BLAST VIBRATION DAMAGE TO STRUCTURES

David E. Siskind
Supervisory Geophysicst

and

Mark S. Stagg
Civil Engineer

Twin Cities Research Center
Bureau of Mines
U. S. Department of the Interior
Twin Cities, Minnesota

INTRODUCTION

The Bureau of Mines conducted a series of field and laboratory research studies between 1976 and 1982, examining the generation, propagation, structural impacts, measurement, and analysis of both ground vibrations and airblast from surface mine production blasting. A significant part of this work is the determination of the frequency dependence of the structural vibration response and, consequently, the cracking potential for low-rise residences.

Researchers found that safe levels of peak particle velocity ranged from 0.5 in/s for low frequencies (<10 Hz) to 2.0 in/s for high frequencies (>40 Hz), being also dependent on the structure characteristics. They also examined fatigue or long-term effects and concluded that damage risk was not related to the numbers of events. In other words, cracking would not occur from a large number of low-level vibrations.

As part of the study, structural responses from human activity in the house and the external environment of wind, temperature, and humidity cycling produced strains and dynamic responses that sometimes exceeded those resulting from blasting at a 0.5-in/s particle velocity. Researchers concluded, therefore, that blasting vibrations below this ambient level of about 0.5 in/s are not significant.

CRACKING IN STRUCTURES FROM VIBRATIONS

Many papers address ground vibrations and blasting. However, few contain actual observations of damage and corresponding measurements of ground motions. In 1962, the Bureau published RI 5968 by Duvall and Fogelson. This was a summary analysis of the three existing blasting damage studies: one from Canada, Edwards, et al., 1960; one from Sweden, Langefors, et al., 1958; and data from Bureau Bulletin 442, Thoenen and Windes, 1942.

This was followed by Bureau Bulletin 656 (Nicholls, et al., 1971), a comprehensive summary of the many problems of blasting, including generation, propagation, and damage from both ground vibration and airblast. Review of RI 5968 and Bulletin 656 indicated that low-frequency vibrations (e.g., 2.5 to 40 Hz) were a significant problem and required additional study, such as response analysis. The 2-in/s safe level had been based on a mixture of both high- and low-frequency damage data. Consequently, the inferred 5-pct damage probability was somewhat artificial and depended on the relative amount of each kind of data available. Using any given number of standard deviations from the mean of the high- and low-frequency data separately would give widely differing safe values for the two cases. The derivation of 2 in/s as the safe level was based on two standard deviations from the 5.4-in/s mean of all the minor damage points. Five values for minor damage were outside the two-standard-deviation damage envelope; all were from Bureau of Mines shaker tests which only approximately modeled transcient blast loads. One of these values was dropped for statistical reasons, appearing to be a measurement error. The 2-in/s criterion was also lower than all the individual major damage points, and as it included all actual blasting damage data, it was recommended as a boundary between damage and nondamage.

The large amount of scatter in the summary analysis at low frequencies is undoubtedly caused by the presence of structure resonances and initial strain states. The lower frequency vibrations also result in large displacements (and strains), and it is strain that ultimately produces cracking. The original Bureau damage summary of 1962 did not have sufficient data for separate analyses of the low and high frequencies because it was based upon only three studies, one of which was not blasting. Since then, four major sets of additional data have become available, including new damage data obtained from two studies by the Bureau (Siskind, 1980 and Stagg, 1984).

Three other studies have supplied a few new damage points each, bringing the total number of relevant studies to 11 (table 1). Direct statistical treatment of the type used in RI 5968 and Buletin 656, probability analysis, and response spectra analysis were all applied to quantify blasting damage potentials.

Recent Bureau of Mines Damage Studies

The Bureau recently completed two studies of ground vibrations impacts. The first involved a few measurements each in a wide variety of structures (Siskind, 1980). Following this, Bureau researchers studied fatigue from repeated loading of one structure over a long period of time, as described and published in Bureau RI 8896 (Stagg, 1984). For both studies, efforts were concentrated on actual measurements of wall, floor, and racking responses and on observations of damage that could be correlated to specific vibration events. A significant part of the work was done near large surface coal mines, with thick soil overburdens and large-diamater blastholes, cases which had not been studied previously. In all, 202 shots out of about 900 produced useful high-level damage and nondamage data. Most of the other shots provided data on structural responses and airblast effects, but were relatively low in level.

A summary of the Bureau data alone is shown in figure 1. Much of the damage was observed in homes with interior walls of plaster on wood lath and consisted of extensions of existing cracks and new hairline cracks. Two houses, one being the Bureau-built fatigue structure, were notable in being modern one-story homes with gypsum board interior walls. Unfortunately, one of these structures was sold by the mine and moved before more than superficial damage consisting of minor crack extensions could be inflicted. The lowest level for observed damage in this structure was 0.79 in/s.

Frequencies were determined directly from the vibration time histories and by real-time spectral analysis. In some cases, the records showed two dominant frequencies: high frequency for the first few hundred msec and then a significantly longer low-frequency wave train. The values of the amplitude and frequency used by the Bureau researchers corresponded to the

TABLE 1. - Studies of damage in residences from blasting vibrations

Study	Damage classifications	Types of damage	Overburden type	Structures studied	Distances to shots, m	Distances to shots, ft	Shot sizes, lb/delay	Frequency range, Hz	Total shots	Damage observed-uniform-classification: Non-damage	Threshold	Minor	Major	Instrumentation
Thoenen and Windes, Bureau of Mines, 1942.	Threshold and minor.	Plaster cracks and fall of plaster.	None....	6 frame, brick, and stone, 1 to 3 story.	None..	None..	None..	4-40	163[5]	103	26	34	0	Displacement.
Langefors, Westerberg, and Kihlstrom, 1958.	Minor and major.	....do....	Rock....	NA....	NA....	NA....	NA[2]..	48-420	105	57	0	32	16	NA.
Edwards and Northwood, 1960.	Threshold, minor and major.	Cracks in masonry, bricks, or stone basement walls.	Soft, wet sand with clay 20 ft down, and well consolidated glacial till.	6 total: 4 with 12-in brick and plaster interiors, 2 frame.	9.1-61	30-200	47-750	2.5-25	22	22	6	8	5	Displacement and acceleration measured on basement walls.
Northwood, Crawford, and Edwards, 1963.	....do....	Basement wall damage close in, and superstructure plus basement damage far out.	Glacial till and limestone overlain by thin till layer.	6 total: 1 frame, 1 stone, 4 9- to 12-in brick.	.91-91	3-300	0.3-1600	7-120[3]	60	51	10	4	5	Velocity, MB-120 gage, measured on basement walls.
Thoenen and Windes, Bureau of Mines, 1942.	Threshold and minor.	None....	10 quarries.	14 total.	218-762	715-2,500	36-1200	3-16	43	11	0	0	0	Displacement and acceleration.
Morris and Westwater, 1953.	Threshold.	Plaster and partition cracks.	1 quarry and 1 surface coal mine.	2 stone with plaster interiors.	35-250	115-820	200-14000	3.7-5.7	3	1	2	0	0	Displacement.
Dvorak, 1962.	Threshold, minor, and major.	Plaster and masonry cracks.	Semihard clay with sand lenses.	4 brick and masonry.	9.1-50	30-164	2.2-44	1.5-15	58	7	25	15	11	Do.
Wiss and Nicholls, 1974.	Minor.....	Drywall cracks.	Glacial till.	Single structure, rubble stone foundation.	10.7-61	35-200	1-85	NA....	10	9	0	1	0	Velocity, MB-120 gage.
Jensen and Rietman, 1978.	....do....	....do....	Rock with 0 to 7 ft of soil overburden.	18 frame structures.	9.1-56	30-185[1]	1.75-12.75	11-126[4]	29	27	0	2	0	Do.
Bureau of Mines, meas. RI 8507, 1980.	Threshold and minor.	Plaster, drywall, and masonry cracks.	Various, usually with soil overburdens.	17 frame structures.	4.3-762	14-2500	18-2600	6.3-71	225	35[6]	30	3	0	Do.
Bureau of Mines, RI 8896, 1983.	....do....	Drywall, brick, and mortar cracks.	Soil over sedimentary rock layers.	Single structure.	90-4400	330-145000			N700	125[6]	8	1	0	Velocity, MB-120 accelerometers and ST-4 seismographs

NA = Not available.
1/ Plus 1 at 5 ft.
2/ Excavation in rock, small shots.
3/ Predominantly 12 to 26 Hz for damage data.
4/ Mostly >30 Hz.
5/ Shaker tests.
6/ Velocities greater than 0.5 in/s

part of the vibration record that produced the larger structure velocity response, and it was invariably the low frequency (7-30 Hz).

Some long-term observations were made of numbers of cracks and their widths and lengths. None of these parameters could be quantitatively related to the blasting. The number of cracks increased with time regardless of the vibration levels, and their widths varied irregularly from a variety of environmental stresses. Consequently, blast damage was assumed only when immediate pre- and post-blast inspections found additional cracks or extensions.

In all cases, except four shown in figure 1, blast damage was superficial cracking of the same type as caused by natural settlement, drying of building materials (shrinkage), and variations in wind, temperature, humidity, and soil moisture. The four minor damage points in figure 1 represent cracks in masonry and large new interior cracks exceeding 0.08 inch in width. RI 8507 includes cracks identified by structure along with descriptions of those structures. Specific damage values from RI 8896 are listed in the fatigue section of this text.

Summary Damage Analysis

Part of the Bureau RI 8507 study involved examination of relevant blast data from all sources (table 1). Figures 2 through 4 give replotted damage data from RI 8507 in sets with similar experimental characteristics. Nondamage values were omitted for clarity. A summary of all these tests, including the two recently conducted by the Bureau, is given in figure 5, as particle velocity versus frequency.

Because of the varied experimental parameters in the 11 studies, no statistical analysis is presented here, such as the means and standard deviations. Most obvious, however, is the far wider scatter of variation of damage observation for the low as compared to high frequencies (fig. 5). The large amount of scatter in the low-frequency data is undoubtedly related to the structure response frequencies being in the same range. Between 4 and 25 Hz, the response and hence the damage for any given structure will depend strongly on frequency. Therefore, the large amount of scatter is to be expected in a summary involving many shots and structures. Also shown in figure 5 is that cracking was observed from low frequencies at vibration amplitudes as low as 0.50 in/s in plaster. Superimposed on the damage plots are the Appendix B Safe Vibration Criteria from RI 8507 (Siskind, 1980).

Probability Analysis

Probability analyses were also applied to the damage data collected for RI 8507 as an alternative to regression analysis and were expected to produce more meaningful predictions. The number of damage observations within particle velocity intervals were plotted for the various sets of data.

Log-normal-scaled damage probability for the summary of the first 10 studies in table 1 is given by figure 6 from RI 8507 (Siskind, 1980). Other probability plots were given in RI 8507, representing the low- and high-frequency data sets separately.

For the summary and also the low-frequency cracking cases, damage probabilities become negligible (<5%) below about 0.5 in/s for these somewhat worst-case structures. Most notable is the downward turn of the damage probabilities at low vibration levels, suggesting a departure from log-normal predictions and some kind of asymptotic probability toward zero damage. However, precise predictions at increasingly lower levels must necessarily become less reliable and more difficult. Accurate probability figures require a large number of observations, and even this summary analysis does not have as much data as desired, particularly for each of the principal experimental variables.

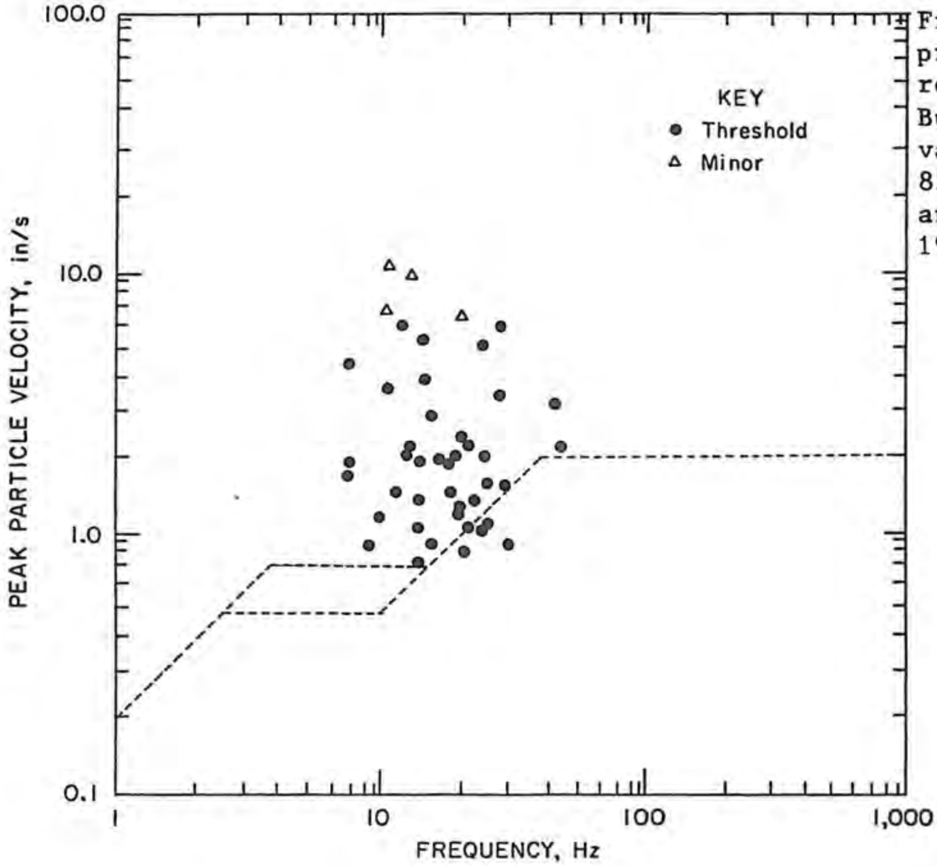

Figure 1 - Blast-produced cracking in residential walls, Bureau of Mines observations only, from RI 8507, Siskind, 1980 and RI 8896, Stagg, 1984.

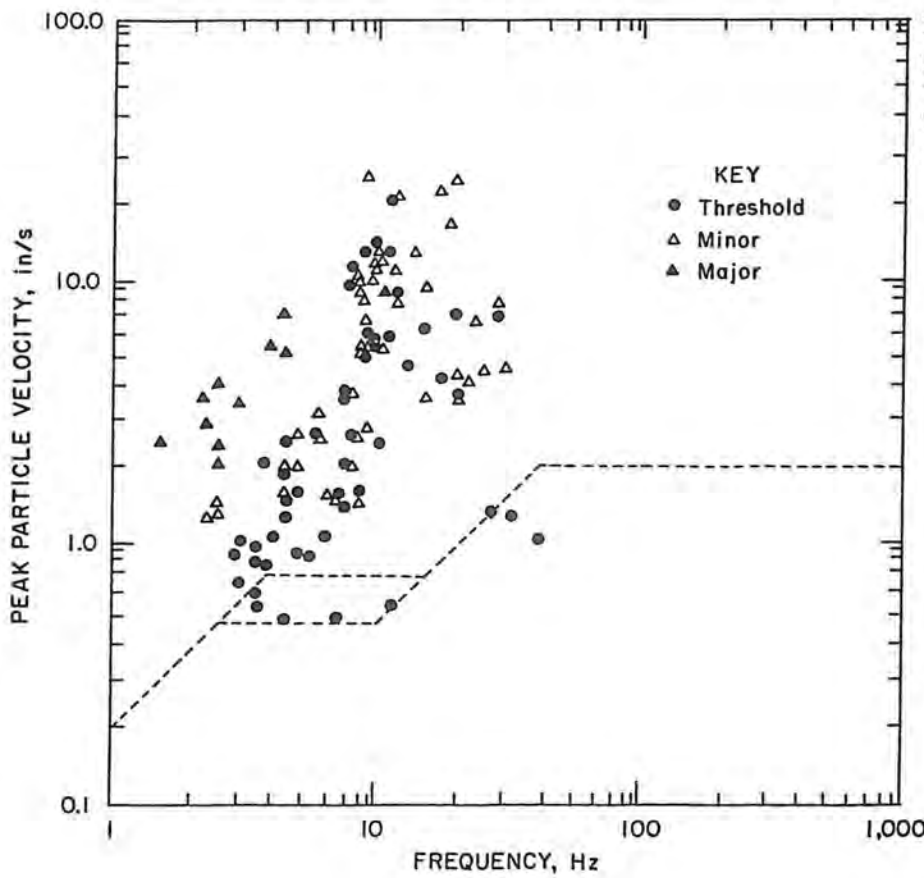

Figure 2 - Blast-produced cracking in residential walls, from Thoenen, 1942, Dvorak, 1962, and Morris, 1953.

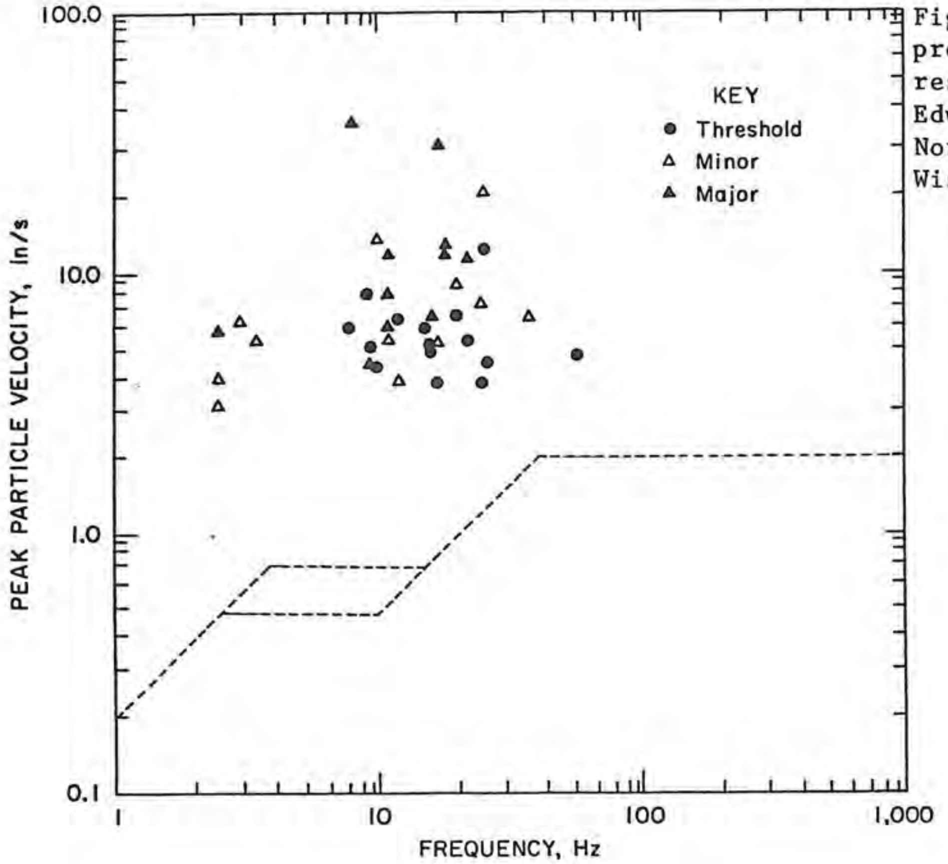

Figure 3 - Blast-produced cracking in residential walls, from Edwards, 1960, Northwood, 1963, and Wiss, 1974.

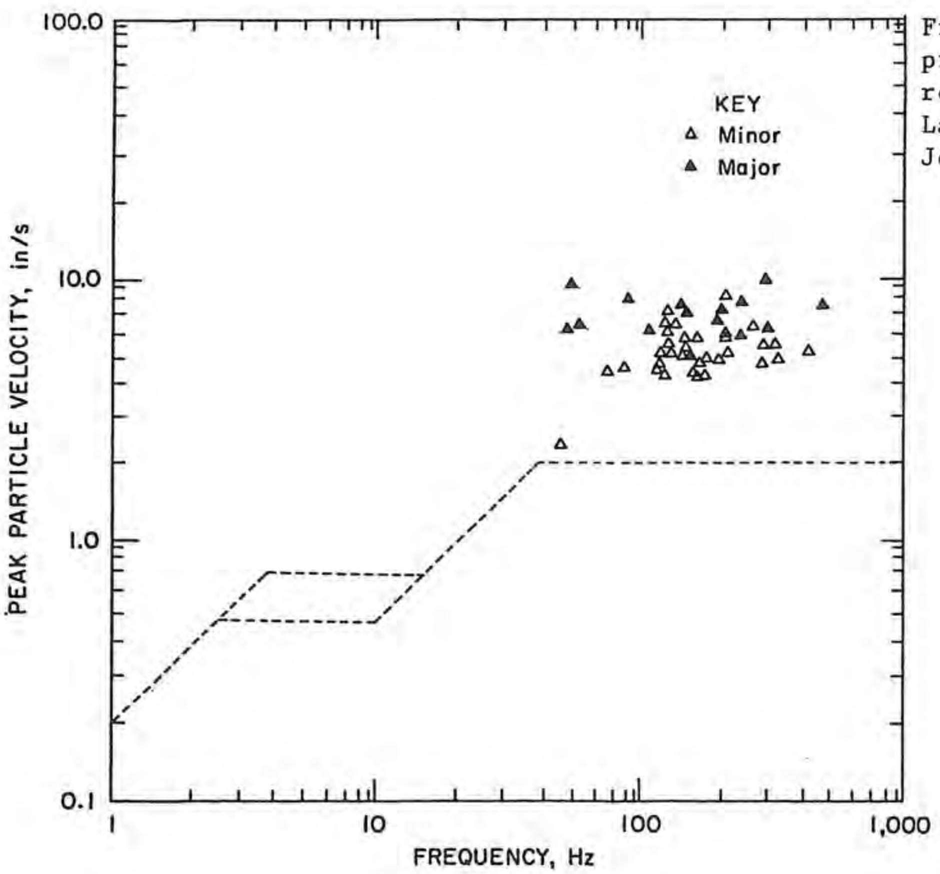

Figure 4 - Blast-produced cracking in residential walls, from Langefors, 1958, and Jensen, 1978.

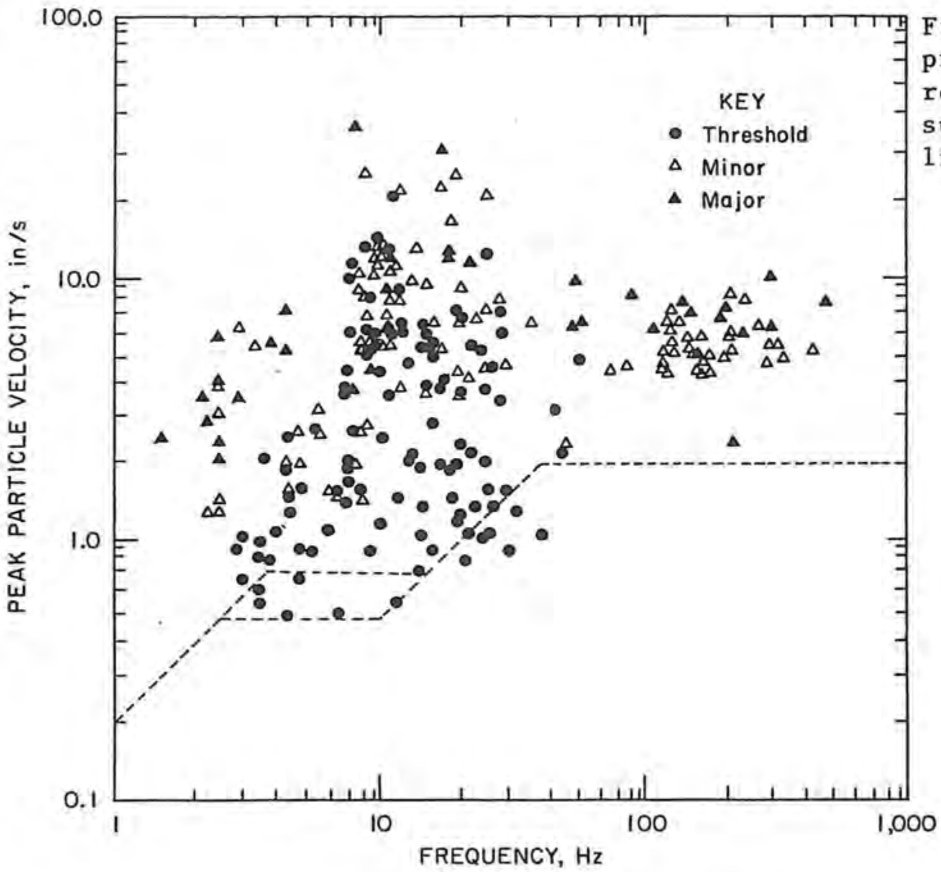

Figure 5 - Blast-produced cracking in residential walls, summary of 10 studies listed in table 1.

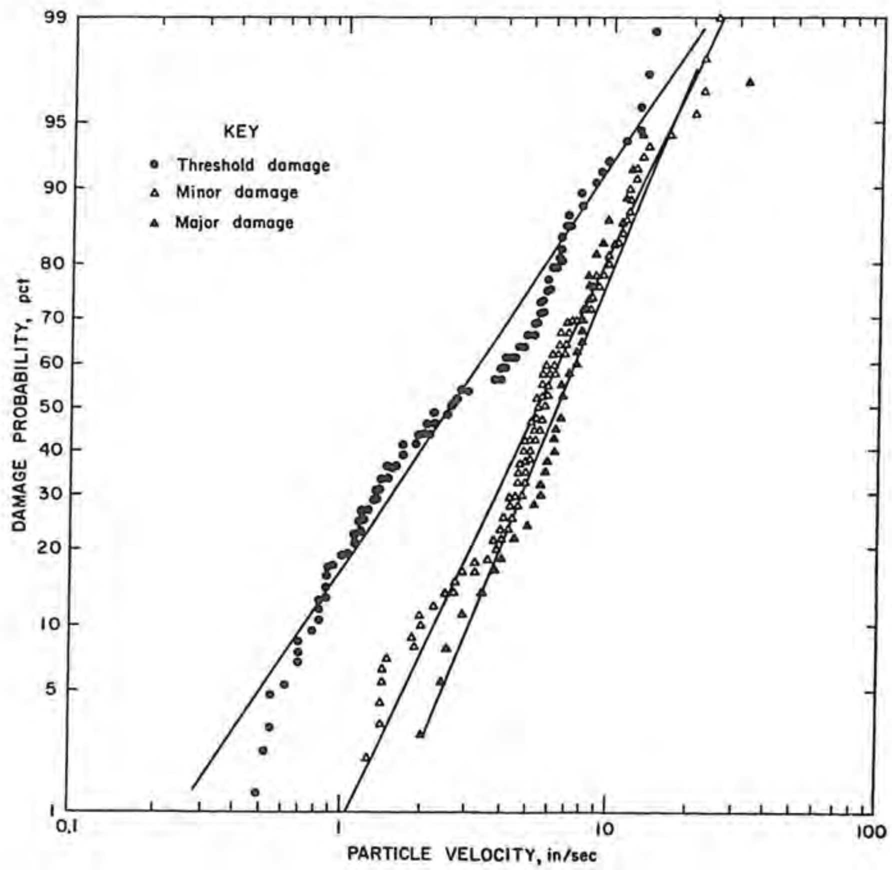

Figure 6 - Blast-produced cracking in residential walls. Summary plot based on accumulated probability, after Siskind, 1980.

Safe vibration levels for blasting are summarized in table 2, being defined as levels unlikely to produce interior cracking or other damage in residences. Implicit in these values are assumptions that the structures are sited on a firm foundation, do not exceed two stories, and have the dimensions of typical residences, and that the vibration wave trains typically do not exeed 1 to 2 s.

For modern frame residential structures, a safe blasting level criterion of 0.75 in/s was determined for frequencies below 40 Hz. Most of the observed damage involved plaster cracking in older structures. Modern gypsum board interior-walled homes are apparently more capable of withstanding vibrations since the paperbacked wallboard is relatively nonbrittle. Only two studies specifically examined gypsum board damage from blasting--Wiss, 1974 and the new Bureau measurements. The lowest vibration level corresponding to very minor crack extensions was 0.79 in/s, and many nondamage observations were made at levels exceeding 2 in/s.

The lowest safe level criterion of 0.50 in/s for blasting was adopted from the probablility analyses of the low-frequency shots and the overall summary. This assumes a 5-pct probability for very superficial cracking. However, this vibration level is also lower than the lowest observed damage case. The almost constant particle velocities for the lower damage probabilities of 2 and 1 pct strongly suggest that the 0.50-in/s level will provide protection from blast damage to greater than 95 pct.

For vibration frequencies above 40 Hz, a 2-in/s criterion is recommended, although the 5-pct value is 3.2 in/s. This is based on the lowest observed damage value of 2.2 in/s and the fact that no observations were made of damage corresponding to the "threshold" criteria of the other studies. Construction and small-scale excavation blasting will often fall in this high-frequency category. The two basically different safe vibration criteria (high and low frequency) were derived from the analyses of the damage data. However, they are also consistent with both the measured responses and the response spectra as described by Siskind in RI 8507.

Alternative Blasting Level Criteria

A more complex scheme of assessing the damage potential of blast vibrations is possible, using a combination of particle velocity and displacement. This permits higher levels for the intermediate frequency cases (15-40 Hz), but requires lower particle velocities for the lower frequencies (4 Hz). The measurement complexity will make this impractical for many situations.

Safe blasting vibration criteria were established for residential structures, having two frequency ranges and a sharp discontinuity at 40 Hz (table 2). There are blasts that represent an intermediate frequency case, being higher than the structure resonances (4-12 Hz) and lower than 40 Hz. The criteria of table 2 apply equally to a 35- and a 10-Hz ground vibration, although the responses and damage potentials are very different.

Table 2. - Safe levels of blasting vibrations for residential type structures

Type of structure	Ground vibration--peak particle velocity, in/s	
	At low frequency[1] (<40 Hz)	At high frequency (>40 Hz)
Modern homes. Drywall interiors	0.75	2.0
Older homes. Plaster on wood lath construction for interior walls	.50	2.0

[1]All spectral peaks within 6 dB (50 pct) amplitude of the predominant frequency must be analyzed.

Using both the measured structure amplifications and damage summary data (fig. 5), a smoother set of safe-level criteria was established. These are given as Appendix B in Bureau RI 8507 (Siskind, 1980) and shown as dashed in figures 1-5. This approach has more severe measuring requirements, involving both displacement and velocity.

Above 40 Hz, a constant peak particle velocity of 2.0 in/s is the maximum safe value. Below 40 Hz, the maximum velocity decreases at a rate equivalent to a constant peak displacement of 0.008 inch. At frequencies corresponding to 0.75 in/s for Drywall and 0.50 in/s for plaster, constant particle velocities are again appropriate. An ultimate maximum displacement of 0.030 inch is recommended, which would only be of concern where frequencies below 4 Hz are encountered.

This scheme is based on the response and damage data, recognizes the displacement-bound requirement for house responses to low-frequency blast vibrations, and provides a smooth transition for the intermediate-frequency cases. This method of analyzing the damage potential of blasting vibrations has the disadvantage of possibly underestimating annoyance reactions. Midwall responses do not decrease nearly as fast as structure or corner responses, as frequencies increase from 10 to 40 Hz. A very nearly linear decrease of velocity amplification was observed for the gross structure; however, the higher midwall response frequencies will make the 20 to 35 Hz vibrations relatively annoying if the maximum safe levels as shown in the figures are attained.

FATIGUE DAMAGE FROM GROUND VIBRATIONS

Cracking in structures from low-level long-term vibrations such as repeated blasting is a legitimate concern either for direct damage or by accelerating ongoing deterioration processes. Tests on construction materials, including masonry walls, were discussed in the two Bureau RI's (Siskind, 1980 and Stagg, 1984). Some of these were done as part of the structure fatigue study. In addition, fatigue damage studies were made on actual residential structures from sonic booms (Andrews, 1965), blasting (Stagg, 1983), and laboratory simulations (Woodward, 1983).

Bureau of Mines Test House

The most extensive tests were on an 1100-square-foot wood frame residence built for the Bureau directly on the AMAX Ayrshire coal mine property in Indiana (Stagg, 1984). For a 2-year period, this house (fig. 7) was subjected to, and monitored for response from, low-level blasts, weather cycling, human activity, and static changes such as settlement. As the mine advanced toward the house, the blasting vibrations increased to damaging levels. In a final series of tests following the last blasting cycle, mechanically induced vibrations were used to produce high-cycle fatigue. During this time, researchers employed up to 50 recording channels at 67 locations for dynamic strain and vibrations. Continuous measurements were made of wind velocity and direction, and of temperature and humidity inside and outside the house. Level-loop surveys were made periodically to assess differential settlement.

The responses to the various dynamic sources were discussed earlier in this paper. The damage risk implications of the study are described in the next section.

Low-Level Blasting Tests. Over a period of 16 months, the test house was subjected to 645 production mining blasts yielding vibrations up to 0.78 in/s. The mining cycle passed the house at roughly monthly intervals, at which time dynamic response monitoring was done. At other times, weather environment, outside vibrations, and airblast were continouosly recorded. Two types of data were collected -

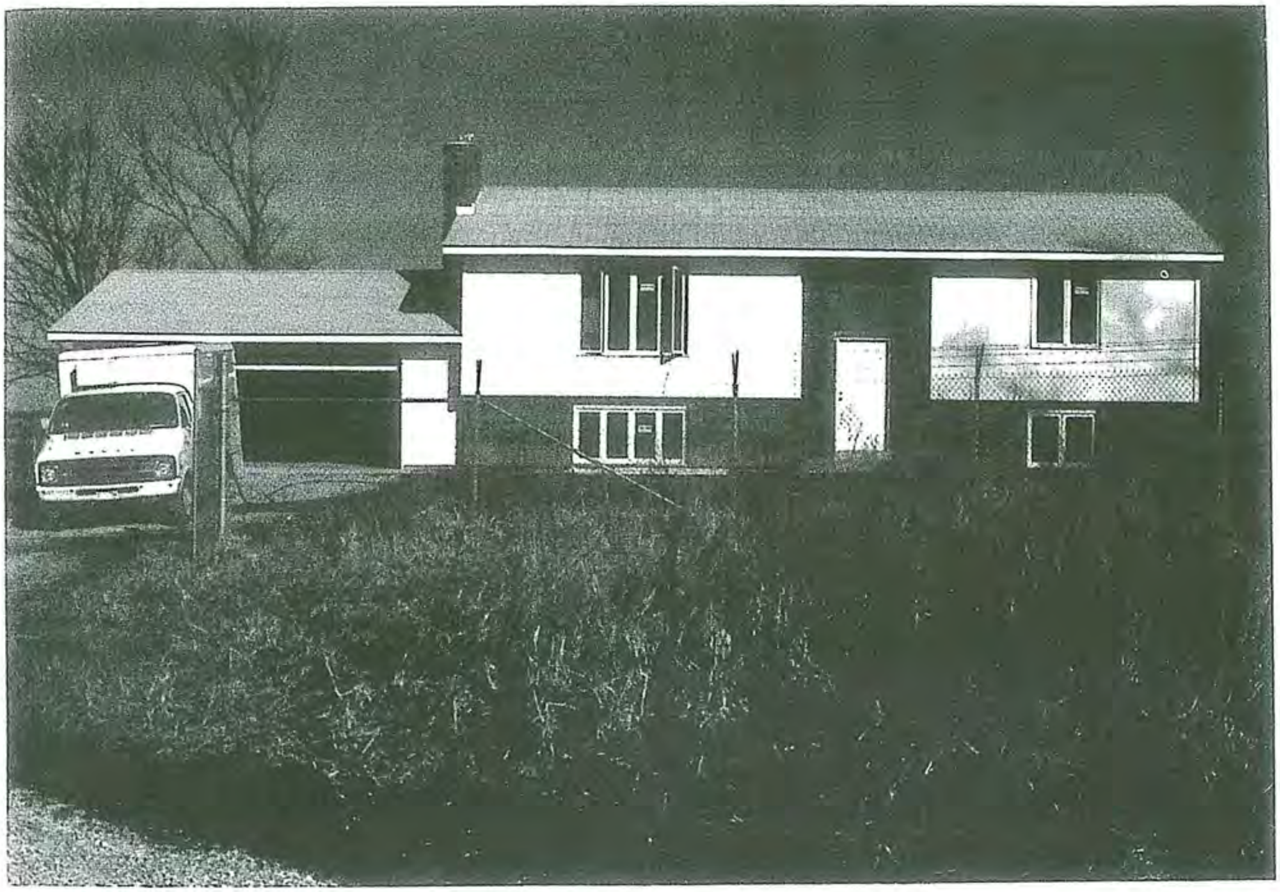

FIGURE 7 - Fatigue test house erected by the Bureau of Mines on the AMAX Ayrshire mine property, Evansville, IN.

damage from specific blasts, and long-term changes.

During this time, no significant damage occurred that could be correlated to specific blasts. Very fine cracks (0.0004-0.004 in) existed initially and continued to occur during the test period. These were considered normal for any house, particularly in the corner wallboard panel joints. Comparison of this long-term cracking with the blast vibrations during this low-level test period showed no correlation (fig. 8). Note: "Earthwork" in figure 8 refers to topsoil moving activities near the house.

High-Level Vibration Tests. As the mine approached the house, the level of vibration at the structure became high enough to produce identifiable damage (fig. 9). Peak particle velocity levels in excess of 0.5 in/s resulted from 108 of the production blasts. One was as high as 6.94 in/s and scaled distances were as close as 11 $ft/lb^{1/2}$. Table 3 summarizes the blast damage observations. Note that only the high-level blasts were numbered, i.e., those for which dynamic vibrational responses were obtained and recorded.

Damage at the lowest levels, i.e., 0.88-1.34 in/s, was cosmetic wallboard corner cracking of the type observed during nonblasting periods. This is consistent with RI 8507, the previous Bureau blasting damage study, which noted a low probability of damage for modern homes at 0.75 in/s. At about 1.8 to 2.2 in/s, it was evident that the walls of the house were working against the frame and loosening the joints. The wallboard nails were observed to be cracking their covering compound and moving perceptibly. The first reliable crack observations on the brick or concrete block masonry were at about 3.4 in/s, being mortar joint cracks.

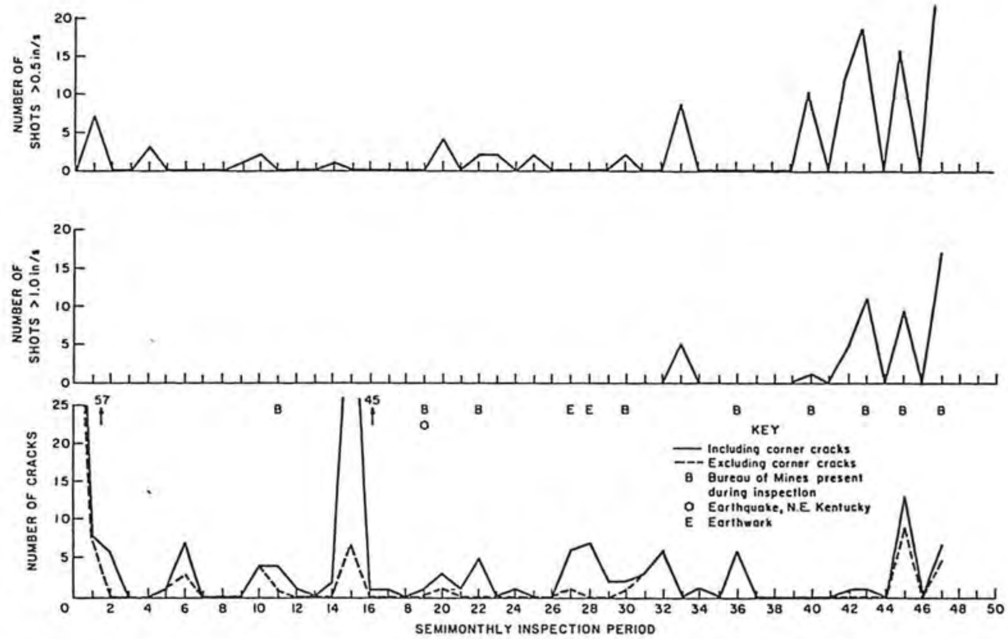

FIGURE 8 - Long-term crack rates for Bureau of Mines fatigue test house after Stagg, 1984.

FIGURE 9 - Bureau of Mines fatigue test house on highwall near end of blasting test series.

TABLE 3. - Cracks observed after blasting, from Stagg, 1984

Shot	Ground vibration level, in/s			Crack observation
	Vertical	East-west	North-south	
45...........	0.38	1.03	0.54	
46...........	.44	1.32	.71	
47...........	.48	1.47	.71	
48...........	.48	.96	.49	Diagonal steplike crack in concrete block wall. Found during detailed inspection after shot 48; unknown if existed prior to shots 45-58.
82...........	2.21	1.41	1.75	Crack in joint compound over nailhead.
83...........	3.05	2.75	1.64	Corner crack extension.
84...........	2.17	2.01	1.44	Crack in joint compound over nailhead.
86...........	.85	1.34	1.15	2 corner crack extensions.
89...........	.40	.88	.78	Corner crack extension.
97...........	1.17	1.11	1.81	Crack in joint compound over nailhead.
101...........	3.12	3.52	2.19	Corner crack extension.
102...........	4.77	3.21	4.25	Plywood subfloor crack.[1]
114...........	3.33	3.43	NA	Brick veneer mortar joint crack.
115...........	6.19	6.22	3.52	Basement block mortar joint cracks.
126...........	6.19	6.94	5.27	Chimney mortar cracks, all sides. Basement block mortar joint separation; minor damage.

NA Not available.
[1]Test house had subfloor only--no underlayment or finish floor.

Long-term crack rates also responded to the closer blasts (fig. 8). Bureau researchers examined the data two ways in terms of the expected damage mechanisms: 1) fatigue damage from accumulated exposure, assessed by successive inspections, and 2) triggering effect of discrete blast events which add the strain from blasting to already existing environmental strain. Researchers found that long-term repetition of the low-level blasts (e.g., 0.5 in/s) produced no significant effect; however, blasts greater than about 1.0 in/s were associated with higher crack rates, as shown in table 4. The data that exclude corner cracks are most realistic.

Surprising to many people is the formation of new cracks continuous regardless of vibration presence. This is a natural process of aging and response to ambient loads and forces. In fact, the rates for this new structure were lower than or comparable to other long-term assessments such as Holmberg, 1981; Andrews, 1965; Wall, 1967. These researchers found long-term crack rates of 12 to 13 per year, 1.5 to 12 per week, and 2.5 per day, respectively.

Mechanical Vibration Tests. Following the last cycle of blasting near the structure, it was tested for fatigue by continuous mechanical excitation at increasngly higher levels. Table 5 lists the 5 fatigue runs and the 11 frequency sweeps which followed the blasting fatigue tests. Sweep runs were used to determine the natural frequency, which decreased as the study progressed (structure became less stiff or looser as the vibration continued).

The vibrational damping was also measured. It did not appreciably change during the test and was higher than in earlier tests on old structures (Siskind, 1980). Equivalent blast-produced ground vibrations for each run in table 5 were based on measured dynamic responses from earlier blasting.

Significant damage was produced by the shaker runs as summarized in table 5. The cracks observed during run 1 suggest that fatigue cracking can occur given a large enough number of vibration cycles. The cracking was only cosmetic, defined as "threshold" in RI 8507, and the number of total cycles corresponds to about 10,000 blasts, each having five vibrational

TABLE 4. - Crack rate versus blast vibration level, from Stagg, 1984

Blast vibration level, in/s	Inspection periods[1]	Number of cracks per week[2] Total	Excluding corner cracks
METHOD 1 (FATIGUE DAMAGING; ACCUMULATIVE WEAKENING OF MATERIAL)			
>1.0	40-47	1.4	0.88
<1.0	1-14	1.2 (0.96)	.61 (0.35)
	16-32	1.1	.35
>0.5, <1.0	1-14	1.2 (.96)	.61 (.35)
	20-32	1.4	.46
METHOD 2 (TRIGGERING EFFECT; SUM OF DYNAMIC AND EXISTING STRAIN IN EXCESS OF THRESHOLD)			
>1.0	33, 40, 42-43, 45, 47	1.8	1.0
<1.0	1-14, 16-32, 34-35, 37-39, 41, 44, 46	.94 (0.86)	.38 (0.29)
>0.5, <1.0	1, 4, 9-10, 14, 20, 22-23, 25, 30	1.2 (.89)	.70 (.33)
<.50	2-3, 5-8, 11-13, 16-19, 21, 24, 26-29, 31-32, 34-35, 37-39, 41, 44, 46	.84	.28

[1]Periods listed in table 13; 2 weeks each.
[2]Values in parenthese are rates calculated without period - 1 data to account for cracks resulting from curing after construction.

TABLE 5. - Cracks observed after shaker excitation, from Stagg, 1984

Shaker vibration equivalency[1] and crack description	Number of cycles at cracking Run	Total[2]
Run 1, ~ 0.5 in/s:		
Entryway tape joint crack	52,000	56,000
Crack in joint compound over nailhead in master bedroom	52,000	56,000
Fireplace mortar joint crack extension[3]	52,000	56,000
Run 2, ~ 0.5 in/s:		
Chimney trim broken loose from siding[3]	>1	>108,500
Mortar joint crack at top of chimney.	>1	>108,500
Run 3, ~ 0.3 in/s:		
Brick veneer mortar joint cracks	15,000	229,500
4 cracks in joint compound over nailheads	25,000	239,000
Run 4, ~ 0.75 in/s:		
Vertical crack through brick veneer mortar	14,500	293,500
Cracks in joint compound over nailheads	60,000	339,500
Basement block mortar joint crack extensions	>1	>339,500
Run 5, ~ 1.0 in/s:		
Brick veneer mortar falling out	>1	>339,500
Basement block mortar joint crack extensions	>1	>339,500
Crack in wallboard	22,000	361,500

[1]Based on envelope response from plot of ground vibration versus structure motion at site A_4 (fig. 13), high corner, east wall, as structure was at resonance.
[2]At vibration equivalency of ~ 0.5 in/s, including cycles induced by blasting and frequency sweeps.
[3]Cracking suspect because superstructure was racked against normally foundation-driven fireplace.

cycles of 0.5 in/s peak particle velocity. Significant cracks, although still cosmetic, required about five times as many cycles (250,000)at 0.75 to 1.0 in/s.

Static Monitoring. Static or long-term strains were assessed three ways:

a) Local point static strain measurements using a micrometer comparitor, LVDT gages, and displacement monitors at 60 locations.

b) Whole-wall deformation measured by a tape extensometer at 17 locations.

c) Level-loop transit surveys outside the structure for differential settlement, monthly.

No damage occurred that could be correlated against static changes; in fact, static changes were nonexistent or of small magnitude. The maximum differential settlement observed by surveying was about 0.01 μin, or basically negligible. At worst, this corresponds to a maximum global strain of about 50 μin/in. Daily changes were reliably monitored with precision displacement systems by Kamen. Long-term seasonal changes were likely present but were not of sufficient magnitude to be detected by the extensometer and micrometer. Static measurement techniques other than level surveying had either insufficient resolution or stability for long-term strains (those occurring over several months). Extensometer and micrometer measurements were ambiguous and inconsistent and consequently not useful. They had a minimum resolution of 150 μin/in.

SUMMARY AND CONCLUSIONS

Bureau of Mines studies of the response and cracking of low-rise residential structures from blasting indicated that cracking damage is not likely below about 0.5 in/s peak particle velocity for the worst case of structure condition and type for typically observed vibration frequencies.

This safe level criterion also appears independent of the number of events and their lengths. Researchers also noticed that strains are produced in the structure walls by normal weather conditions, such as daily temperature cycles, and human activities, such as door slams, which are equivalent to blast vibrations of up to 0.5 in/s. This, therefore, provides a minimum value of concern for external transients and impacting wood-frame, low-rise residential structures typical of those studied by the Bureau of Mines.

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EDITED BY:

Michael Karmis
Department of Mining and
Minerals Engineering
Virginia Polytechnic Institute
and State University

Gavin Faulkner
Department of Mining and
Minerals Engineering
Virginia Polytechnic Institute
and State University

William H. Sutherland
Mine Safety and Health
Administration
U.S. Department of Labor

David R. Forshey
Bureau of Mines
U.S. Department of the Interior

J. Richard Lucas
Department of Mining and
Minerals Engineering
Virginia Polytechnic Institute
and State University

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