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by Hsai-Yang Fang and Robert M. Koerner

Fritz Engineering Laboratory Report No. 384.15
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This work was conducted under the sponsorship of Fisher, Fang and Associates, Inc., Engineering Consultants. The opinions, findings, and conclusions expressed in this report are those of the authors, and are not necessarily of the project sponsor.

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Bethlehem, Pennsylvania

January 25, 1982

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Abstract

A field study of ground vibrations and crack movement of selected walls of nine residential houses near a rock quarry has been evaluated. The data includes particle velocity, acceleration, distance, scaled distance, face height, face orientation, total amount of explosive charge and soil-structure response in terms of wall crack opening during many blasts. The wall movement data shows poor correlation with ground motion parameters, but appears to be in reasonable agreement with scaled distance values.

Also presented is a procedure, based on linear fracture mechanics, which can be used to predict the fatigue life of brittle construction materials. The technique is still in its formative stage but could lead to an ultimate solution of this difficult type of soil/structure interaction problem.

Introduction

Owing to an increased number of complaints by residential house owners to nearby quarry blasting activities, a field study was undertaken to evaluate the associated soil/structure interaction from the blasts. It should be recognized, however, that the procedures and methods used herein would also be appropriate for monitoring vibrations resulting from surface mines, deep mines, and construction blasting activities.

In the initial phase of the project, ground motion displacements, velocities and accelerations were measured along with distance, scaled distance, face height, face orientation, total explosive charge and other commonly used blasting parameters. The correlation of these parameters to structural damage (as evidenced by cracking in the brittle construction materials of the houses involved) was very poor. In no case was the ground motion above 0.5 ips, which in turn is much less than the generally accepted limit of 2.0 ips (21). Reasons for this poor correlation are uncertain, but are felt to be mainly influenced by an unknown and variable soil/structure coupling mechanism.

Subsequent legal action forced an alternative measurement procedure to the conventional type of seismograph monitoring (2,14,21,25,26). What was eventually used was a direct crack monitoring technique whereby a clip-type strain gage was installed over the crack(s) in question. The measuring

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unit is a 6 inch (15.24 cm) piece of spring steel with tension and compression strain gages mounted on opposite faces as shown in Figures 1 and 2. The connecting leads are brought to conventional strain gage readout equipment which provides crack movement (opening or closing) to a sensitivity of 0.0001. Rise time of the system is sensitive enough to capture the entire movement. Nine houses were monitored over a period of eighteen months using this technique. The details of this measuring and instrumentation system have been presented previously (6,7,8).

Presented in this paper is the field data resulting from the monitoring which brings focus upon the structural crack vibrations rather than on ground motion parameters as is customarily used. However, rather than solving the problem, this creates a new, but perhaps more tractable, problem of analyzing the fatigue life of brittle construction materials. It is felt that this is best accomplished by linear fracture mechanics and some insight into the complete solution of this difficult problem is suggested.

Figure 1 Clip Type Strain Gage Used in this Study to Monitor Wall Crack Opening During Blasting Activity
General Site Conditions

The quarry site consists of a ledger dolomite formation which is beneath 3 to 7 meters of overburden. The bedding planes are very tight and are at approximately 0.6m intervals. There are numerous outcrops of the rock at distances up to 1,000m from the quarry site where the monitored residences are located. Some typical data on the limestone is as follows:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity(apparent)</td>
<td>2.84</td>
</tr>
<tr>
<td>Absorption</td>
<td>0.2%</td>
</tr>
<tr>
<td>Sodium Sulfate Loss(5 cycles)</td>
<td>0.0%</td>
</tr>
<tr>
<td>Deval Loss</td>
<td>3.8%</td>
</tr>
<tr>
<td>Moh's Hardness</td>
<td>3 to 3.5</td>
</tr>
<tr>
<td>Compressive Strength(average)</td>
<td>127,500 kPa</td>
</tr>
</tbody>
</table>

Field Test Data and Discussion

Using the clip type strain gage as shown in Figures 1 and 2, nine different residences were monitored for existing wall crack movements for approximately eighteen months. A summary of test locations, structural types of the residences, and instrumentation are presented in Table 1. In some cases, temperature gages were also installed as indicated in the
When the data was compared to peak particle velocity, poor correlation was observed, see Figure 3. Further correlations were attempted, as shown in Figure 4 for total pounds of explosive, with similarly poor correlation results. Not until scaled distance was used however, was agreement noted. Scaled distance is a commonly used blasting parameter (21) which is defined as the distance from the blast to the point in question (in feet) divided by the square root of the pounds of explosive detonated per delay. Most state regulations limit its numeric value to a minimum of fifty as per reference (21). The typical behavior of crack opening to scaled distance is presented in Figures 5, 6, and 7. In each figure an approximate exponential decay is noted. This appears to be reasonable since both greater distance and/or lower explosive size should reduce the amount of crack opening. The results appear to be somewhat independent of face orientation since the monitoring locations were at a considerable distance from the location of the blasts.

While such a correspondence was fairly general around the entire quarry site, it unfortunately does not answer questions as to limiting magnitude of crack opening or number of repetitions required to bring about structural failure. If the number of repetitions increases to a point where the wall opening is getting greater and no maintenance or repairs are made to the wall, then the fatigue life of the wall will decrease sharply and eventually result in a structural failure.

Theoretical Considerations of Fracture Behavior of Brittle Materials

Repetitious loads applied to a material even though far lower than the static failure strength of the material will eventually cause failure. The literature contains many such studies although it is rather lacking in the field of masonry materials (stone, brick, cement block) as used in house construction (17). The actual structural behavior is further complicated by many interacting environmental factors such as wind, temperature and moisture variation, etc., but a theoretical attempt must be made. Most theoretical considerations are focused on the ground movement. They study the energy transmitted from the blast to the ground, and through the ground as reported by Leet (18), Nicholls, et al. (21), Newmark (20), Hendron (14,15) and Fogelson and Dowding (4,10). Unfortunately, data is lacking on the energy transmitted from the ground to the structure, and especially on how the structure responds to the energy it absorbs (7).

Some insight into the problem can be gained by utilizing the basic theory developed fifty years ago by Griffith (13). It has acquired a considerable amount of success in predicting failure caused by crack propagation for metals (16,19,22,23,24). More recently, it has been applied for predicting fracture behavior in rocks, stabilized materials (5,11,12) and for compacted clays (9). Strictly speaking, the theory is limited to linear-elastic materials despite the fact that plastic or nonlinear strains unavoidably prevail in the vicinity of flaws or cracks. Nevertheless, it does provide an ideal and simply way of estimating the amount of energy required to create free surfaces in the material. The degree of simplicity is achieved by focusing attention on the leading edge of the crack, where nonlinear strains exist but are regarded as localized within a zone of negligibly
<table>
<thead>
<tr>
<th>Test Site Designation No.</th>
<th>Type of Structures</th>
<th>Instrumentation (Clip Gages)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Locations</td>
</tr>
<tr>
<td>WTP</td>
<td>2-story Reinforced Concrete Public Building</td>
<td>a. Outside R.C. Foundation Wall 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Inside Wall (tile brick) 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c. R.C. Retaining Wall 2</td>
</tr>
<tr>
<td>M</td>
<td>2-story Brick-Block Utility Building</td>
<td>a. Outside Old Brick Wall 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Outside New Block Wall 1</td>
</tr>
<tr>
<td>Mn</td>
<td>2-story Brick House with Stone Foundation Wall</td>
<td>a. Inside House Ceiling (on plaster) 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Inside Wall 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c. Outside Wall, above basement (stone foundation wall) 1</td>
</tr>
<tr>
<td>A</td>
<td>3-story Stone House</td>
<td>Outside Stone Wall 2</td>
</tr>
<tr>
<td>S</td>
<td>1-story Stucco-block House</td>
<td>Outside Stucco Wall 2</td>
</tr>
<tr>
<td>SP</td>
<td>2-story Brick Public Building with Stone Foundation Wall</td>
<td>a. Inside Wall, 2nd Floor 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Inside Wall, 1st Floor 2</td>
</tr>
<tr>
<td>W</td>
<td>1-story Stucco-block House</td>
<td>Outside Stucco Wall 2</td>
</tr>
<tr>
<td>GA</td>
<td>1-story Block House</td>
<td>Outside Block Wall 2</td>
</tr>
<tr>
<td>J</td>
<td>1-story Block House</td>
<td>Outside Block Wall 2</td>
</tr>
</tbody>
</table>

* Includes Temperature Gages
Figure 3  Wall Crack Opening Versus Peak Particle Velocity for all Nine Locations for 400 lb/delay Blasts Showing Lack of Correlation (200 lb/delay Blasts Show Similar Scatter)
Figure 4  Wall Crack Opening Versus Total Pounds of Explosive per Blast for 200 lb/delay Showing Lack of Correlation for Location No. S
Figure 5: Wall Crack Opening Versus Scaled Distance (Distance to Monitoring Location Divided by the Square Root of Pounds of Explosive per Delay) for Location Number SP Showing Anticipated Exponential Behavior.
Figure 6  Wall Crack Opening Versus Scaled Distance (Distance to Monitoring Location Divided by the Square Root of Pounds of Explosive per Delay for Location Number J) Showing Anticipated Exponential Behavior.
Figure 7 Wall Crack Opening Versus Scaled Distance (Distance to Monitoring Location Divided by the Square Root of Pounds of Explosive per Delay) for Location Number S Showing Anticipated Exponential Behavior.
small dimensions. Although the stresses and strains within this zone cannot be analyzed in fine detail, linear-elastic fracture mechanics theory is able to give an adequate description of the gross feature of the stresses and strains near the crack. In particular, one can calculate the strain-energy release rate, \( G \), which is in a formal sense the force driving the fracture process (16). At present, plastic and nonlinear strains can be included in the fracture mechanics treatment only in a rather superficial way without incurring serious losses of clarity and simplicity (3,23,24).

In practice the value \( G \) is measured in a simple laboratory test (1) designated ASTM E-399-74. It uses a cracked specimen which is pulled apart by a load \( P \). For a gage length "L" and a crack length "a" one obtains the strain energy release rate "G" for the material under testing as follows:

\[
G = \frac{1}{2} P^2 \frac{\delta(\Delta L/P)}{\delta a}
\]  

where \( \Delta L/P \) is the compliance and the test itself is often referred to as a compliance test. This allows for computation of a stress intensity factor "K" of the newly created fracture surface as follows:

\[
K = \frac{GE}{\pi(1 - \mu^2)}
\]  

The above equation is satisfied for a specimen whose thickness is large in comparison with the crack size (1,3,22). In equation (II), \( \mu \) is Poisson's ratio, \( E \) is Young's modulus of the material, and \( K \) is the stress intensity factor. The central idea behind the \( K \) factor is that all information relating to crack loading and geometry is contained therein. The factor \( K \) changes from problem to problem which is dependent on the stress state near the crack tip (3,23).

The value of \( K \) in equation (III) can now be used to determine the crack growth of the material in question (3,19,22) as shown in the following equation:

\[
\frac{da}{dN} = C(\Delta K)^n
\]  

where
- \( a \) = crack growth
- \( N \) = number of cycles
- \( K \) = stress intensity factor
- \( C,n \) = material constants

The rate of change of crack growth with number of cycles of applied stress is all important in this type of application. With such a value curves similar to Figure 8 can be prepared which form the basic guidelines for crack growth in brittle construction materials. There it is seen that an initial crack of size "a_0" can remain constant for a large number of load cycles "N" before an increase is noted. It is during this stage, called the monitoring stage in Figure 8, that inspections must be made. Shortly
Figure 8 Schematic Representation of Fatigue Crack Growth in Masonry Materials.
thereafter the useful life of the structure is met (at "a") and if no remedial work is done the fatigue life "a" will rapidly come about.

**Summary and Conclusions**

This study on blasting vibrations in residential houses has revealed a number of points which depart from standard procedures. It points out, for example, that ground motion measurements might be inadequate to assess structural damage in some cases. Furthermore, use of a direct structural monitoring system, such as the clip type strain gage described herein, appears to be a more logical approach to the problem.

Results from this type of monitoring produces crack information - opening and/or length - which can be related to blasting parameters (as in the field study) or to number of stress cycles involved (as in the proposed theory). Regarding the theory for predicting the fatigue life of brittle construction materials, a proposed scheme based on Griffith crack propagation theory is suggested. When coupled with a compliance experiment for the material constants, a crack propagation predictive technique becomes available.

While the proposed methodology is still being researched, it has the distinct advantage of monitoring the crack movement directly. This is of prime importance to both the home owner and the blasting operator for it gives a direct and instantaneous assessment of the blasting potential. With continued effort this crack movement might be related to ground motion or blasting parameters to gain insight into this difficult and important soil/structure interaction problems.

**Acknowledgement**

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References


