Response of Historic Structure to Long-term Environmental and Construction Vibration Effects

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ABSTRACT

Reconstruction of Pennsylvania Avenue in Washington DC provided a unique opportunity to instrument the historic Blair House to determine its response to construction vibrations. To that end three cracks in the house, two on the interior and one on the exterior were instrumented with a micro-meter crack displacement sensor capable of measuring changes in crack width as small as 0.4 micro meters. This one sensor was employed to measure the micro-meter response of the crack to both dynamic (construction vibration) as well as the long term (weather) effects. As has been found with many other structures, the long term climatological effects produce greater crack response than do construction vibrations at levels that can be perceived and at times can be described as annoying.

INTRODUCTION

Vibrations are often a concern in urban reconstruction because they are perceived as bothersome, and this concern becomes acute with historic structures. It is important that this human perception be proactively addressed. One possible means of doing so is to compare the construction induced vibratory response of cracks with their naturally occurring climatologically induced response.

Reconstruction of Pennsylvania Avenue in Washington DC provided a unique opportunity to instrument the historic Blair House to determine its response to construction vibrations. To that end three cracks in the house nearest construction, two on the interior and one on the exterior, were instrumented with a micro-meter crack displacement sen-

FIG. 1: Construction activities nearest Blair House showing trench excavation within several meters of Blair House. (Alverez, 2004)

sor to measure response of the crack to both dynamic (construction vibration) as well as the long term (weather) effects. Output of these sensors, along with that of particle velocity sensors to measure ground motion as well as temperature and humidity sensors was combined to compare the crack response to vibratory and environmental effects. This case study is divided in sections that focus on the project setting, construction environment, crack response to long-term effects, occupant effects, comparison of environmental and construction response, restoration after instrumentation. This paper summarizes the heretofore unpublished complete study (Baillot ,2004), which, along with some dozen similar studies, is described on the autonomous crack monitoring web site, www.iti.northwestern.edu/acm.

PROJECT SETTING

This study arose as a result of the reconstruction of Pennsylvania Avenue as a pedestrian walkway, which as shown in Figure 1 required ditching as close as three meters to the building and instrumented cracks during the study. Because of occupant concern, the Blair house shown in Figure 2 was instrumented to determine the impact of the adjacent roadway reconstruction. The study was sponsored jointly by the Department of State, Government Services Administration and was funded by the Federal Highway Administration (FHWA) Eastern Federal Lands Division, and the United States Department of Transportation.

Instrumented cracks shown in Figure 2 were located in three different materials to cover the wide variety of concerns. Two interior cracks were monitored: the joint between two components of the floor molding on the 2nd floor (crack 2) and crack above a door frame on the 3rd floor (crack 3). The second floor floor molding joint is not really a crack, but

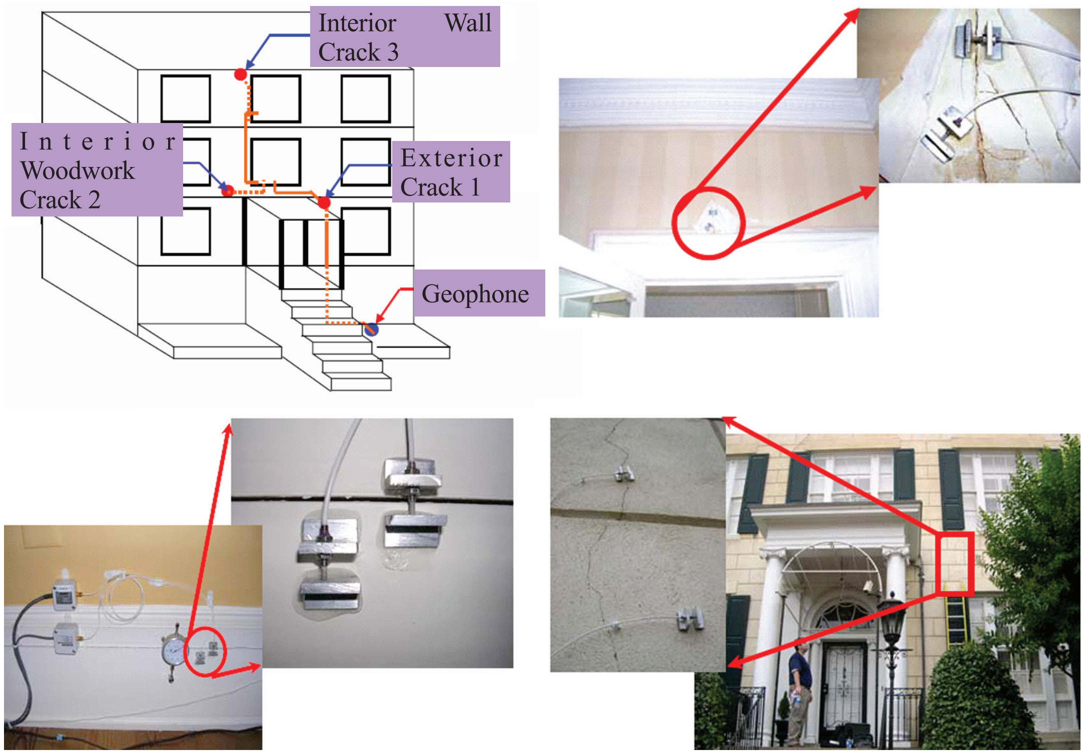

FIG. 2: Crack sensors on Blair House. Clockwise from upper left: Location relative to exterior, interior doorway crack (3), exterior stucco crack (1), molding lap joint (2).

was a concern because of the independent movement of the two components, which would normally move together. The third floor crack is in the plaster lath wall behind the wall paper, which was carefully peeled back for mounting. The exterior crack (crack 1) is located just above the portico in the stucco just the façade closest to Pennsylvania Ave., which faces south in the direct sunlight.

Response of the cracks to construction vibrations blasting, occupant activities and changes in climate (temperature, humidity) was measured with Kaman, eddy current, micro-meter displacement sensors. The locations of the crack and null sensors on the structure are shown in Figure 2. As has been the case with similar installations (McKenna and Dowding, 2005), the crack sensor is mounted on a small bracket glued or epoxied on one side of the crack while the target sensor is affixed to the other side. Crack response is the micro meter change in crack width or change in distance between target and sensor. This same sensor is employed to monitor both long-term response to changes in climate and the dynamic response to construction and occupant induced excitation. The null sensor is affixed in the same fashion on adjacent, but uncracked wall material to measure wall and sensor material response. This wall-sensor response is then subtracted from the crack response to compensate for response of the sensor-wall material itself. Although this sensor-wall material response is small, the null sensor is normally employed as a precautionary measure. Both crack and null sensor are attached to a eDAQ field computer (Balliot, 2004) to record response. Long-term response is obtained by sampling the crack

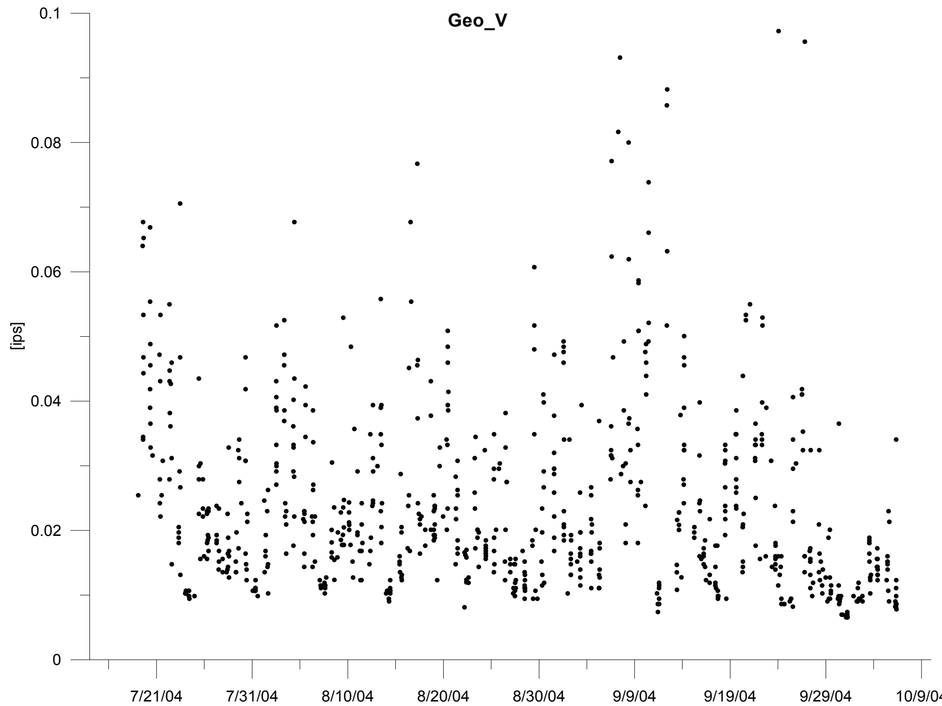

FIG. 3: Vibration environment during the project shown by the plot by date of the highest single axis peak particle velocity (PPV). (1 ips = 1 in. per second = 25.4 mm/s).

and null sensors every hour, while dynamic response is obtained by sampling at 1000 samples per second for three seconds upon triggering by the exterior seismograph.

Several other instruments were employed to describe the climatological and construction environment. Temperature and relative humidity are recorded both internally and externally with Vaisala digital weather loggers. The external sensor was mounted just above the portico and the internal sensor was located in the same room as the molding crack on the second floor. The ground motion produced by the construction activity was recorded with a standard vibration monitoring geophone block buried at a depth of 10 cm in the garden between Pennsylvania Ave. and the house, one half a meter from the house. Standard geophone blocks consist of three orthogonal, single axis velocity transducers oriented in the longitudinal (parallel to the street), transverse and vertical directions.

CONSTRUCTION VIBRATION ENVIRONMENT

Figure 1 is a photograph that is representative of the closest construction activity during the period of observation. Reconstruction activities during the period of observation included back hoe excavation of a 1-meter wide trench several meters from the south façade on which crack sensors were affixed. The photo shows the small back hoe employed for the excavation of junction boxes in the trench immediately in front of the Blair House. Excavation was followed by vibratory placement of the back fill to prepare the surface for the walkway.

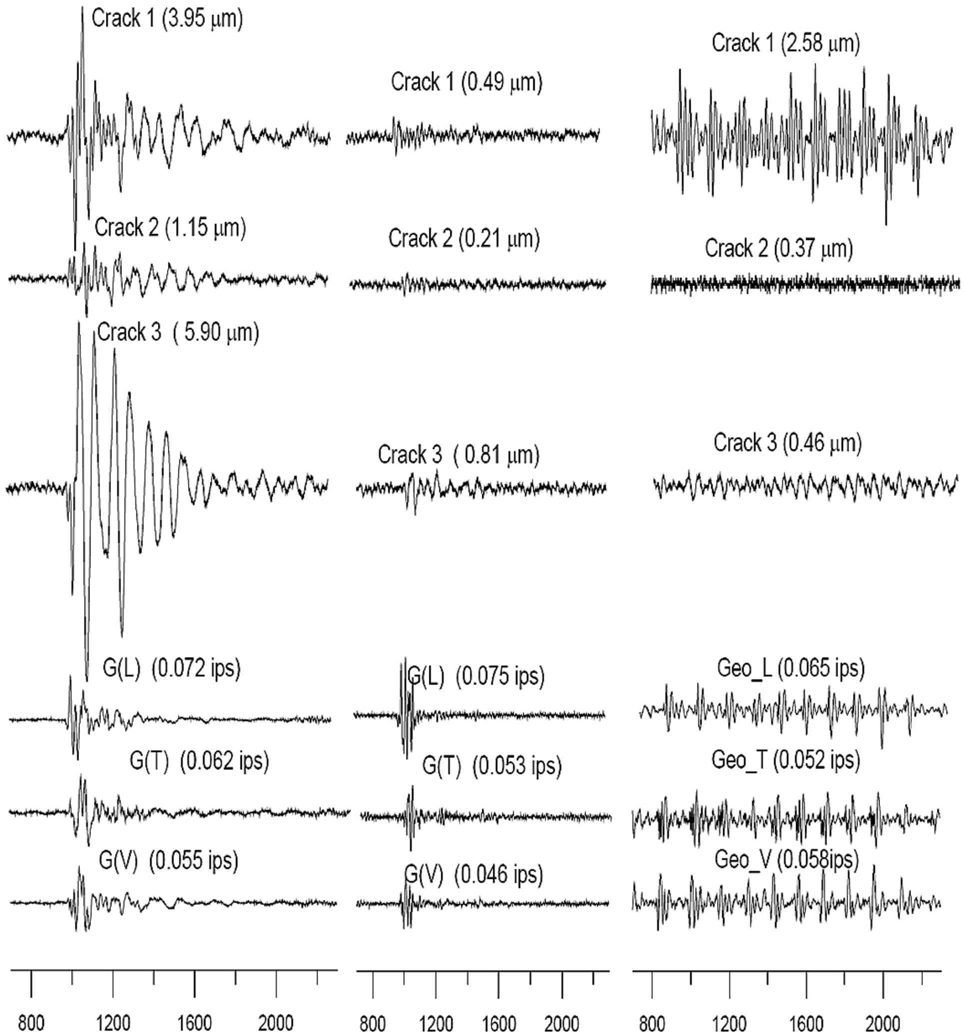

FIG. 4: Time histories of crack responses (upper 3) and ground motion components (lower 3) for three constructions events: 3 and 9 (left) produced by back hoe operation and 22 (right) produced by motorized tamper.

The general vibratory environment is shown by the time history of the peaks shown in Figure 3. These peak data were obtained by recording all channels continuously at a 1000 Hz for 60 seconds (60,000 points), but saving only the peak value. Then another minute or 60,000 point recording period begins and so on and so forth. This triggering mode was developed to capture vibratory roller data, but the hand tampers were employed instead and the approach was useful for recording that data instead. Only the peak particle velocities for the ten largest events for each day are reported in Figure 4. Most PPV's fall below 2.54 mm/s (0.1 ips) with only a few larger events. These construction events were separated from noise spikes, which were not reported (Balliot, 2004).

Time histories of ground motions and crack response from three of the 30 vibratory events 3, 9 and 22 are compared in Figure 4. Events 3 and 9 were produced by backhoe

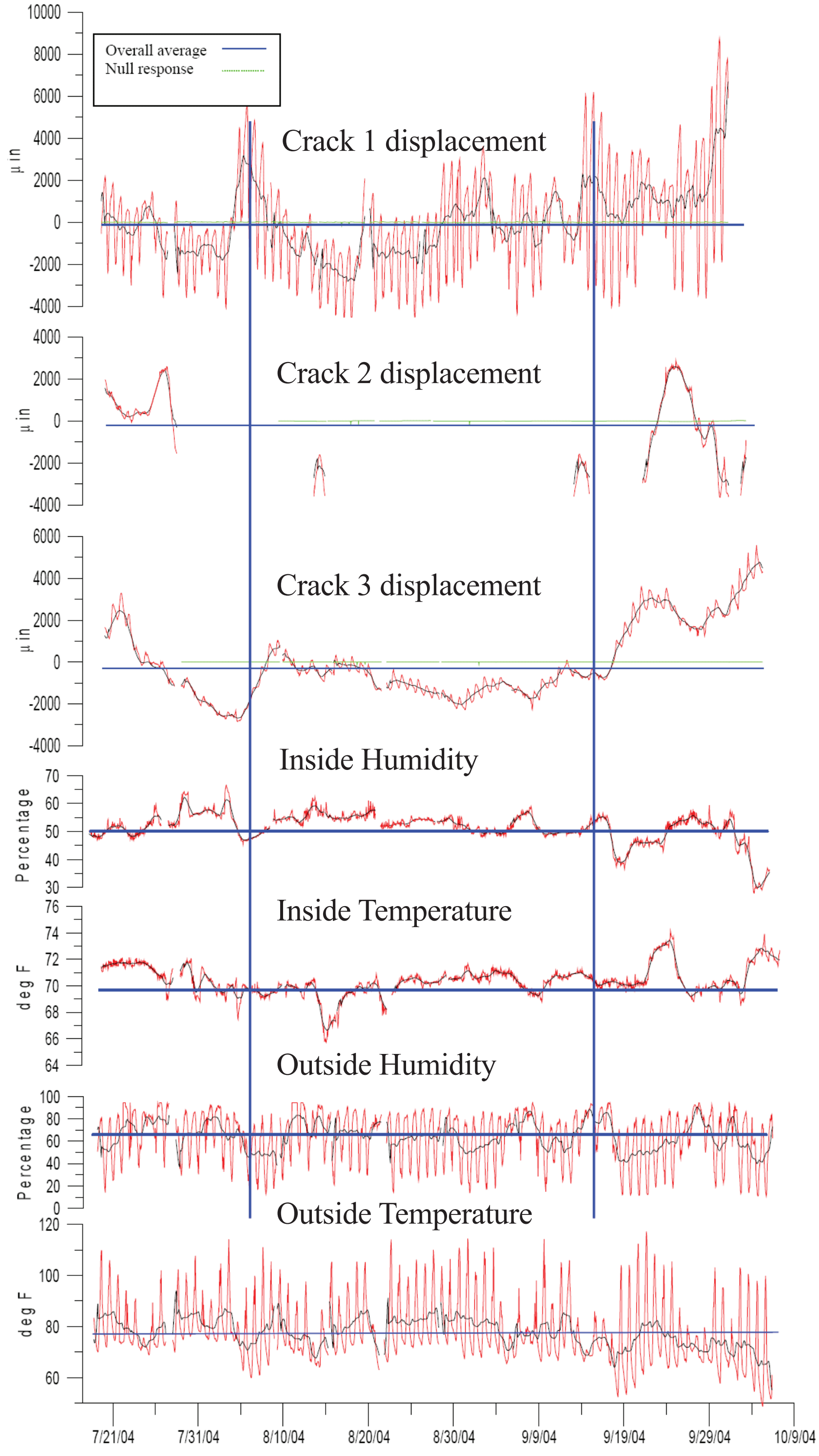

FIG. 5: Comparison of long-term crack responses (upper 3) with inside (middle 2) and outside (lower 2) changes in temperature and humidity showing responsiveness of cracks to climatological effects.

activity. Event 22 was produced by a motorized but hand operated tamper. Earlier it was thought that the ground motions were produced by a jack hammer, but subsequent discussion reveled that the hand tamper was the most likely source.

Event 3 produced the largest response of all three cracks. This high response is a result of the lower frequency of the ground motion. Event 9 involved the same PPV, yet produced only 1/8th the response. Response spectra of the longitudinal motions of the two events (Baillot, 2004) show that the dominant excitation frequency of event 3 is 12.5 Hz whereas that for event 9 is some 41 Hz. As discussed by Dowding (1996), motions at the natural frequencies of structural components will produce the greatest response. Many walls and floors have frequencies in the 10 to 20 Hz range. Thus ground motions whose dominant frequency is near 12 Hz (event 3) would be expected to produce greater structural response than ground motions whose dominant frequency exceeds 40 Hz (event 9).

Event 22 was produced by tamping and was one of 99 events recorded that morning. Crack 1's response was the greatest for this event and was consistently the greatest of all three of the cracks for these repetitive motion events. Crack 2's response never exceeded the noise level. Crack 3's response was lower than that typically produced by back hoe activity.

CRACK RESPONSE TO LONG-TERM WEATHER EFFECTS

Long-term response to weather and human activity provides the background crack response against which vibration response should be compared. Response to weather induced changes will be discussed first. These long-term effects are obtained by measuring crack response each hour and graphing the response for each crack over time as shown by the 3 time histories in the upper half of Figure 5. Herein opening and closing of a crack will be called displacement or response to simplify discussion and to follow terminology in other reports. Crack responses are then compared to hourly measurements of the outside and inside temperature and humidity shown by four time histories in the lower half of Figure 5.

There are four lines in the graph of the response of the exterior crack, 1. The dark horizontal line is the average crack displacement. Since only changes in crack width, not the absolute width are measured, the average is just a reference number that represents the initial setting of the sensor, which has been set at zero for graphical purposes. The null response is a thin line parallel to the horizontal line, which shows it is invariable for the period of observation and will not be discussed further. The highly variable and oscillating line is the variation of the hourly measurements. Finally the less oscillating but still variable line through the center of the hourly readings is the 24 hour rolling average of the long-term response. It is obtained by averaging the 12 readings before and after any point and plotting that average at the mid hour. This rolling average portrays the weather fronts that pass through every week or so. Since this system was not left in place for an entire year, seasonal effects have been found to be even larger than daily events.

Crack 1 responds the most to daily temperature changes as it is located on the south facing façade, which is heated daily by direct sunlight. Thus there is considerable response to the direct insolation as would be expected. In addition there is a significant long-term response that is probably the result of the façade responding to long term changes in ex-

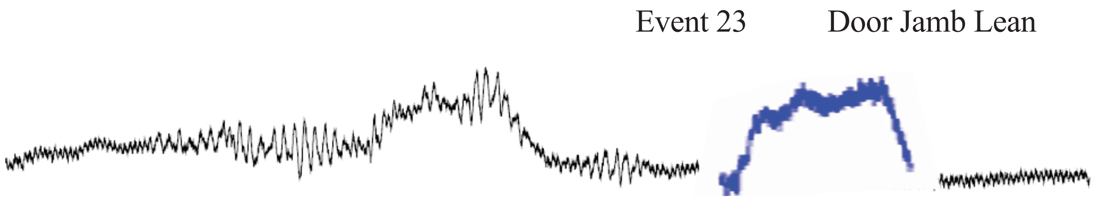

FIG. 6: Comparison of unusual, low frequency hump in the vibratory crack response time history (left) to that produced by leaning on door jamb (right) later determined to be result of workers inside structure.

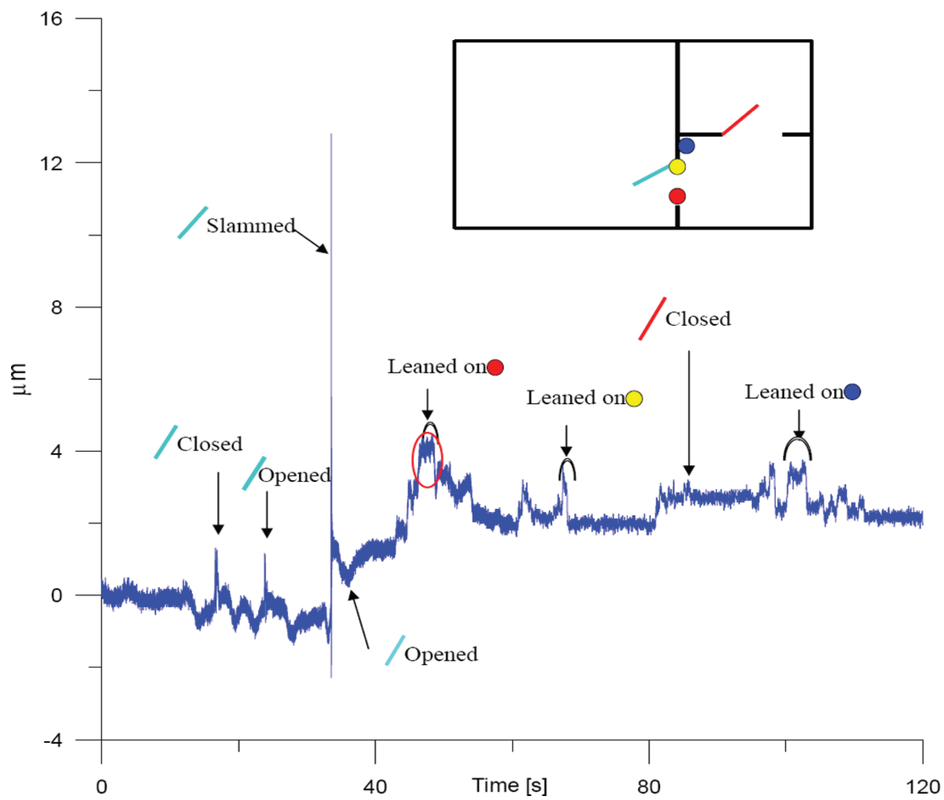

FIG. 7: Response of plaster and lath doorway crack (3) opening and closing, slamming and leaning on door jamb and wall to be compared with ground motion induced response in Fig. 6 (39 µ in. = 1 µm).

terior humidity and temperature as seen along the two vertical lines in Figure 5. While looking stone like, the façade is stucco applied over a wooden stud wall, which responds to changes to humidity.

Crack 2 is not really a crack but the joint between two pieces of floor molding. It responded the most to long term changes. In fact so much so that it went out of range. This change, at least 287 µm (11,500 µ in.) was confirmed by the dial gauge adjacent to the crack sensor. Since this joint was that between two separate pieces of molding, differences in grain orientation and surfaces to which they were affixed could explain this large response.

Crack 3 was located in plaster and lath above a doorway and was probably initiated by differential settlement of the structure, which is founded upon compressible soils. It also responded considerably to long term changes in humidity as shown by the dotted lines in the interior humidity and crack response on Figure 5. The interior humidity and temperature were moderated by air conditioning; however there were times when the system was overwhelmed by exterior conditions, workers opening windows, etc.

OCCUPANT INDUCED CRACK DISPLACEMENT

Crack responses to deliberate occupant activities were recorded at 1000 samples per second in order to identify crack response time histories produced by human activity. The most interesting occupant response was first discovered during crack 3's response to tamping vibration as shown in Figure 6. The large hump also appeared at another time when there was no ground motion. The day this "mysterious" hump occurred coincided with the day repairs were made to the room to which the doorway lead. This discovery lead to the question, "how could repairs in the room itself generate this type of crack response?"

Results of a deliberate occupant test shown in Figure 7 revealed the mechanism for the hump response. The figure is a time history of crack response to activities involving the doorway, which included (from left to right) opening the door, leaning on the door frame (south then north) closing the door, and finally leaning on the wall. The encircled leaning response (1.2 µm) in Figure 7 is compared in Figure 6 with the mysterious hump (1.9 µm)

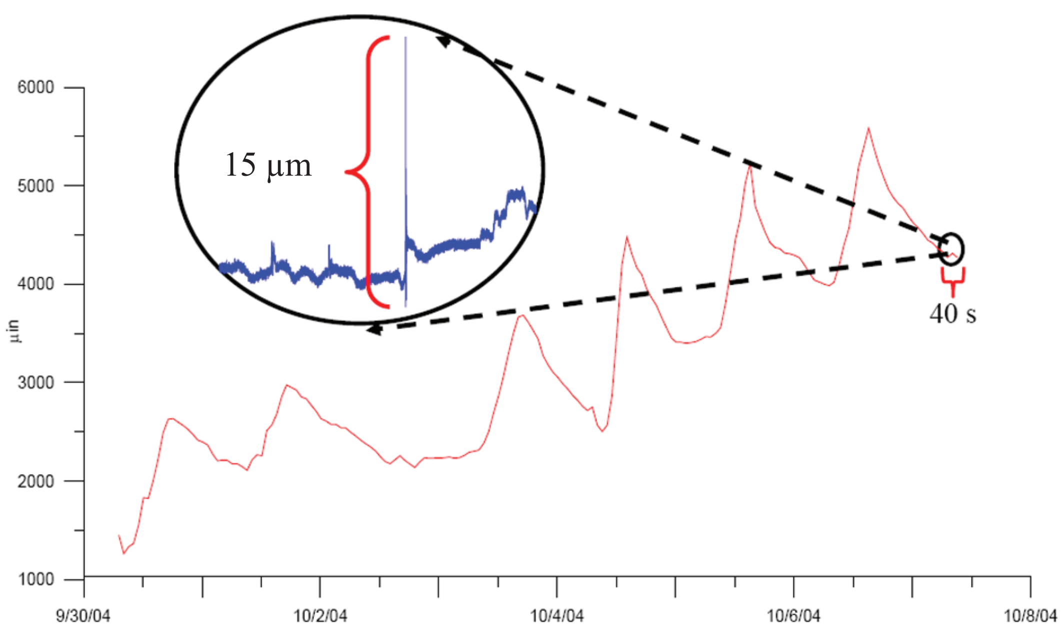

FIG. 8: Comparison of crack 3 response to slamming of door immediately below (in insert) to 8 days of long term climate induced change again showing high responsiveness of cracks to climatological effects (39 µ in. = 1 µm).

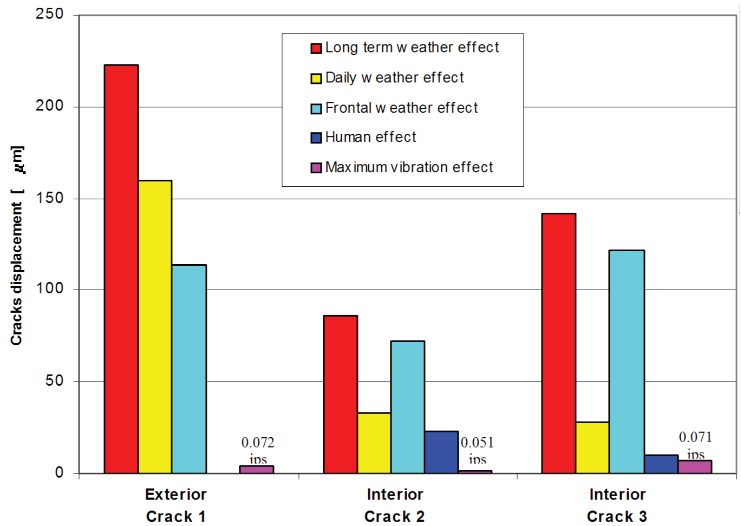

FIG. 9: Comparison of crack response to climatological (daily and long term) occupant (human) and maximum construction vibration induced events (39 µ in. = 1 µm).

recorded with event 23. As can bee seen with the similarity of response, the hump is most likely the result of someone leaning on the door frame. As would be expected slamming the door produced the greatest response.

COMPARISON OF VIBRATION AND LONG-TERM CRACK DISPLACEMENT

The enormity of the temperature-humidity responses is best demonstrated by the graphical comparison in Figure 8 of the door slam in the inset with a typical daily temperature induced response of crack 3. Some 8 days of long-term response is easily recognized by the daily cyclic temperature induced response. The insert is that of 40 seconds surrounding the door slam. Over the eight days a combination of temperature and humidity response produced some 100 µm of response, while every day the trough to peak change was some 50 µ m. Finally, the door slam produced only 15 µm of trough to peak response.

Vibratory, long-term, and occupant induced crack responses of all three cracks are compared as a bar graph in Figure 9. The bars for each crack are the maxima of (from left to right) of the long-term, daily, frontal, human (occupant) and vibration induced crack responses. In all three cases the long-term weather effect produces the greatest response, which is orders of magnitude greater than the vibration effects. The frontal weather effects are also an order of magnitude larger than the construction effect. In this plot the long term effect is the maximum excursion from the horizontal average of the 24 hour rolling average. Daily effect is the maximum excursion from the 24 rolling average curve. Frontal is the maximum excursion of the 24 hour average curve from the average of all the 24 hour averages (the horizontal line). Finally as discussed above, simply leaning on the door jamb produces greater crack response than vibratory motion.

exterior
stucco
crack 1

interior
molding joint
crack 2

interior
plaster and lath
crack 3

wire
harness

kaman
brackets

FIG. 10: Photographic comparison of in-place instrumentation (left) and post investigation conditions illustrate the small footprint (bottom) of Kaman micrometer displacement sensors.

RESTORATION AFTER INSTRUMENTATION

To demonstrate the ease of restoring the attachment locations of the sensors, before and after photographs were taken of the sensor attachments. A collage of these comparisons is shown in Figure 9. The small foot print of the brackets minimizes repair. Stucco almost needs no repair. Wood requires only touch up painting. Removal of the epoxied brackets from the plaster left small, shallow divots less than the size of a quarter. Wire runs required only one penetration of a window by drilling holes through the window frame, which can be filled with plastic wood or the equivalent.

Wireless sensors like those described in the companion paper, "Multi-hop Wireless Measurement System" (Dowding, et al, 2007) will be even less intrusive than the system described herein. Given the expected growth of wireless communication, low cost, continuously operating wireless displacement sensors will be common place within five to ten years. Deployment of these wireless sensors will allow observation of the response of historic structures to natural climatological effects heretofore unimaginable.

CONCLUSIONS

- Small backhoe and small machine compaction tamping within a few meters do not cause significant ground motions, which were less than 6 mm/s (0.25 ips).

- Long term climatologically induced crack displacement was 20 to 60 times greater that that caused by the largest construction vibration induced ground motion of 5 mm/s (0.2 ips).

- Occupant activity induced crack displacements were 2 to 16 times larger than the largest construction vibration induced crack displacements.

- Attachment of the small foot print sensors to wood, plaster and lath, and stucco left behind easy to repair marks.

- Installation of the system allowed those with concerns to observe the response of the structure in a comparative fashion.

ACKNOWLEDGEMENTS

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