Micrometer Crack Response Substantiates Conservatism in Vibration Control Limits

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MICRO-METER CRACK RESPONSE TO VIBRATION AND WEATHER

CHARLES H. DOWDING

A variety of readers with a wide range of educational backgrounds will find this book useful and understandable. For instance, professionals from the following fields will find this book useful for at least the following reasons:

Regulators
Gain an appreciation of the degree of conservatism in the current control limits and explore the possible use of autonomous micro-meter crack measurement to explain to the public why they are more sensitive to vibration than are structures.

Litigants
Explore the large effect of natural phenomena on crack response and its effect on questions of causation.

Owners of Vibratory Sources
Investigate the use of graphical display of crack response to educate neighbors about various natural phenomena that affect their house.

Engineers
Explore use of micro-meter crack response to study the response of structures to natural phenomena as well as for the control the construction process.

Instrumentation Specialists
Learn how to measure micro-meter crack response and how to integrate the process with seismological systems and instruments.

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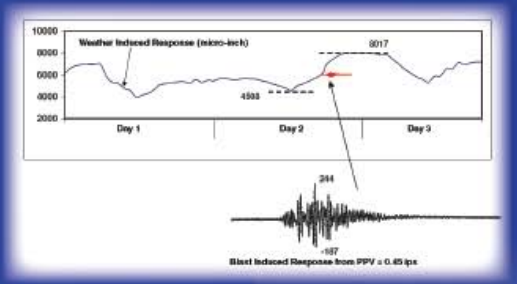

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Concept of Autonomous Crack Measurement (ACM)

Measures crack response, a major source of homeowner anxiety
Augments regulatory measures of ground motion
Avoids complexity of ground motion
Measures response of the same crack to
both long term (climatological) and dynamic (vibratory) effects
Integrate with internet display to enhance community interaction

Conclusions

Climatological crack response overwhelms vibratory response for
both typical (~ 2.5 mm/s) and regulatory (< 12 mm/s) PPV's
Large climatologically induced crack response occurs more often than
maximum vibratory response
Since climatological response is larger than vibratory response at
12 mm/s and occurs more often, restriction to
current control limits produces less effect than nature.
Crack response follows strains in walls and structural response
Wind induces large crack response

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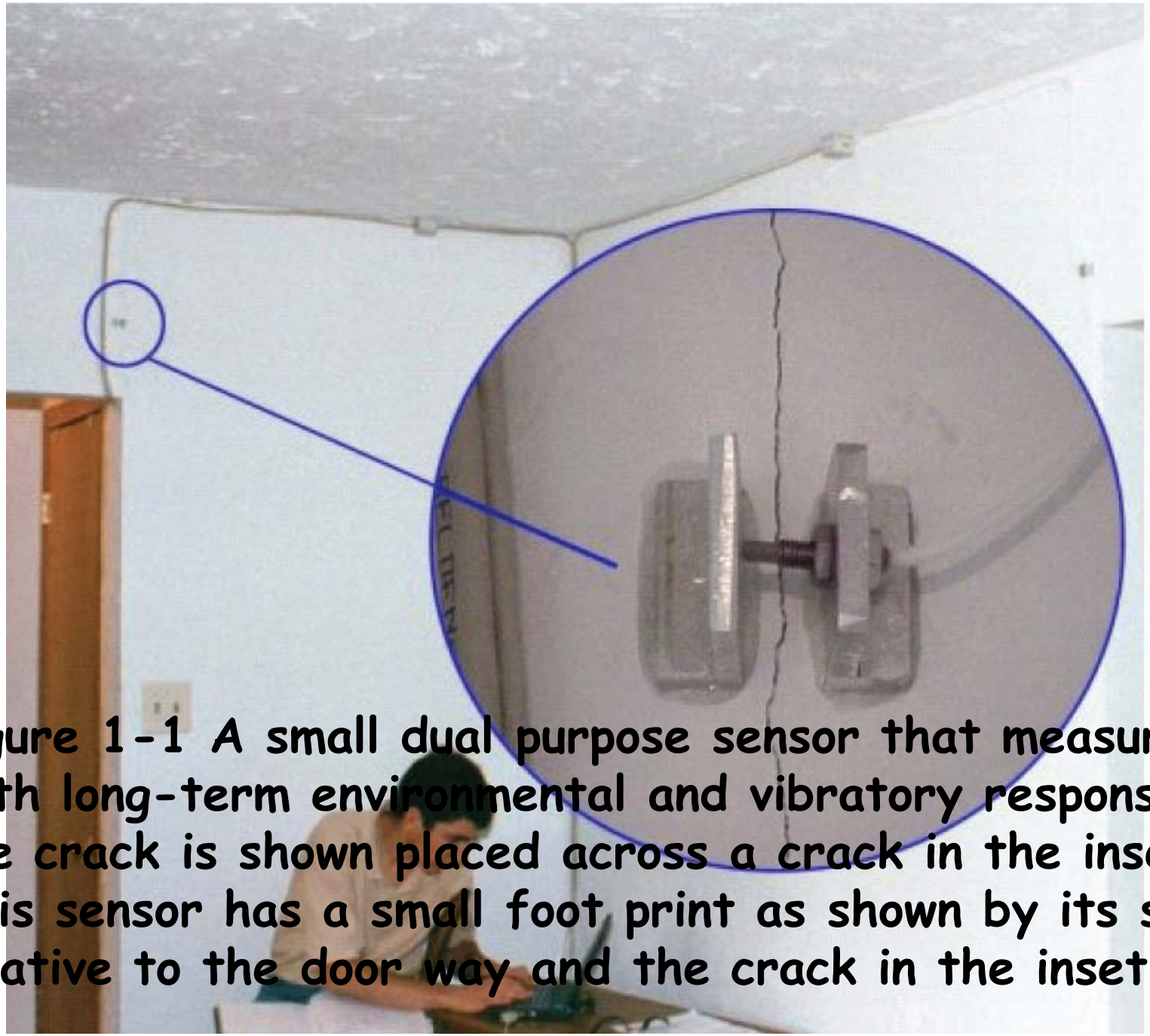


Figure 1-1 A small dual purpose sensor that measures both long-term environmental and vibratory response of the crack is shown placed across a crack in the inset. This sensor has a small foot print as shown by its size relative to the door way and the crack in the inset.

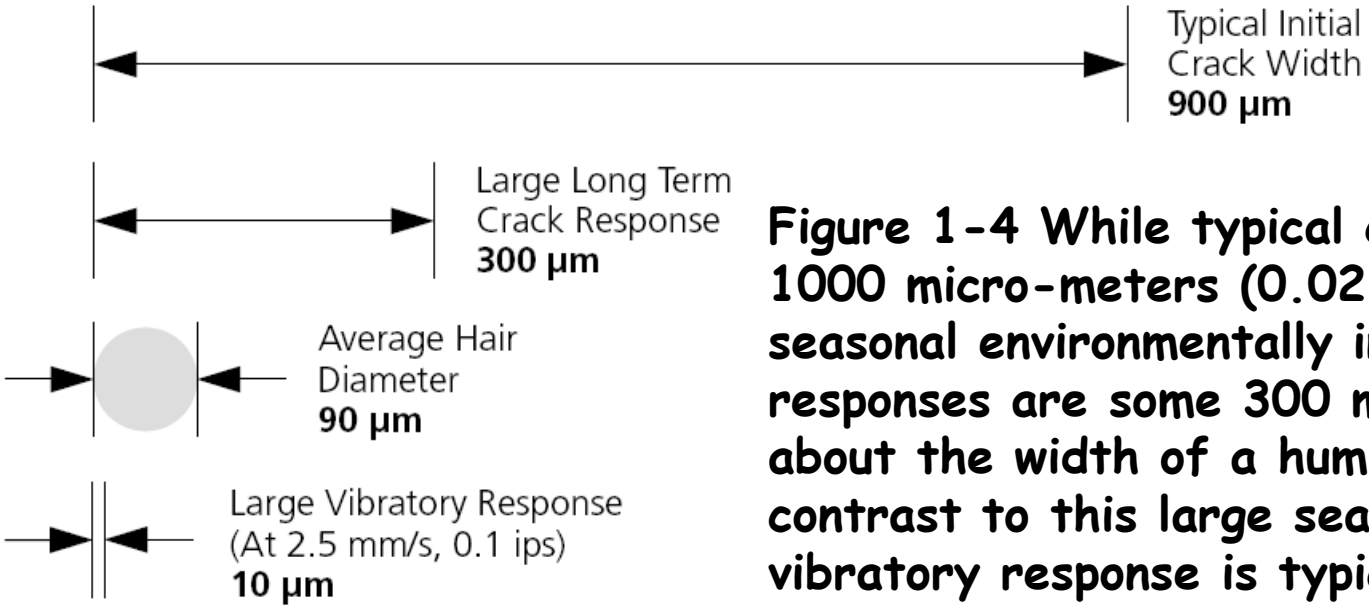


Figure 1-4 While typical cracks are 500 to 1000 micro-meters (0.02 to 0.04 in.) wide, seasonal environmentally induced crack responses are some 300 micro-meters or about the width of a human hair. In contrast to this large seasonal response, vibratory response is typically only 5 micro-meters from ground motions of 2.5 mm/s (0.1 inches per second).

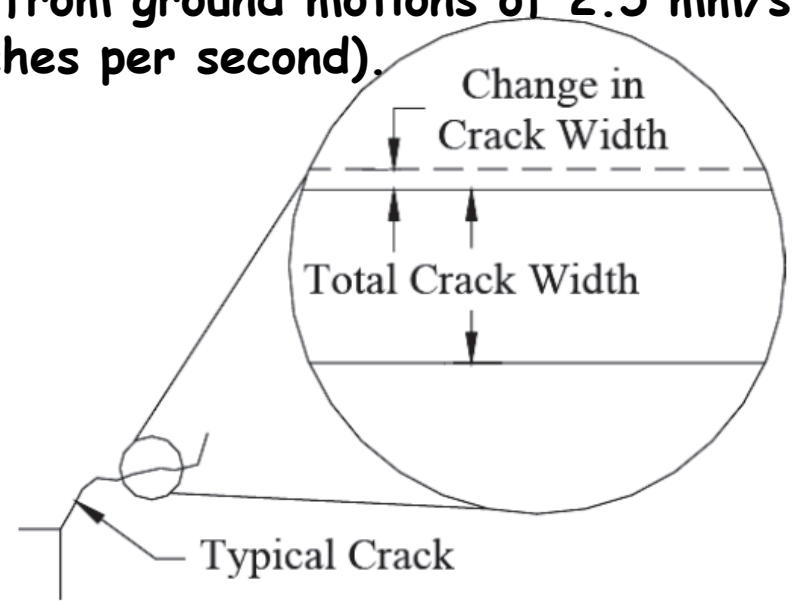


Figure 1-3 ACM captures the micro-meter change in crack width produced by both long-term climatological and vibratory crack response.

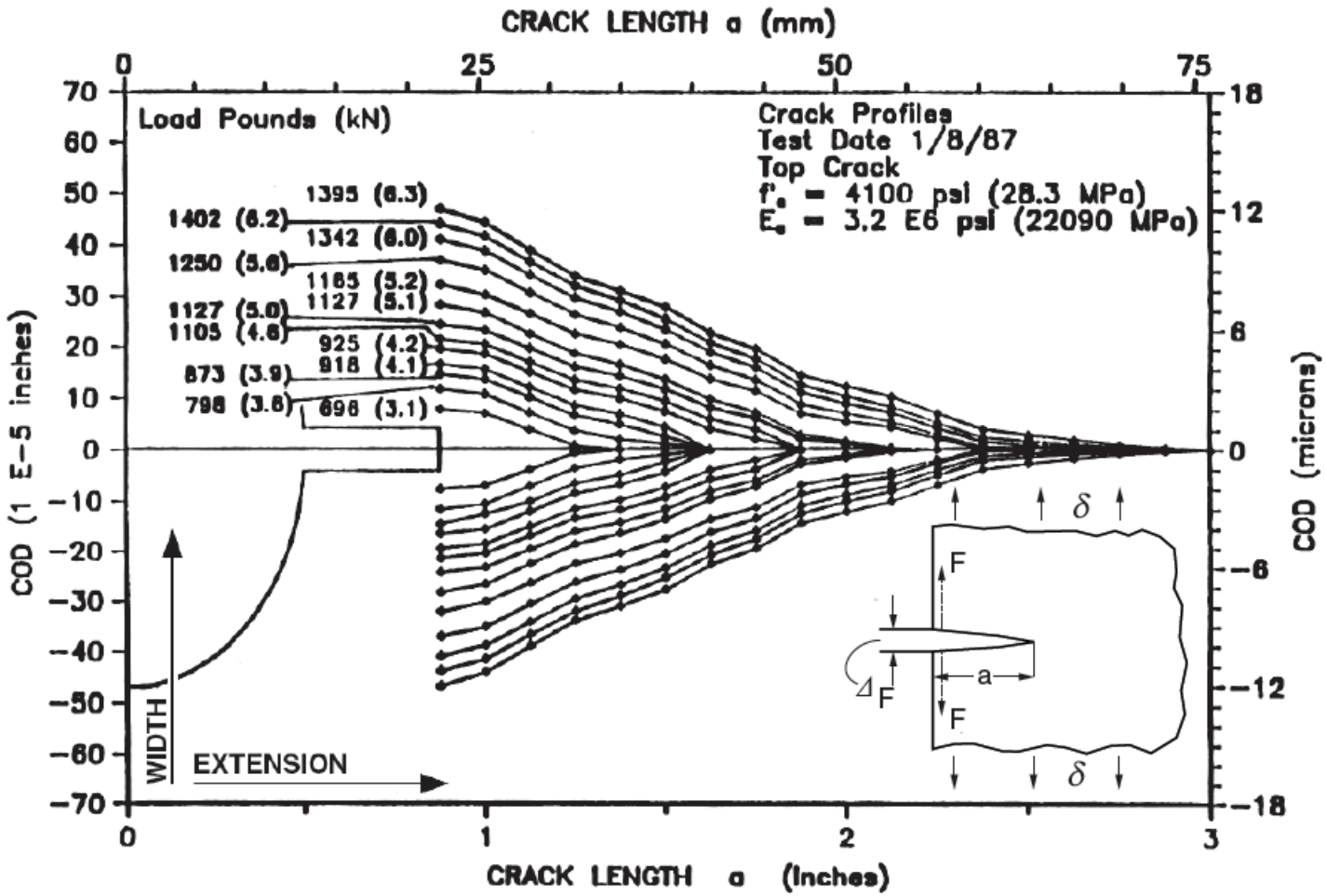


Figure 1-5 Experimental observation that cracks extend as their width increases forms the foundation of fracture mechanics as well as the ACM measurement approach. Special visualization techniques were employed to measure the extension of a crack (marked by the rightward extension of the ">") as its width (COD or "crack opening displacement) increases (marked by the increasing width of the mouth of the ">" on the left. (Miller, 1989)

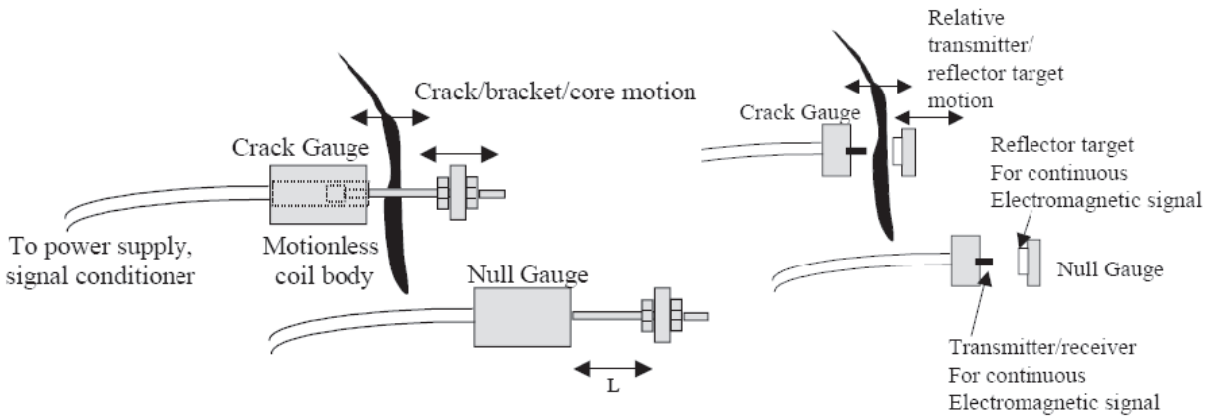
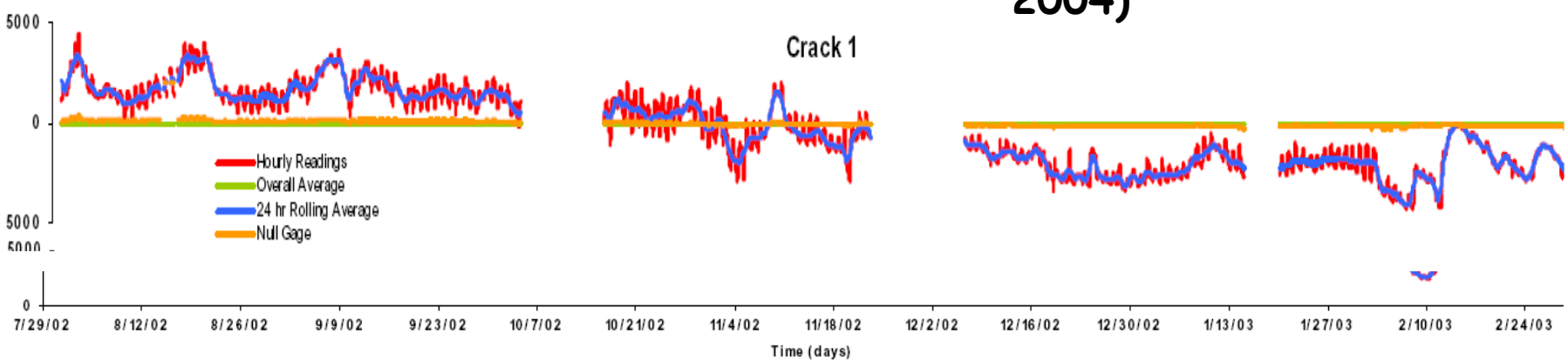


Figure 10-1 Micro-meter crack and null displacement sensor pairs; LVDT's on the left and eddy current sensors on the right. Null sensors measure response of instrument and wall material to ensure response is only that of the crcak...(Petrina, 2004)



Comparison of measured indoor crack response (red) with null response (orange) over 7 month period shows little need for null sensor after field verification. (Snider, 2004)

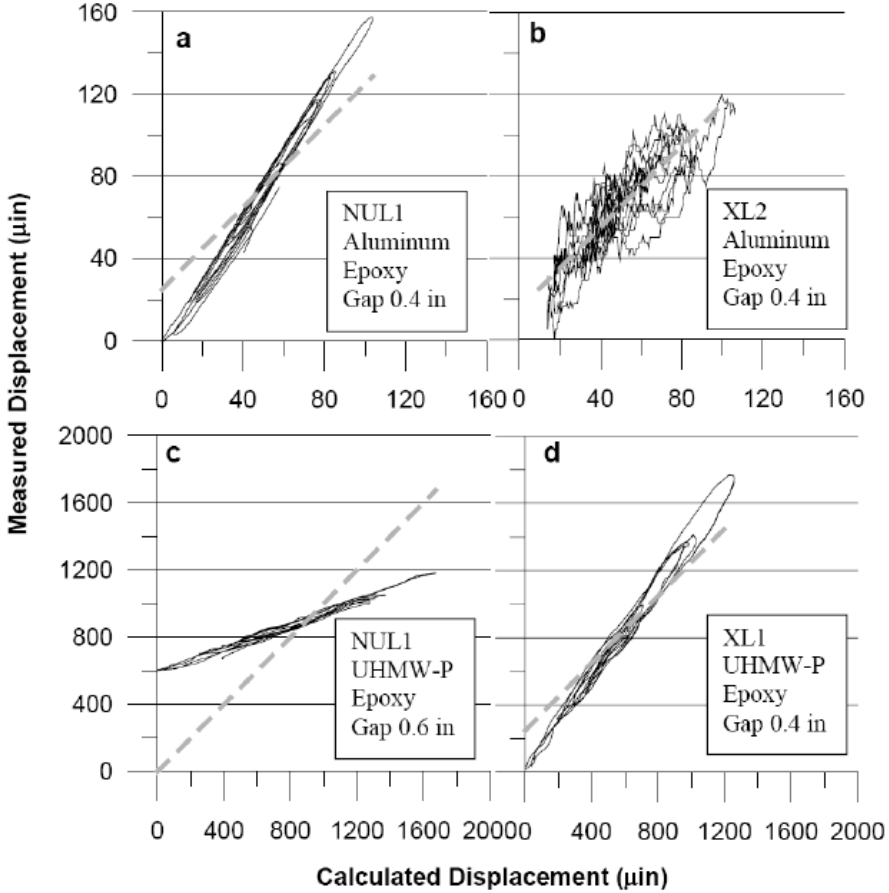


Figure 10-3 Comparison of measured (y axis) to calculated (x axis) response to thermally induced response for system X LVDT sensor (right, b and d) and NU Kaman system left (a and c) when epoxied to plates of aluminum (upper a and b) and plastic (lower c and d). (Petrina, 2004)

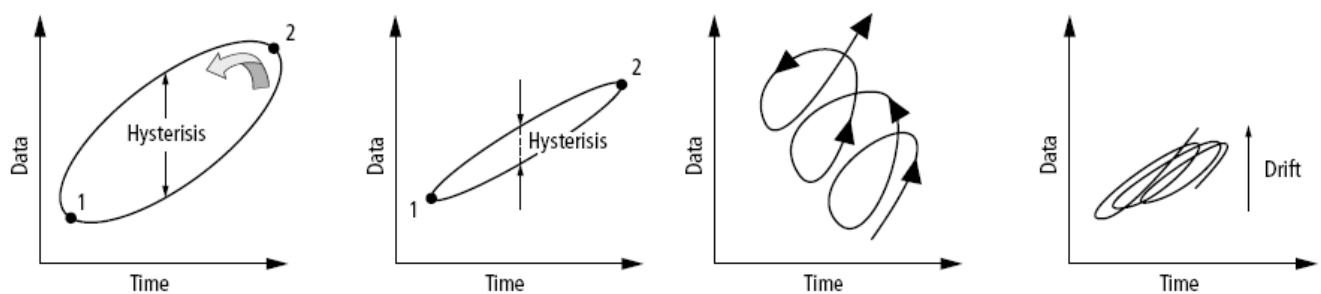


Figure 3-10 Illustration of hysteresis (left two graphs) and drift (right two graphs), where behavior in the left graph of each pair is undesirable. (Baillot, 2004

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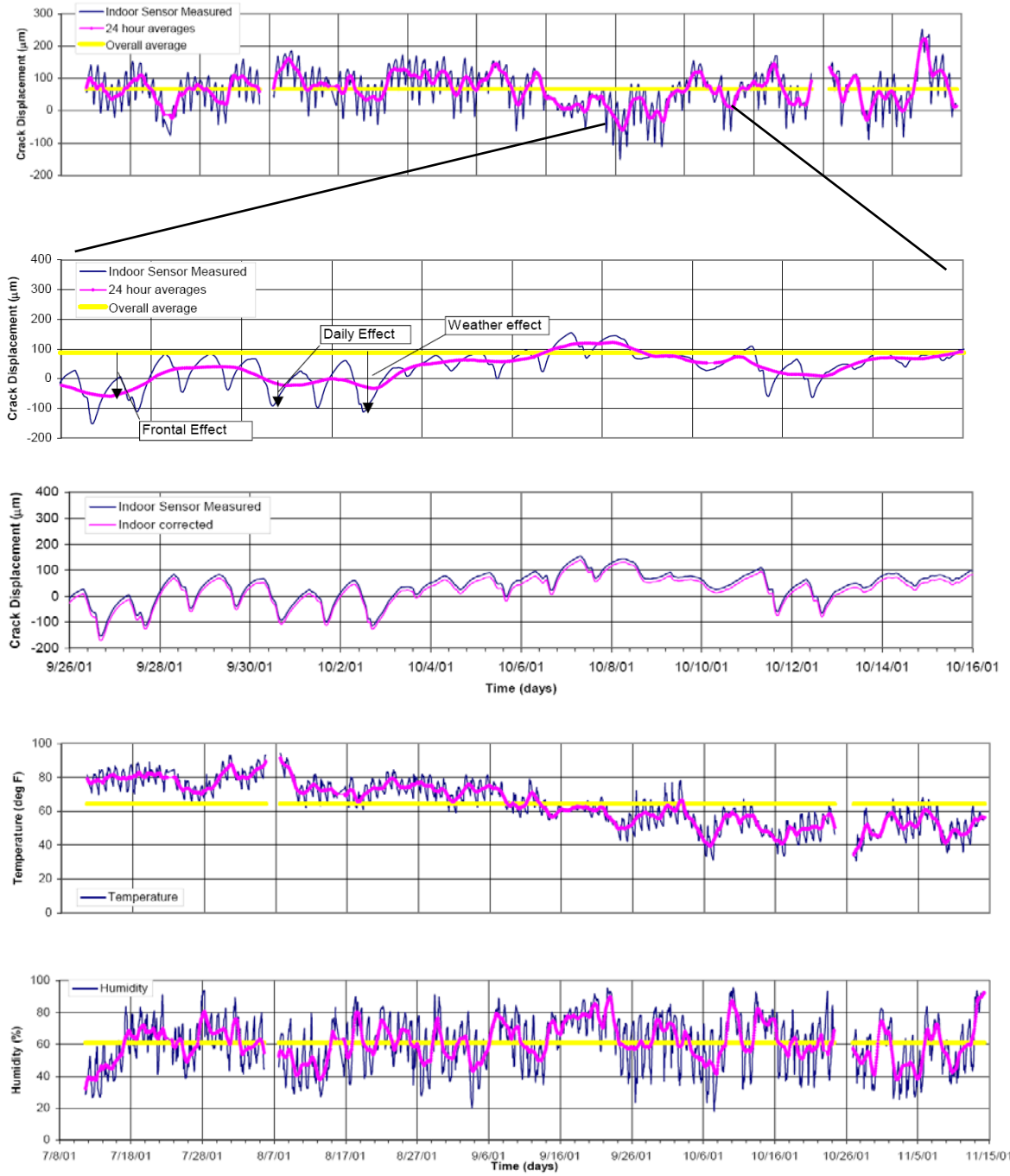

Long Term Response
(measured every hour)

Five months of climatologically-induced crack response illustrates typical daily temperature-induced response, quasi weekly humidity/temperature response produced by the passage of weather fronts, as well as one or two extreme events. Negligible effect of correction for null shown in middle. (McKenna, 2002)

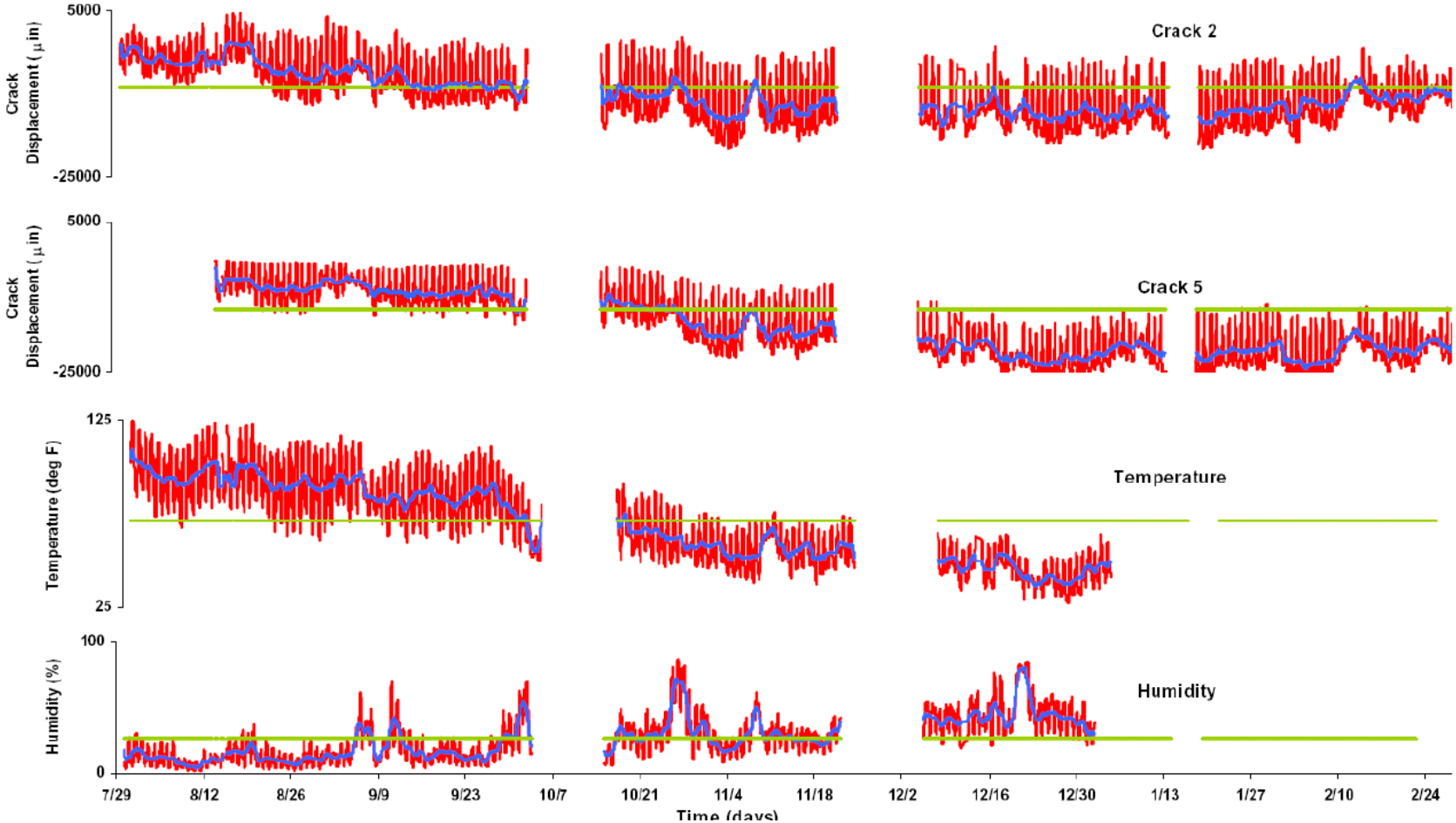

Figure 4-12 Long-term response of exterior stucco crack reveals seasonal trend in transition from summer (August) conditions to winter (February) as well as response to rainfall events (high humidity spikes in desert climate). (Snider, 2003)

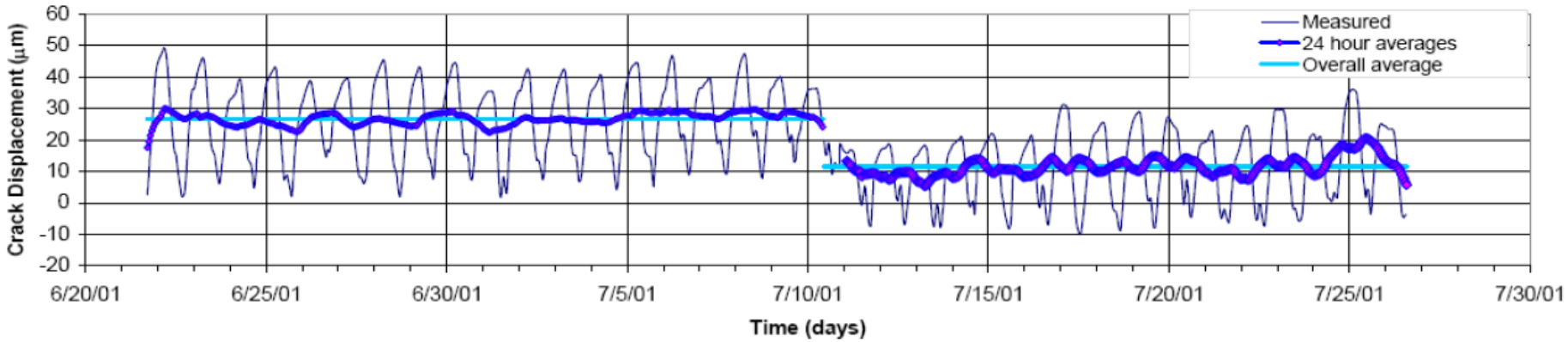

Figure 4-13 Long-term response of external crack in stucco over adobe brick at a window corner shows permanent offset after 16 mm rain storm on 11 July. This is the only monitored crack to exhibit such an obvious permanent change in response. (McKenna, 2002)

Dynamic Response Measured w/ Same Crack Sensor

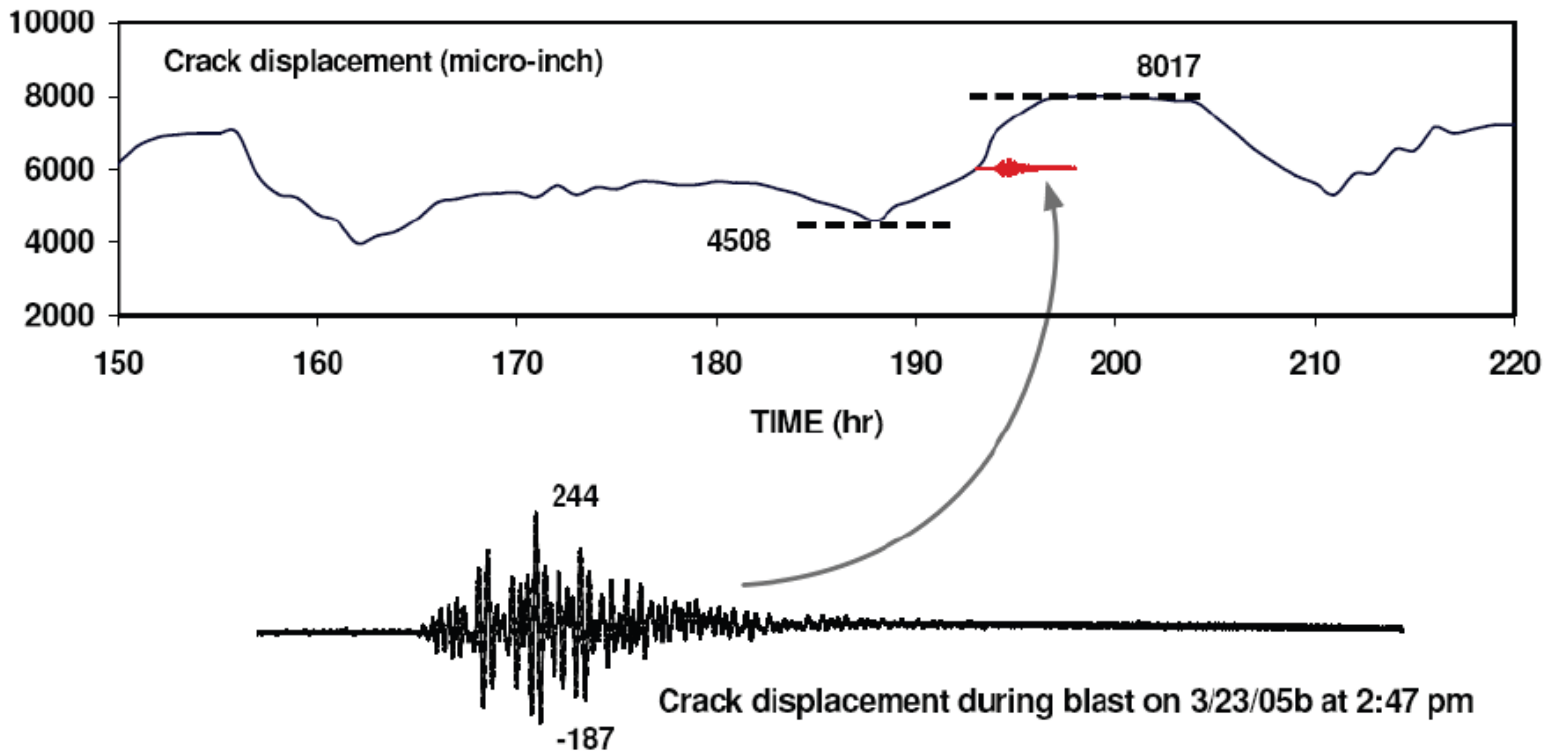

Figure 1-9 The miniscule vibratory response compared to the climatological response challenges graphical comparison. Even in this case where ground motions were as high as 10 mm/s (0.4 ips), vibratory crack response was still only 1/6 that of the daily temperature response. (AMA, 2005)

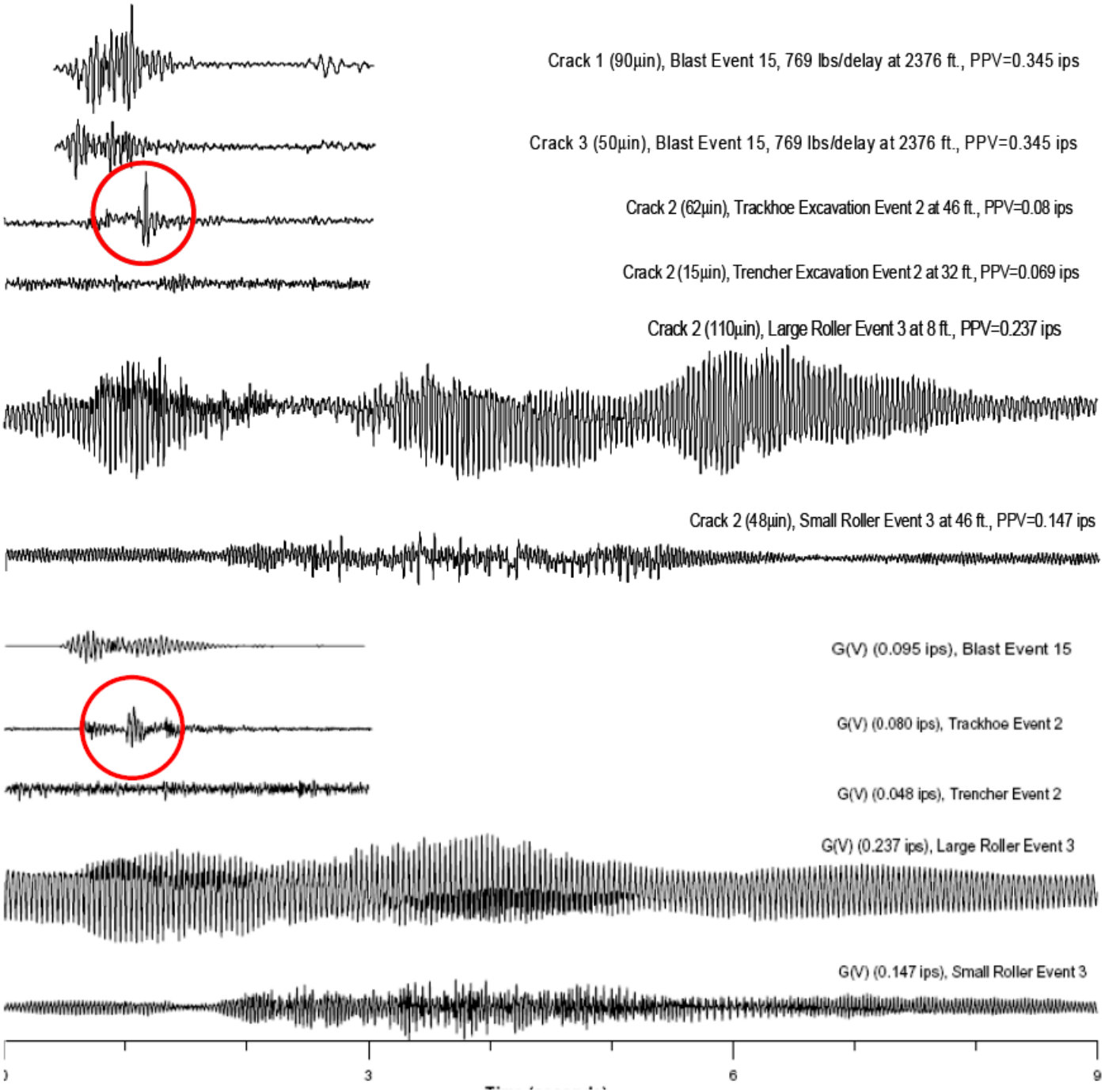

Figure 1-8 Comparison of vibratory responses of cracks (upper 5 time histories) to the excitation ground motions (lower 5 time histories) shows that the responses last only as long as the excitation, the form of which varies with the type of construction or blasting activity. (Snider, 2003)

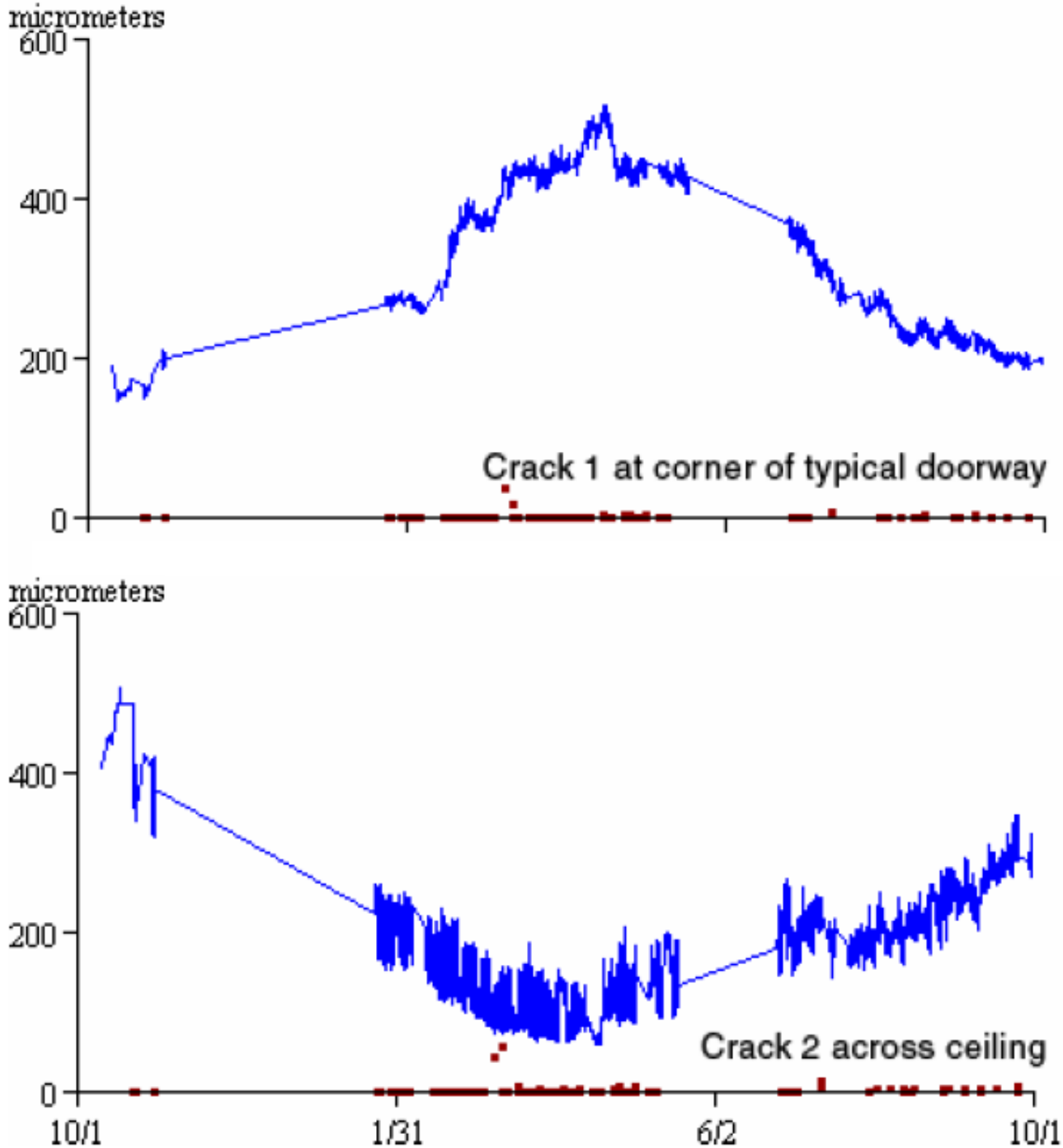

Figure 1-7 Twelve months of crack response reveals a seasonal crack response of some 300 micro-meters (12,000 micro-inches or 0.012 in). This response is probably the result of the seasonally heating of this residence during the winter heating season.

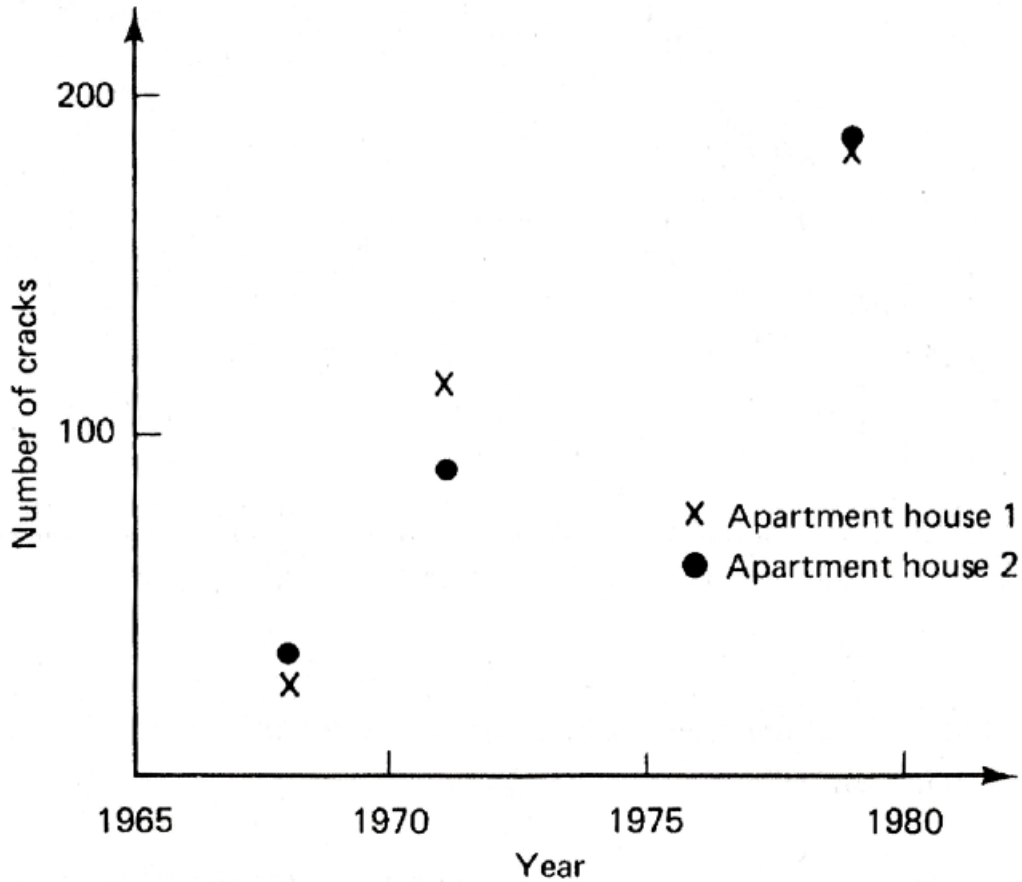

Figure 2-4 Crack appearance with aging of buildings.(Holmberg et al, 1981) demonstrates natural causation of cracks

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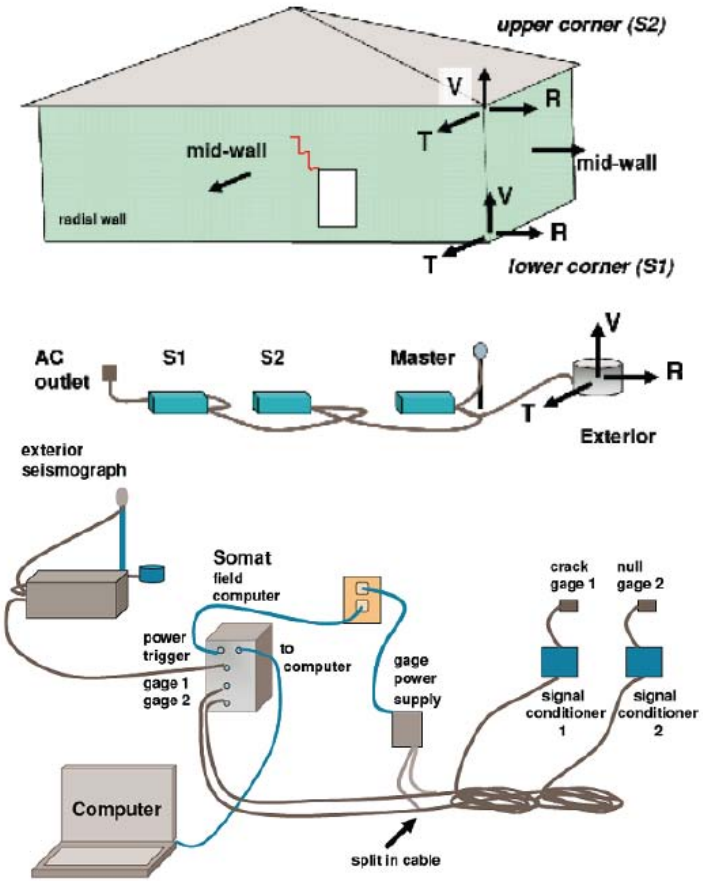


Figure 7-3 Placement of transducers for cases where structural response was recorded. Location of corner transducers and linkage of standard vibration monitors to crack sensors (a) and photographs of the placement of the single axis velocity transducers in the upper corner of a home (b). (Aimone-Martin et al, 2003).

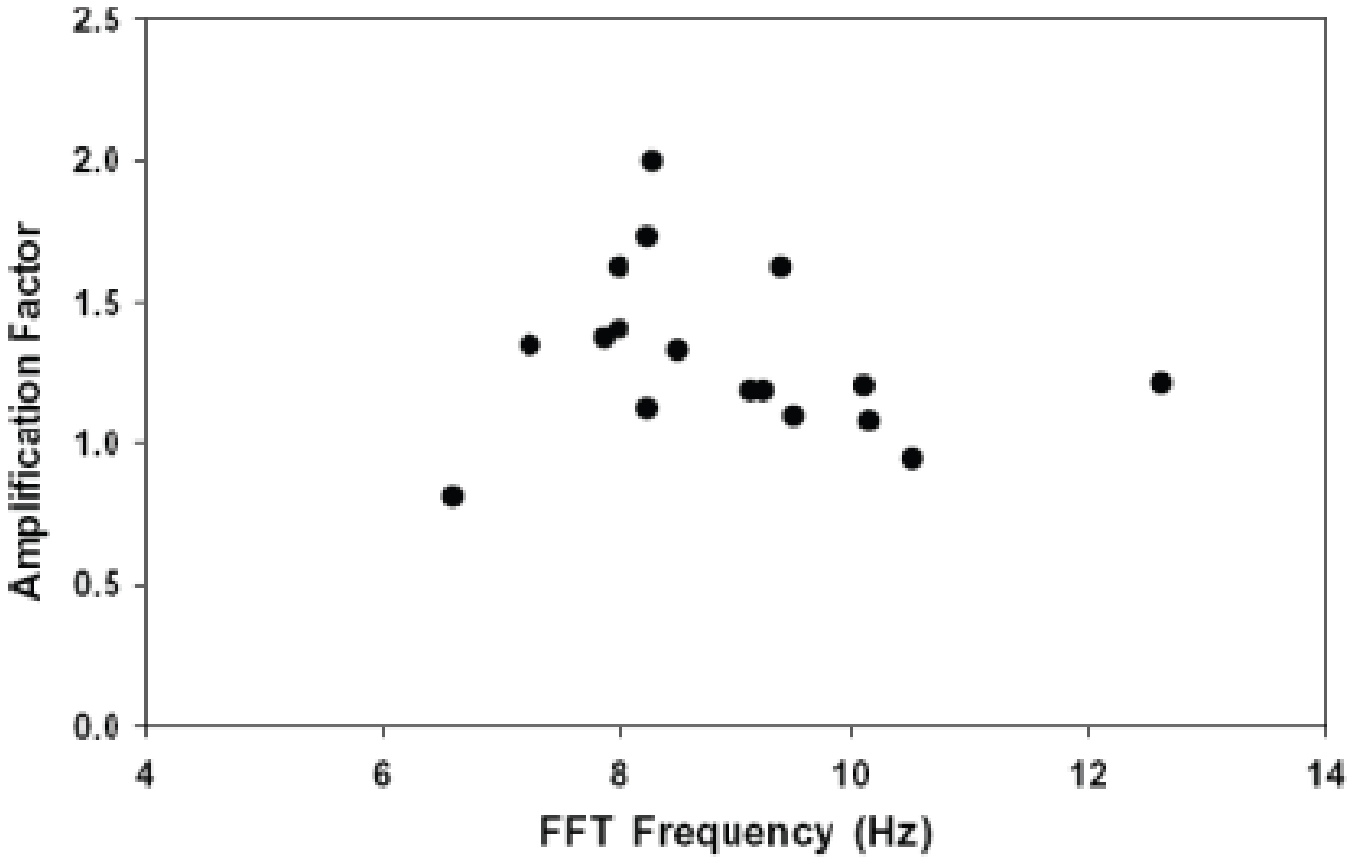


Figure7-1 Variation of the ratio of peak corner velocity divided by associated peak ground velocity (Amplification Factor) with dominant excitation frequency shows amplification to maximize at 8 Hz, the natural frequency of single story structures. Responses from the Albuquerque, NM case history (App. AN). (Aimone-Martin & Dowding, 2005)

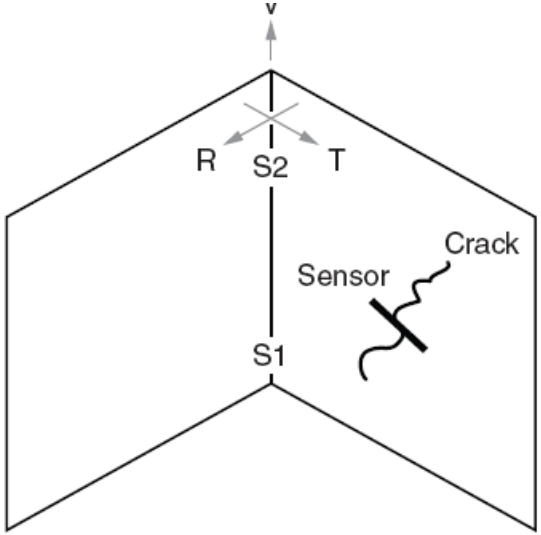
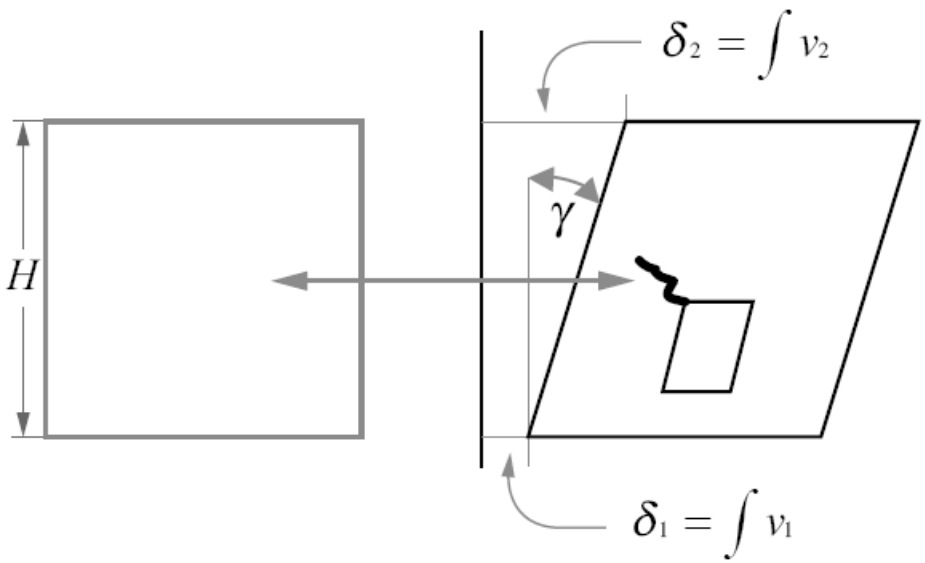


Figure 1-11 Structural response, measured by the time correlated difference of the displacement of the upper and lower wall corners, can be employed to calculate shear strain in the wall containing the crack for comparison with crack response.



Tensile Strain

$$\varepsilon \sim \gamma \sin\theta \cos\theta$$

Shear Strain

$$\gamma \sim \frac{(\delta_2 - \delta_1)}{H}$$

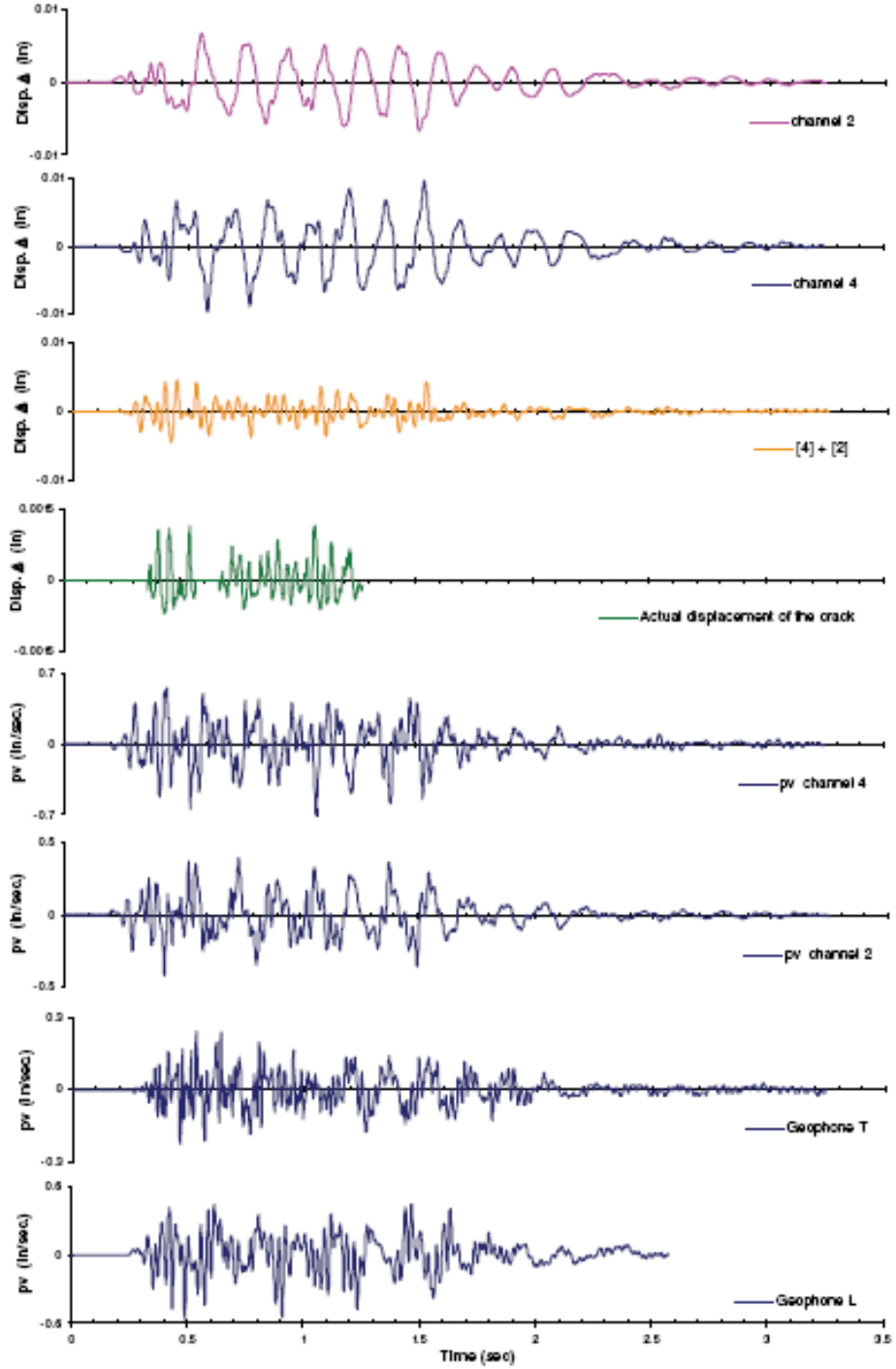


Figure 6-13 Time history of crack response to high (20 mm/s) peak particle velocity excitation motions can be reproduced from measured structural motions. (Louis, 2000)

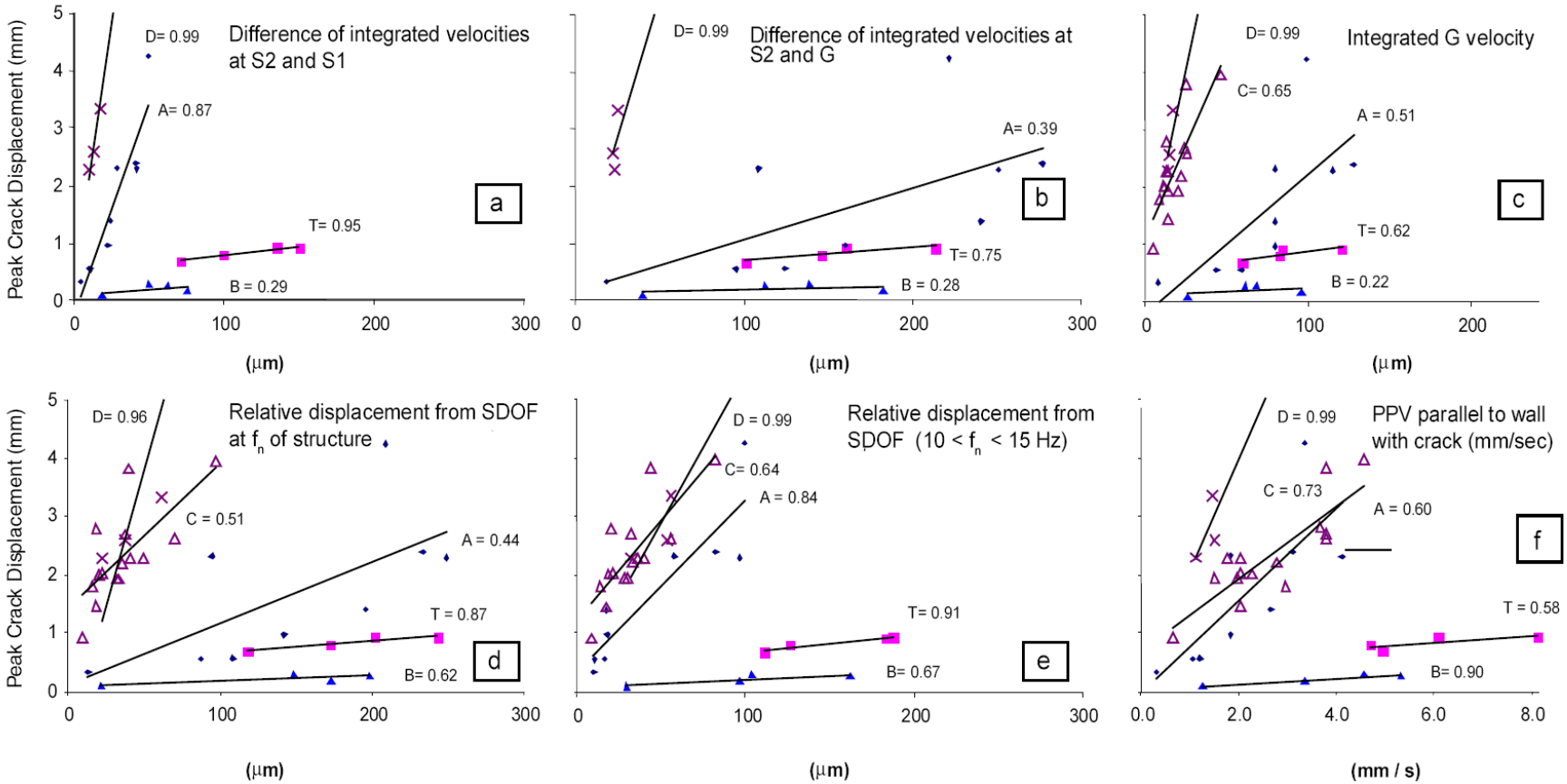


Figure 7-7 Comparison of peak crack displacement (y axis) with various measures that have been or could be employed to estimate structural response for the 5 instrumented cracks. These measures are described in the boxes and lines connect the trends of the responses of individual cracks. (McKenna, 2002). Crack response correlates best with relative displacement of wall ("a" above)

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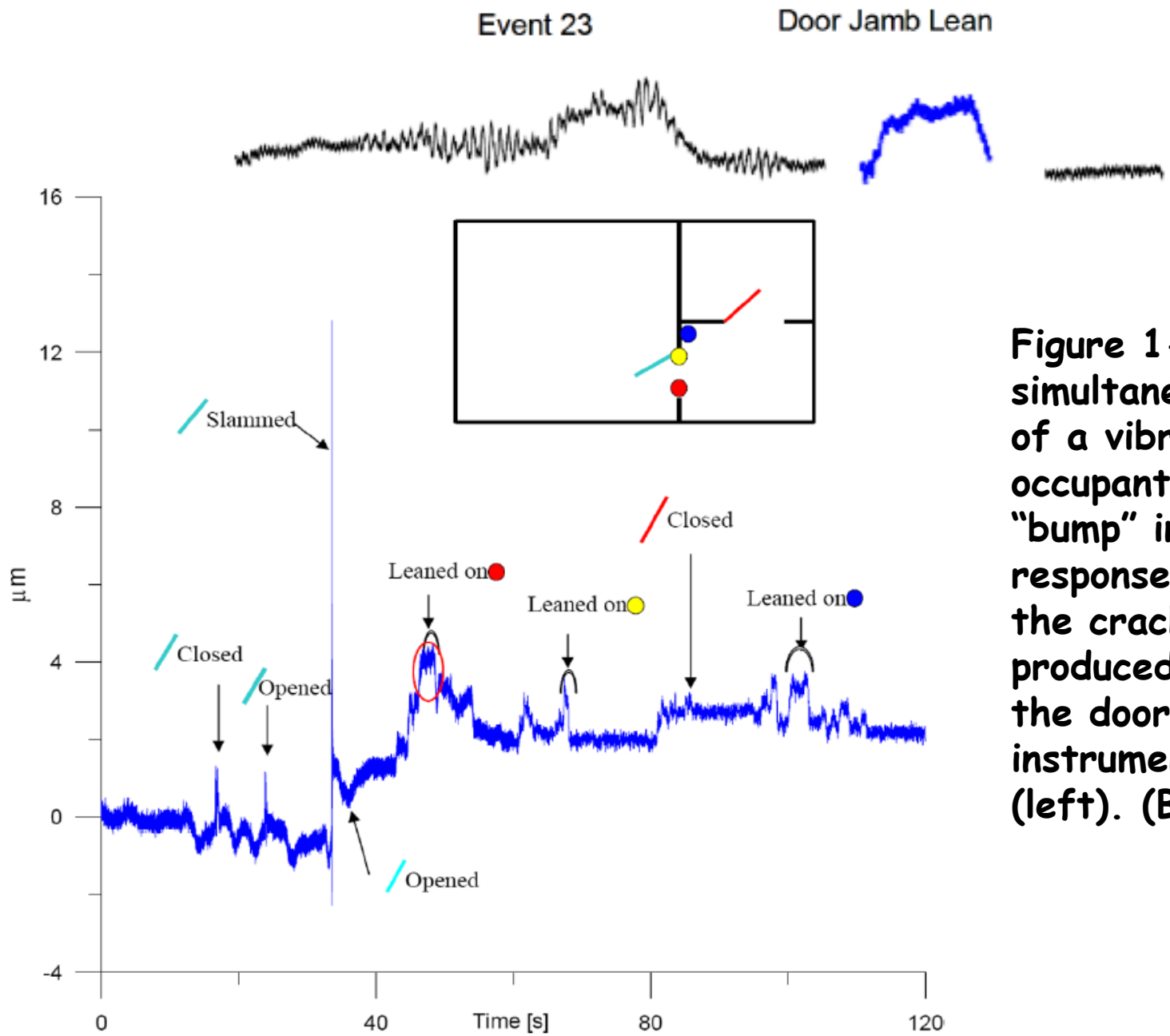


Figure 1-10 (above) The simultaneous occurrence of a vibratory event and occupant activity (large "bump" in the vibratory response) is compared to the crack response produced by leaning on the door jamb below the instrumented crack (left). (Baillot, 2004)

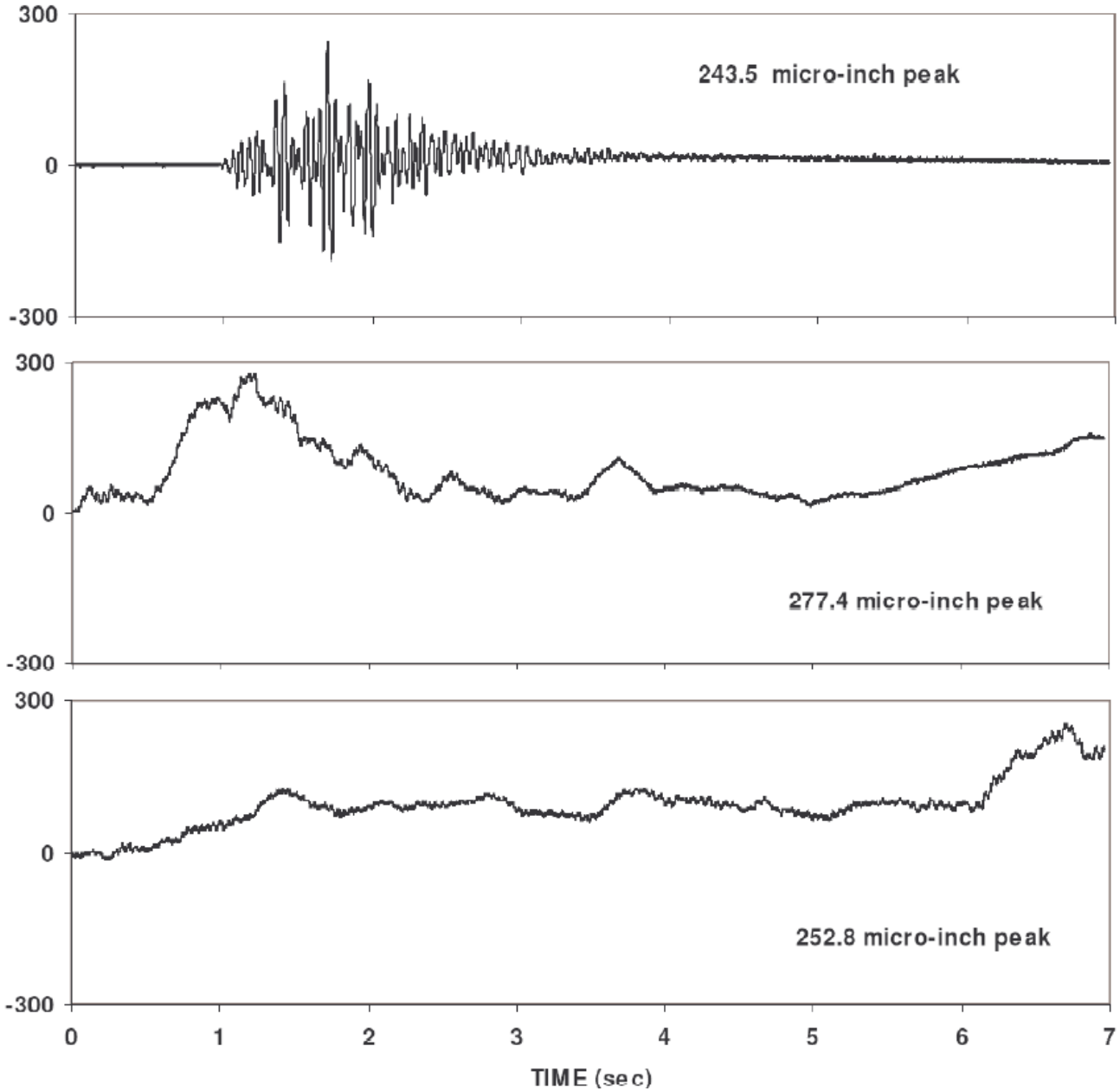


Figure 1-13 Comparison of crack response to ground motions at 80% of the control limit (upper time history) and wind gusts associated with average wind speed of 45 to 64 km per hour (28 to 40 mph) shows that wind storms can produce significant crack response. (AMA, 2005)

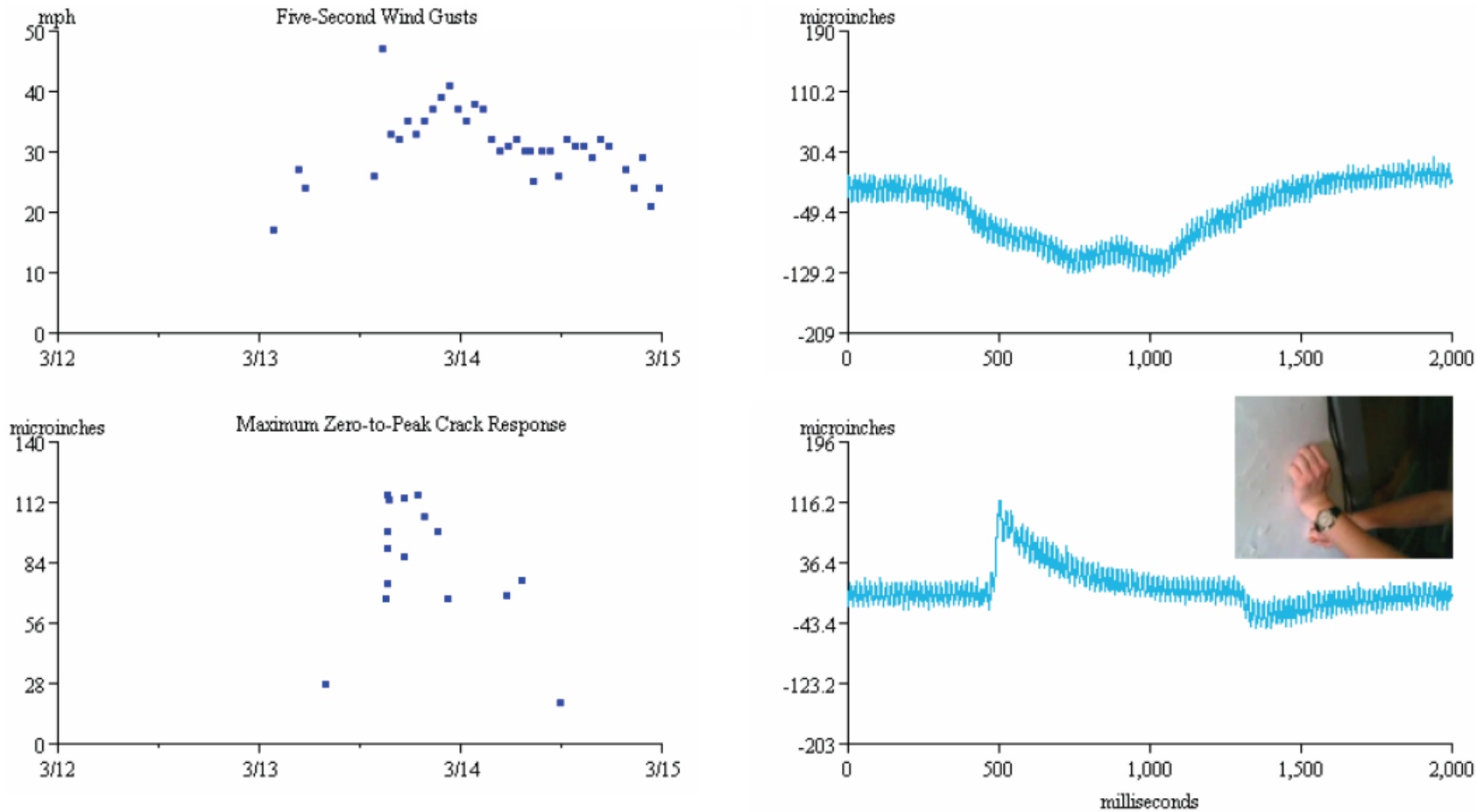
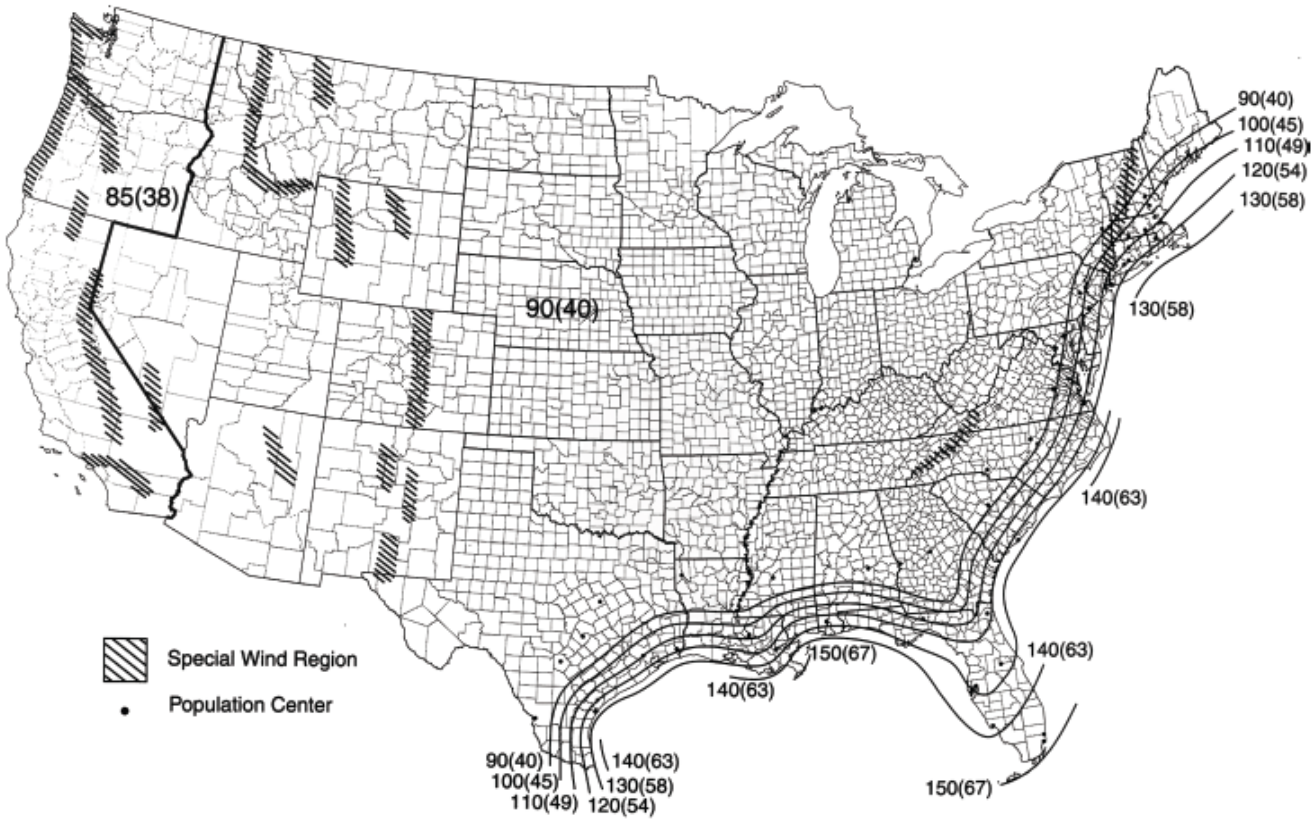


Figure 9-11 Comparison of event timing of wind gusts recorded at near by airport (left) with measured air over-pressure crack response events (right). Comparison of a wind gust event (top right) with occupant induced event (bottom right), confirm the same long period wind gust time history as observed in the Henderson test case.



Notes:

1. Values are 3-second gust speeds in miles per hour (m/s) at 33 ft (10m) above ground for Exposure C category and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is permitted.
3. Islands and coastal areas shall use wind speed contour of coastal area.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

Location	V mph	(m/s)
Hawaii	105	(47)
Puerto Rico	125	(56)
Guam	170	(76)
Virgin Islands	125	(56)
American Samoa	125	(56)

Figure 9-15 Map of United States showing wind speeds for the design of structures. These 150 km/hr (90 mph) design speeds greatly exceed the 48–80 km/hr (30-50 mph) wind speeds necessary to generate significant crack response. (VII, 2004)

Over a 10 year period in north central Tennessee wind storms (with multiple gusts) would produce maximum pressures of:

km/hr	*kPa*	*mph*	*psi*	*events*
48	0.112	30	0.016	20
64	0.196	40	0.028	10
80	0.308	50	0.44	3

An air over-pressure wave of 133 dB produces a pressure equivalent to 0.013 psi or 1.87 psf.

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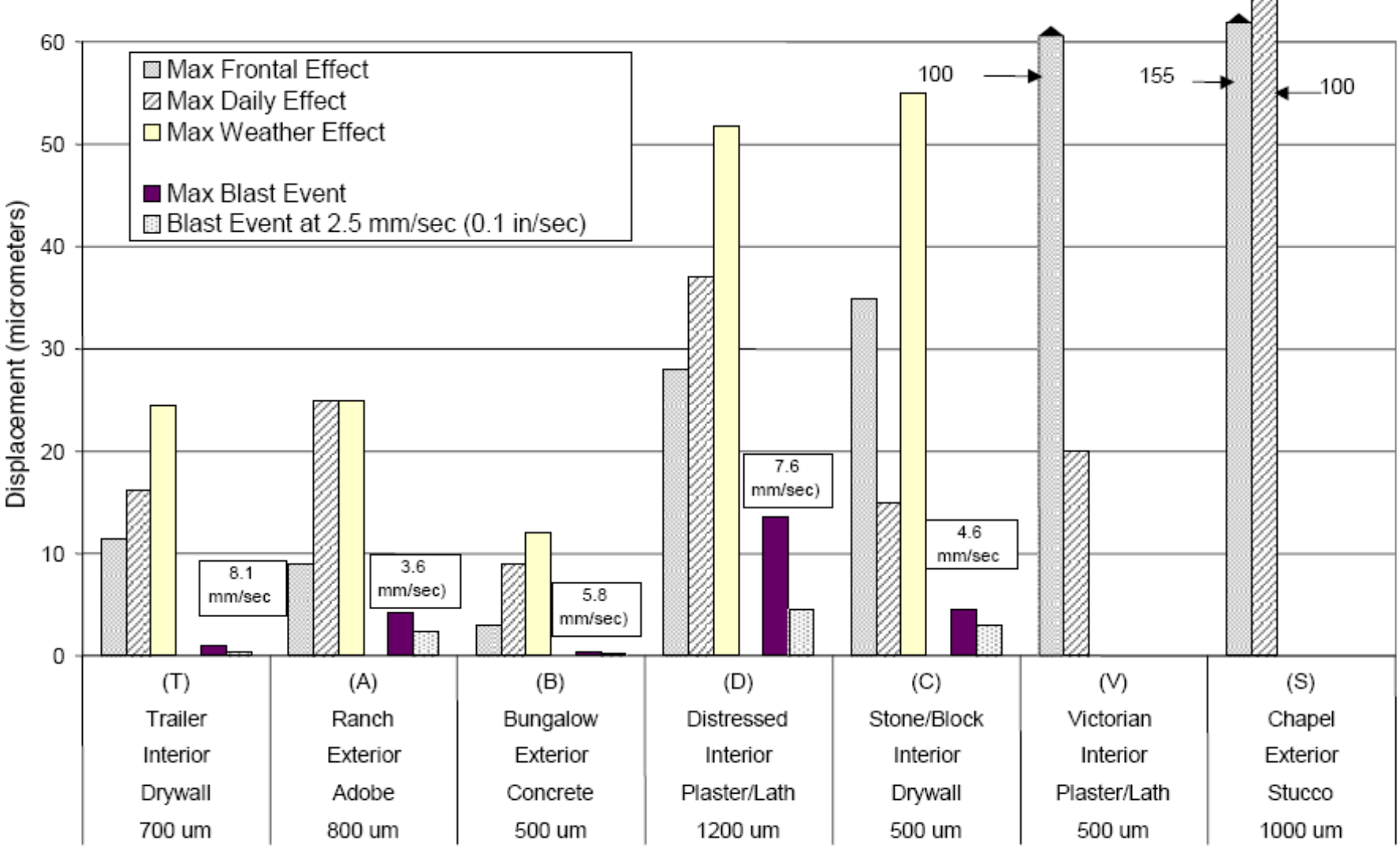
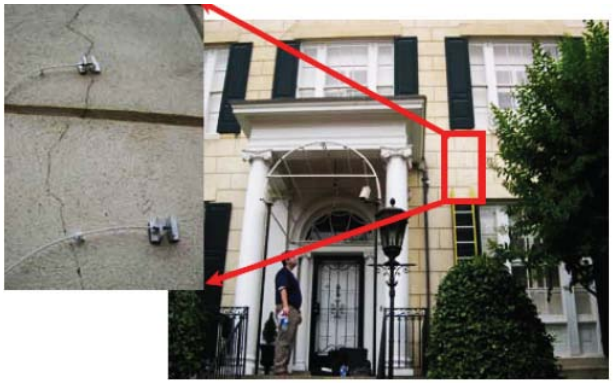


Figure 5-4 Comparison of 7 cases in bar chart form based upon simplification of long-term climatological response to define effects relative to weather patterns with a daily, ~weekly (frontal) and maximum shows the negligible effect of vibratory excitation. (McKenna, 2002)

Table 1-1 Comparison of Crack Responses to Environmental and Vibration Effects

Vibration Source / Structure location		Frame	Found-ation	Stories	Wall Ext.	Wall Int.	Obs. Time (weeks)	Crack Location	Sens Type	Crack Width (μm)	Max Crack Response[12]: Weather Season (μm)	Weather Max (μm)	Daily (μm)	Vibration (μm)	Max PPV (mm/s)	Max Air Pressure (db)	Comp-arison	Vibration /Max Weather[11]
Coal Mining																		
Evansville, IN	(EV)	w[1]	wo[2]	1	w/br[3]	dw[4]	0.2	i[5]-dw[4]-jt[6]	lvdt[8]				22		12.0		p-p[9]	0.160
									lvdt				58		12.0			0.160
Universal, IN	(UN)	w	b[2]	2	al/br[3]	dw	36.0	i-dw	ec[8]		75	75		13.0	20.0		p-p	0.173
Kittanning, PA	(KI)	t[1]	b	1	al[3]	?	0.7	i-dw	ec	700		24	16	0.9	8.1	119	[illegible]	0.038
Farmington, NM	(NM)	?	?	1	ad[3]	dw	5.0	e[5]-s	ec	800		9	25	4.2	3.3	117	0-p	0.168
Francisco, IN 1	(FN1)	w	b	1	al	pl[4]	0.4	e-bk-f[6]	ec	500		12	9	0.3	5.8	117	0-p	0.025
Francisco, IN 2	(FN2)	w	b	1	al	pl	0.3	i-pl	ec	1200		52	25	13.6	7.6	[illegible]	0-p	0.262
Wales, UK	(UK)	bk[1]	s[2]	1	s[3]	p	1.0	i-p	lvdt				>45					
Aggregate Quarry Blasting																		
Miami, FL	(MF)	bk	s	1	s	dw	8.0	e-s	ec				75	46.0	[illegible]		0-p	0.613
Ft Lauderdale, FL	(FL)	bk	s	1	s	dw	0.3	e-s	ec				72	0.7	11.2		p-p	0.010
								i-jt	ec				44	[illegible]	11.2		p-p	0.021
Franklin, WI	(FW)	bk	wo	1	st[3]	dw	>52.0	i-dw	ec	500	300	43		[illegible]	2.3		p-p	0.013
								i-dw	ec		300	132		9.0	2.3			0.030
								i-dw-c[6]	ec		300	134		7.0	2.3			0.023
Southbury, CT	(SC)	w	wo	2	w[3]	dw	6.0	i-dw-c	ec			211	[illegible]	2.9	9.0	132	0-p	0.014
								i-dw	ec			55	29	1.8	9.0			0.033
Albuquerque, NM	(AM)	w	s	1	br	dw	5.0	e-br	ec			[illegible]	38	13.4	7.3	122	p-p	0.141
Franklin, KY	(FK)	w	wo	1	br	dw	16.0	i-dw	ec		308			2.9	4.3		p-p	0.009
								i-bk	ec		18[illegible]			11.1	4.3			0.059
								e-br	ec				685	17.1	4.3			0.025
Glen Allen, VA	(GV)	w	cs[2]	2	w	dw	28.0	e-br-f[6]	ec			185	63	6.8	1.5		p-p	0.036
		w	cs	1	br	dw		i-dw	ec			382	80	29.2	2.4			0.076
Construction Equipment & Blasting																		
McAllen, TX	(MT)	w	s	1	br	dw	>12.0	i-dw-jt	[illegible]				900	75.0	25.0		0-p	0.083
								i-wd-b jt	lvdt				500	83.0	25.0			0.166
								i-dw	lvdt				500	83.0	25.0			0.166
								[illegible]	lvdt			975		125.0	25.0			0.128
Las Vegas, NV	(LV)	w	s	1	s	dw	28.0	[illegible](2)	lvdt			335	272	11.4	11.4		0-p	0.034
								i-dw(3)	lvdt			109	32	1.8	11.4			0.017
								e-s(5)	lvdt			394	254	2.5	11.4			0.006
Washington D.C.	(DC)	w	½b	4	s	pl	12.0	i-pl	ec			141	28	7.1	4.1		0-p	0.050
								i-w	ec			287	33	1.4	4.1			0.005
								e-s	ec			220	160	4.0	4.1			0.018
Henderson, NV	(HV)	w	s	1	s	dw	4.6	e-s	ec			100	75	2.8	1.1		0-p	0.028
		w	s	2		dw		e-s	ec			62	38	6.1	11.4			0.098
Albuquerque, NM	(AN)	w	s	1+	s	dw	11.0	es	ec			394	263	124.0	9.3		p-p	0.315
Without Vibration																		
Evanston, IL	(IE)	w	b	3	w	pl	12.0	i-pl	lvdt			25						
								i-pl	lvdt			10						
								i-pl	lvdt			250						
Minneapolis, MN	(MM)	[illegible]	b	3	s	dw?	17.0	i-dw?	lvdt	1000		217	100					
								e-sb	lvdt			107	57					

[1]w=wood, t=trailer, bk=block,
[2]wo=walkout basement, b=basement, s=slab
[3]w=wood, br=brick, s=stucco, al=aluminum
[4]dw=dry wall, pl=plaster & lath, p=plaster
[5]i=interior, e=exterior
[6]jt=dw joint, c-ceiling, f=foundation,
[7]fp=fire place
[8]lvdt = lvdt sensor, ec = eddy current sensor
[9]p-p = peak to peak, 0-p = zero to peak
[10]Direct from Table EV-1 assuming maximum ppv of 12 mm/s
[11]Max Weather = maximum of Season, Max or Daily response
[12]Max = maximum of frontal or maximum observed



Sampling of the more than 20 structures instrumented to date

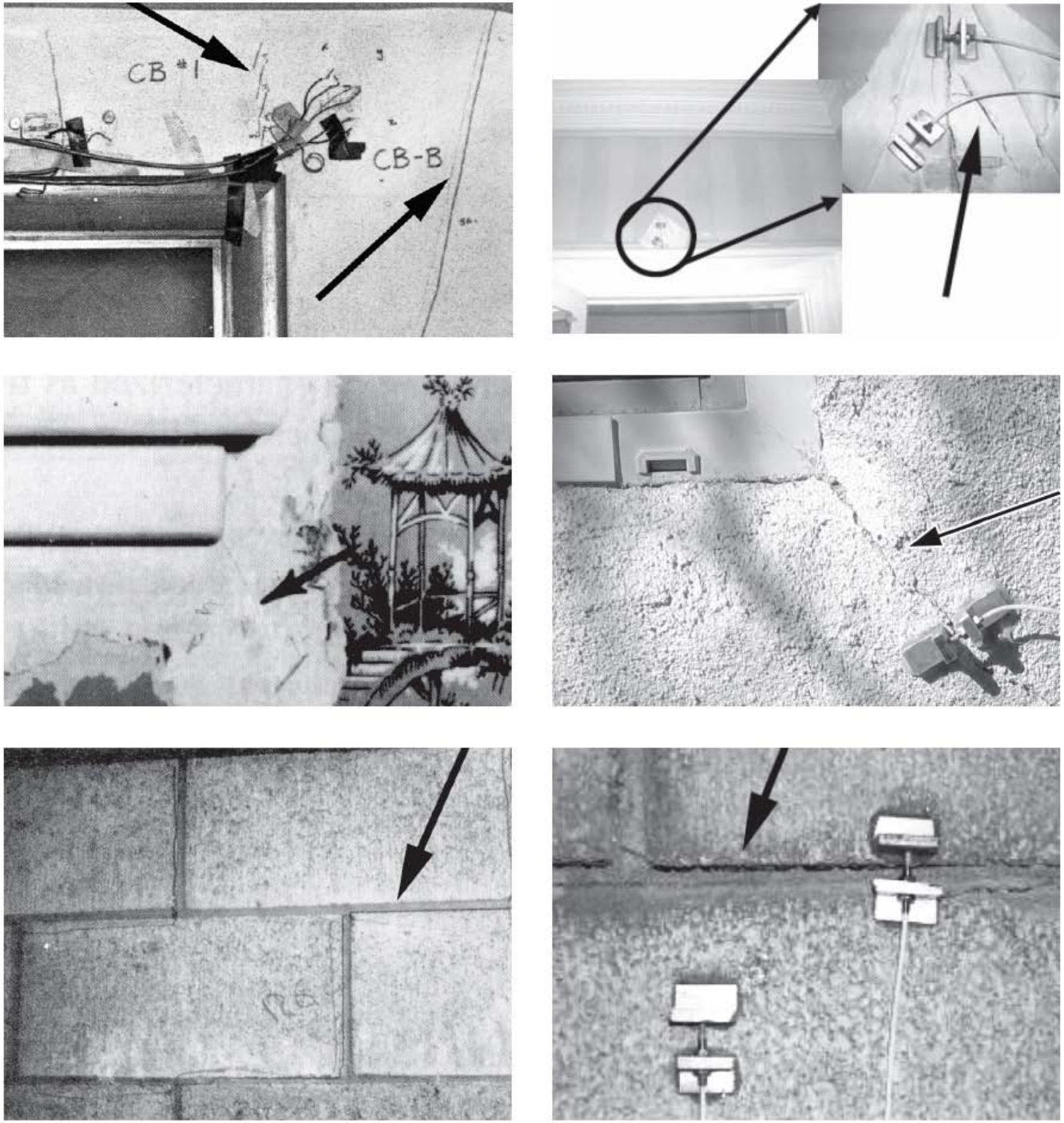


Figure 2-1 Comparison of vibration induced cosmetic cracks (left column) with non blast-induced cracks monitored in this study (right column) shows their similarity. PPV's inducing the cracking for the left (top and bottom) were 225 and 172 mm/s.

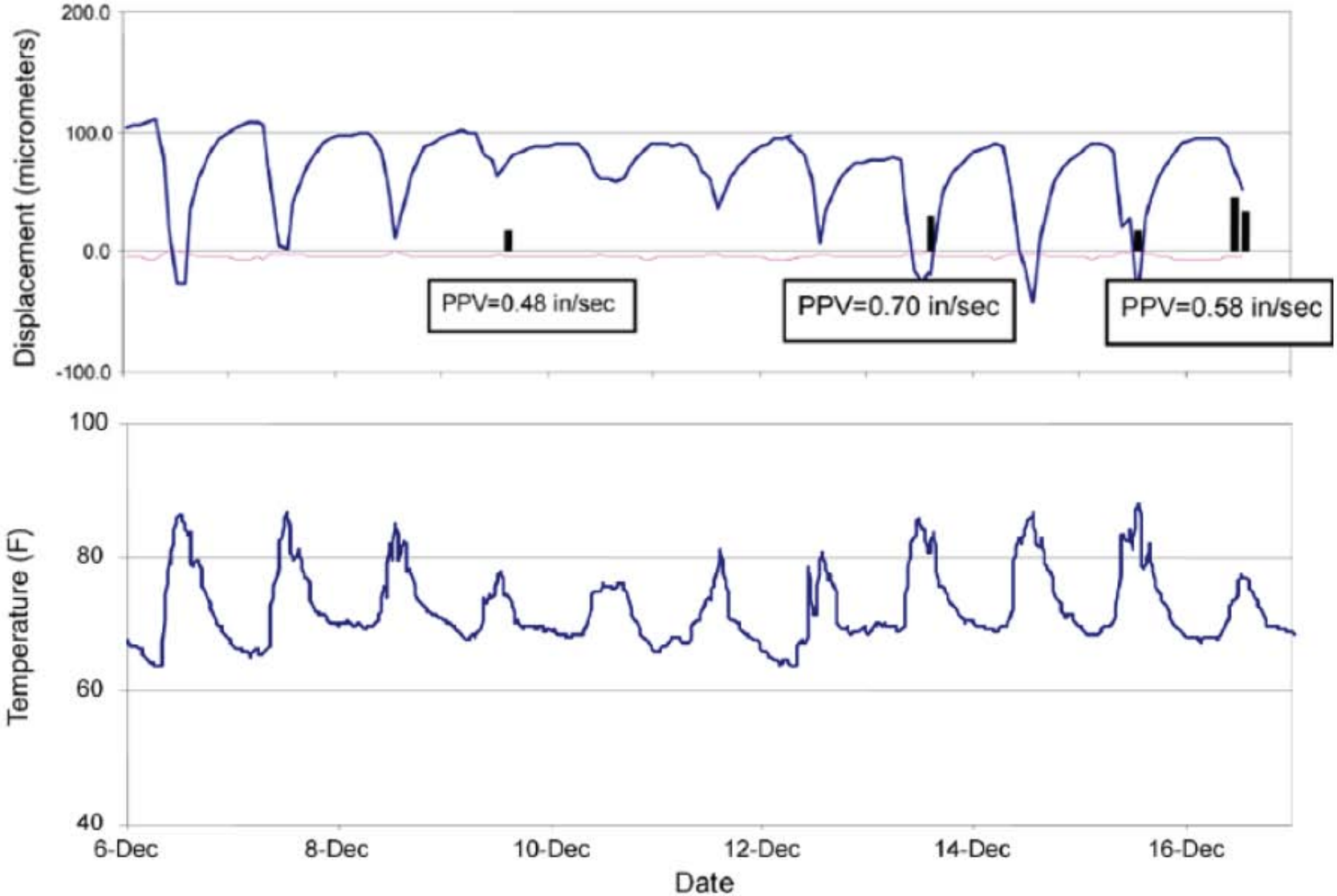


Figure 2-2 Continuity of pattern of crack response despite blast excitation of more than 12 mm/s (0.48 ips) demonstrates overwhelming nature of natural climatological effects. (Louis, 2002)

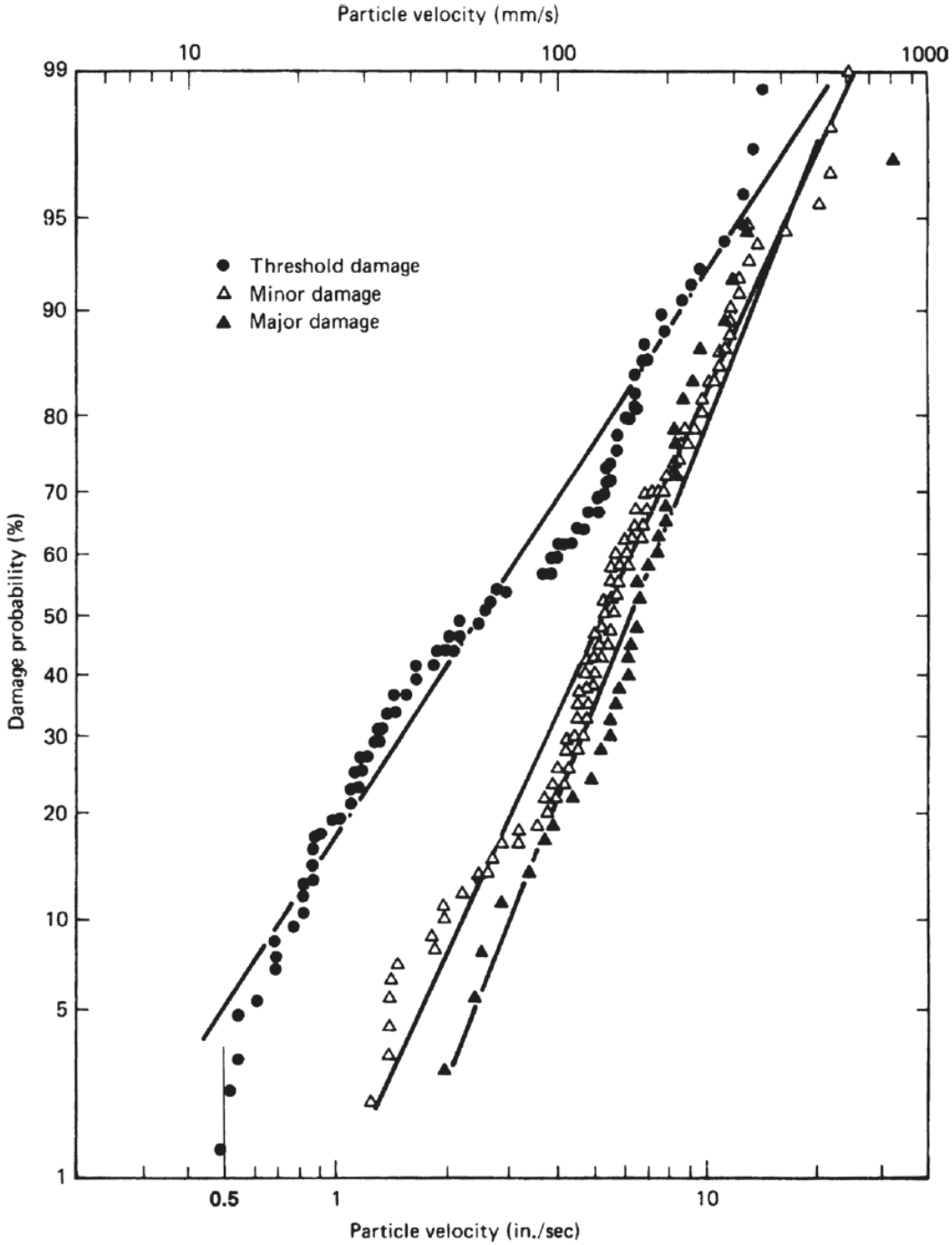


Figure 2-7 Probability of threshold or cosmetic cracking demonstrates the absence of data below 12 mm/s or 0.5 ips and leads to conclusion of zero probability of cracking below 12 mm/s for even low frequency excitation. (Siskind et al, 1980)

Micrometer Crack Response
Substantiates Vibration Control Limit Conservatism

Measurement of Micro-Meter Crack Response

Principles of System Operation

Structural Response

Occupant Activity & Wind

What Do These Measurements Mean?

Integration with Other Systems

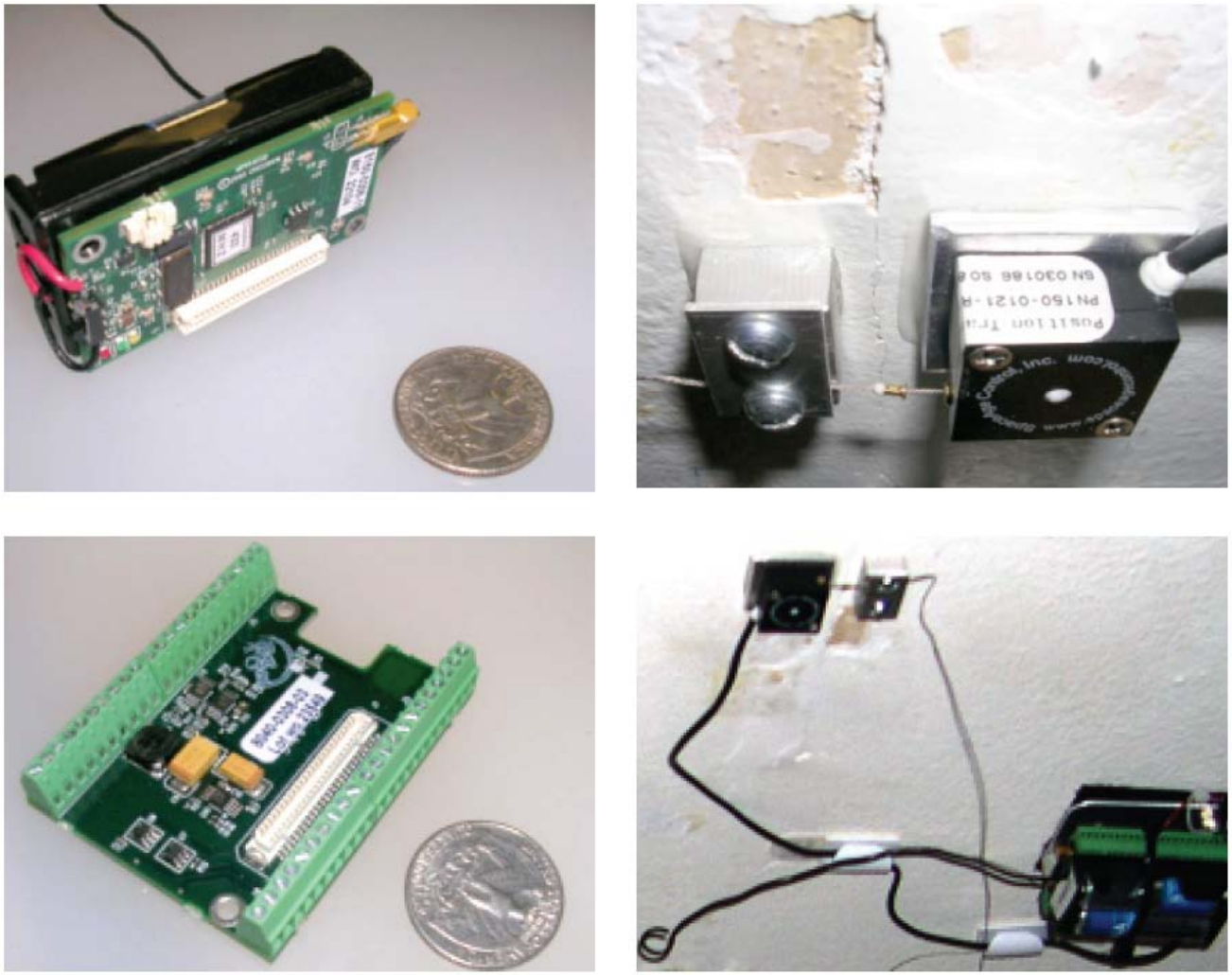


Figure 1-14 Components of wireless ACM units the size of a deck of playing cards eliminate the need for wires shown in Figure 1-1. Clockwise from lower left: sensor adaptor, data logger and communications, displacement sensor, combined units in place across a crack. (Dowding, Ozer and Kotowsky, 2005)

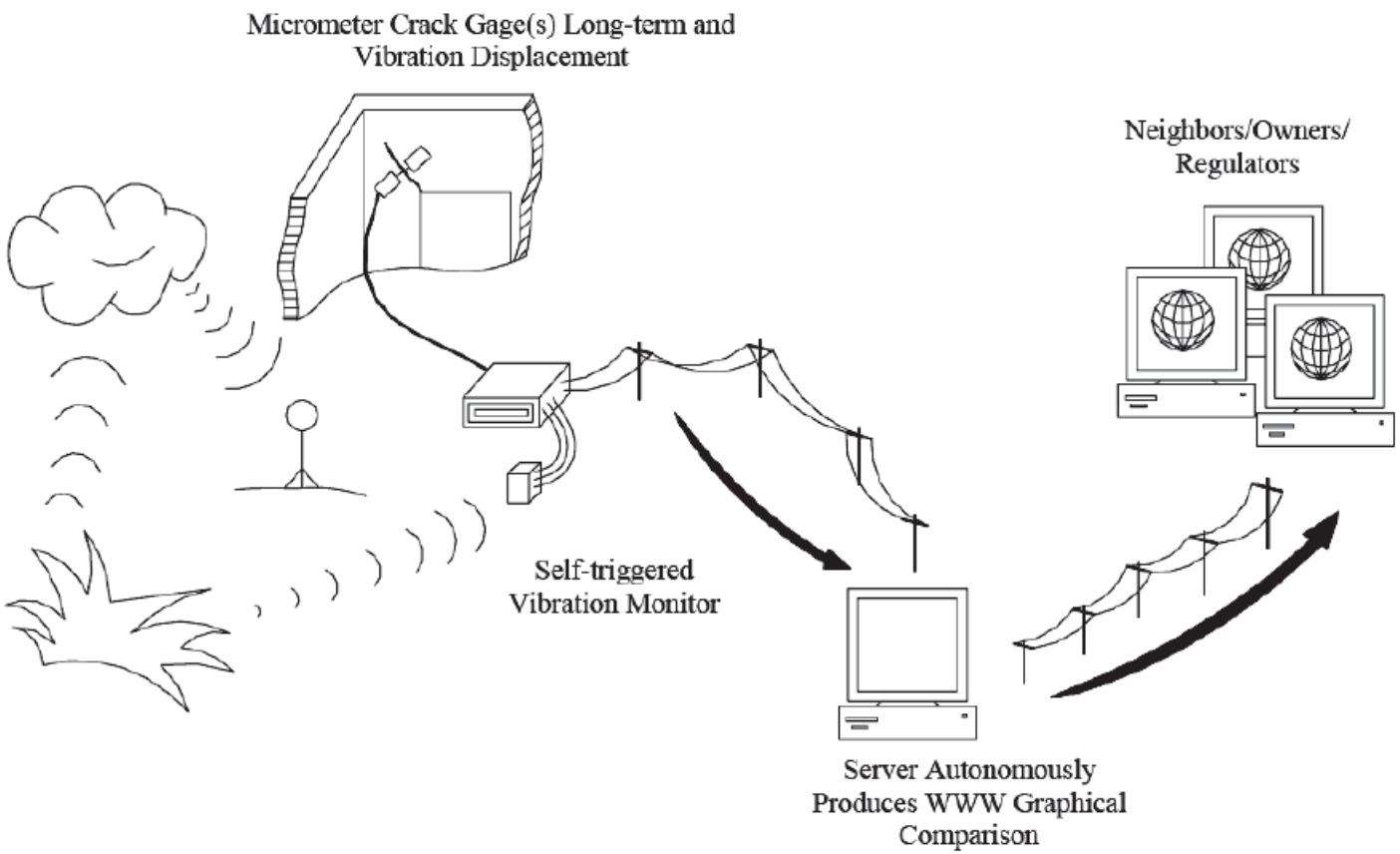


Figure 1-2 Autonomous Crack Measurement (ACM) in its most communicative form involves automatic 1) measurement of vibratory crack response and ground motion as well as long-term environmental response (left), 2) telecommunication of the data to the central computer (center) for 3) storage and processing, and 4) linkage to the internet for viewing by anyone with a password (right).
(Dowding and Siebert, 2000)

Figure 1-15 Comparison of graphics in ACM thesis (left) and mid 1980s study (right) that required several weeks and eight months respectively to condense and graph demonstrates the efficiency of collecting data via autonomous systems. (Siebert, 2000)

Figure 1-16 ACM web site provides access to reports as well as archived and on-going projects: http://www.iti.northwestern.edu/acm.

Concept of Autonomous Crack Measurement (ACM)

Measures crack response, a major source of homeowner anxiety
Augments regulatory measures of ground motion
Avoids complexity of ground motion
Measures response of the same crack to
both long term (climatological) and dynamic (vibratory) effects
Integrate with internet display to enhance community interaction

Conclusions

Climatological crack response overwhelms vibratory response for
both typical (~ 2.5 mm/s) and regulatory (< 12 mm/s) PPV's
Large climatologically induced crack response occurs more often than
maximum vibratory response
Since climatological response is larger than vibratory response at
12 mm/s and occurs more often, restriction to
current control limits produces less effect than nature.
Crack response follows strains in walls and structural response
Wind induces large crack response