U.S. Department of the Interior
Geological Survey

Vibration Investigation of the Museum Building at White Sands National Monument, New Mexico

by

Kenneth W. King, David L. Carver, and David M. Worley

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INTRODUCTION

White Sands National Monument is located in south-central New Mexico near the White Sands rocket testing center and the Alamogordo Air Force Base (fig. 1). This report presents the results of a study on the building response of the museum-administration building at the White Sands National Monument. The study evaluated the vibration response of the building, some sources of vibrations which are suspected to be the cause of cracking damage in the building's adobe material; this report suggests remedies to minimize future cracking as a consequence of induced vibrations. The park building under investigation is an adobe, two-tier in height that has parapets on the roof surfaces that give the structure the visual elegance and grace of the ancient Taos pueblos. The structure was originally constructed in 1936-38 using adobe materials in the Southwest-Spanish-Pueblo traditional style. The Pueblo style of construction consists of thick adobe vertical walls with flat roofs supported by large, exposed log beams (vigas) (fig. 2). The outside surface of the adobe walls of the structure presently has a cement-gunnite type covering to help prevent weathering of the adobe and to improve the cosmetic appearance. The current structure consists of the original building with several additions and modifications. Most of the changes, with the exception of the gift shop and workshop additions, used similar building methods and materials as in the original building. The recent external surface covering (gunnite walls and latex roof) and the concrete block wall cores of the gift shop and work shop differ from the original adobe-type building materials and methods. Most of the observed damage is visible in the gunnite-type covering and the damage cracks pass through the older adobe materials. Major cracking is located on the walls and are visible at several places on the building. An inventory and photographs of the wall cracking were made for the study. The general locations of the more visible cracks are shown on figures 3-A, B, C, D.

OBJECTIVE AND SCOPE

The purpose of this study was to determine the vibration response of the museum-administration building and to evaluate the sensitivity of the structure to vibrations as a possible cause of the cracking damage. This included on-site measurements of response to determine parameters such as natural resonant frequency and damping characteristics, which are important in analysis of vibration-caused damage. Determination of these parameters by strictly analytical techniques is questionable due to the irregularity of the building and due to the complex interaction between native construction materials. However, a cursory attempt was made during the study to define the probable sources of some of the ground motions which may induce potentially harmful vibrations into the structure. Finally, some recommendations are made to minimize future cracking due to vibration.

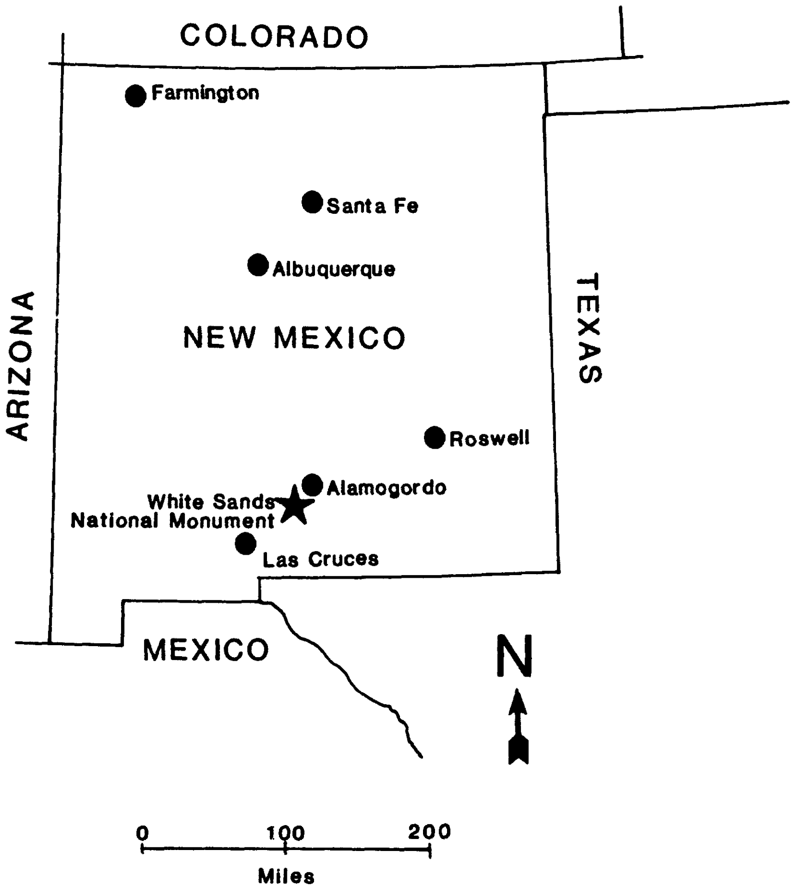

Fig. 1. Location of White Sands National Monument.

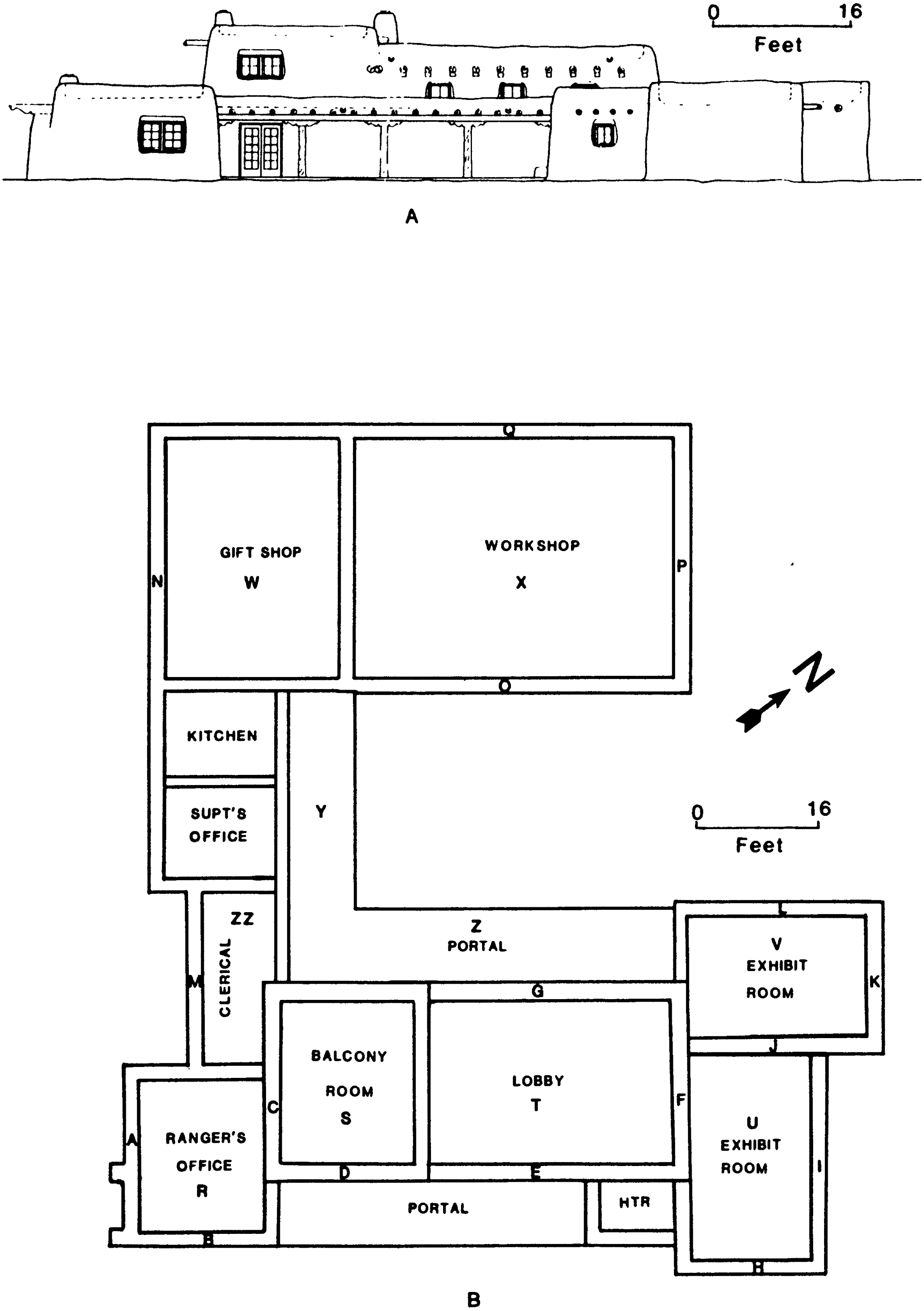

Fig. 2. (A) White Sands National Monument Museum and Administration Building, front view (Southeast elevation). (B) plan view showing wall and roof identifiers and locations of long-term instruments.

BUILDING DAMAGE

A visual inventory and photographs were taken of all wall cracking to document the damage for current and future studies. The more apparent cracking is shown in figures 3 A, B, C and D. The cracking which passes or extends through the gunnite covering and into or through the adobe material is in areas where dissimilar materials (adobe, concrete block, wood) are joined (fig. 3 B-1); at or near window-mounted air-conditioner supports (figs. 3 B-2-3 and C-3); at window and door headers (figs. 3 A-1-2, B-2-4, C-2); and at viga-parapet-roof junctions (figs. 3 A-3-4, B-5-6-7, C-4-5, D-1-2-3). All of these places are typical areas of stress concentration resulting from the load-bearing elements of the construction or from the addition of elements such as air conditioners and vents. The basic construction elements concentrate the stress but generally, the actual initiation of cracking is probably from differential settlement, thermal expansion-contraction, moisture expansion-contraction, vibration, or a combination of all of these sources.

The extent of cracking was used to assign a damage scale to the building. The measurement or scaling the degree of damage to the building was necessarily subjective and was done according to the methods developed during the Chaco Canyon, Hovenweep, and Paguate studies which gave a basic frame of reference (King etal. 1985, King etal. 1986, King etal. 1987). The damage scale derived from those studies range from a degree of 1 (which consists of light visible cosmetic cracking) to a degree of 5 (which has visible structural damage as cracking, movement or distortion present on interior and exterior walls which are wider or greater than 12 mm and longer than 10 cm in length) (table 1). The extensive cracking shown in figure 3 A on the parapet walls has a maximum cracking that is 2 to 8 mm wide and up to 25 cm in length. The average cracking generally falls into the range of degree of 3 to 4. No apparent visible evidence was found to indicate that the damage was caused by differential settlement or by thermal effects (except in the areas of adobe and concrete block wall junctions). It is suspected that moisture, although not a primary cause of the damage, could have accelerated the damage once the initial crack was formed.

FIELD TESTS

Important parameters in the analysis of vibration-induced damage to building structures are the natural resonant frequency and damping coefficient. Seismic and acoustical field instrumentation was installed and tests were conducted to determine these parameters and to identify possible sources of vibrations. These parameters were determined initially from vibration sources applied directly to the building components and later were compared with results from known external vibration sources. Long-term (six weeks) seismic and acoustical instrumental monitoring was used to observe magnitudes and possible sources of induced vibrations to the structure.

BUILDING VIBRATION RESPONSE TESTS

The procedure for obtaining the natural frequency of vibration and damping coefficient of the walls generally consisted of installing portable horizontal motion-sensing seismometers on the top and at the midpoint of bearing walls of the structure (King, 1969). Vibrations were then induced by body movement of a person in close synchronization with the structure's

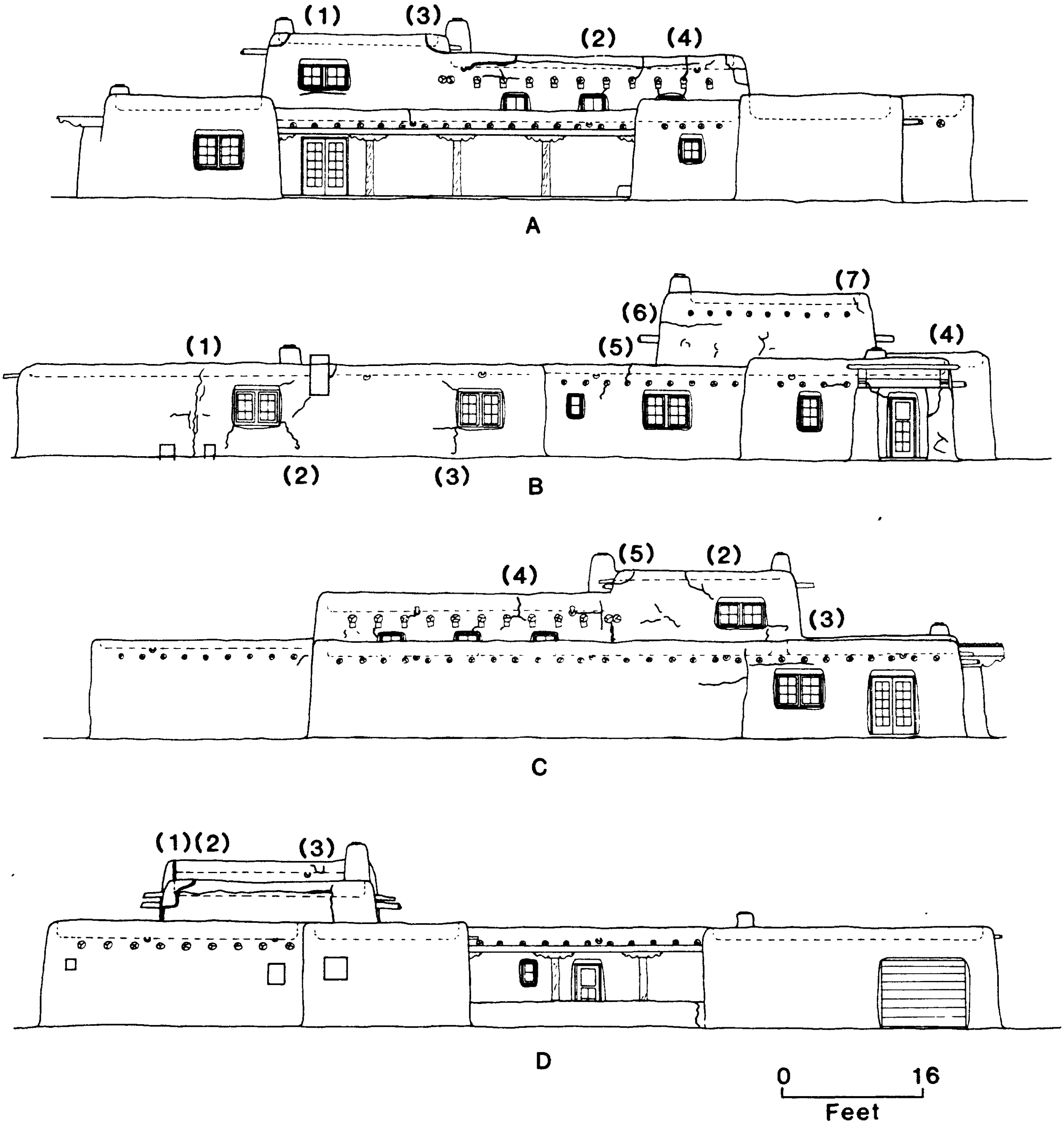

Fig. 3. Elevation views of the Museum and Administration building showing the prominent visible wall cracks. Small numbers identify cracks discussed in text. (A) Southeast elevation, front, (B) Southwest elevation, (C) Northwest elevation, back, (D) Northeast elevation.

TABLE 1

PRELIMINARY INSPECTION DAMAGE SCALE FOR ADOBE/ROCK STRUCTURES

Degree 1

Light visible cosmetic cracking in interior or exterior walls. Fine cracks less than 1 mm wide.

Degree 2

Visible cracks (2 mm or less wide) in interior or exterior walls. Fine cracks (less than 2 mm wide) apparent near windows, doors and/or support members (not in a polygonal configuration).

Degree 3

Thin visible cracks (2 to 5 mm wide) which connect areas of stress concentration. Length of cracks generally exceed 10 cm. Erosion of cracks (from water invasion) may be present. Cracks penetrate 1/2 or more the width of wall/roof. Slight structural damage is possible (ceiling or viga cracking; bearing wall, door, or window framing distortion).

Degree 4

Visible cracking (5 to 12 mm wide) with lengths generally over 10 cm. Fine to thin cracks extend through width of walls. Large amount of 2 to 5-mm cracking on the interior and exterior walls which are not in a polygonal pattern. Cracking continues from original construction through newer construction. Distortion or evidence of movement of walls, vigas, door and window frames and/or other structural members. Moderate structural damage present.

Degree 5

Visible damage (cracking, movement, distortion) present on interior and exterior bearing walls. Cracks larger than 5 mm through thickness of wall. Extensive cracking on interior and exterior walls with moderate amount of cracks wider than 12 mm and longer than 10 cm in length (Feline cracks). Major distortion or evidence of major movement at areas of stress concentrations (windows, doors, vigas, wall supports etc.) Visible gaps at joining points such as wall to wall or wall-to-roof junction.

approximate natural frequency. Roofs were similarly shaken except that a vertical motion-sensing seismometer was placed in the midpoint of the roof and shaking was induced by a person doing knee-bends or by a weight drop. This technique has been described in detail by Hudson and others (1964), and King (1969). Seventeen walls and ten roofs of the building complex were tested.

The records of the induced vibrations were analyzed to determine the response of the walls and roofs. Vibration time histories of some of the tests are shown on figure 4.

SHORT-TERM MONITORING TESTS

The vibrations of pertinent walls induced by several different sources were documented and analyzed. Vibrations induced in the building by vehicle traffic on the interstate highway adjacent to the museum, vehicular traffic on Park Service access roads, vehicle traffic in the parking lot, wind, personnel traffic in the building, and acoustic/ground-coupled vibrations from aircraft overflights were recorded. The seismic data from the vibration sources were analyzed and compared to the spectra amplitudes of the normal background vibrations in the structure.

LONG-TERM MONITORING TESTS

The vibration monitoring instruments were installed semi-permanently on the building and an acoustical transducer was located adjacent to the building. The seismic system was programmed to continuously operate with solid-state memory, data-storage in wrap-around mode which would turn the recorder on only when the acoustic noise exceeded a specified level. The equipment was programmed to record only those events that were caused or accompanied by an acoustical emission in the 1- to 40-Hz frequency band and had energy greater than approximately 90 dB sound level. The acoustical monitoring and triggering experiment was to confirm that the source of vibration inducing the structural response of the buildings was an acoustical emission and not an induced ground motion source and further, to indicate those acoustical frequencies that were being emitted. The total acoustically-induced vibration energy levels could not be accurately determined from the data since the full instrumentation needed for an overpressure evaluation was beyond the scope of this study. Accordingly, no attempt was made to use the acoustical data to determine the total over-pressures on the structure.

The location of the sensors are shown on figure 2. All triggered vibrations were recorded in digital mode on magnetic tape for approximately 30 seconds pre-event and 3 minutes post-event.

ANALYSIS AND DISCUSSION OF DATA

The vibration and acoustical data were digitized at 200 samples per second by the field seismic systems. The sample rate allowed frequency resolution sufficient to analyze data in the 1- to 40-Hz spectral range which will contain the natural frequencies of the walls and roofs. Approximately 10 seconds of event or ambient vibration signal was windowed and tapered with a whole-cosine-bell (Hanning window) before being Fourier transformed by a Fast Fourier Transform (spectral algorithm, used by E. Cranswick, unpub. data, 1986). Only the duration of the induced vibrations from a helicopter

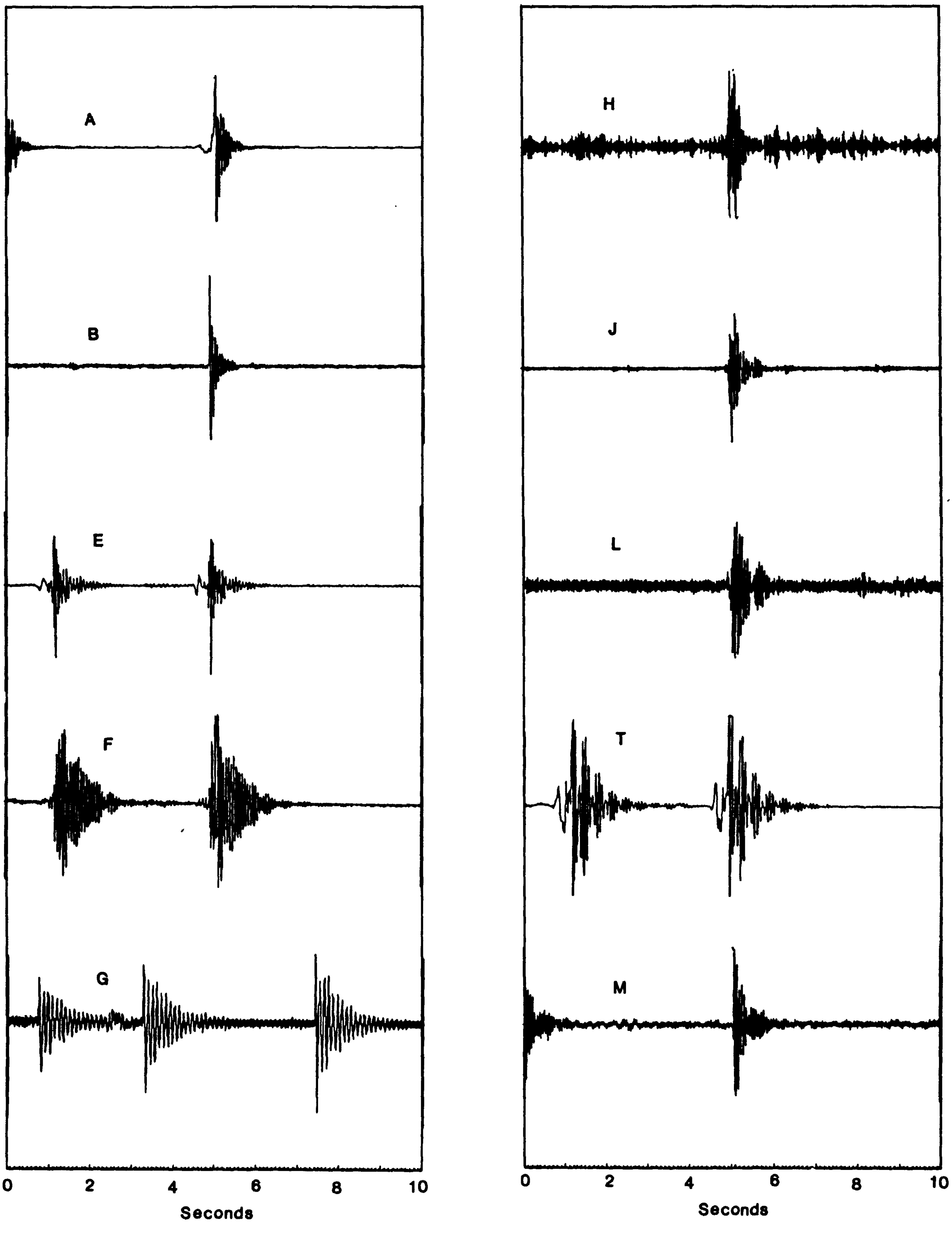

Fig. 4. Examples of wall and roof vibration velocity time histories from wall tests. Amplitudes are normalized to display space. Letters refer to wall identifiers shown on Fig. 2. "T" is the lobby roof.

overflight and a convoy of trucks exceeded the selected 10-second duration used for most of the analysis.

BUILDING VIBRATION RESPONSE TESTS

The peak frequency determined from the spectrum derived from the wall test data was considered to be the frequency to which the wall was most sensitive (fig. 5 and table 2). Many of the secondary peaks derived by the spectral analysis as shown in figure 5 are either harmonics of the natural frequency of the wall, or induced motions from adjacent walls/roof, or secondary torsional motions. The wall-roof vibrational frequency of most concern ranged from approximately 9 to 22 Hz (table 2).

The data were analyzed to obtain the approximate percentage of critical damping using the following formula:

$$b=\frac{1}{2\pi}[-\ln(\frac{X_{n+1}}{X_n})]$$

where b is the percent critical damping and X_n is the velocity amplitude for the nth cycle of motion. The percent of critical damping for the walls and roofs ranged from 2 percent to 5 percent of critical. The natural frequencies of the roofs (figs. 5 J, L and T) are within the same general frequency range as the walls but, in general, have lower damping coefficients (Table 2). These frequencies and damping values are generally comparable to those found in one-to-two story structures (King and Algermissen, 1985, King and others, 1986). It is interesting to note that the vibration frequencies of the roofs (due to diaphragming motion) is similar to the walls but the damping of the roof structure is slightly lower for the diaphragming motion. In general, the roof beams (vigas) are approximately the same length as the walls are high, which accounts for the similar natural frequencies. But the roofs do not have the additional support (and added stiffness) from bearing walls, braces and foundations which explains the difference in the damping between the roofs and the walls.

SHORT-TERM MONITORING

During the wall-testing phase, building shaking induced by several identifiable sources (other than by testing personnel and ambient background motions) were documented and later analyzed. Some of these sources were personnel activity in the museum, doors closing, driveway traffic, aircraft flying at various altitudes and speeds, and traffic on the interstate highway. The jet aircraft (F-15's ?), helicopters, and semitrailer-truck traffic gave the highest peak velocity values. A comparison of the seismic velocity time histories are shown in figure 6. The low-to-medium altitude high-speed accelerating F-15's? gave the highest peak values during this testing period. The highest peak values of 1.1 mm/sec were approximately four times higher than the largest value recorded from traffic (0.3 mm/sec). However, the average duration of the high speed jet aircraft was a factor of 10 less than the traffic (1 sec. versus 10 sec.). The induced vibrations from the helicopter had the longest duration, at a continuous vibration level (0.9 mm/sec for approximately 25 seconds), of all the sources documented during the test period. The vibrations induced by the jet aircraft during routine take-off patterns (which always consisted of two aircraft in a similar pattern of direction, altitude, and speed during this testing period) were at a slightly

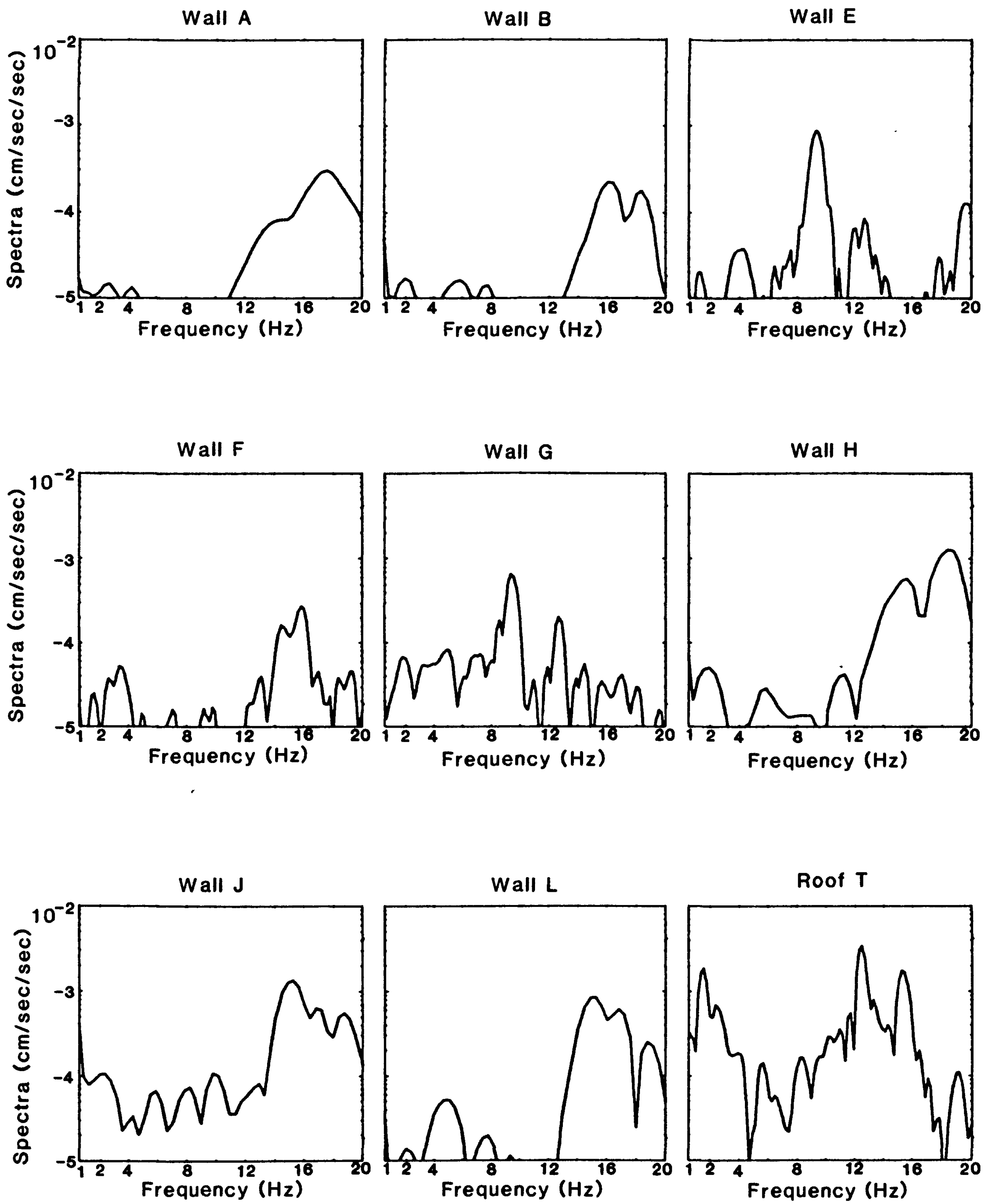

Fig. 5. Examples of spectra (FFT) derived from the time histories of the vibration tests. The spectra show the predominant peaks at the wall's natural frequencies.

TABLE 2

STRUCTURE DIMENSIONS			RESPONSE FREQUENCIES			% DAMPING
WALL	HEIGHT	LENGTH				
A	12	25	17.0	34		---
B	12	21	16.2	17.1		1.8
C	19	27	12.0	26	35	---
D	19	22	11.5	15.8	25	---
E	17	36	9.3	12.5	34	4.5
F	17	27	16.1	9.5	28	4.6
G	17	36	9.4	13.	32.5	3.5
H	12	20	18.2	26	35	2.5
I	12	30	16.8	9.5	28	4.0
J	12	26	15.3			3.1
K	12	20	16.8	29		4.1
L	12	28	15.8	18.1	34	4.0
M	10.5	28	17.5	22	38	2.2
N	11	36	19.8	33.5		2.2
O	11	43	16.0	25.5		2.3
P	11	36	14.8	18	34	2.0
Q	11	43	15.5	27.5		4.2
ROOF	LENGTH	WIDTH				
R	25	21	15.5	23.5		2.0
S	27	22	13.2	22.5		---
T	36	27	12.5	18	35	2.5
U	30	20	15.0	17.2	27.5	2.5
V	28	20	15.5	19	36	2.2
W	36	28	10.5	23.5		---
X	46	36	11.0	20		4.0
Y	37	9	28.5			---
Z	41	10	19.0			---
ZZ	26	11	22.0	4.5		1.5

Height and width measured in feet, frequencies in Hz, damping in percent of critical damping. The locations of the walls designated by letters are shown on Fig. 2. The response frequencies are given in order of predominance during induced vibrations.

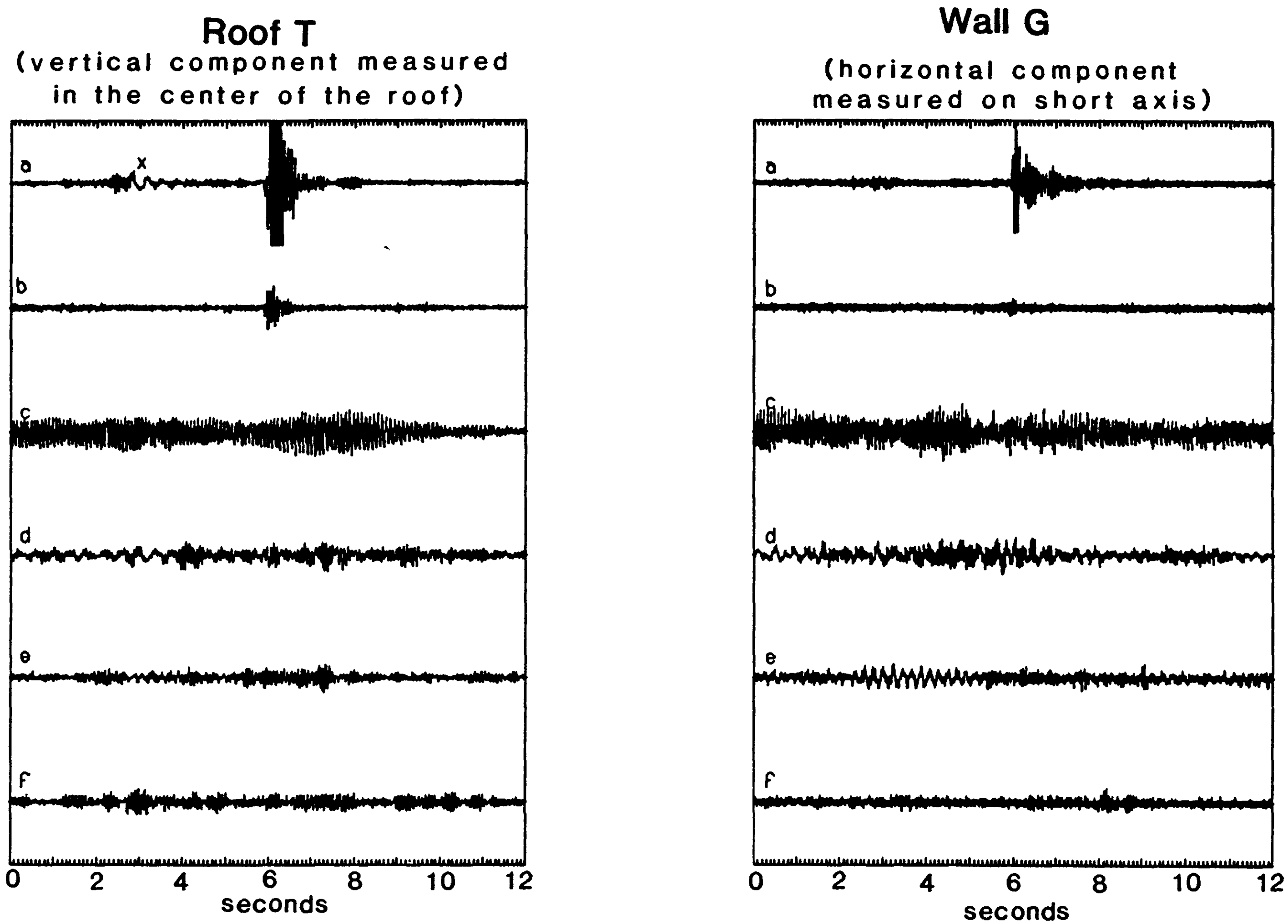

Fig. 6. Examples of vibration velocity time histories from and instrument located on a roof (T), and a wall (G). The vibrations were induced by specific and identifiable events (visual observations): (A) low-flying, high speed jet aircraft (F-15?) within 3,000 ft. of the museum. (B) High flying, high-speed jet aircraft (F15?) higher than 3,000 ft. over the museum. (C) Helicopter flying within 3,000 ft. of the museum. (D,E) Pairs of F15's(?) flying in the normal take-off pattern. (F) Vibrations induced by a semi-trailer truck on the interstate adjacent to the building traveling at approximately 60 mph. (x) Ground coupled acoustic waves arriving before the acoustic signals traveling a direct path to the building. All amplitudes normalized to (A).

higher level than the vibrations from heavy vehicles but considerably lower than the vibrations induced by the helicopters and the single high speed jet aircraft. It was apparent that the take-off pattern of the aircraft was such as to avoid overflights of the National Park structures. The helicopter and the single high-speed jet aircraft were not in the take-off pattern and were at a near over-flight attitude to the structures and therefore, were closer to the buildings by several thousand feet. This project was not designed to test the broad scope of acoustic effects; therefore, the true azimuth and distances to the aircraft and parameters of the aircraft (weight and speed) could not be accurately documented, but the general altitudes and distances were visually estimated, with estimates shown in figure 6.

The spectra derived from the event data from induced sources, such as aircraft and vehicular traffic, were compared to the wall-testing data. The comparisons of event spectra with the wall test spectra show that the wall tests do accurately indicate those frequencies which will be excited and amplified by the structural elements during induced vibrations to the structure (fig. 7). The tests indicate the general energy level increase (and in what frequency band) that is introduced to the structure from external ground motion sources.

The event data from the induced sources were compared to the ambient vibration background of the structures. A similar time duration of ambient vibrations measured at the same positions on the building were transformed into velocity spectra. The ambient vibration durations for analysis were selected from seismic records at a time position of either approximately 5 to 10 seconds pre-event or 60 to 100 seconds post-event. The spectra of the ambient background was divided into the spectra of the induced sources as: $CF(f)=SS(f)/AS(f)$ where f=frequency in Hz, CF= comparison factor, SS= Source spectrum. AS = ambient or general background spectrum. These analyses indicate the general frequencies and intensity levels induced from several sources as compared to the ambient vibrations at that time. The heavy traffic on the highway and aircraft in the take-off pattern induced a general level of vibration in the structure wall and roof approximately 2 to 8 times the ambient level across the 1- to 40-Hz frequency band. The induced vibrations from the low flying, high-speed jet aircraft and the helicopter introduced the highest contrasts to the vibration ambient background level (fig. 8). These results are similar to those shown by the peak amplitudes on the vibration time histories. The high-speed, low-flying jet aircraft introduced a general vibration level to the building that was 10 times the ambient background with some selected frequencies as high as 60 times the ambient background level of that particular time period. The vibrations from the helicopter induced a narrow frequency band; that is, the induced frequency spectral width was less than the induced frequencies from the other sources. The helicopter induced peak vibrations at 10.5, 21.5, and 32 Hz frequencies. These selected frequencies induced motions in the roof and wall that were approximately 30 to 40 times higher than the ambient levels.

LONG-TERM MONITORING

An average of 20 acoustical events per day, inducing vibrations at or above the 0.1 mm/sec level in the 1- to 40-Hz frequency band were recorded during the monitoring period. Some 24-hour recording periods had only two or three events that would trigger the start function of the recorders, whereas

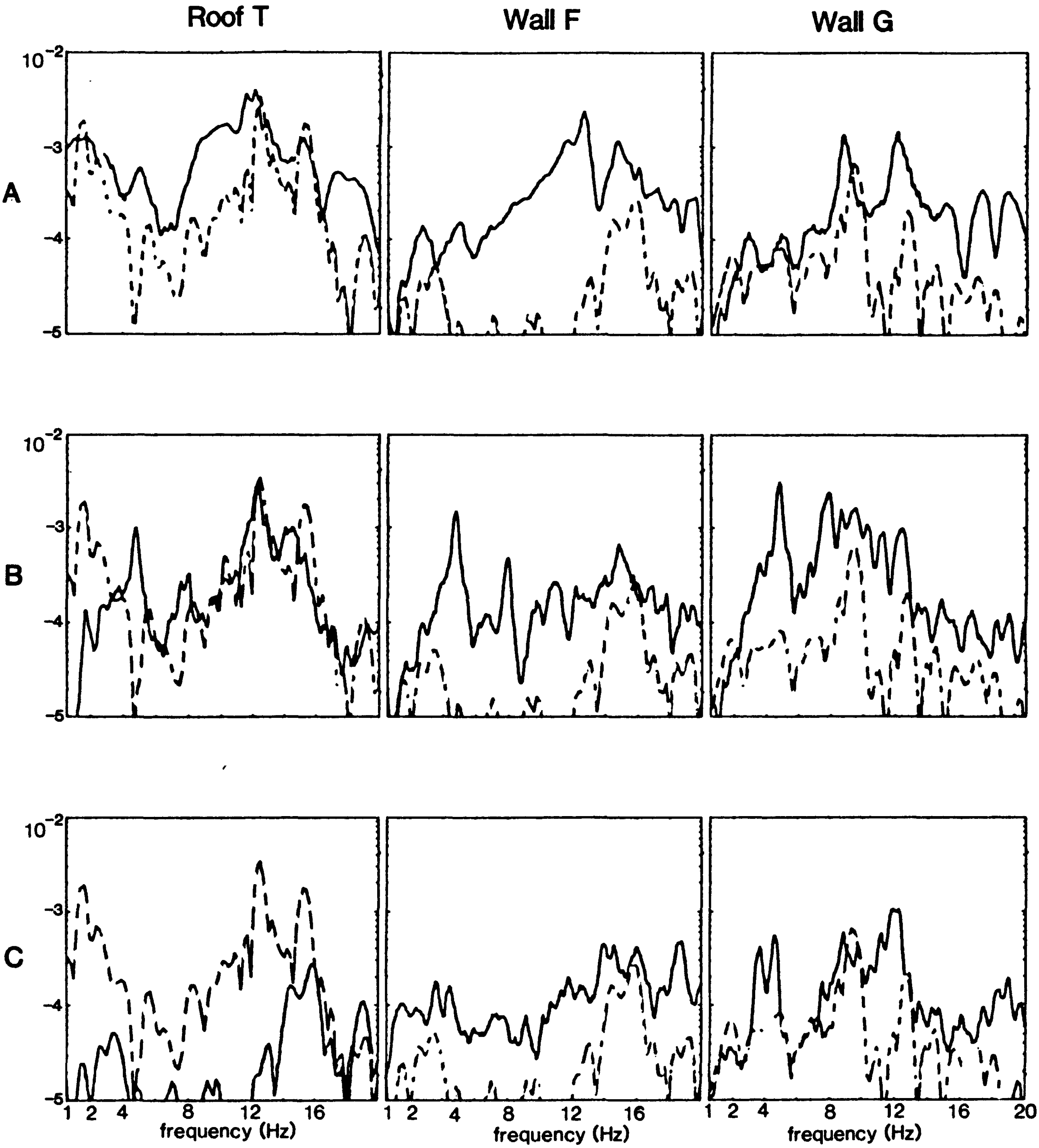

Fig. 7. Comparisons of the spectra derived from the wall tests (dotted lines) and the identified events (solid lines) on a roof(T) and two walls (F and G): (A) Low-flying, high-speed jet aircraft. (B) Pair of jet aircraft (F15's?) on normal take-off pattern. (C) Semi-trailer truck on the interstate highway. Amplitudes normalized to display space.

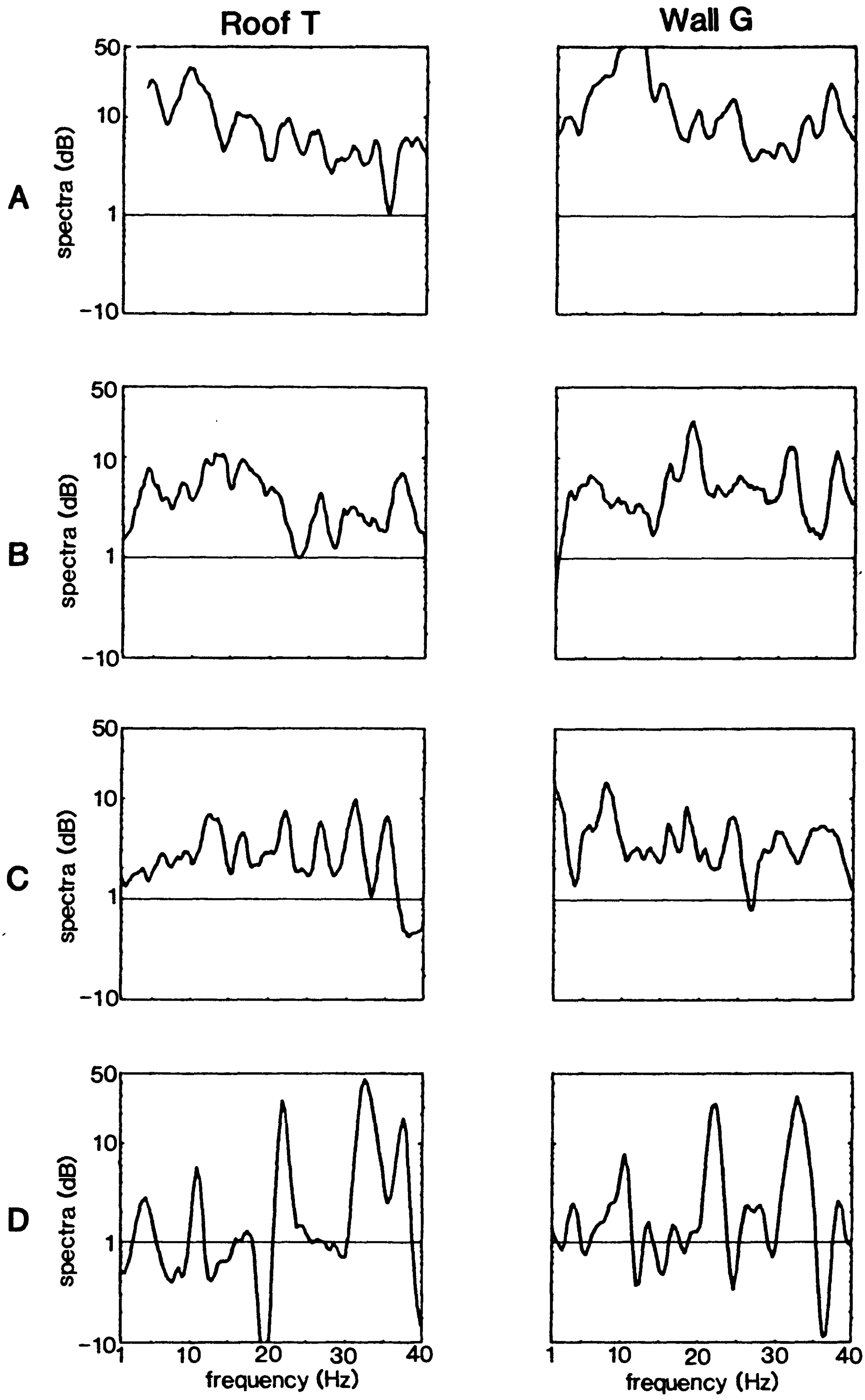

Fig. 8. Spectral ratios obtained by dividing the spectra derived from ambient vibrations and the vibrations induced by a specific event on roof T and wall G (Fig. 2): (A) Low-flying, high-speed jet aircraft. (B) Pair of jet aircraft flying in normal take-off pattern. (C) Semi-trailer truck on the interstate highway. (D) Helicopter.

several other 24-hour periods had 50 or more events which were at or above the triggering level. Examples of the vibration time histories are shown in figure 9. Events A and C (fig. 9) are examples of the maximum motions recorded during this period. The peak vibration value for event A is 1.8 mm/sec and for C is 2.6 mm/sec (fig. 9). Comparison of the frequency signatures from the recorded vibrations indicates that events A, B, and C (fig. 9) were induced by low-flying, high-speed jet aircraft; however, this assumption is based only on vibration time-history and spectral comparisons from the project data and not from visual verification. The vibrational time histories shown in figure 9 indicate the range of recordings. The amplitudes have been normalized to the maximum size event (A & C) for ease of visual comparison. This method makes the relative amplitude of the smallest event (F) seem undetectable but, in reality, it is at the 0.1mm/sec level. Approximately 80 percent of the events were similar to events D and E which are probably routine flights in the Alamogordo Air Force base airport take-off pattern. Adequate quantitative analysis could not be made from the acoustical data since only one transducer was used as a detection and identification device; however, the point detection data indicate that the maximum overpressures were probably in the 0.001 lb/in^2 range.

DISCUSSION AND RECOMMENDATIONS

The areas of major cracking shown in figures 3A-3, 4, 3B-6, 3C-5, and 3D-1, 2 and 3 are at probable structurally-weak locations at the junction of the parapets and the vigas. There were no strong indicators that differential settlement or major thermal-moisture changes are the cause of this particular area of damage. The cause of cracking is probably a combination of a junction of material difference (wood, adobe, gunnite), a structural design that incorporates vigas which help concentrate the stress in an area of low support (the parapets), and the continuous roof diaphragming and wall shaking. If a new covering is put on the outside of the lobby walls, the parapets should be re-engineered and rebuilt to better absorb the stress induced by the vigas. The cracking near the windows on side B (fig. 3) 2 and 3 are probably due to the increased stress from the window mounted air conditioners. The air conditioners on side D which are independently supported away from the structure have caused no damage to the building. The cracking present at B-4 is probably due to a change of stress due to the removal of the vigas and colonnades which supported a portal that has been removed; this area should stabilize over a period of time. The major cracking at B-1 is due to the joint of dissimilar (thermally different) materials (cement block and adobe). An elastic-type material will be needed for rehabilitation of this section since either adobe or cement-gunnite will continue to crack due to the difference in the thermal expansion rates. It is probable that all the cracking in these areas of weakness has been accelerated by induced vibrations.

The response values shown on table 2 are the values that will be amplified by the structure and are the frequencies to be most avoided to prevent vibration damage to the structure. Past investigations have shown that a low-rise structure wall will amplify selected frequencies 2 to 10 times (King, 1979). It is apparent from this study that vibrations induced by heavy vehicular traffic, helicopter flights, and jet aircraft flights consist of frequencies that coincide with the natural frequencies of the walls and roofs of the museum building. However, due to the distance from the building which

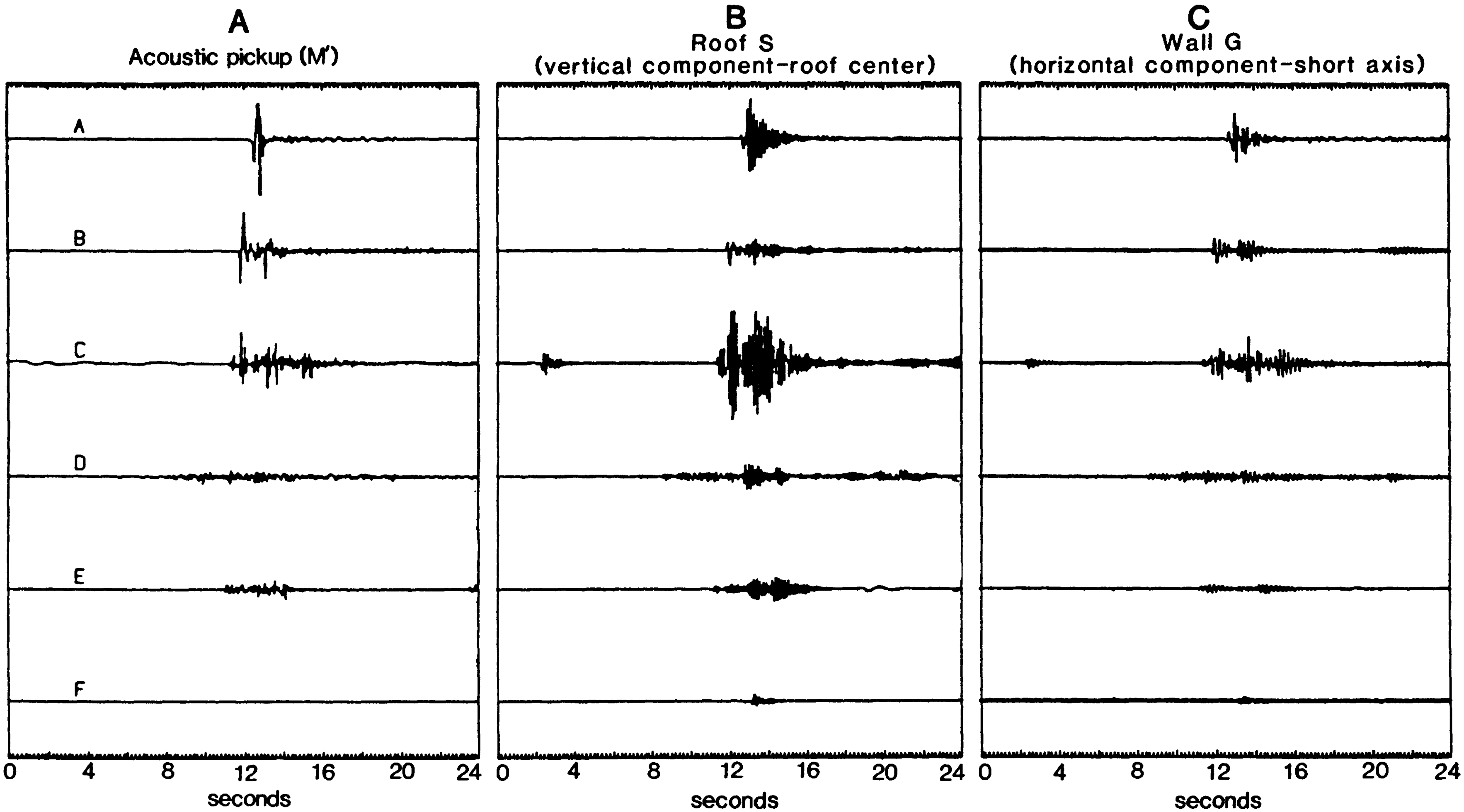

Fig. 9. Examples of the maximum and minimum vibration time histories recorded during the unmanned observation period. Events were not visually identified. (A) Acoustic time history near location M (Fig. 2). (B) Vibration time histories of roof S. (C) Vibration time histories of wall G. Amplitudes are normalized to event a. All events triggered by the acoustic transducer.

allows sufficient attenuation of the acoustic and vibration energy, the generally continuous induced vibrations from highway traffic and jet aircraft in the normal take-off pattern are probably causing no detrimental structural effects to the building. The low-flying helicopters and low-flying, high-speed jet aircraft which were not in the flight patterns and which were much closer to the building are very close to the maximum vibration limits usually set for historic and archeological structures (King, etal.1985, 1988). The specific type of construction (long beam roof supports and extended flat roofs) make the structures more sensitive to the vibrations and overpressures induced by the acoustical emissions of the aircraft. The maximum vibration levels that were documented during this study are well within the safe zone as designated for mine blasts near frame and brick houses (Siskind etl. 1980).

However, the acceptable vibration level should be considerably less for an irreplaceable historic structure, especially those of flat roof and adobe construction than for typical houses in general which usually have either a rafter- or truss-supported sloped roof. Also, a standard structure or house can be repaired without risk of loss of history. The generally accepted maximum vibration values are established statistically from a data base collected from frame or concrete block buildings constructed according to recent building codes and not for historic adobe or masonry buildings. Since we know little of the cumulative effect of medium level vibrations (1-20 mm/sec at 1-30 Hz) on adobe-type construction and materials, a safe allowable upper level of induced vibrations which will afford the best protection, according to present knowledge on vibration and materials, without overly restricting normal cultural and industrial activities should be accepted. In general a maximum velocity particle motion level of 2 mm/sec in the 1- to 20-Hz band was accepted at the Chaco Culture National Historic National Park for construction of an intra-park highway and direction and planning of traffic. The highway was constructed within 200 feet of the historic buildings without exceeding the vibration level and resulted in no damage to the structures.

We would recommend the 2 mm/sec level for the structures at White Sands National Monument. If this is adopted, then the normal take-off pattern used by the nearby airport would be acceptable, but the low-flying helicopters and low-flying, high-speed jet aircraft flying within a few thousand feet of the structures would not be acceptable. Also, additional road construction or heavy earth-tamping should not be nearer than approximately 200 feet of the main museum building. This vibration level is recommended only for historic, irreplaceable adobe-masonry structures or for those structures that may have irreplaceable mud-adobe artifacts within.

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