

ONE DIMENSIONAL VIBRATION TEST AND SIMULATION ANALYSIS FOR HTGR CORE

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SUMMARY

The highlight of this paper is to describe the seismic model test of the hexagonal graphite blocks of the General Atomic Company High Temperature Gas-Cooled Reactor (HTGR) core. A straight array across the core was selected as the object of the study. The purposes are to clarify the seismic behavior of the graphite blocks by experiments and to establish the method of computer analyses by feeding back the test results into computer codes. The results of importance are outlined as follows:

1. Collision test

Two-block pendulum collision tests were performed to measure the coefficient of restitution of the full scale graphite blocks. Then, the coefficient of restitution of graphite blocks was obtained as around 0.65 regardless of the relative velocity of two blocks.

In addition, the multi-block pendulum collision tests were conducted using the 1/5-scale blocks. The coefficient is again obtained as about 0.65.

2. One dimensional forced vibration test

The 1/5 scale blocks across the center part of the core were suspended by fine wires and reflector blocks were set at both ends by springs supported on the shaking table.

The sinusoidal waves (max. 0.3 g) and the synthetic sinusoidal waves (max. 0.3 g) were provided as stationary input waves, while the ground motions (0.3 g and 0.5 g) and their PCRV responses were provided as random waves. The behaviors of collision were observed as follows:

- (1) The motion of blocks were random even in case of stationary inputs.
- (2) The number of collision occurrences between block and reflector were unexpectedly few in case of random inputs. The occurrences were 5 times by the El Centro wave with an intensity of 0.5 g for 3 seconds of the main shock.
- (3) The reflector reaction P became large with the increase of the stiffness of the supporting spring, and also with that of the input g-level. For example, in case of the spring natural frequency of 185 Hz, the P/W (namely, the ratio of the reflector reaction P to the total weight of blocks W) was observed to be 5 in case of stationary waves of 0.1 g, while the ratio was 10 in case of those of 0.2 g. The P/W was observed to be 2.5 in case of El Centro of 0.3 g, while 12 in case of that of 0.5 g.

3. Simulation analysis

The computer code called COLLAN-I was developed for the above-mentioned tests using the collision theory based on coefficient of restitution. When the coefficient of restitution of 0.65 is adopted, the computer code is able to produce a good simulation between the test and analytical results in both cases of stationary and random waves.

Moreover, in order to catch visually the collisions, an animated film was produced by a COM (Computer Output Microfilming) system. The following phenomena could be observed:

- (1) Blocks as a whole move following the input motion.
- (2) All blocks become nearly lumped at the time the maximum reflector reaction occurs.

1. Introduction

HTGR developed by the General Atomic Company is a nuclear reactor with high performance. The active core in case of large HTGR (1100 MW(e)) is made up of 577 hexagonal graphite columns (about 8,000 blocks in total) vertically stacked with nominal gap of 4mm between individual columns. If an earthquake should occur, an intricate chain reaction of collisions results as a great number of the blocks, as many as 8,000 pieces, bump against one another.

The Electric Power Development Company which will introduce HTGR into Japan has been doing research on seismic studies of HTGR core by a study arrangement with the Muto Institute of Structural Mechanics since 1973. In 1974, the 1/5 scale one dimensional straight array across the center part of the large HTGR core shown in Fig.1 was selected as the object of the first study. The purposes are to clarify the seismic behavior of the graphite blocks by experiments and to establish the method of computer analysis by feeding back the test results into computer codes. The second stage of testing started in 1975 on the 1/5 scale two dimensional (vertical section) model of the core. The follow on tests after 1976, subsequent to the above mentioned tests are planned on the two dimensional (horizontal section) model and the three dimensional model.

This paper is focussed on the one dimensional forced vibration test and computer analysis for the straight array of core using 1/5 scale hexagonal graphite blocks.

2. Forced Vibration Test

2.1 Testing Model of Fuel Element

The actual hexagonal fuel element (about 36cm across flats and about 80cm long) was reduced to the 1/5 scale graphite block model (7.2cm across flats and 16cm long) as shown in Fig.1. The physical constants of graphite material (artificial nuclear grade) are as follows; 1.70 of bulk density; 0.03% of ash; 136,000 kg/cm² of Young's modulus (extrusion direction); 0.65 of coefficient of restitution.

2.2 Model Arrangement

The 25 graphite blocks of 1/5 scale were suspended by fine wires as pendulums and two reflectors were supported by two cantilever reflector springs with square section as shown in Fig.1. Each reflector was also hung by a pendulum to follow the rotational movement of an adjacent hexagonal block, and two kinds of springs were used; a soft spring of 700.kg/cm and a hard spring of 2200.kg/cm. The forced vibration tests were conducted by shaking the 25 blocks through both the springs and the reflectors using a shaking table of a Hitachi electric-hydraulic system.

2.3 Input Waves

The sinusoidal waves ($A=0.4-4\text{cm}$, $f=0.5-5\text{Hz}$, $\alpha_{\text{max}}=0.3g$) and the synthetic sinusoidal waves were provided to the shaking table as stationary waves, while the ground motions (EL Centro 1940(NS), Taft 1952(EW) and Parkfield 1966(EW); 0.3g, 0.5g) and their PCRV responses were used as random waves.

The time scale and the displacement were reduced into $\sqrt{1/5}=0.46$ and $1/5=0.2$ respectively considering the law of similarity.

2.4 Measuring Items

The main measuring items were reflector reactions by strain gauge, impact accelerations of blocks by high-frequency accelerometer and contact time by contact gauge. All measured data were recorded in magnetic tapes.

2.5 Test Results

Fig.2 indicates the relationship between reflector reactions P(ordinate) and input g-levels (abscissa). The upper and lower figures show the cases of the sinusoidal wave and the EL Centro wave respectively. The comparisons of reflector reactions in two cases of hard and soft reflector springs are also shown in both figures. The time histories and impulses of reflector reactions are shown at the right side of both figures as examples of the sinusoidal wave ($f=1.5\text{Hz}$, $0.11g$) and EL Centro wave ($0.3g$).

The test results can be summarized from Fig.2 as follows:

(1) Dynamic Behaviors in Case of Stationary Wave

- a. The motions of blocks are random even in case of stationary inputs. There are several collision patterns which differ at the left and right reflectors. (see Fig.4.(a).)
- b. The reflector reactions increase in proportion to the increase of input g-level.
- c. The reflector reaction in case of the hard spring is larger than that in case of the soft spring. The impulses of the hard spring are three or four times compared with those of the soft spring.
- d. The duration of reflector reaction is about 0.020 seconds in case of the hard spring, while the time is about 0.040 seconds in case of the soft spring as shown in the right side of Fig.2. Each duration corresponds to the frequency of vibration created when all blocks are lumped to become one body with a reflector.

(2) Dynamic Behaviors in Case of Random Wave

- a. The motions of blocks nearly followed the input motion as shown in Fig.5.(b). The remarkable reflector reactions can be seen when the input accelerations become large. The occurrences are about 5 times by the EL Centro wave with an intensity of 0.5g for 3 seconds of the main shock.
- b. The reflector reactions are very small at the low g-level, but increase extremely with the increase of input g-level. The reflector reaction is less than that in case of the stationary waves under the same g-level.
- c. The reflector reaction in case of the hard spring is quite larger than that in case of the soft spring. This tendency is similar to the case of the stationary wave.
- d. The impact phenomena are similar to the case of stationary wave as mentioned in 2.5.(1).d.

3. Simulation Analysis

3.1 Analytical Model

Fig.3 shows the mathematical vibration model to simulate the test results by computer. The computer code named COLLAN-1 was developed for the one dimensional forced vibration of the HTGR core. The characteristics of the code are as follows:

- (1) The block is assumed to be a rigid body.
- (2) The block velocities before and after a collision can be obtained from the collision theory based on a constant coefficient of restitution and the law of conservatism of momentum.
- (3) The equations of motion are applied for the pendulum and reflector parts.

3.2 Comparison between Analyzed and Tested Results

Fig.4 indicates the comparison between the analyzed and tested reflector reactions in two cases of the sinusoidal and EL Centro waves. From this figure, a fairly close coincidence can be found between both time histories.

This demonstrates that the one dimensional behaviors of the core can be computed for any input wave and any reflector spring.

3.3 Dynamic Behavior by Computer

Fig.5.(a) shows the computed absolute displacements of blocks in case of the sinusoidal wave (1.2cm, 1.5Hz). In addition, Fig.5.(a) shows the time histories of the reflector reactions and displacements at both side, and those of the acceleration and displacement at the shaking table. It can be seen from this figure that the motion of each block is random and the pattern of impact peaks are different between the left and right reflectors. These phenomena coincide with the test results as shown in Fig.4.(a).

Fig.5.(b) shows the computed results of the EL Centro of 0.5g. The absolute displacements of blocks are very similar to the displacement of the shaking table and all blocks are almost lumped in vibration.

3.4 Dynamic Behavior by COM

An animated film was produced by means of a COM (Computer Output Micro-filming) system in order to catch visually the intricate chain reaction of collisions among blocks.

Fig.6 shows examples of hard copies from the animated film which shows the behaviors of blocks at 0.2415 and 1.2485 seconds after occurrence of the EL Centro wave of 0.5g. In Fig.6, vertical boundary line when not appearing between blocks indicates lumping which is defined by the assumption that the gap between blocks becomes less than 0.08mm (one tenth of the initial gap).

The right side of Fig.6 indicates lumping patterns before and after 0.2415 and 1.2485 seconds. Black mark shows the lumping of blocks, while white circle indicates the collision between block and reflector. According to Fig.6, when the shaking table moves to the left direction, the right reflector begins to contact with the adjacent block at the right side and lumpings spread gradually from the right to the left. After the shaking

table shows the maximum displacement, lumpings occur irregularly in all blocks.

4. Conclusion

The main remarks can be drawn from the test and simulation analysis as follows:

(1) Test

a. Input g-level and Reflector Reaction

The reflector reactions are random even in case of the stationary vibration inputs and increase in proportion to the intensities of input g-levels. The reflector reactions in case of the random wave such as EL Centro inputs increase extremely, but are less than that in case of the stationary waves under the same g-level.

b. Reflector Spring and Reflector Reaction

The reflector reaction in case of the hard spring is larger than that in case of the soft spring in both cases of the sinusoidal wave and the EL Centro wave.

(2) Simulation Analysis

a. Computer Code COLLAN-1

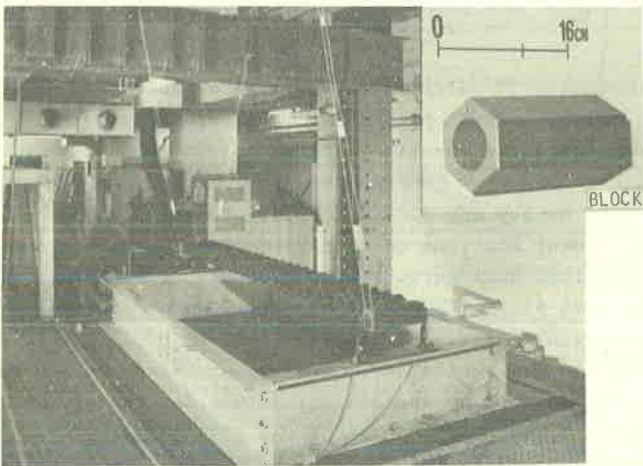
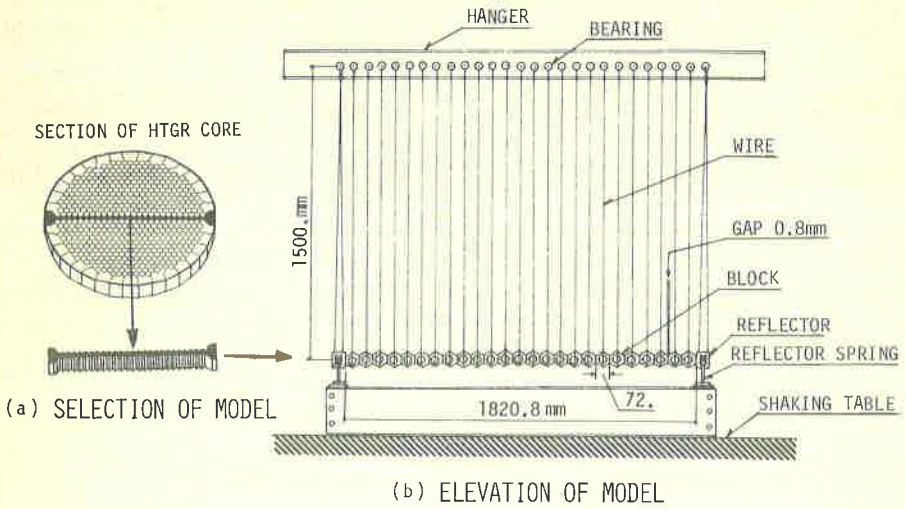
The computer code COLLAN-1 can simulate the test results fairly well and will be effective for parameter analyses using such data as input wave, stiffness of reflector spring, coefficient of restitution and gap between blocks.

b. COM

The COM makes it clear that blocks as a whole move following the input motion and all blocks become nearly lumped at the time the maximum reflector reaction occurs.

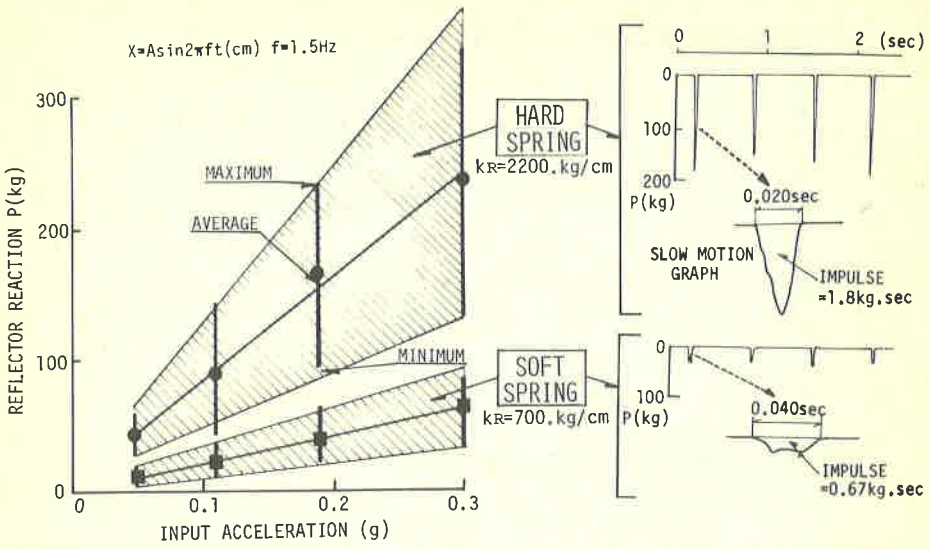
[REFERENCES]

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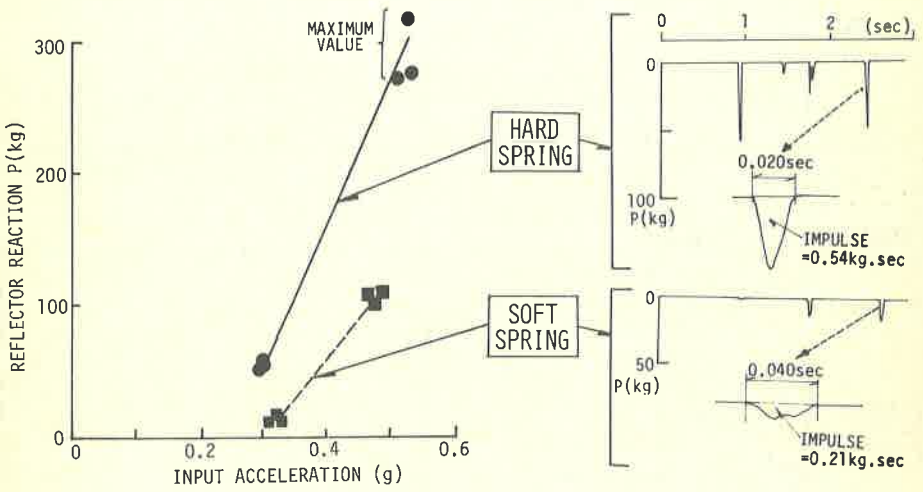


(c) GENERAL VIEW OF MODEL

FIG. 1 1/5 SCALE MODEL FOR 1-D FORCED VIBRATION TEST



(a) SINUSOIDAL WAVE



(b) EL CENTRO WAVE

FIG. 2 RELATIONSHIP BETWEEN INPUT G-LEVEL AND REFLECTOR REACTION

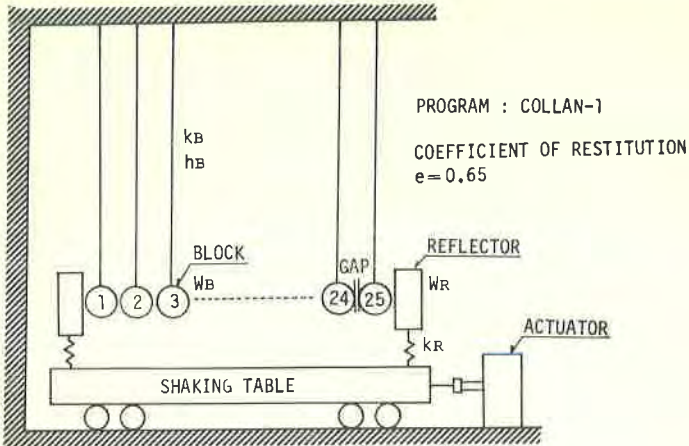


FIG. 3 MATHEMATICAL MODEL FOR 1-D FORCED VIBRATION ANALYSIS

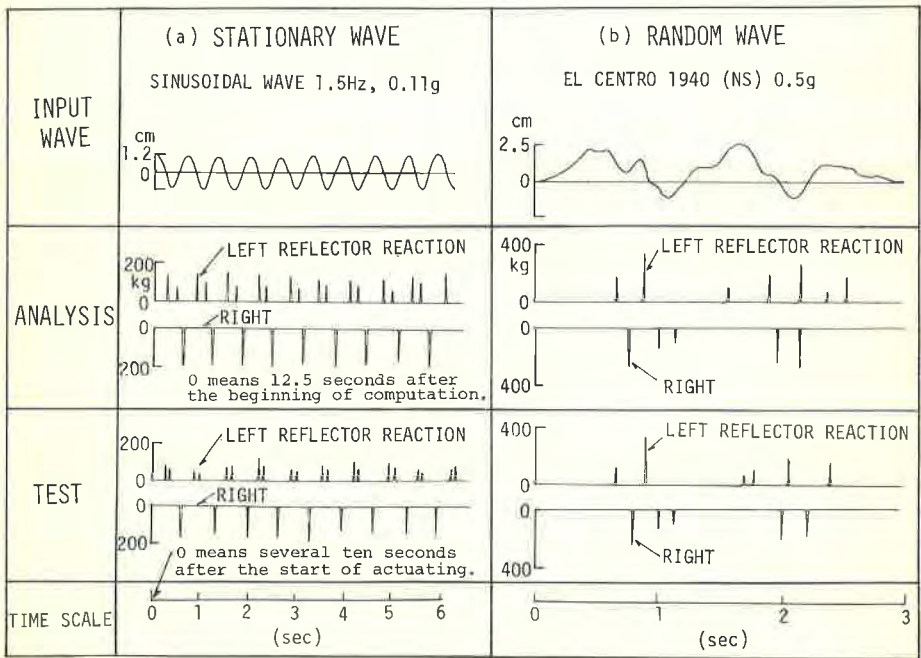
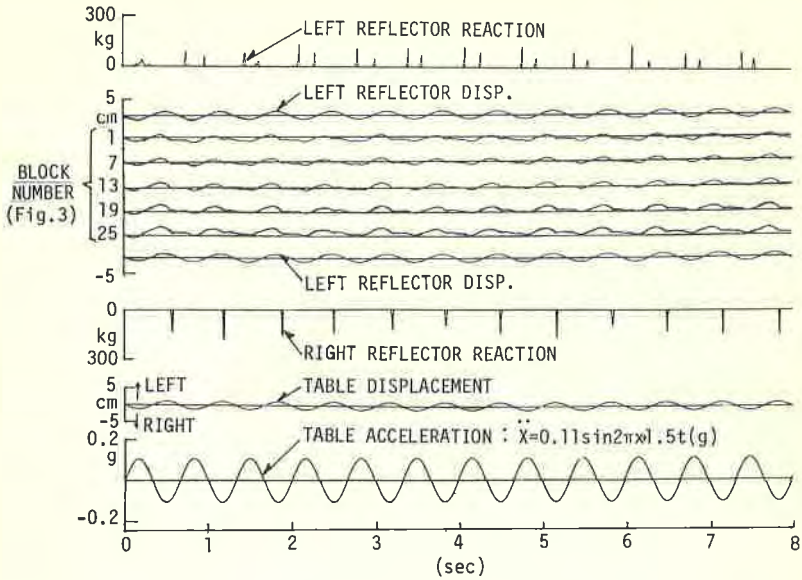
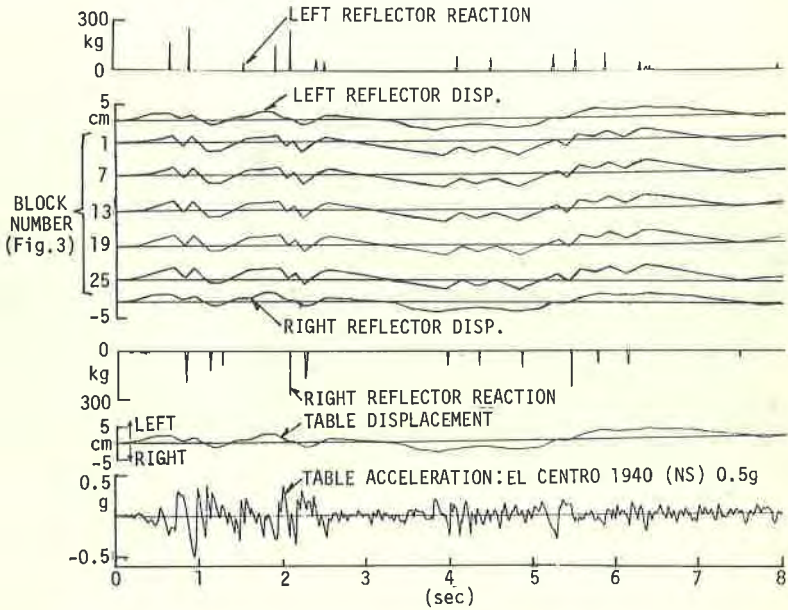


FIG. 4 COMPARISON BETWEEN ANALYZED AND TESTED REFLECTOR REACTIONS IN CASE OF HARD SPRING



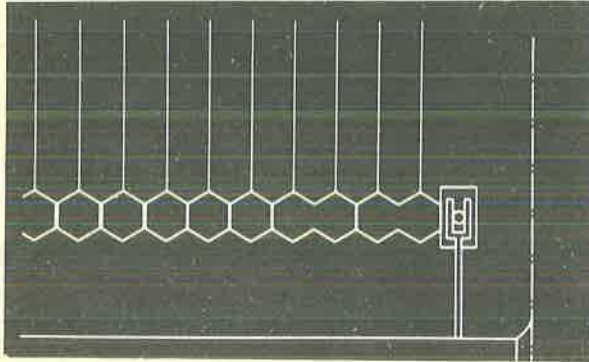
(a) SINUSOIDAL WAVE



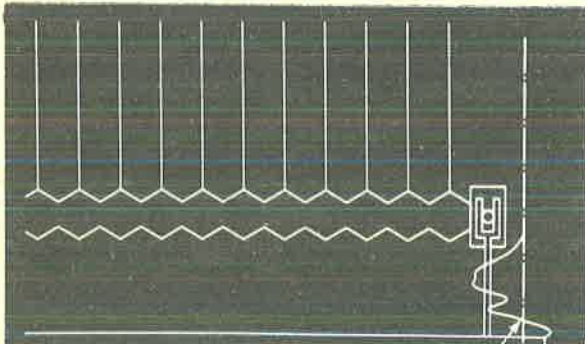
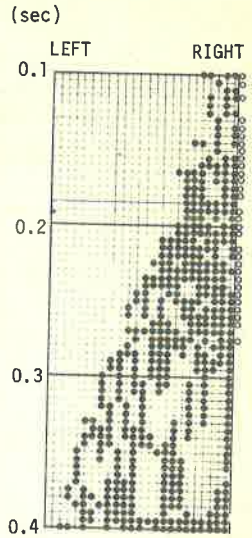
(b) EL CENTRO WAVE

FIG. 5 COMPUTED TIME HISTORIES OF REFLECTOR REACTIONS AND BLOCK ABSOLUTE DISPLACEMENTS

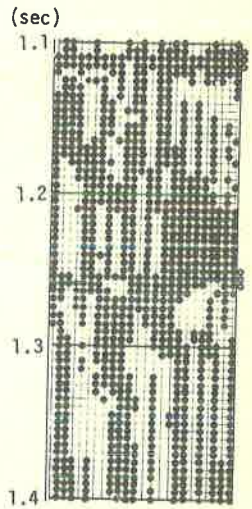
EL CENTRO 1940 (NS) 0.5g



(a) 0.2415 sec



(b) 1.2485 sec



- shows lumping between each block.
- shows collision between block and reflector.

FIG. 6 LUMPING PATTERN