COMPARISON OF MICRO-INCH IN-PLANE AND OUT-OF-PLANE RESPONSE OF CRACKS TO BLAST VIBRATION AND WEATHER

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ABSTRACT

Most studies of crack response have focused on opening and closing of a crack in the plane of the wall in which the crack occurs. Crack movement also occurs perpendicular or normal to the plane of the wall. This paper will examine and compare the in-plane and out-of-plane (normal) response of cracks in two different residences near limestone quarries. In two locations, sensors that measure in-plane and normal displacement were installed side-by-side on the same crack, allowing direct comparison of the two modes of response. In a third location, a perpendicular pair of displacement sensors was installed in a corner of a room to observe the bidirectional response of the structure at a corner. Both long-term and dynamic data were recorded with the same sensors; temperature, humidity, and air over pressures were also recorded to compare blast and weather effects. Measurements show that ratios of out of plane to in plane response to dynamic events can vary. However, the ratios of out of plane (normal) response to vibratory events to that of climatological change is still as small as the ratio for in plane crack responses.

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1. Background

To fully define crack response, it is important to consider all three directions (A,B,C) in a which a crack may displace as shown in an isometric view of a room in Figure 1. Autonomous Crack Measurement (ACM) studies have focused primarily on opening or closing perpendicular to the orientation of the crack in the plane of the wall containing the crack; direction "A". Direction "B" (shearing in the direction of the crack) also lies in the plane of the crack; but is parallel to the long axis of the crack. Crack opening and closing has been employed as the index of crack extension.

This paper describes measurements of crack response in the direction C, perpendicular to the plane of the wall containing the crack. Such "out of plane" measurement required development and qualification of a new technique for mounting the displacement sensor (Waldron, 2006). Crack faulting, or deformation perpendicular to the plane of the wall may result from a number of different effects, wall or floor bending, differences in responses at junctions of different materials or different construction techniques, etc.

Development of a technique to measure perpendicular response also lead to the ability to measure crack responses in a concave wall corner, which will also be described in this paper. Figure 1 illustrates the opposing directions of measurement at the wall corner, x (east and west) and y (north and south). Concave wall corners automatically provide the perpendicular surface needed to measure out of plane motion in the middle of the wall.

A crack at a material interface of a doorway provided another opportunity to measure unique out of plane crack response. This situation is also shown in Figure 1. Here a large crack was produced by the response of a lightly attached interface between a wooden door-frame and a concrete masonry wall. This type of interface will obviously be heavily affected by the impact produced by opening and closing of the door within inches of this weak interface.

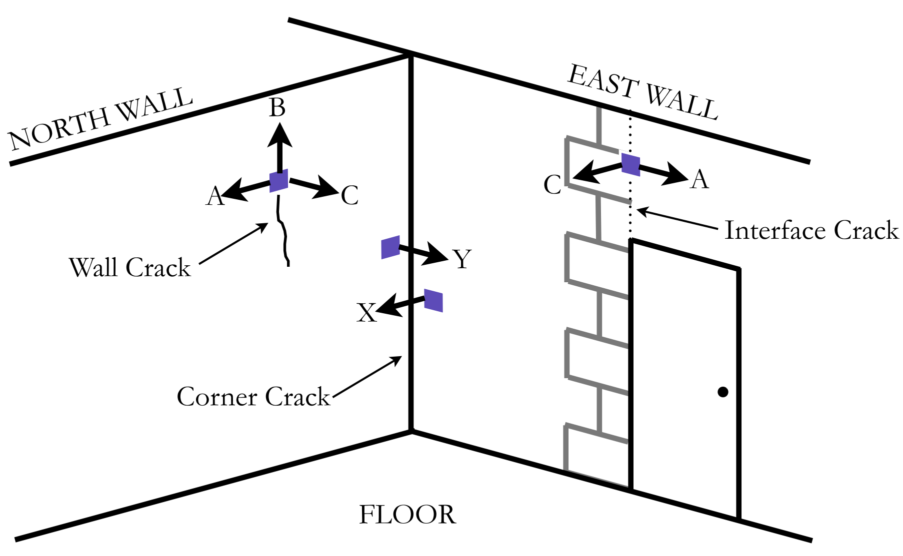

Figure 1 - Idealized room with cracks, corners and interfaces to illustrate locations of multidirectional crack sensors and their orientation

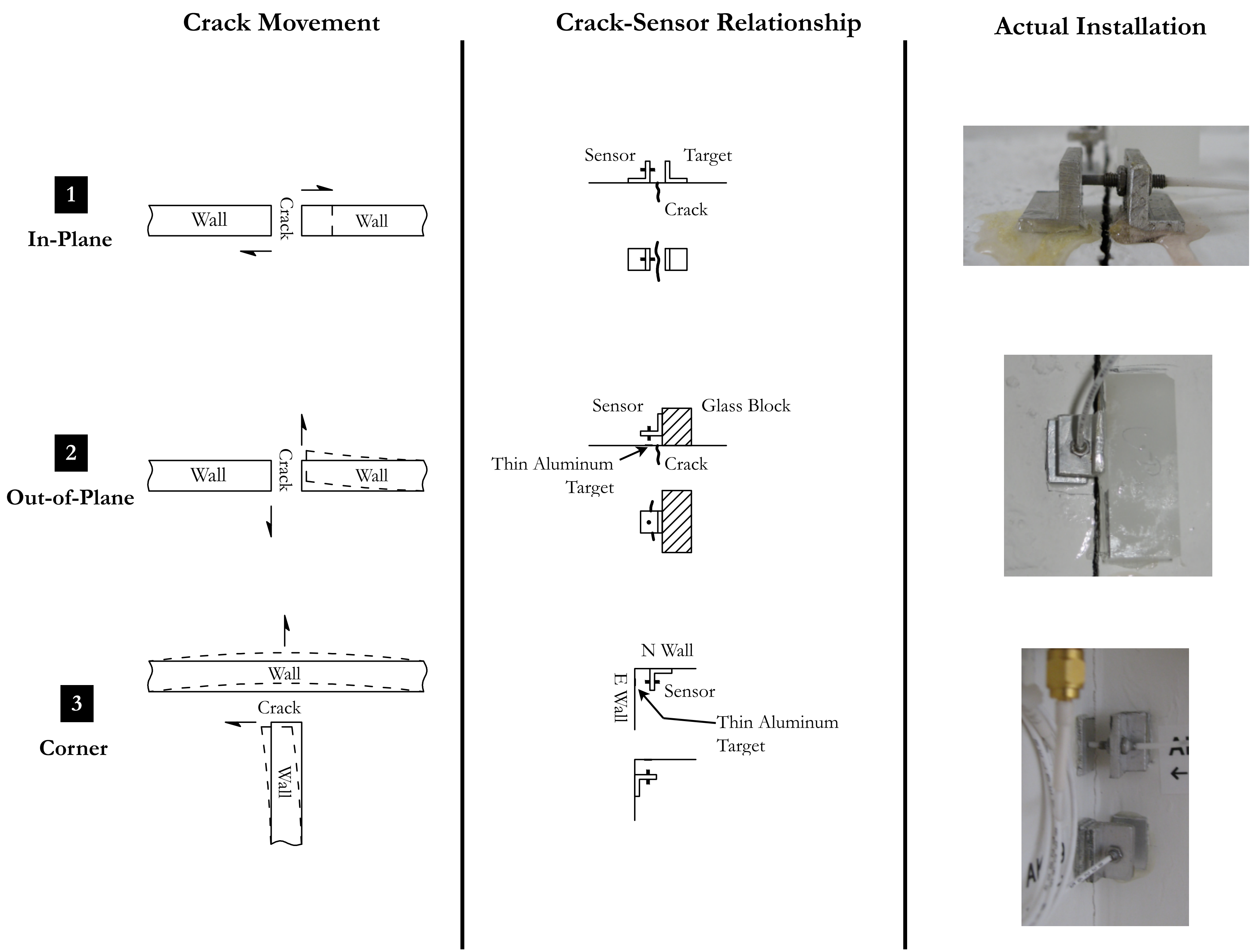

Figure 2 - Comparison of the differing deployment geometries for measurement of crack geometry - TOP: crack open/close in the plane of the wall - MIDDLE: crack distortion perpendicular to the plane of the wall - BOTTOM: two directions of corner crack distortion.

2. Details of Sensor Construction

Geometries of the three differing crack responses and sensor deployment (1) in-plane, (2) out-of-plane, and (3) corner are compared in Figure 2. Crack responses are all measured with Kaman displacement gauges for consistency. The most often deployed -- in plane -- installation is illustrated in the top row of Figure 2 with the crack response on the left, sensor and crack relationship in the middle and photograph of the actual installation on the right.

Out of plane crack response and the relationship of crack and transducer is shown in the middle row of Figure 2. Since movement out of the plane of the wall must be measured, the sensor must be oriented perpendicular to the wall. This orientation required a perpendicular attachment surface, which is provided by a glass block. Glass was chosen for the block because of its low coefficient of thermal expansion. The non-crack side of the glass block serves as a mounting surface for the null sensor, which was not shown in this photograph but is on the lower right of Figure 4. See Waldron (2006) for further details). A thin aluminum plate that is glued to the wall across the crack from the glass block replaces the large "L" shaped target employed for in plane measurement.

Corner crack response, crack-sensor relationship, and photo are shown along the bottom row of Figure 2. Since it is not known in which direction response is greatest, both must be measured, which requires two transducers as shown. As with the out-of-plane deployment, the target can be placed directly on the opposing wall.

3. House/Crack Descriptions and Vibration Environment

Measurements described herein were made in two houses whose photographs and floor plans are shown in Figure 3; one near Naples, Florida and the other near Milwaukee, Wisconsin. The Florida house contains the corner crack and the interface crack. It is a slab on grade structure, whose exterior, stucco covered walls are built with concrete masonry units (CMU), and interior walls were most likely constructed of wood and gypsum drywall. The Wisconsin house contains a ceiling crack across which both in and out of plane responses were measured. It is also built with exterior CMU with wood and gypsum drywall interior walls, but is founded on a full basement. Locations of the cracks are shown in the plan views of the structures.

Context (left) and details (right) of the installations are shown in Figure 4. In the Florida house both cracks occur between two differing materials. The corner crack in the living room, shown in the top row, occurs at the concave corner between the CMU-stucco north wall and the perpendicular wood stud and gypsum drywall west wall. The interface crack in the kitchen-garage door shown in the middle row in Figure 4 also occurs between the CMU wall on the left and the wooden, door frame and wall on the right. Both in and out of plane responses were measured across this highly responsive interface crack. The large response of this interface upon door closings in the house is indicative of the ineffective connection between the two components. In and out of plane response was measured in the ceiling crack in the Wisconsin house shown along the bottom row of Figure 4. This crack occurs at the center of an unusually long span ceiling constructed of the traditional wooden joists and drywall ceiling.

Both structures are located adjacent to surface limestone aggregate mines, which require blasting. The Florida house is located some 3000 to 5000 ft from shots with 30 to 50 holes, each loaded with 50 to 60 lbs of explosive (Kosnik, 2009). These detonations produce ground motions with peak particle velocities of some 0.05 to 0.18 ips with dominant frequencies between 5 and 33 Hz. The

Wisconsin house is located some 1500 to 2000 ft from the quarry detonations that produce ground motions that vary between 0.05 and 0.25 ips with dominant frequencies between 10 and 30 Hz.

Figure 3 - The two houses near Milwaukee, Wisconsin (left) and Naples, Florida (right) containing the specialized crack instrumented in this study; top photographs; bottom plan views showing sensor locations

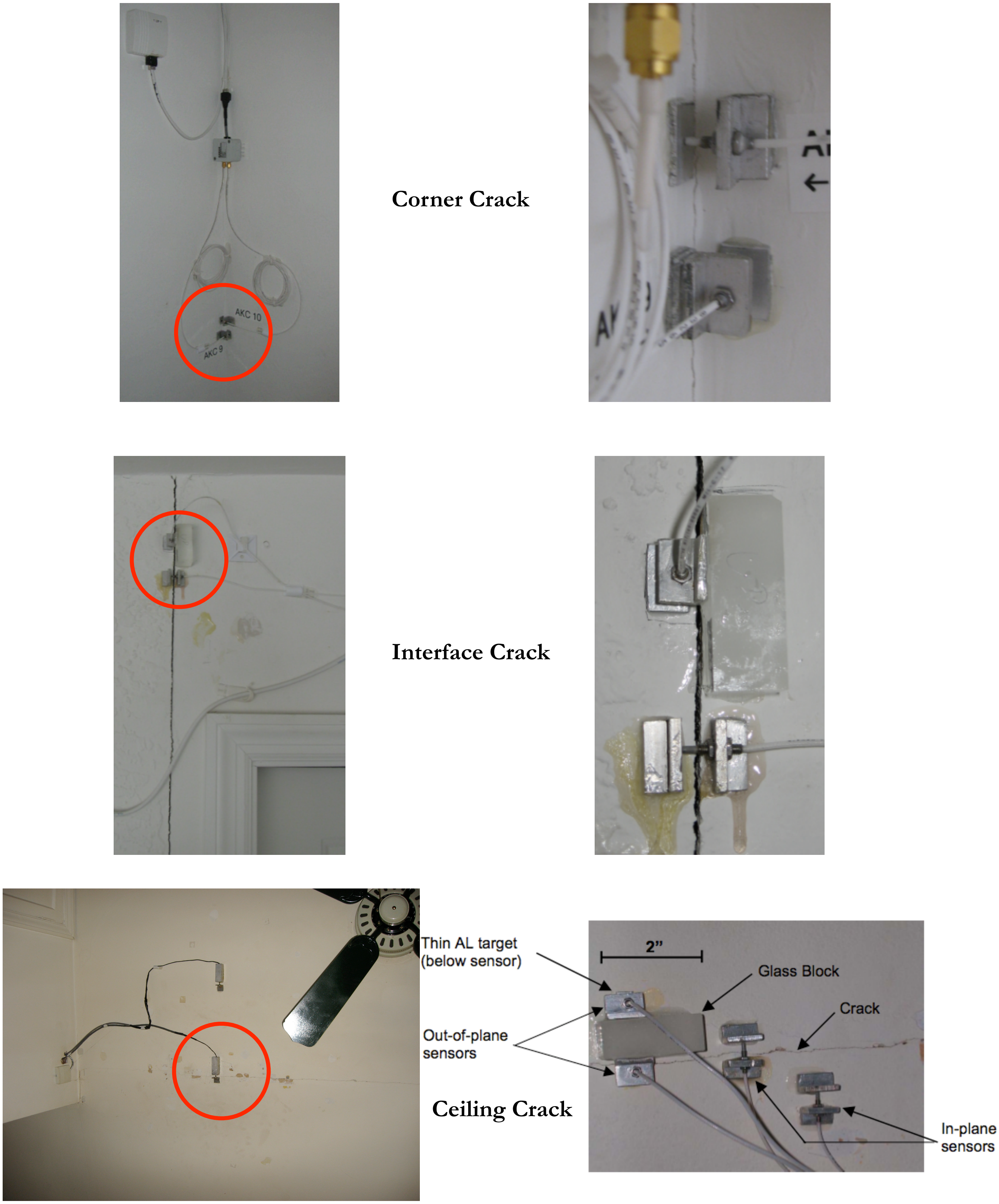

Figure 4 - Installed details of crack perpendicular sensors installed in Florida house in corner (top) and across CMU-door frame interface (middle) and Wisconsin house across ceiling crack.

4. Comparison of Climatological and Vibratory Responses

Perpendicular responses of the three cracks to climatological effects are compared in Figure 5. The top two pairs are those from the Florida house. The two responses of the CMU-wooden wall and door-frame interface are at the top and the two CMU-wooden wall corner crack responses in the center. Null gauges were not installed in Florida, as the small null responses shown in the Wisconsin house at the bottom were assumed to be the same in Florida and thus inconsequential.

Responses for a typical time span of ten days are displayed at the same day "time" scale. Response scales (in the vertical direction on the graphs) are the same for the two Florida cracks for comparative purposes, while those for the Wisconsin ceiling crack were enlarged to display the relatively small response perpendicular to or out of the plane of the wall. It is unusually small in absolute amplitude. Thus in the Wisconsin case, use of the null gauge is helpful given it's small response. The only other case where such small daily crack response was observed was for a CMU crack in the foundation block of a house with no basement (Dowding & McKenna, 2005). As found in past studies, daily crack response is defined as the difference between the hourly reading and the 24-hour central moving average (thin black dotted in all crack response time histories).

Several observations can be made regarding these 10 days of data. For a frame of reference, this is a small time span and thus does not capture large weather front induced responses or even yet larger seasonal responses. Out of plane responses to climatological effects do not seem to be larger than the in plane responses, although more cracks need to instrumented to see if this is always the case. They may not even be large in an absolute sense, as shown by the Wisconsin example where the out of plane daily response was small on an absolute scale. Second, the out of plane crack responses are variable. Ratios or out of plane to in plane responses for the non-corner cracks were 0.6 for the Florida crack and 0.2 for the Wisconsin crack.

Dynamic response time histories of crack response to both blast induced effects and occupant activity are shown in Figures 6,7 & 8. Figures 6 & 7 present dynamic responses for the kitchen-garage door frame interface crack and the corner crack respectively. The ground motion and air overpressure excitation time histories are shown as the upper four time histories for each of the three crack responses. While the air overpressure time history is not translated to psi units for the Wisconsin case, Figure 8, (our sensor was not calibrated at the time) it is added to show that the large, low frequency crack response results from air overpressure interaction. The Florida house, despite similar, CMU wall construction, does not respond to the air overpressure.

Responses to occupant activity, shown at the bottom of Figures 6,7 & 8, is high for all three cracks. For Florida, the door being opened and closed is some 20 to 30 feet away from the cracks. Both cracks respond more to the door opening than they do to ground motion with a peak particle velocity of 0.18 ips or air over pressures of 0.007 psi or 130 dB. For the Wisconsin house, the door is in the same room as the crack, so it is closer than the Florida example. Yet it is not on the same wall since the crack is in the ceiling. In the Florida case, opening the distant door creates the largest response, whereas in the Wisconsin case, closing the door produces the largest response.

Vibratory responses of the cracks to typical ground motion excitation shown in Figures 6-8 are smaller than the responses to long term or climatological effects as has been measured in past studies. Both in plane and out of plane vibratory responses are less than the climatological responses. When "in plane" climatological responses are larger than those out of plane, the "in plane" vibratory responses are the largest. When "out of plane" climatological responses are larger than those in plane, the out of plane vibratory responses will be the largest as well.

Response to air over pressures varies as well. The corner crack and door-CMU interface in the Florida house responded most to the ground motions and very little to the air overpressure. On the other hand, the ceiling crack in the Wisconsin house most often responded more to the air overpressure than to the ground motion as shown in Figure 8. This response to air over pressure events occurs for natural events as well as shown for responses to wind gusts in Figure 9. Here wind gust responses and air pressure transducer output are plotted vs time. Response data were acquired continuously at 10 samples per second for 20 hours during a windy period where 5 second average wind speeds exceeded 30 miles per hour recorded at an airport 5 miles distant. For these extended periods of time, responses of the crack to wind pressure in the out of and in plane directions were similar ~ 100 μ in. Again the air overpressure transducer output is relative and was not calibrated in pressure units.

Crack responses to vibratory ground motions, occupant induced activity, and climatological effects are compared more succinctly by the bar graph for each set of cracks in Figure 9. As has been the case for in plane responses in other studies (Dowding, 2008), out of plane crack responses are the largest for climatological effects for even the short, 10 day time spans shown in Figure 5. The maximum daily weather responses are the maximum response minus the 24-hour rolling average. These out of plane maxima are some 10 times greater than those produced by ground motions and air over pressure associated with a peak particle velocity of 0.18 and 0.07 ips for Florida and Wisconsin cracks. The out of plane motions were similar to those produced by closing (not slamming) the non-adjacent doors. The door in Florida was in another room and in Wisconsin the door was between the instrumented room and the adjacent kitchen as shown in Figure 3.

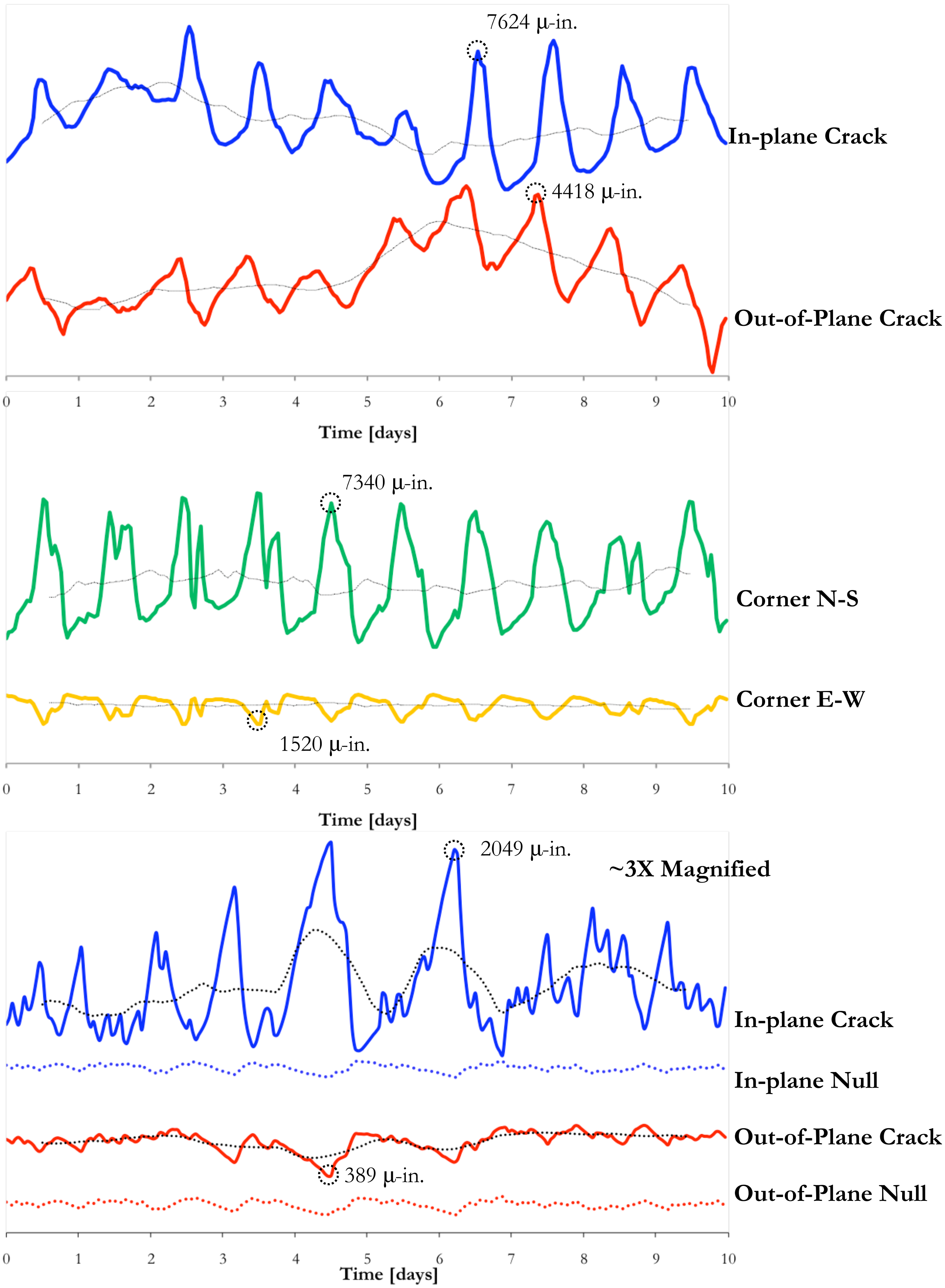

Figure 5 - Comparison of ten days of climatologically induced perpendicular responses of Florida interface crack (top), corner crack (middle), and Wisconsin ceiling crack (bottom). Vertical scales for Florida responses are the same and that for Wisconsin is expanded to show the small null response.

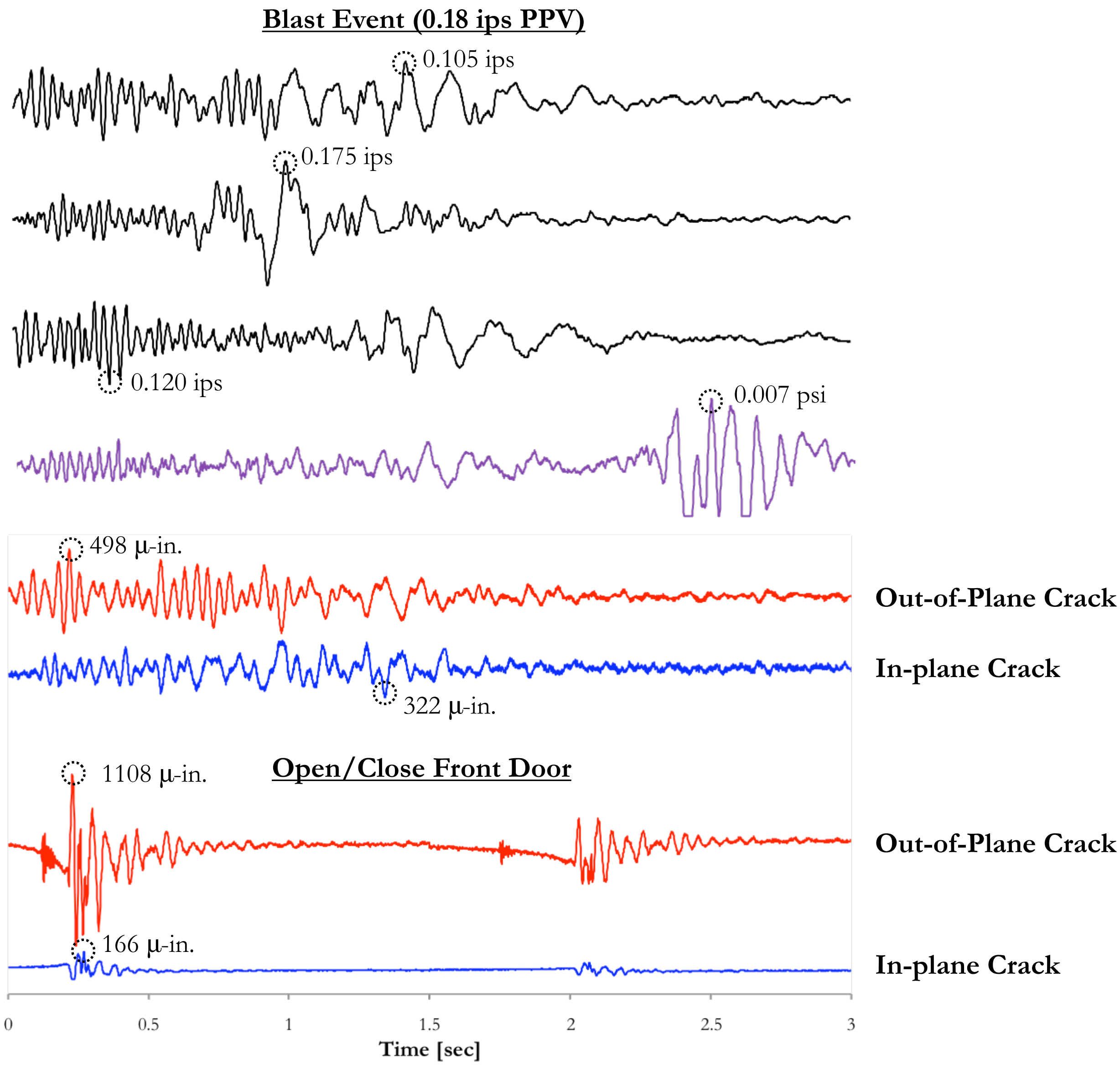

Figure 6 - Comparison of perpendicular crack responses of the Florida CMU-door frame to a blast event (0.18 ips PPV) with response to opening and closing of a distant front door

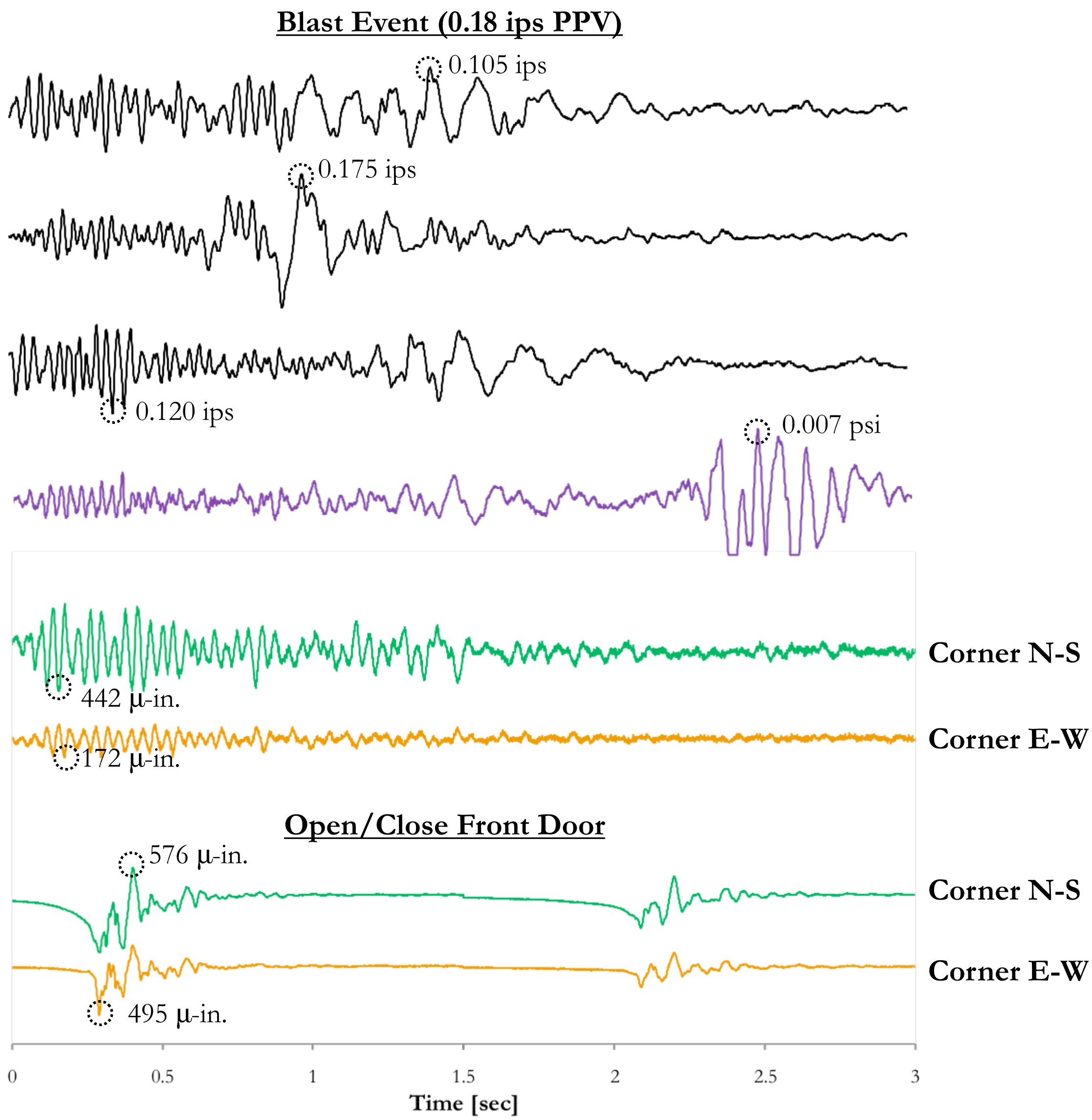

Figure 7 - Comparison of Florida perpendicular responses of the corner crack to a blast event (0.18 ips PPV) with response to opening and closing of a distant front door

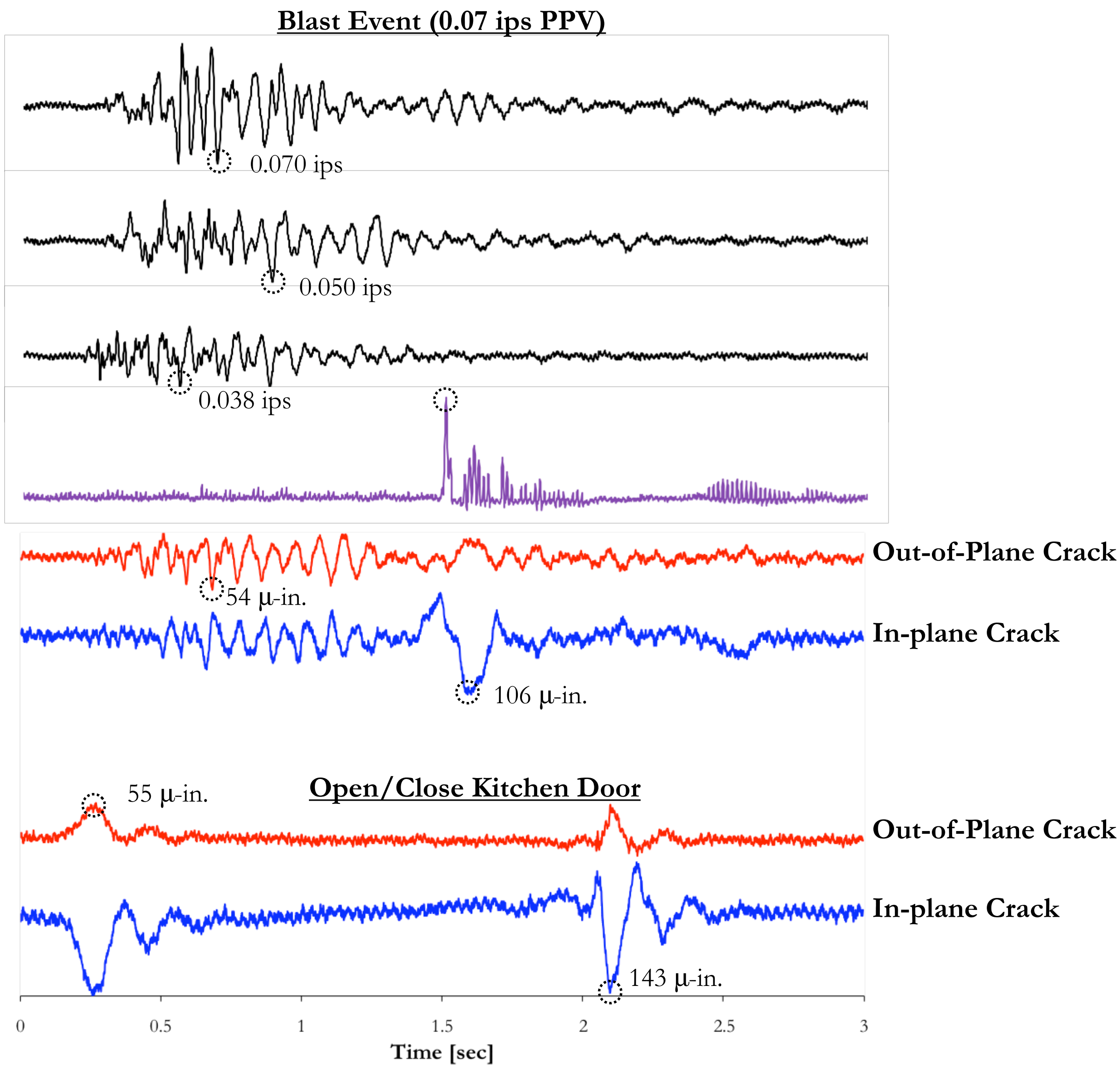

Figure 8 - Comparison of Wisconsin perpendicular responses of the ceiling crack to a blast event (0.07 ips PPV) with response to opening and closing of a distant front door

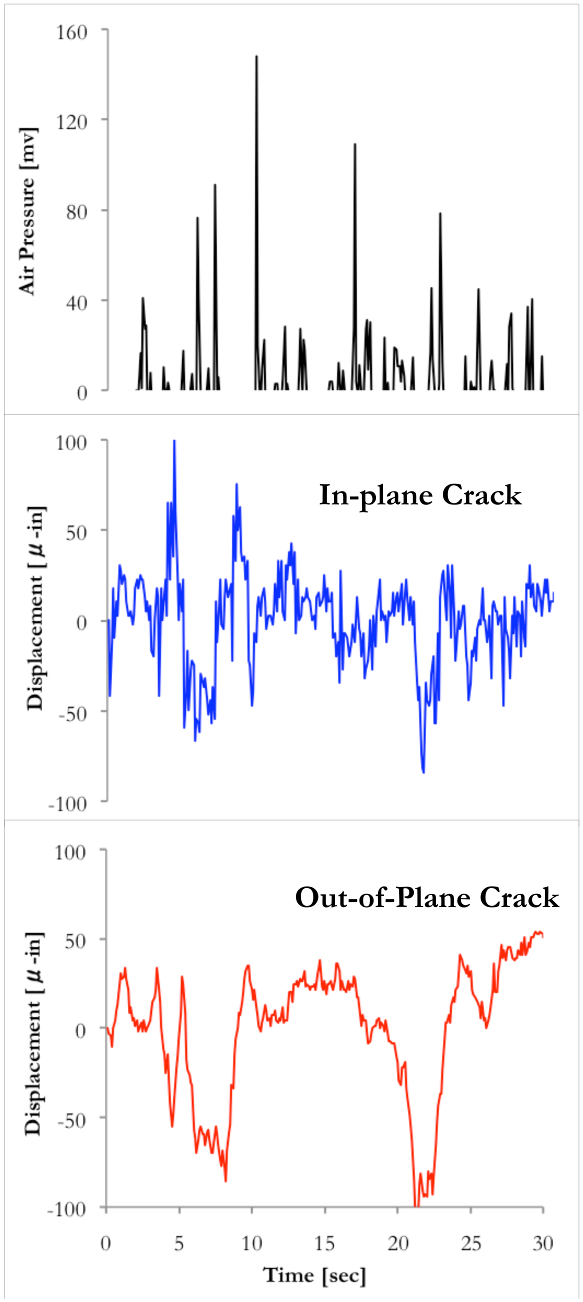

Figure 9 - Comparison of Wisconsin perpendicular responses of the ceiling crack to 30 seconds of wind pulses with the timing and relative size of the wind induced air pressure events

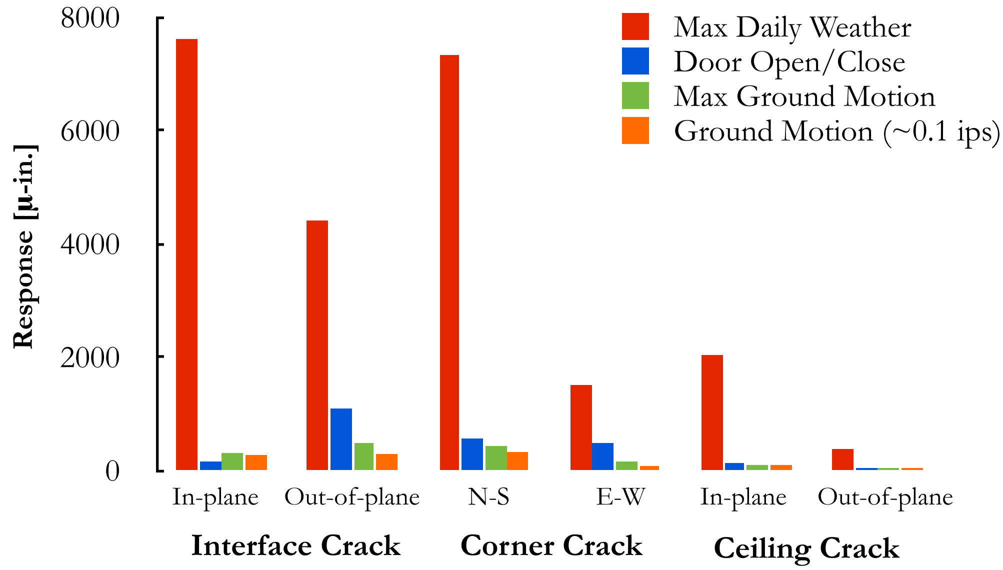

Figure 10 - Comparison of the relative magnitude of perpendicular crack responses to climatological effects, blast induced and occupant induced events. Out-of-plane response to blast events is smaller than the response to climatological effects just as it is for in plane response. Max ground motion is 0.18 ips in Florida and 0.09 ips in Wisconsin.

5. Conclusions

This paper examined and compared the in-plane and out-of-plane (normal) response of cracks in two different residences near limestone quarries. These measurements expand the data base of crack response as heretofore measurements were only made in the plane of the crack. Comparison of the "in" and "out of" plane responses was achieved by placing the two different (in and out of plane) sensors adjacent to each other over the same crack and observing both long term, climatological and vibratory response. In two locations, sensors measured in-plane and out of plane response to cracks in a wall and in a third location perpendicular responses were measured at a wall corner. The following conclusions can be drawn from this study:

Out-of-plane crack response can be measured with sensors similar in nature to those employed for in plane response.

The ratio of "in" and "out-of" -plane responses will vary.

As with in-plane responses, out of plane responses to vibratory and air overpressure events are much smaller than responses to climatological effects.

Wall corners are a special case since there is no analogous "wall plane." Response at a wall corner will vary by direction and may be influenced by building material and style.

Interfaces are highly individualized and responses are dependent on material types, yet their response to climatological and vibratory effects follows the same pattern as cracks in a single material.

Proximity of weaknesses and interfaces to occupant activity may result in unusually high response to occupant activity.

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