Blast Induced Micrometer Response of Cracks in Concrete Block Structures

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ABSTRACT: Blasting and climatological response of cracks are compared for structures constructed of concrete block typical of home construction in Europe. While much has been written comparing micrometer crack response of wood frame structures typical of residential construction in North America, little has been written concerning response of structures more typical of European construction. Responses of cracks in four different structures are compared with the following locations and (wall materials): Wales, UK (Concrete Block), Florida, USA (Concrete Block – 2 cases), Wisconsin, USA (Concrete Block and Stone). Time histories of micrometer response of cracks to both blast induced dynamic effects as well as long term climatological effects are compared. These comparisons show that even for concrete block construction without wood, climatological and home heating effects have greater influence on crack response than blast induced ground motions with a wide range in intensity.

1 INTRODUCTION

This paper compares vibration and climatological crack & structural response of four residential structures with exterior walls constructed of concrete blocks. These cases are important because they allow a determination of the degree to which cracks in concrete block structures respond to climatological effects. It has been surmised that construction of homes with concrete blocks are less prone to climatological crack response than homes constructed of wooden frames, which are subject to shrinkage and swelling of the wood frame from changes in humidity. The four cases involve two in Florida, one in Wales and another in Wisconsin. Vibration and climatological crack response was measured in the Floridian and Wisconsin homes. While vibration crack response of cracks was not measured in the Welsh case history, before and after blast measurement of the crack opening allows an indirect conclusion concerning long term change in crack width. In this paper each structure is introduced in Figure 1. Each case study is then described in detail. After the four cases have been introduced, they are compared to evaluate differences and similarities in the responses of cracks to dynamic and long term climatological effects.

2 MIAMI, FLORIDA; (LOUIS, 2000)

The concrete masonry unit (CMU) house shown in the top left in Figure 1 was located on mine property and thus could be subjected to ground motions far greater than with non owned structures. Its response was monitored with a hybrid autonomous crack monitoring system (ACM), as well as two multi channel vibration monitoring systems, both of which were constructed by GeoSonics. Like the hybrid described in the 2001 surface coal mining studies (Aimone-Martin et al , 2003) this combination recorded vibratory time histories of crack & structure response, ground motions and air over pressures as well as well as long term, climatological crack response.

This single story ranch house was constructed with external concrete CMU walls and was founded on a concrete slab as are almost all homes in southern Florida. The external CMU walls were covered with a coat of stucco to produce a uniform surface. Internal walls, ceiling joists and roof trusses were constructed of wood. Internal walls were covered with gypsum drywall. Locations of the transducers are shown in the plan view of the house on the top right in Figure 1. An external crack in the stucco over CMU below the south facing window shown in the inset in the house photograph was monitored with a Kaman eddy current micro meter displacement sensor. Velocity transducers 2 and 4 were attached perpendicularly (low and high respectively) to the N-S wall in the SE corner of the structure, as shown in the house plan in Figure 1 (top right). Thus super structure motions are measured in a direction parallel to the wall containing the crack.

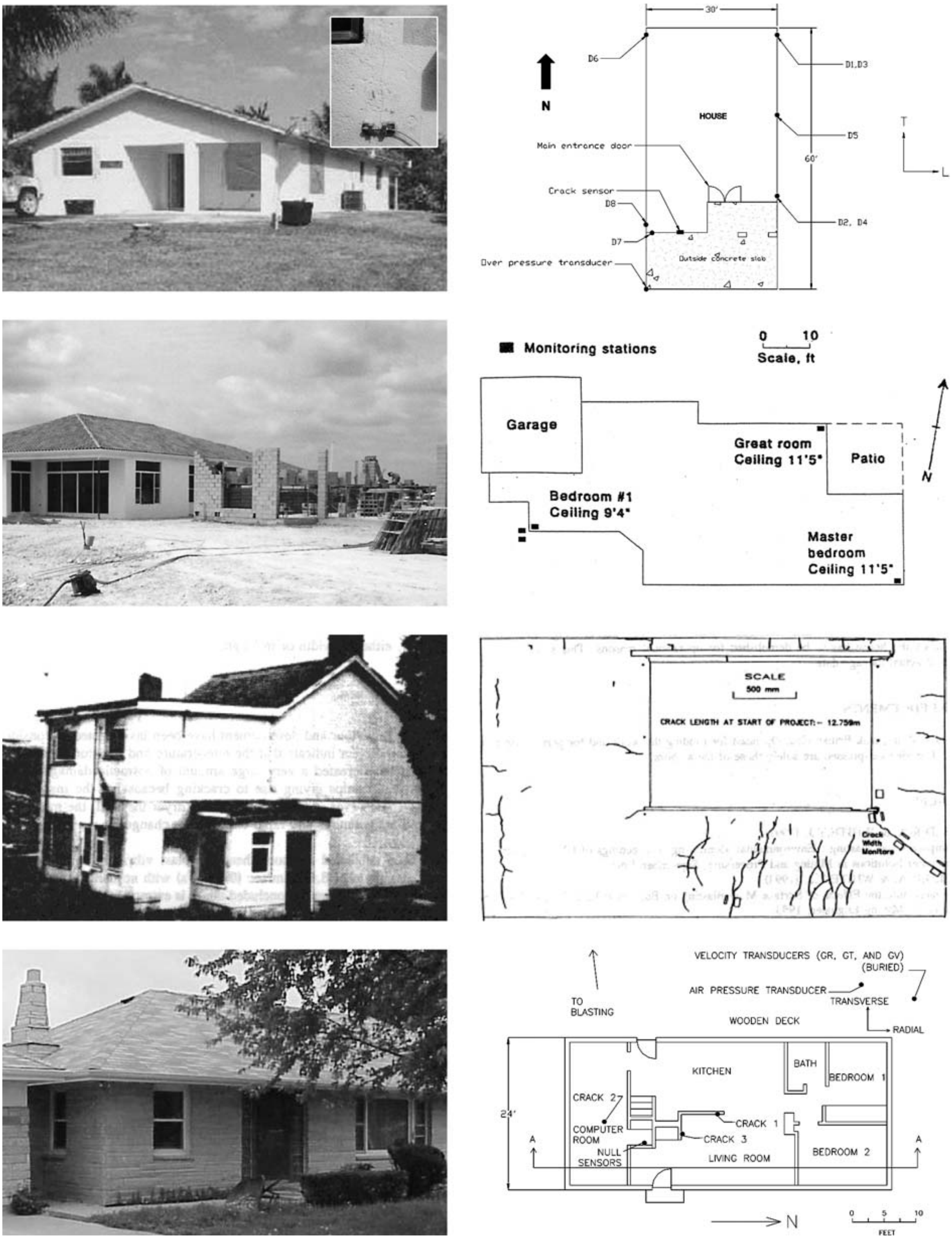

Figure 1. Photographs (left) and crack locations (right) of block structures from (beginning at the top) Miami Florida; Ft Lauderdale, FL; Gilfach Iago, Wales, UK, and Franklin, WI.

Crack and wall motions in the plane of (parallel to) the wall containing the crack for the 16 December event are shown in Figure 2. Measured crack response, the 4th time history from the top of the figure correlates well in terms of frequency content with the calculated relative displacement between the top (channel 4; D4) and bottom (channel 2; D2) shown in the time history third from the top.

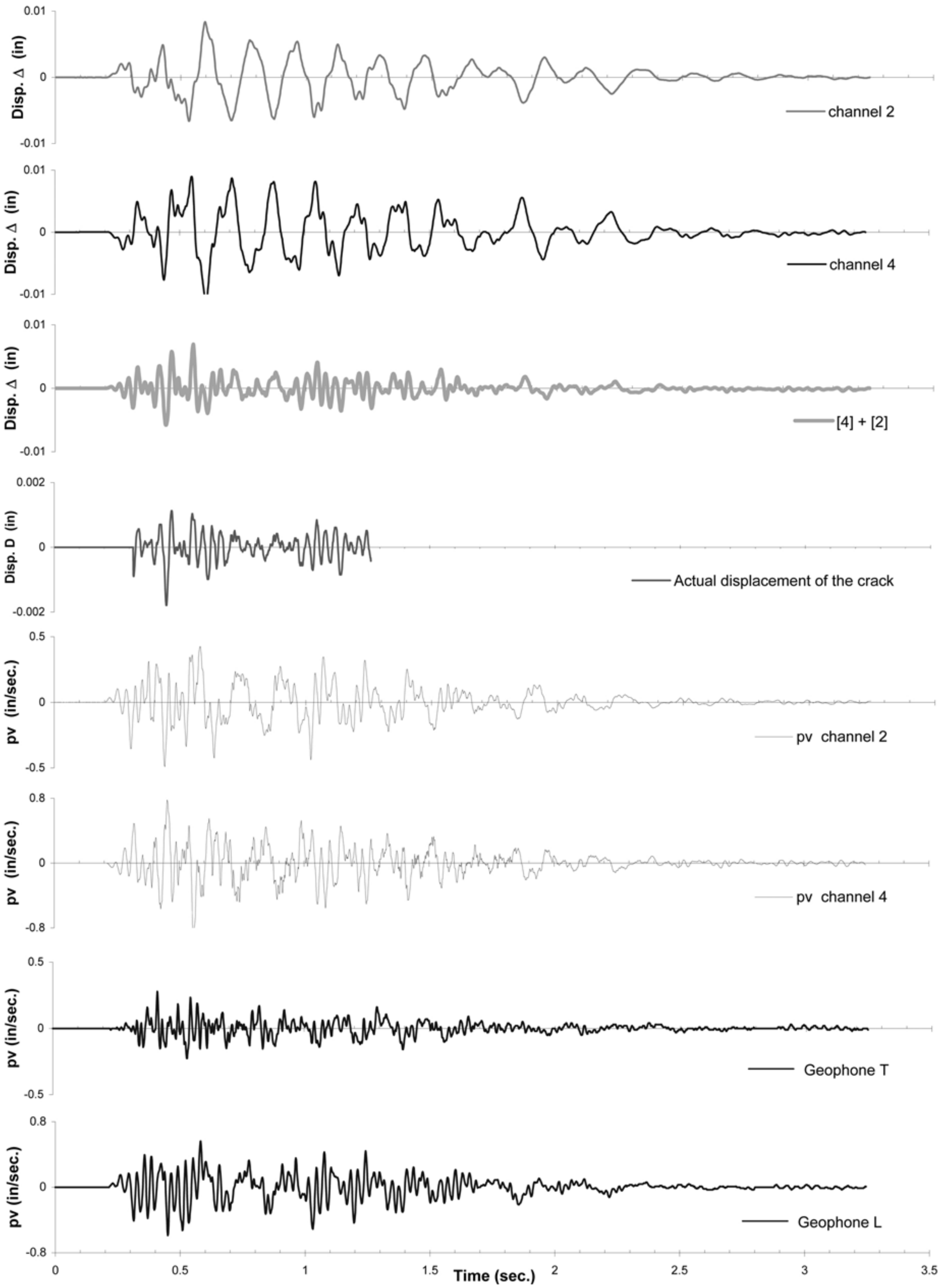

Figure 2. Time histories produced by 17.8 mm/s (0.7 ips) Miami FL blast (from top to bottom) A) structural displacement response (2 & 4) and their difference (4+2) compared to crack response (actual…); B) structural velocity response (pv ch. 2 & 4) compared to ground motions (Geophone T & L).

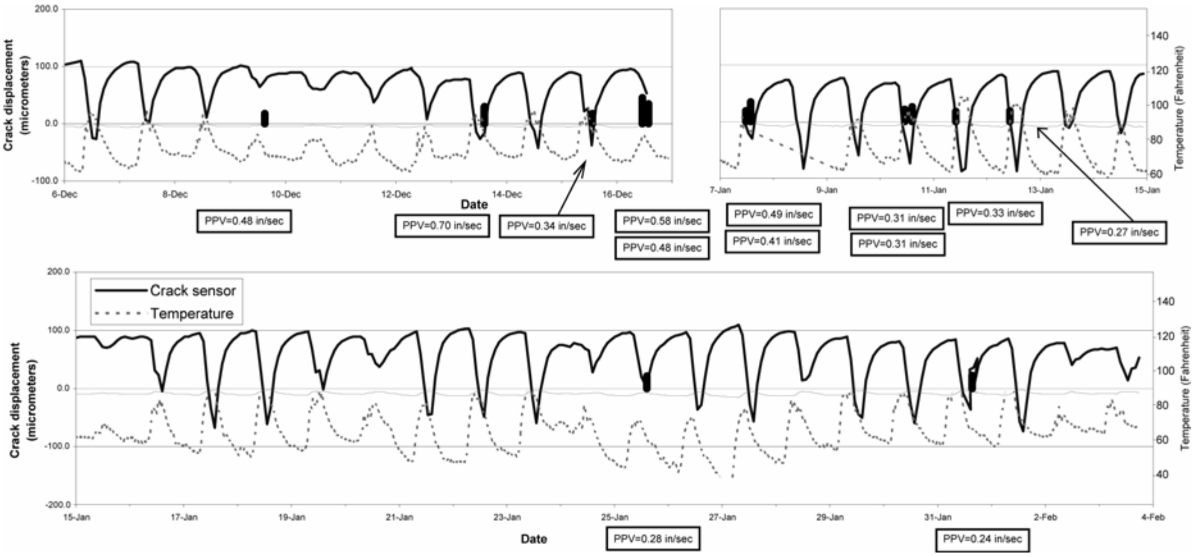

Figure 3. Comparison of vibratory crack responses (solid vertical bars) with cyclic long term responses (solid line) shows that even motions exceeding regulatory limits cannot produce crack responses as large as those produced by temperature change. Comparison of long term response with temperature variation (dotted line) shows the high correlation with temperature change.

Climatologically induced crack response from mid November to early February in Figure 3 shows the heavy influence of the direct solar heating on the south facing wall. This graph compares blast-induced crack response (solid vertical bars) with the long term time history of climatologically induced crack response (thin solid line). The long term crack response pattern can be compared with the variation of external temperature (dotted line) as well as the response of the null sensor (vanishingly thin solid line). The null sensor is another Kaman sensor placed across an adjacent, uncracked section of the south wall to measure sensor and wall material response. Despite the high degree of solar heating (compare temperature and crack response), the null sensor response was small. Comparison of the time history of the crack response with that of the temperature in Figure 3 shows less crack response on days with more constant temperatures, which is most likely a result of cloudiness and lower temperature induced strains from direct sun exposure (insolation) on the south facing wall containing the crack.

Close-by quarry blasting produced ground motions with peak particle velocities (PPV) as high as 17.8 mm/s (0.7 ips) in the direction parallel to the wall containing the crack as shown by the PPV values in the boxes in Figure 3. Peak crack responses to these events are shown as bars, which extend upward from the 0.0 crack displacement line, whose height is proportional to the 0 to peak crack response. This comparison shows that even motions that are 140% of the frequency independent control limit of 12.7 mm/s were unable to produce crack responses greater than 0.61 (61%) of those induced by typical daily temperature changes.

3 FT. LAUDERDALE, FLORIDA; (SISKIND ET AL, 1996)

The single story structure in the photograph second from the top in Figure 1 was constructed with external CMU walls, and was founded on a concrete slab like that in Miami. Details of the block construction can be seen on the right side of the same photograph at the house under construction adjacent to the instrumented house. Critical corners of the outer walls are constructed of cast-in-place reinforced columns and a continuous reinforced concrete beam is poured on top of the outer walls. Interior walls, ceiling joists and roof framing are constructed of wood or equivalent steel “C” steel members. The exterior walls and surfaces are covered with stucco to produce a uniform surface.

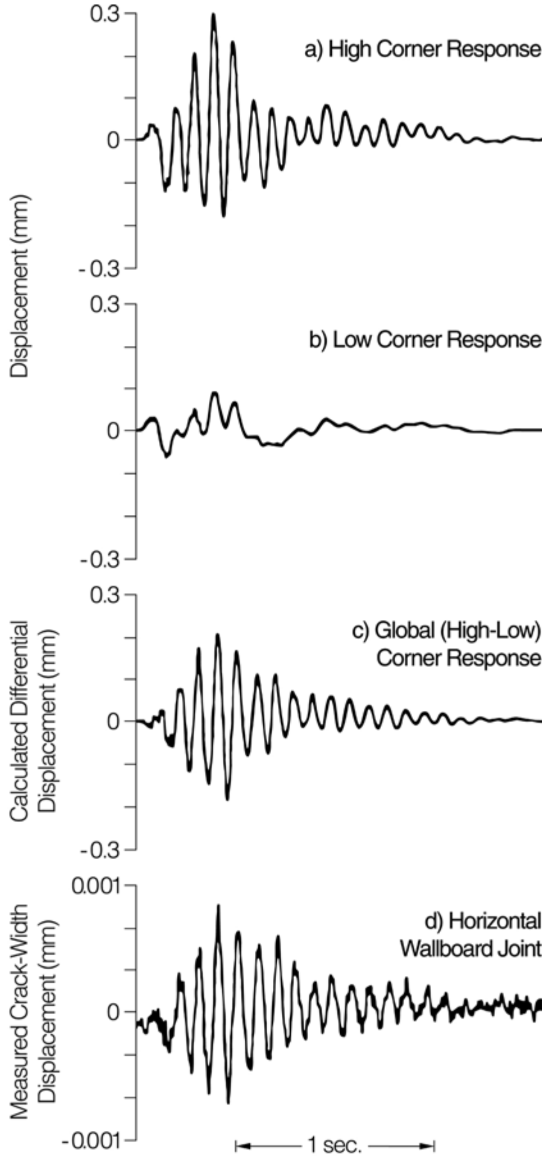

Figure 4. Time histories produced by 11 mm/s (0.43 ips) Ft Lauderdale blast (from top to bottom like that in Figure 2): structural displacement response (upper -a- and lower -b- corner) and their difference (c, high minus low) compared to the response of dry wall joint (d - bottom).

Kaman crack sensors were placed across an interior, taped dry wall joint on the north wall and on the exterior patio ceiling across an exterior stucco crack between two metal mesh sheets on which the stucco was applied. Geometry and sensor (monitor) locations for this structure are shown in the plan to the right of the photograph in Figure1. Taped drywall joints are interfaces between adjacent sheets of drywall that are spanned only by paper tape covered with a 1 to 2 mm thick plaster coat to smooth the interface. Field measurements verify that the joints are more responsive than wall materials (Dowding, 1996). Velocity transducers were placed at the upper and lower corners of the NE and SW corners to measure relative displacement of the walls.

Structural response time histories from the shot producing the highest PPV's, 11 mm/s (0.43 ips), are compared to the time history of the taped horizontal dry wall joint in Figure 4. Response of the horizontal wallboard joint (bottom of figure) on the north wall is compared with the north-south "displacement" responses at the high and low corners (top of figure) as well as the relative displacement between bottom and velocity transducers. This differential displacement produces a relative displacement time history that matches that of the drywall joint.

Climatological joint response was difficult to capture with this instrument array as it could not be operated autonomously and required human intervention. As a result climatological response of the two monitored joints was only obtained for a single, two-day period. During that two-day interval the interior dry wall joint and exterior stucco crack displaced 11 and 18 μm (440 & 720 μ in.) respectively with only a 5 ºF (3 ºC) change in exterior temperature. By linear extrapolation, during a normal daily temperature change of 20 ºF (11 ºC), the interior joint and exterior crack would change width by 44 and 72 μm.

Blasting in this case study was needed to simultaneously 1) excavate poorly cemented clastic limestone for foundation pads for the homes from 2) form adjacent lakes. This activity produced PPV's that ranged from 2.3 mm/s sec (0.09 ips) at a 50 Hz dominant frequency to 11 mm/s (0.44 ips) at a 20 Hz dominant frequency. These motions produced maximum tape joint and stucco crack responses of 10 μm (40 μ in.). Thus ground motions nearly equal to the frequency independent control limit of 12.7 mm/s would produce crack responses only a quarter that might be produced by changing temperature during a typical day – on the north and shady side of the house.

4 GILFACH IAGO, WALES, UK; WHITE ET AL (1993)

The two-story house second from the bottom in Figure 1 was fitted with LVDTs and a continuous blast monitoring system (White, Farnfield and Kelly 1993) to record ground motions and structural response generated by near-by surface coal mine blasting. Vibration and L VDT responses were measured separately and thus the system differs from an Autonomous Crack Monitoring system; however the LVDT measurement of crack response can be employed for comparison with the other case studies to assess possible similarities and differences.

Cracks were fitted with LVDTs in two rooms in the newer rear extension of the elderly stone cottage because of the poor condition of the original portion. The extension was a "double skin concrete block construction with external rendering and internal plaster" (White et al, 1993). Internal walls were constructed of "plaster board". External walls were founded upon a trench filled with concrete and brick. Lack of a structural connection between the two portions exacerbated differential movement and resulted in a large, external active crack between the extension and original structure.

Typical long term crack responses are compared for a week with external and internal room temperatures in Figure 5a and b with and without active room heaters respectively. Response of three cracks is compared: one external crack and two internal. The external crack was that between the old and new portions. Internal crack B 1 is on an external block wall and internal crack B4 is on an internal "plasterboard" wall. Wall B 1 is shown in on the right hand side of Figure 1 (second from the bottom), with its cracked condition along with the location of the crack monitors. The crack at the corner of the window extended into the concrete block. There is no description of the frame for the internal wall, which is likely to be wood given the presence of plasterboard, and is assumed to be similar to gypsum dry wall in the US.

Interior heating affects interior cracks on both plasterboard interior and block exterior walls. Without heaters response of the external crack between the addition and original structure was absolutely large and larger than that of the internal cracks showing a daily peak to peak response of 0.36 mm or 360 μm (14,400 μ in.) The cracks within the addition responded far less and more typically: 27 and 45 μm for the plasterboard and block walls respectively. Operation of the heaters twice per day changed the periodicity of responses of the internal cracks to match the heater activity but not that for the crack between the new and old portions. In addition the larger temperature swings induced larger responses of the cracks inside the addition. The large daily swings of the crack response between the two sections of the structure are probably the result of numerous differences in the structures; foundation depth, materials, framing, etc.

LVDT readings were obtained every 20 minutes and immediately after each coal mine blast and other dynamic events. Thus the change from the last reading before any blast event could be measured to determine the possibility of a permanent crack response such as an offset. Some 656 blasts occurred during the monitoring with only 141 greater than 1 mm/s (0.039 ips) only 6 greater than 5 mm/s with a maximum of 8.7 mm/s (0.34 ips). During this period of observation the only change the width occurred in crack B4, which was only associated with opening and closing of the door below. Thus the temperature induced crack response is much larger than that produced by blast induced PPV's of 8.7 mm/s (0.34 ips).

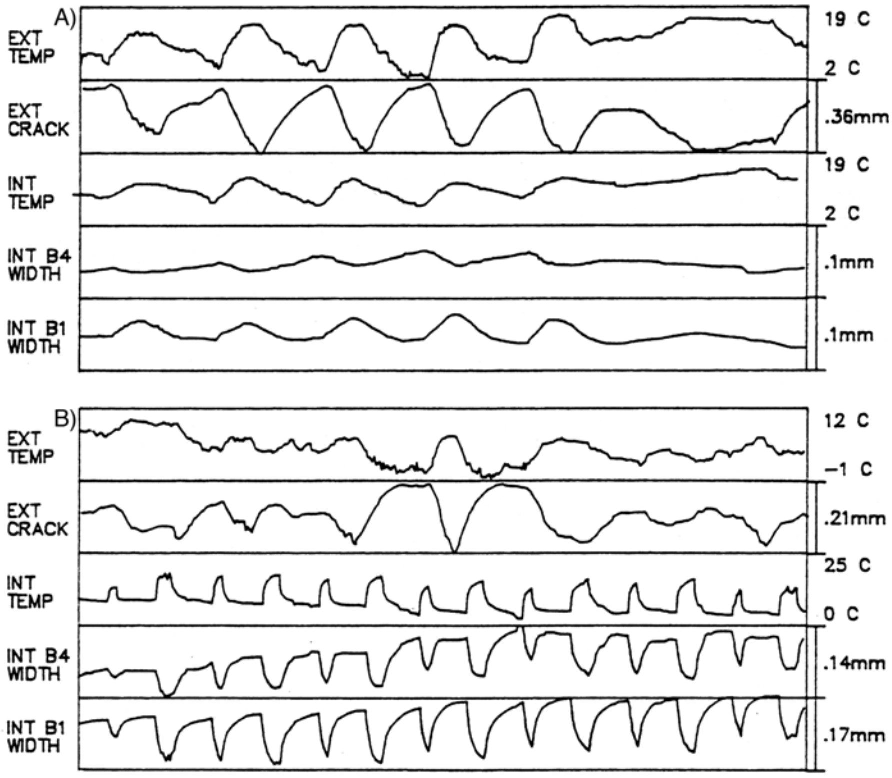

Figure 5. One week's worth of long term change in width of 3 cracks compared with temperature for the Wales house similar to that shown in Figure 3 for the Miami, FL house. Response with no internal heat at the top and that with internal heat twice a day at bottom. Crack B1 is in an external block wall (White et al, 1993).

5 FRANKLIN, WISCONSIN; (LOUIS, 2000,. & MCKENNA, 2002)

As shown in the photograph at the bottom of Figure 1, this ranch style house's exterior load bearing walls are constructed of stone cemented to a concrete masonry load bearing wall. Interior walls are constructed with typical wood framing. The interior surfaces of the exterior walls are covered with gypsum drywall. A full CMU basement, with a walkout entrance, serves as the foundation.

Kaman crack sensors have been placed across the three cracks located in the plan view on the bottom of the right hand side of Figure 1. Cracks 1 and 3 were located at the corners of openings between rooms, with that between the living room and kitchen (beneath crack 1) some 3 doors wide. The ceiling crack, 2, is in the center of the study where a ranch style house's typical center wall support would be located.

Discussion in this article will focus on crack 3 as it responded most to lower frequency excitation. Velocity response of an exterior wall was not measured with the as it was for the other three case studies. Instead the dynamic response of the crack was employed to estimate the natural frequency of the superstructure. Unfortunately, space does not permit presentation of the vibratory and long term climatological response time histories. They can be found at the ACM web page at *www.iti.northwestern.edu/ACM* in the pdf version of the theses by either Louis (2000) or McKenna (2002).

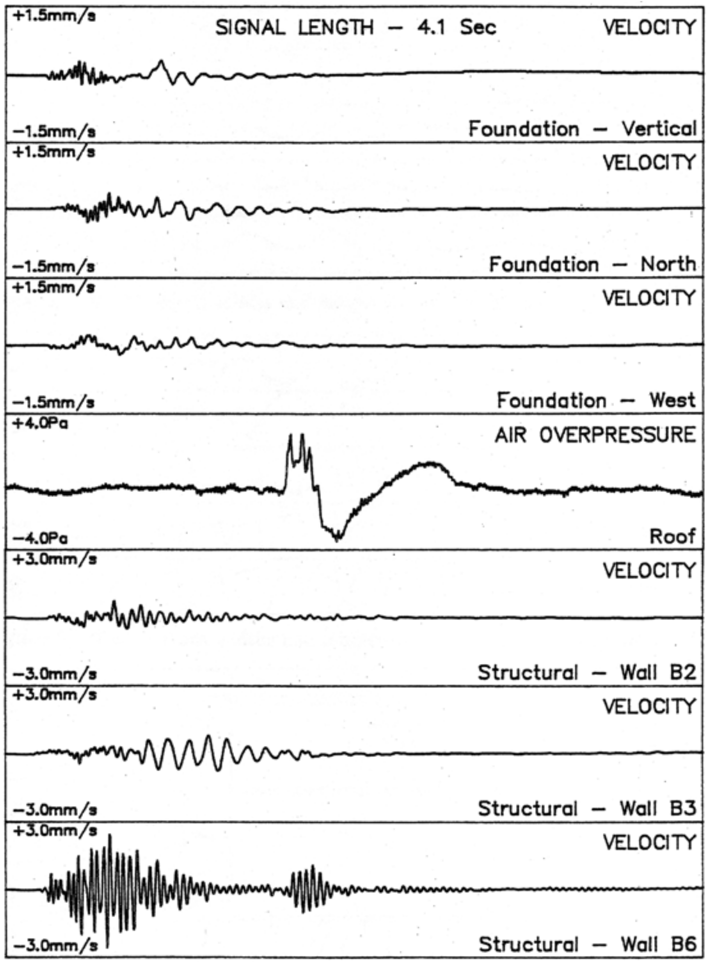

Figure 6. Comparison of typical low level velocity excitation and wall response time histories reveal a variety of wall responses (from White et al, 1993).

Surface quarry blasting some 450 m (1500 ft) away, produced peak particle velocities of 0.8 to 3.3 mm/s (0.03 to 0.13 ips) in the direction of the wall containing crack 3 during the two month period of observation summarized by Louis (2000). The largest of these motions induced maximum crack responses of 9 μm, which were only 40% of those induced during intensive heating in November. A full year of the observation of the three cracks shows that through one season the cracks opened and/or closed some 300 μm (Dowding, 2007).

6 COMPARISON OF RESPONSES OF BLOCK STRUCTURES

It has been surmised that research on residential structures in the United States is not directly applicable to structures elsewhere. Responses presented in this paper can be employed to investigate differences that may exist. First consider comparisons possible between cases presented herein. Next, response of block structures reported herein can be compared to other case studies of wood frame residential structures, which are more typical of residential structures in the US.

Table 1 compares the attributes of the 4 case histories in this paper to investigate similarities and differences between the response properties of the Welsh and Floridian houses (Miami & Ft Lauderdale) all of which are constructed of block walls. This table contains comparisons of dynamic response properties, dynamic crack responses and long term, climatological crack responses.

Table 1. Comparison of Block Structures and Their Response to Climatological and Blast Effects.

Case Study	Building	Natural Frequency (Hz)	Damping (%)	Excitation Frequency (Hz)	Particle Velocity (mm/s)	Crack Type	Max Crack Response: Blasting p to p (μm)	Max Crack Response: Daily p to p (μm)	Crack Temp Sensitivity: Δ Temp Daily (°C)	Crack Temp Sensitivity: Δ Crack / Δ Temp (°C)
Miami, FL	1 Story SOG	7	5	6 to 38	4 to 18	Block Wall Exterior	46.0	150.0	16.6	9.0
Ft. Lauderdale, FL	1 Story SOG	10		10 to 60	2 to 11	Stucco Ceiling Exterior	10.0	72.0	11.1	6.4
Wales	2 Story SOG	9	6	10 to 33	1 to 10 R	Block Wall Interior	NR	36.0 120.0	12.3[1] 11.3[2]	2.9[1] 10.6[2]
Milwaukee, WI (#3)[3]	1+ Story BMT	~9		6 to 39	1 o 3	Wall Board Interior	9.0	40.0		

SOG = Slab On Grade, Block = Concrete Block, BMT = Basement, R = Resultant
[1] Unheated
[2] Heated
[3] Louis, 2000

Dynamic structural response properties in Table 1 were obtained from free vibration response like that at the ends of response time histories like that in Figures 2 and 6. Estimates of natural frequency and damping from time history data (some of which is presented here) in Table 1 show that the single story Florida structures have natural frequencies (7 – 10 Hz) that bracket that for the Welch structure. Since one would expect the natural frequency of a 2-story structure to be less than that of a single story structure, this might imply that the Welch 2 story structure is slightly stiffer than a typical US structure. However, it appears that responses of the Welch structure were of the walls and not the super structure. Therefore more response motions at the corners of European block structures are needed. Similar calculations can be made to determine damping constants, which are 5 and 6% for that Floridian and Welch structures respectively. Thus they have similar damping constants.

Dynamic crack responses comparisons are more difficult to make, since the crack response data for the Welch house were collected before it was possible to autonomously collect dynamic crack response. However, White et al (1993) indicate that no permanent crack offsets were observed in the Welch case despite excitation with PPV's up to 10 mm/s. This observation is consistent with observations of structures in the US.

Finally and most importantly the response of cracks to climatological effects is compared on the far right of Table 1. It appears that crack response is similar for the Welch and Floridian homes. First consider compare responses of cracks on exterior block walls: the Miami exterior crack and the interior Welch crack on wall B1. The crack on wall B1 penetrated the entire wall thickness and thus its behavior reflects behavior of the exterior wall, not just the interior surface coat. If the maximum daily peak to peak (p to p) crack responses shown in Figures 3 & 5 are divided by the p to p changes in temperature, the temperature sensitivity is 2.9 to 10.6 μm/°C for the B1 crack and 9 μm/°C for the Miami crack. The range in the Welch crack response is a function of the heat source. The heated test for the Welch crack employed local heat blowers and the Miami crack was affected by direct sunshine heating. Thus both involved localized heat sources. The Ft Lauderdale case involved response of a stucco ceiling crack between two sheets of wire mesh supports, which does not involve localized heating.

Crack response is compared to peak particle velocity in the direction of the wall containing the crack in Figure 7 to for the Milwaukee and Miami cases. As can be seen, the Milwaukee case involved typical ground motions near quarries (0.8 to 3.3 mm/s). On the other hand the Miami case involved unusually high PPV's 17.5 mm/s because it was owned by the quarry and was located on their property. There exists a rough correlation between PPV and crack response (left graphs), but since excitation frequency and time history (number of pulses, exact timing, etc) are not included in the PPV magnitude, the correlation coefficient (R) can be low. In this case correlation can be improved through comparison of crack response with the single degree of freedom response spectrum of the ground motions as shown in the right hand graphs (Dowding and McKenna, 2005). The smaller Milwaukee excitation and responses are included in the Miami graphs in the insets at the lower left of both Miami graphs.

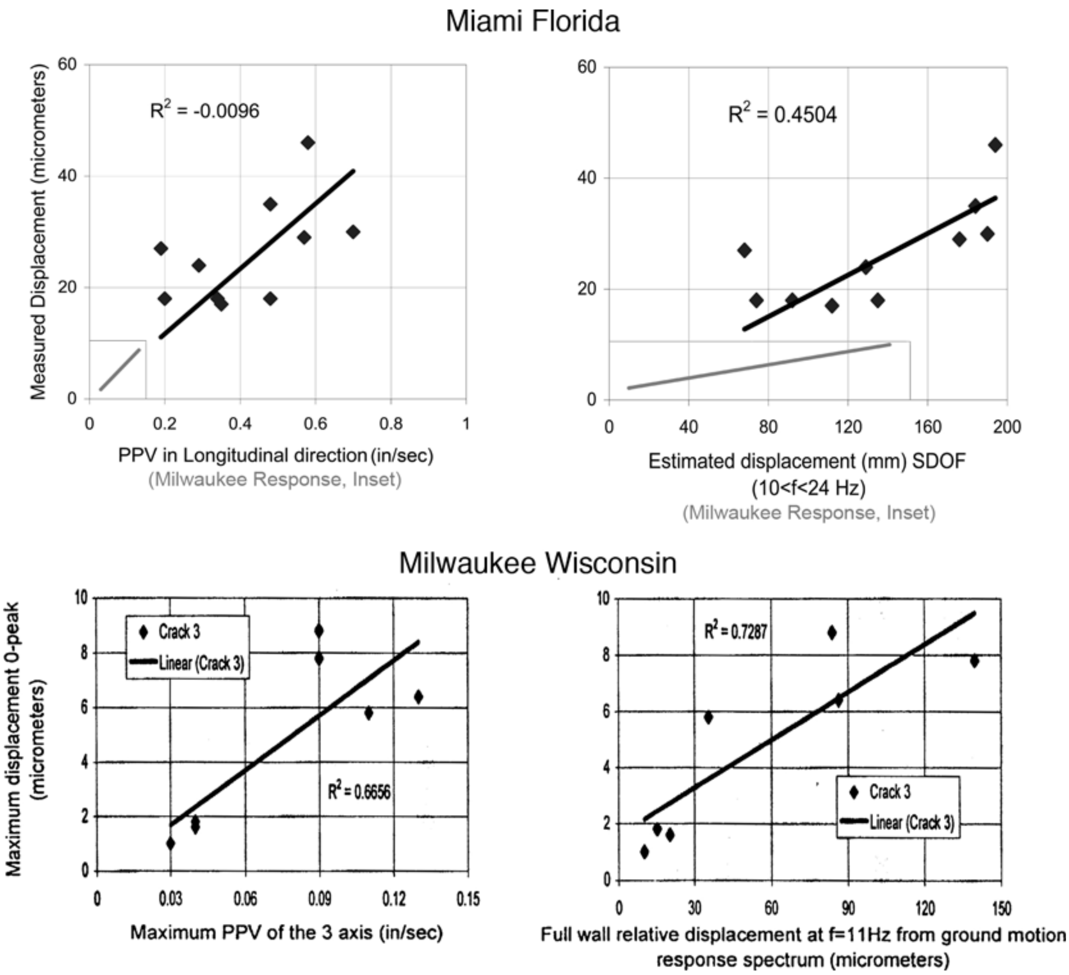

Figure 7. Comparison of crack response with peak particle velocity PPV (on left) and single degree of freedom response SDOF (on right) for the Miami case (top) and the Milwaukee case (bottom) shows rough proportionality with PPV but a higher correlation with SDOF response because of the inclusion of excitation frequency. (PPV in ips where 1 ips = 25.4 mm/s)

Comparison of crack response in a range of structures and building types reveals that for each crack there is a rough proportionality between ground motion descriptors and dynamic crack response. However it is different for each crack. This variation is logical since cracks are the result of structural details, and will vary from structure to structure and from cracking mechanism to cracking mechanism. Examples of this variation in the ratio of PPV with ground motion descriptor can be seen in Dowding and McKenna (2005).

7 CONCLUSIONS

Cracks in concrete block structures do respond to changes in temperature.

Temperature induced crack responses of block structures are large, some 3 to 15 times greater than response to ground motions with PPV's of 3 mm/s that typically that cause concern.

Thermal response sensitivity of cracks in external block walls is similar for both the Welch and Miami houses.

ACKNOWLEDGEMENTS

This paper is the result of research sponsored and supported by the Infrastructure Technology Institute (ITI) at Northwestern University, which is funded by a block grant from the US Department of Transportation. The author wishes to thank the ITI research engineers for their guidance and contribution and the Civil & Environmental Engineering graduate students who wrote the theses upon which much of this article is based.

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