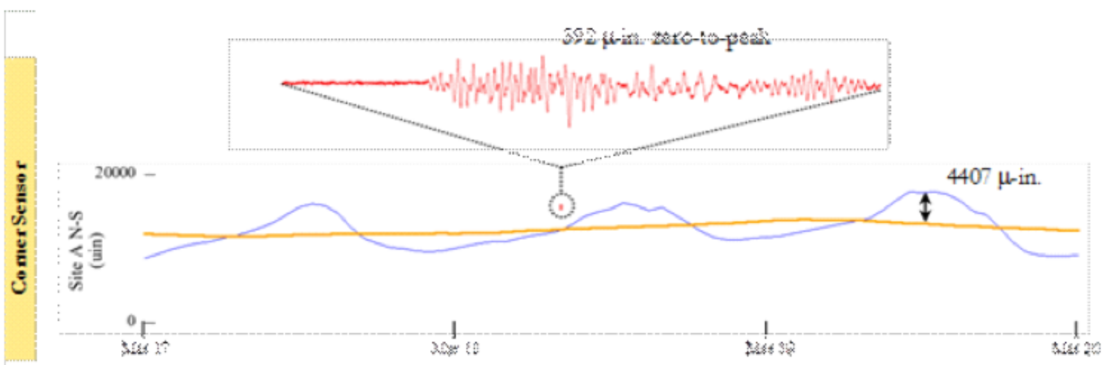

Figure 12. Example of a 10 micro-meter (400 micro-inch) blast induced crack response compared to the 100 micro-meter (4000 micro-inch) daily crack response.

Now consider the exposure time for an occupant induced dynamic response of the same crack (N-S component of a corner crack), the time history of which is shown in Figure 14. The event is produced by opening and closing the front door to this house. The front door was located some 30 feet away in another room (Meissner, 2009), and demonstrates how occupant induced dynamic events can affect many locations in a house. A study of occupant induced door opening and closing shows that there were over 300 such events in a three month period. These 300 some events were produced by a single person occupying the house. The minimum, maximum, and median amplitudes of the induced dynamic crack responses were, ~1.5, ~11, and ~2.5 micro-meters respectively. Application of the same procedure used to determine the exposure time described above with a 5 micro-meter (200 micro-inch) crack response returns an exposure time of 40 minutes.

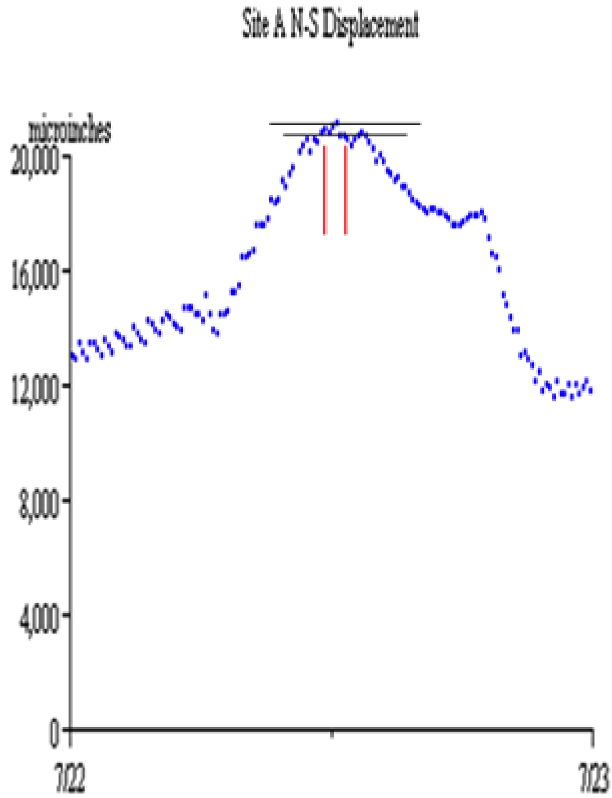

Figure 13. Specific example of the "critical" exposure time (between the red lines) for a ground motion that produced a 10 micro-meter (400 micro-inch) crack response. This critical exposure time is that during which that dynamic response might produce an extension by adding to peak climatologically induced crack response. The daily heating and cooling response is over 100 micro-meters (4000 micro-inches).

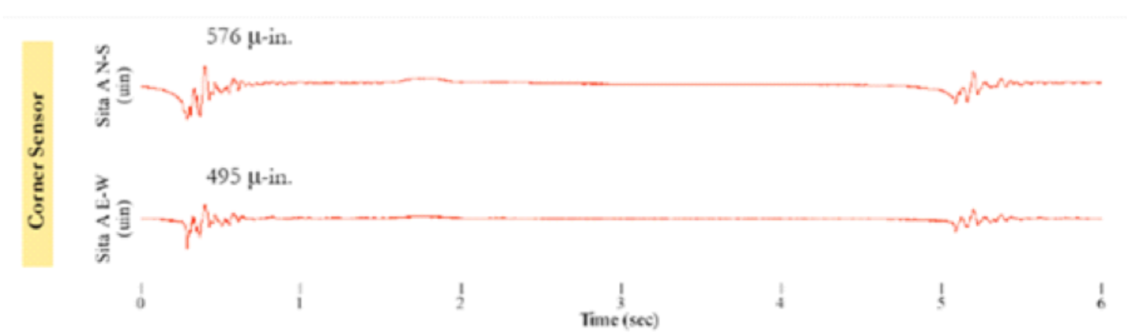

Figure 14. Crack response of some 14 micro-meters (575 micro-inches) from opening and closing of the front door located some 30 ft (10m) away

Comparison of probabilities of occupant and blast induced events occurring during the maximum crack opening.

Increasing sophistication of autonomous crack monitoring (ACM) systems has led to the observation that occupant activities produce significant crack responses. To what degree do these occupant induced crack responses affect possible cracking?" In early ACM systems, memory was limited and there were no mechanisms to trigger recording of crack response produced by occupant activities; thus occupant induced crack responses were not observable. Present ability to operate newer ACM systems at data rates of 50 samples per second for days at a time have allowed detection of occupant activity (Dowding, Revy & Waldron, 2007). More recently addition of internal wall mounted velocity gauges has allowed detection and recording of occupant induced activity. This increased measurement of occupant induced crack response has led to increased understanding of their importance.

Measurements of occupant- and blast- induced crack responses of an occupied test house can be employed to determine the comparative probabilities of event occurrence during the exposure time. The following example comparison is based upon measurements made in the concrete masonry unit (CMU) framed house near Naples, FL described in Section 1 (Dowding & Meissner, 2010, Meissner, 2009).

First, the period of observation, "T", must be chosen and will be assumed to be 6 months or half a year. One half of a year was chosen as the shortest period of observation to begin to be able to detect larger, long-term, environmentally induced crack response. Generally a full year is required because the season during which the maximum opening occurs is unknown.

Second, the "n" and the "t" need to be determined for occupant and blast induced events, which will vary for each. The blast events are those from October through July shown in Table 2. The crack response is that of the North-South direction response of the corner crack monitored by sensor E2. Where there were no data for E2, its response was estimated as three times that of E1, which was based upon typical ratios where there were data. Occupant events are only those of door closing, the three-month distribution of which is shown in Figure 15. In both cases, the "n" associated with a specific "t" will vary. Distributions of these "n's" and "t's" are shown in Table 3 for occupant events (left) and blast events (right).

Table 2. Quarry blast-induced ground motion and corner evade response in the N-S direction (E1)

Date	PPV [mm/s]	E1	E2
Oct 23	2.0 [L]	5.08	1.55
Dec 8 (1)	1.9 [L]		1.42
Dec 8 (2)	2.9 [T]		1.57
Mar 18 (1)	2.8 [L]	9.96	2.90
Mar 18 (2)	2.5 [L]	8.66	2.18
Mar 23 (1)	1.3 [L]		1.19
Mar 23 (2)	2.3 [V]		1.50
Mar 26	2.4 [L]	6.20	2.21
Apr 1 (1)	1.5 [L]		1.91
Apr 1 (2)	3.4 [V]		1.50
Jul 8 (1)	1.3 [L]	7.34	2.46
Jul 8 (2)	2.5 [T]	7.44	3.12
Jul 14 (1)	1.8 [V]	12.40	4.17
Jul 14 (2)	1.3 [L]	7.21	1.91
Jul 22 (1)	2.2 [T]	8.23	3.05
Jul 22 (2)	4.4 [T]	11.23	4.37

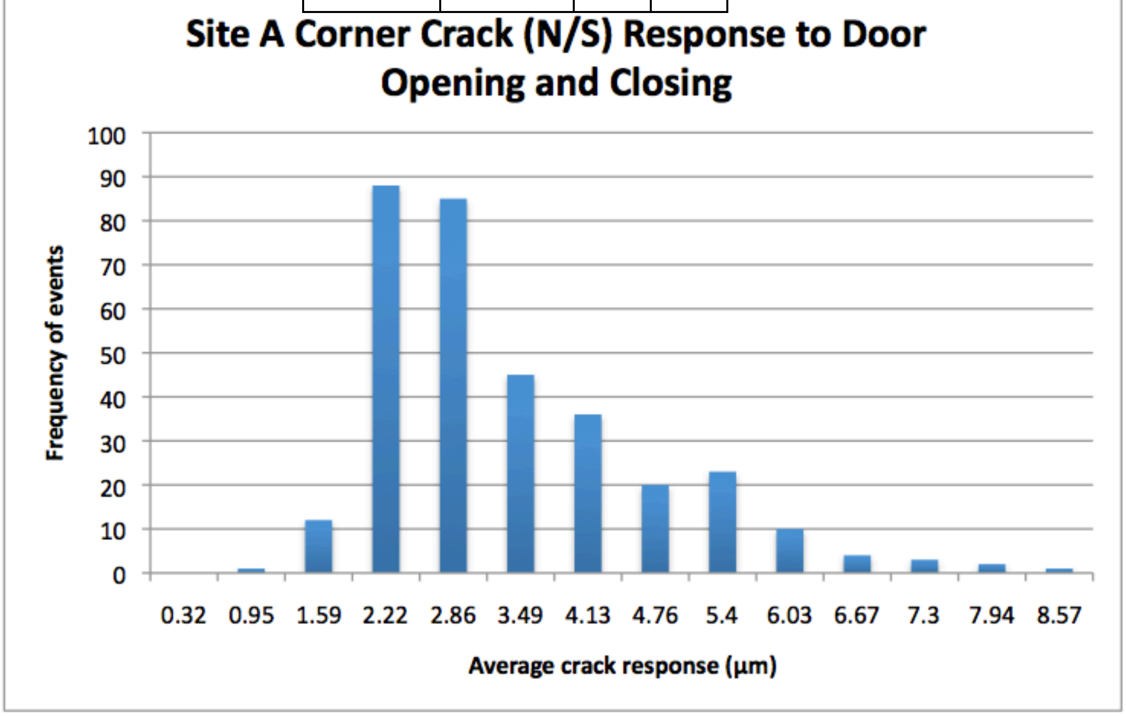

Figure 15. Frequency of occurrence and amplitudes of dynamic events produced by opening and closing of font door in the test Florida CMU house.

Table 3 compares occurrences, n, micro meter crack responses, and periods of exposure or maximum vulnerability, “t” for both occupant- and blast- induced events during a 6 month period of time, T. As illustrated in Figure 10, larger micro-meter crack response amplitudes produce larger periods of exposure or vulnerability, “t”. For this corner crack, determinations of “t” as illustrated in Figure 13, showed that dynamic responses of 10 and 5 micro-meters would produce "t's" of 80 and 40 minutes. Accordingly "t's" were extrapolated and interpolated in proportion to the measured crack response and compared in Table 3.

The probability of one of the series of dynamic events occurring during the period of vulnera-

Occupant events (July-September)				Blasting events (October-July)				
Events	Crack response	Exp time		PPV	Events	Crack response	Exp time	
	μm	minute		mm/s		μm	minute	
n		t	n(t/T)		n		t	n(t/T)
1	11.43	90	0.0003424	2.0	1	5.08	40	0.0001522
5	7.62	75	0.0014269	1.9	1	4.06	32	0.0001218
4	6.65	64	0.0009741	2.9	1	4.57	36	0.0001370
10	6.02	52	0.0019787	2.8	1	9.96	80	0.0003044
23	5.38	40	0.0035008	2.5	1	8.66	68	0.0002600
20	4.70	40	0.0030441	1.3	1	3.81	30	0.0001141
36	4.24	35	0.0047946	2.3	1	4.57	36	0.0001370
45	3.48	30	0.0051370	2.4	1	6.20	49	0.0001857
85	2.84	25	0.0080860	1.5	1	5.59	44	0.0001674
88	2.29	20	0.0066970	3.4	1	4.57	36	0.0001370
317		Σ(n(t/T)) = 0.0359820		1.3	1	7.34	58	0.0002200
				2.5	1	7.44	59	0.0002230
				1.8	1	12.40	98	0.0003713
				1.3	1	7.21	57	0.0002161
				2.2	1	8.23	65	0.0002466
				4.4	1	11.23	88	0.0003363
					16		Σ(n(t/T)) = 0.003330	

bility or exposure time, "t" and thus might cause cracking can be calculated by adding the products of n(t/T) for each set of dynamic events that produced similar micrometer crack responses. Since there were so many occupant events they were grouped as described in the frequency distribution chart in Figure 15, where "n" varied from 88 to 1. The number of blast events was small enough that they could be entered individually, and "n" was "1" for the entire calculation.

The Σ(n(t/T)) at the bottom of each case in Table 3, is the probability of a dynamic event occurring within the exposure time "t". This sum does not include consideration of the probability of observing the crack response during the most extreme environmental exposure. To account for the unlikely condition that the observation occurred during this extreme period, the Σ should be multiplied by the "state" probability of 0.05 for ½ year of observation during a 10-year interval during which an extreme event might occur. This adjustment is necessary to determine an absolute probability of occurrence during observation time, T.

Conditional probability calculations in Table 2 show that occupant induced dynamic events are more likely than blast events to be the "straw that breaks the camel's back" when a house is at the brink of crack extension. The difference is not small; in this specific case the probability of occurrence during the exposure time is some 10 times greater for the occupant-induced events than for blast-induced events. In other words, occupant induced events are 10 time more likely to occur during the one period of vulnerability than are blast induced events.

Table 3. Calculations of the probability that any one of a collection of dynamic events with differing exposure or vulnerability times (t) and frequencies of occurrence (n) will occur during the exposure or vulnerability time, “t”.

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. There are three most often heard concerns. 1) Cracking relieves strains and strains concentrate elsewhere, which reduces the sensitivity of cracks to excitation relative to uncracked locations. 2) There are not enough observations of crack response in low excitation frequency - high particle velocity environments that may cause greater amplification. 3) There is a critical combination of effects that renders a crack so vulnerable that a small event may extend (widen) the crack.

These measurements show the following. 1) A cracked joint does not respond less than other uncracked weaknesses in the wall covering to either climatological or vibratory effects. . 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. 2) Even in high particle velocity (10 to 23 mm/s or 0.4 to 0.9 ips) and low excitation frequency (5 to 7 Hz) environments, cracks continue to respond more than do uncracked weaknesses. 3) Comparison of crack responses to occupant- and blast-induced events shows that the probability of cosmetic crack extension by occupant-induced events can be larger than externally induced events. Thus ongoing processes of crack widening are subject to occupant-induced effects that should be considered in any discussion of causation.

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