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7727

ONE STACKED-COLUMN VIBRATION TEST
AND ANALYSIS FOR VHTR CORE

July 1978

Takeshi IKUSHIMA, Hiroshi ISHIZUKA*, Akira IDE*
Hitoshi HAYAKAWA* and Kazuteru SHINGAI*

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One Stacked-Column Vibration Test and Analysis for VHTR Core

Takeshi IKUSHIMA, Hiroshi ISHIZUKA*, Akira IDE*,
Hitoshi HAYAKAWA*, and Kazuteru SHINGAI*

Division of Power Reactor Projects
Tokai Research Establishment, JAERI

(Received May 29, 1978)

This paper describes experimental results of the vibration test on a single stacked-column and compares them with the analytical results.

A 1/2 scale model of the core element of a very high temperature gas-cooled reactor (VHTR) was set on a shaking table. Sinusoidal waves, response time history waves, beat wave and step wave of input acceleration 100 - 900 gal in the frequency of 0.5 to 15 Hz were used to vibrate the table horizontally.

Results are as follows:

(1) The column has a non-linear resonance and exhibits a hysteresis response with jump points.

(2) The column vibration characteristics is similar to that of the finite beams connected with non-linear soft spring.

(3) The column resonance frequency decreases with increasing input acceleration.

(4) The impact force increases with increasing input acceleration and boundary gap width.

(5) Good correlation in vibration behavior of the stacked-column and impact force on the boundary between test and analysis was obtained.

KEYWORD: HTGR Core, Core Seismic, Earthquake, VHTR, Seismic Test, Core Structure, HTGR Fuel, Column Vibration

* Fuji Electric Co., Ltd.

高温ガス実験炉炉心の1コラム振動試験と解析

日本原子力研究所・動力炉開発安全性研究管理部

幾島 毅・石塚 宏*・井出 朗*

早川 均*・新貝 和照*

(1978年5月29日受理)

多目的高温ガス実験炉の炉心要素である1コラムの $\frac{1}{4}$ 縮尺模型を使用して振動試験を実施した。コラムを振動台上に取付け、正弦波、地震波、ビート波およびステップ波によって、入力加速度で100~900 gal, 入力周波数域で0.8~15 Hz の範囲で試験を実施した。得られた結果は次の通りである。

- (1) コラムは非線形共振特性を有し、跳躍を伴った履歴現象を示す。
- (2) コラムの振動特性は柔かい非線形ばねによって連結されたはりと同じである。
- (3) コラムの共振周波数は入力加速度の増加に従って下降する。
- (4) 衝突力は入力加速度およびギャップの増加に従って増加する。
- (5) 振動挙動および衝突力の試験結果と解析とが良好な一致をみた。

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1. Introduction

1.1 General description

The VHTR core is capable of high temperatures (max. 1200 ~ 1400 °C) and is composed of many graphite blocks. It is not known presently whether such a VHTR core can withstand possible major earthquakes. When such a reactor plants are to be installed in areas of high seismicity, analysis and experiments in earthquake-resistance design are necessary.

For the past five years, Japan Atomic Energy Research Institute (JAERI) has been studying the VHTR core behavior during earthquake excitation.^{(1),(2)} Simplified models were used to predict the core behavior, but the non-linear behavior due to block rocking and impact are an important aspect of the core seismic response. In the present study, a vibration test has been performed with a single-stacked-column-a fundamental element of the VHTR core structure.

Purpose was:

- (1) to examine core dynamic behavior and response characteristics,
- (2) to develop mathematical models and computer programs on the basis of test results obtained,
- (3) to provide preliminary design data of the VHTR core structure with model scaling law.

1.2 Structure of Experimental VHTR

Arrangement of experimental VHTR is set as in reactor plant of Fig.1. Reactor vessel is placed in the central part of building and fixed to concrete barrier.

The structure of reactor core for experimental VHTR is shown in Fig.2. Reactor core formed a structure capable of supporting its weight

through high temperature plenum (core supporting block and core supporting post). Its side is coupled to core barrel with side restraint structure of the core as shown in the structure of the core in Fig.3 (the reactor core plan).

(1) Structure of reactor core

The core of experimental VHTR shown in Fig.2 is composed of graphite block (fuel block, movable reflector, fixed reflector), lower part structure of core, its surrounding core supporting structure, core side restraint structure and orifice block for flow adjustment.

Horizontal arrangement of core as shown in Fig.3 is set in 73 columns of fuel block, its neighboring 66 columns of movable reflector, and 18 columns of fixed reflector and core restraint structure. Vertical arrangement shown in Fig.2 is set with seven-layer fuel block and two-layer movable reflectors with blocks in above and below. Orifice block for flow control is set on the top of the reflectors, and graphite block and thermal barrier forming high temperature plenum are set in lower section

(2) Graphite block (fuel block)

Fuel block shown in Fig.4 is pin-in-block type with inserted fuel rod inserted into cooling channel which opens in graphite block of hexagon pillar shape. One region for fuel replacement, control and flow control is formed from those seven columns of fuel block.

Of the seven columns, surrounding six columns of fuel block is called as standard type fuel block in which twelve cooling channels opened. The fuel block in the central column is called control fuel block in which three cooling channels, two holes for inserting control rod and one hole for insertion of back up shutdown element (boron) opens.

This positions of those graphite blocks are decided by three dowel pins each in the direction of upper and lower and coupled, but are not restrained to the horizontal direction because of gap between each column. Orifice block in the upper top of column is made mutual key coupling in one region. Furthermore, upper part block in high temperature plenum in lower part of reactor core is also made mutual key coupling.

(3) Core side restraint mechanism

As shown in the core mechanism drawing of Fig.3, fixed reflector is directly coupled to core barrel through core restraint mechanism. This core side restraint mechanism is turnbuckle mechanism and 18 pieces are fixed to direction of circular and 15 stages are fitted to direction of height.

(4) Core bottom support mechanism

Core bottom support mechanism consists of a structure in which the core is set on high temperature plenum block and supported by core support post and further the whole core is supported by diagrid fitted to bottom of core barrel (See Fig.2).

2. Vibration Test

The test has been carried out with a shaking table. Twelve 1/2 scale graphite blocks and steel orifice block are stacked in a frame, which is set on the shaking table shown in Fig.5. Sinusoidal waves, response waves from earthquakes such as El Centro, Taft and Ibaragi (Japan), a beat wave and a step wave are used to vibrate the table horizontally. The range of acceleration was from 100 to 900 gal in the frequency range from 0.8 to 15 Hz.

Test apparatus is so constructed to be able to change horizontal block direction, boundary gap and top block gap and top block weight. Effects of the change were also examined.

Graphite blocks were of nuclear-grade graphite SMI-24 from Anglo-Great Lakes Co. (AGL).

Test objectives are summarized in Table 1 and test conditions in Table 2.

3. Test Results

3.1 Coefficient of Restitution

The coefficient of restitution was determined by two-block pendulum collision test and single block rocking test. The coefficient of restitution is about 0.6 in two-block collision, and 0.8 in block rocking collision.

3.2 Resonance

Fig.6 shows lateral displacement of 9-th block from bottom in the case of sinusoidal sweep test. The column has a non-linear response and shows a hysteresis with jump points. This characteristic is similar to that of the finite beams connected with non-linear soft spring.

The resonance frequency is 1.6 to 5 Hz as shown in Fig.7. The resonance frequency decreases with increase of the input acceleration level.

3.3 Sinusoidal Test

- (1) Effects of input wave frequency and acceleration level on the impact force

Fig.8 shows effect of the input wave frequency on the impact force of block and boundary. The maximum impact force increases with increase of frequency and maxima appear at certain frequencies, beyond this frequency the force decreases remarkably. The maximum impact force shifts to higher frequency with increase of the acceleration.

- (2) Effect of gap width on impact force

Fig.9 shows the relation between gap width and impact force. The impact force increases with increase boundary gap and input acceleration level.

(3) Effect of top block gap and weight on vibration behavior

The first deflection mode of the column has a loop around the 9th block from bottom (shown in Fig.13). The top block gap and weight influence the column motion. Increase in the top gap pushes the maximum deflection point of column upward and makes the motion more unstable. Increase in the top weight has the reverse effect.

(4) The effect of block vibration direction on the resonance frequency is almost negligible (shown in Figs.6 and 7).

(5) Change in the block vibration direction results in about 20 % changes of response displacement and impact force.

3.4 Random Wave Test

Table 3 shows comparatively impact force with various input waves, i.e. the sinusoidal wave and seismic waves. The maximum responses of the column for seismic waves are about 40 to 75 % that for the sinusoidal wave.

The maximum response for the beat wave input is the same as that for sinusoidal wave.

The step wave is used to estimate a damping factor of the column. It is obtained as about 30 % of critical damping.

3.5 Block Failure

The blocks was subjected to more than 600 vibration tests during test period at acceleration up to 900 gal. The graphite blocks received more than 20000 load cycles of impact. There occurred no failures of blocks and dowels.

4. Analysis

4.1 Analysis Model

In the VHTR core, this group of blocks and columns extends three-dimensionally. In the present study, the following simplified model as shown in Fig.10 for calculation was considered.

- (1) Block is treated the rigid body.
- (2) This calculation system is two-dimensional and each element has three degrees of freedom, two translational displacements and one rotation at the block center gravity.
- (3) Impact phenomenon is treated with impact spring-damper.
- (4) The dowels are deformable and the interface of blocks has friction force.

The equations of motion for the i-th block of the single column may be written as:

$$m\ddot{x} = F_D^U + F_D^L + F_F^U + F_F^L + F_B^R + F_B^L - C_x \dot{x} - m\ddot{x}_O, \quad (1)$$

$$m\ddot{z} = F_V^U + F_V^L - mg, \quad (2)$$

$$I\ddot{\theta} = M_D^U + M_D^L + M_F^U + M_F^L + M_B^R + M_B^L + M_V^U + M_V^L. \quad (3)$$

For the i-th impact plates, equations of motion are as:

$$m\ddot{x}_B^L = F_M^L - F_B^L - m_B\ddot{x}_O^L, \quad (4)$$

$$m\ddot{x}_B^R = F_M^R - F_B^R - m_B\ddot{x}_O^R. \quad (5)$$

Two computer programs, SONATINA and COLUMN-3 were prepared in JAERI and Fuji Electric Co. respectively for analysis of the test results. The present results are by SONATINA.

4.2 Free Vibration Response

To confirm validity the analytical equations and the computer programs, analytical results are compared with test results for single block free rocking and single column free vibration.

Fig.11 compaires between the analytical and test results in free vibration of the column. Close correlation between analysis and test was obtained.

4.3 Sinusoidal Wave Response

Fig.12 shows the compares the analytical and the test impact forces of blocks in the sinusoidal wave. Correlation is also good.

4.4 Graphic Representation of Vibration Behavior

The VHTR core is made up about 2000 blocks. It is impossible to grasp the motion of the whole blocks from the computer output. If a computer-generated movie showing clearly the pattern of block motion is used, the core seismic behavior can be vividly shown. For the purpose, a graphic presentation program has been developed.

Fig.13 shows an example of column behavior produced from test and analytical results.

5. Conclusion

The following were revealed by the vibration test and analysis.

- (1) The column has a non-linear resonance and exhibits a hysteresis response with jump points.
- (2) The column vibration characteristic is similar to that of the finite beams connected with non-linear soft spring.
- (3) The column resonances of displacement response occur in the frequency range of 5 to 1.6 Hz at input accelerations 100 ~ 900 gal. The column resonance frequency decreases with increase of the input acceleration.
- (4) The column resonances of impact force occur in the frequency range 1.7 to 7.5 Hz at input accelerations 150 ~ 750 gal and boundary gaps 25 ~ 5 mm. The impact force increases with increase of the input acceleration and boundary gap width.
- (5) The first deflection mode of the column has a loop around the 9th block from bottom.
- (6) The top block gap and weight have effects on the column deflection mode. Increase in the top gap pushes the maximum deflection point of column upwards and makes the motion more unstable. Increase in the top weight has the reverse effect.
- (7) The effect of block vibration direction on the resonance frequency is almost negligible, but change in the block direction results in about 20 % changes of response displacement and impact force.
- (8) The column damping factor is about 30 % of critical. It increases slightly with increasing in the deflection amplitude.
- (9) The maximum response of the column for seismic waves are about 40 % to 75 % of that for the sinusoidal input.

(10) There occurred no-failures of blocks and dowels at acceleration up to 900 gal with the boundary gap 5 to 25 mm.

(11) Good correlation in vibration behavior of the stacked column and impact force between test and analysis was obtained.

Results are summarized in Table 4.

Reference

- (1) T. IKUSHIMA, JAERI-M 5560, (1974).
- (2) T. IKUSHIMA, M. KAWAKAKI, Proceedings 3rd SMIRT Paper K8/7, (1975).
- (3) T.H. LEE, Nucl. Eng. Des. 32, pp.337 ~ 350, (1975).

NOMENCLATURE

Cx: Damping constant of displacement detector

F : Force

g : Gravity constant

I : Rotation of inertia

M : Moment

m : Mass

x : Lateral displacement

z : Vertical displacement

θ : Rotational degree

Upper subscripts

L : Lower

L : Left

R : Right

U : Upper

Lower subscripts

B : Boundary

D : Dowel

F : Friction

M : Impact plate

V : Vertical

i : i-th element

Others

• : Velocity

'' : Acceleration

Table 1 Test Objectives

Column vibration characteristics
Effects of various parameter on response Gaps Top block weight Block excitation direction
Design data for block impact force
Column Damping factor
Data for computer program development

Table 2 Test Condition

Collision test 2-block collision test Single block rocking test
Column free vibration test
Column forced vibration test Sinusoidal sweep test 1 → 15 → 1 Hz Sinusoidal response test Sinusoidal beat test Seismic response test Step response test

Table 3 Impact forces vs. input waves

Wave	Maximum acceleration (gal)	Gap between block and boundary (mm)	Impact force (kg)
Sinusoidal 3.5 Hz	500	15	710
Seismic wave			
El Centro 1940 NS			267
Taft 1952 EW			222
Ibaragi 1964 NS			400

Table 4 Results

Coefficient of restitution	
2-block collision	0.6
Single block rocking	0.8

Resonance Characteristics	
Non-linear soft spring beam	
Hysterisis response with jump point	

Displacement resonance	
Acceleration increase → Resonance frequency decrease	

Impact force	
Acceleration	} Increase → Impact force increase
Gap width	

Column 1st mode	
Loop around 9th (2/3 length) block from bottom	

Table 4 (continue)

Effect of block gap		
Gap increase → Impact force increase		
Effect of top block gap		
Gap increase → Column vibration unstable		
Effect of top block weight		
Block weight increase → Column vibration stable		
Effect of block excitation direction		
	Resonance freq.	Displacement & Acceleration
Block flat (0°)	Same	1.0
Block edge (90°)	Same	20% smaller than above
Seismic wave response		
Sinusoidal wave	Beat wave	Seismic wave
1.0	1.0	0.4 - 0.75

Table 4 (continue)

Column damping factor
30% of critical damping
Computer program development
SONATINA (JAERI)
COLUMN - 3 (Fuji Electric Co.)

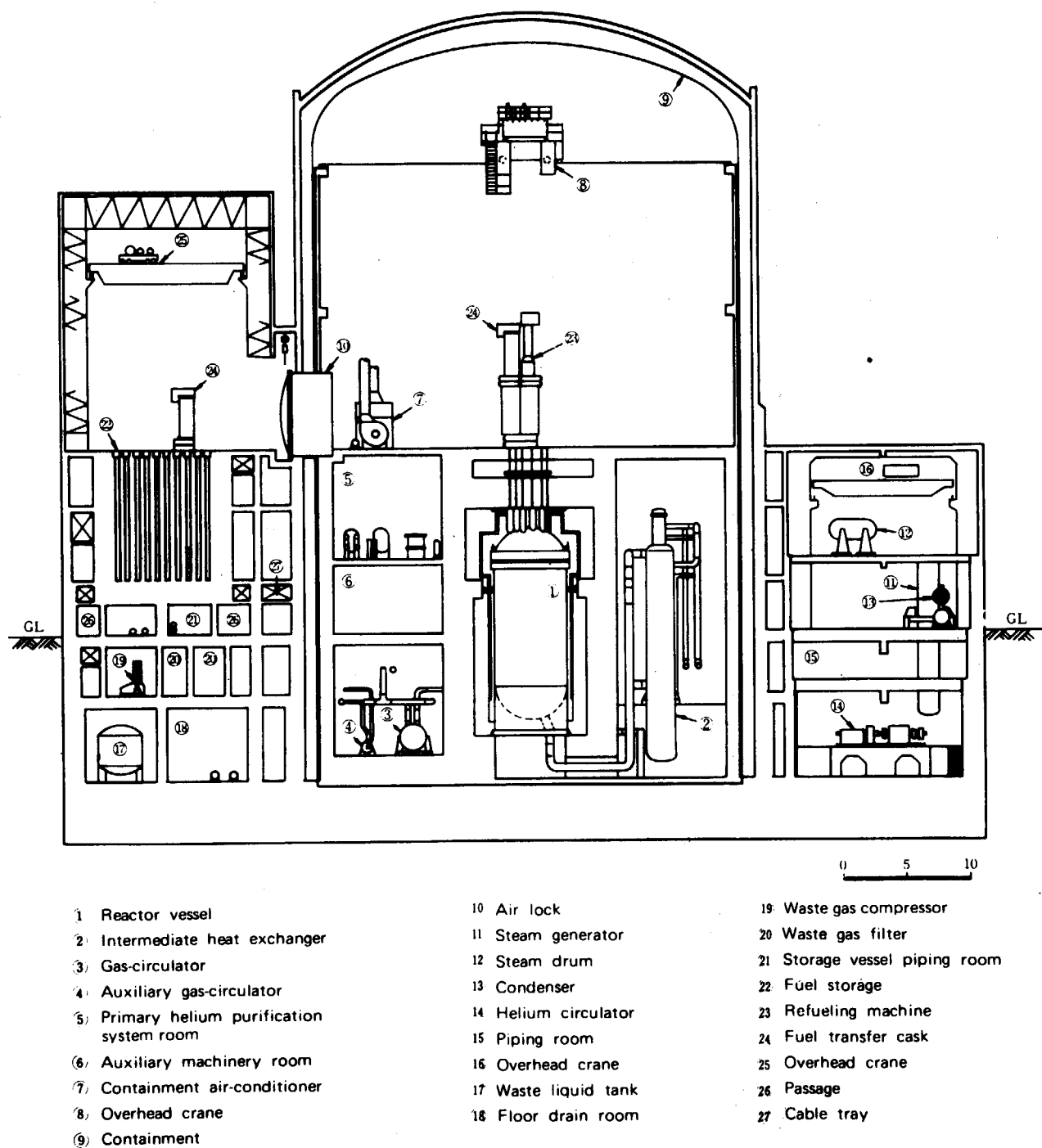


Fig. 1 Section through VHTR building (the first conceptual design)

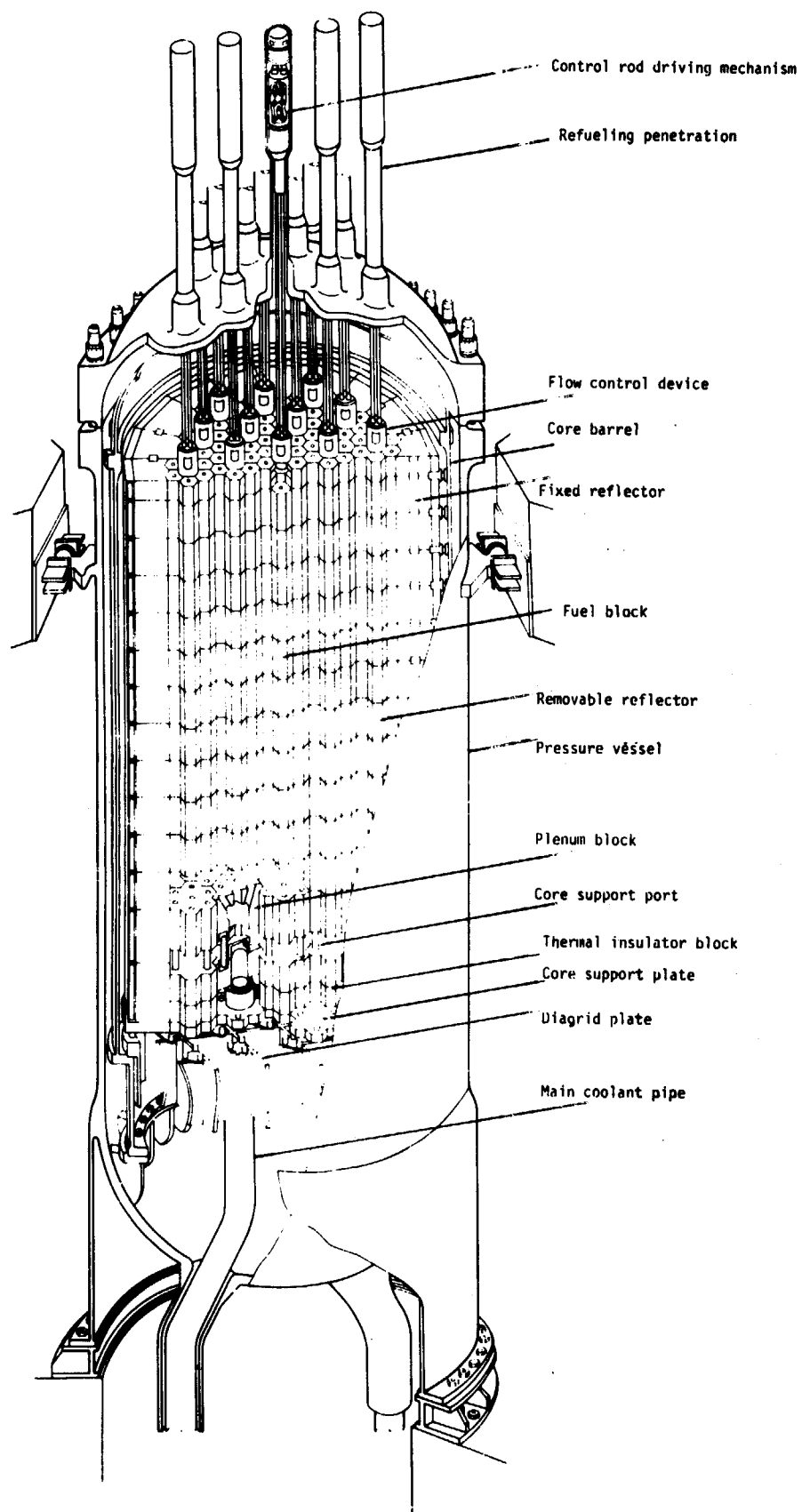


Fig. 2 Reactor vertical view of VHTR

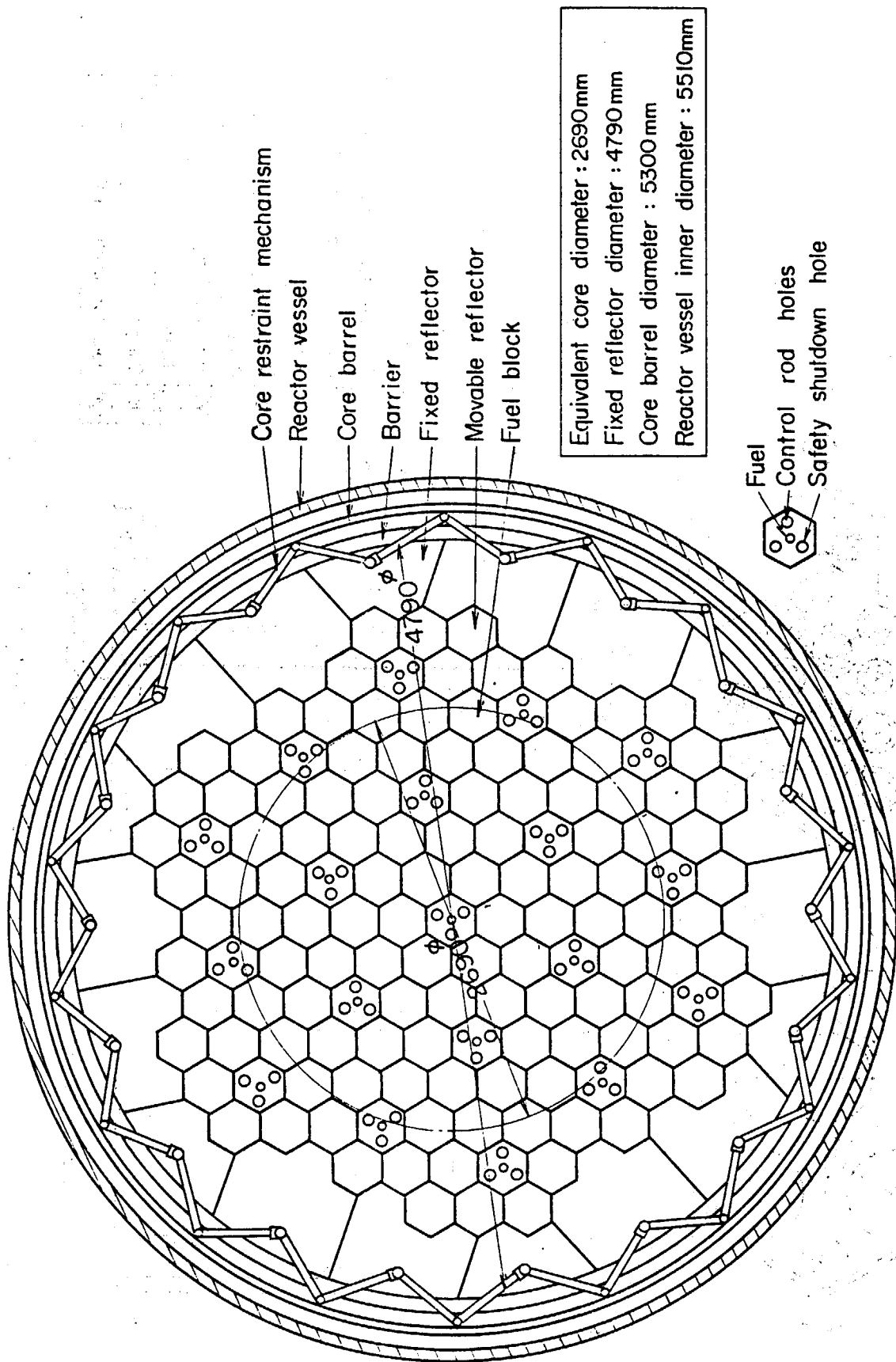


Fig. 3 Core horizontal view

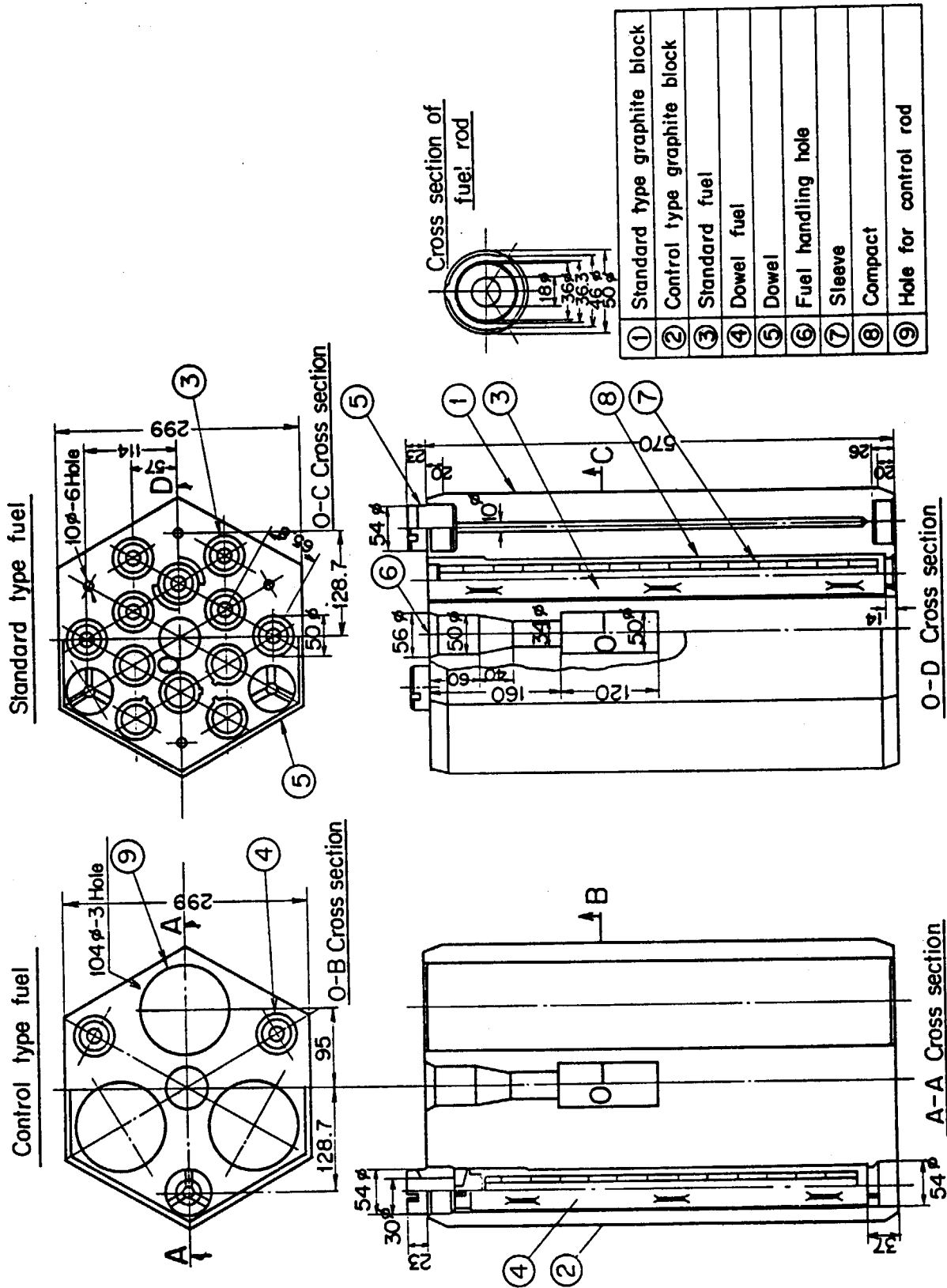
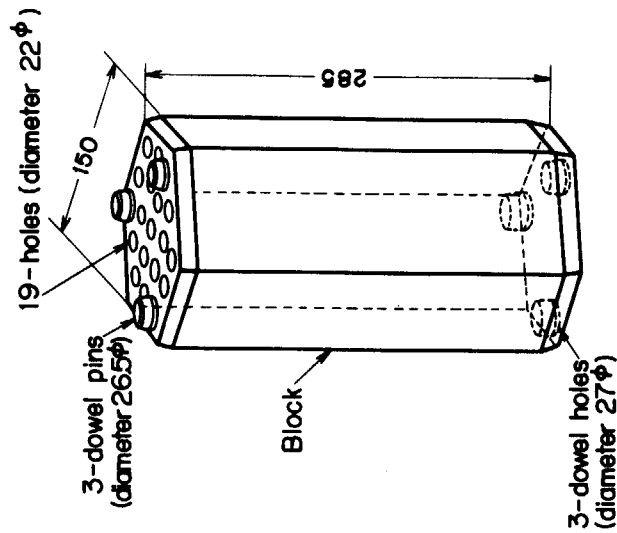
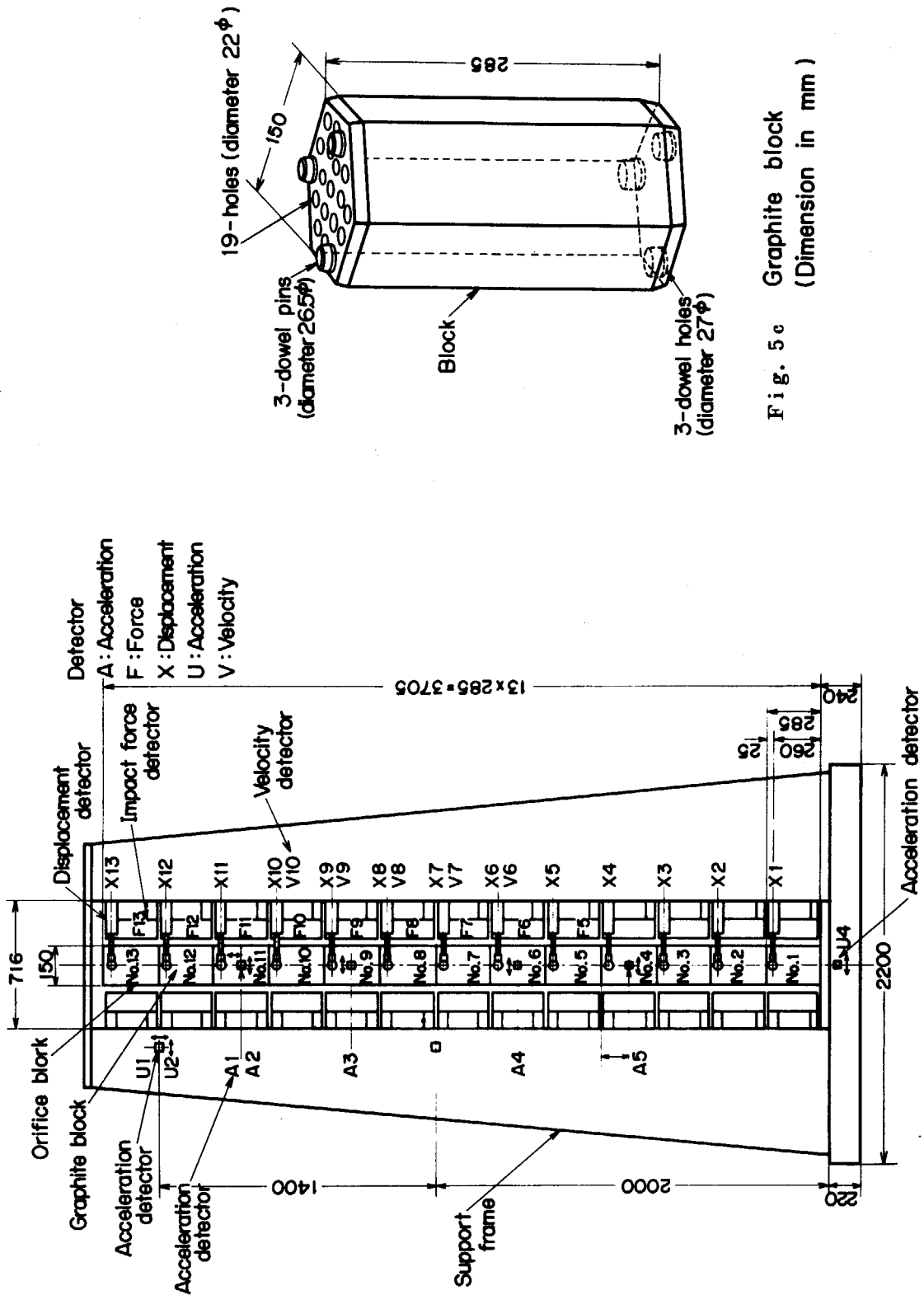


Fig. 4 Graphite block



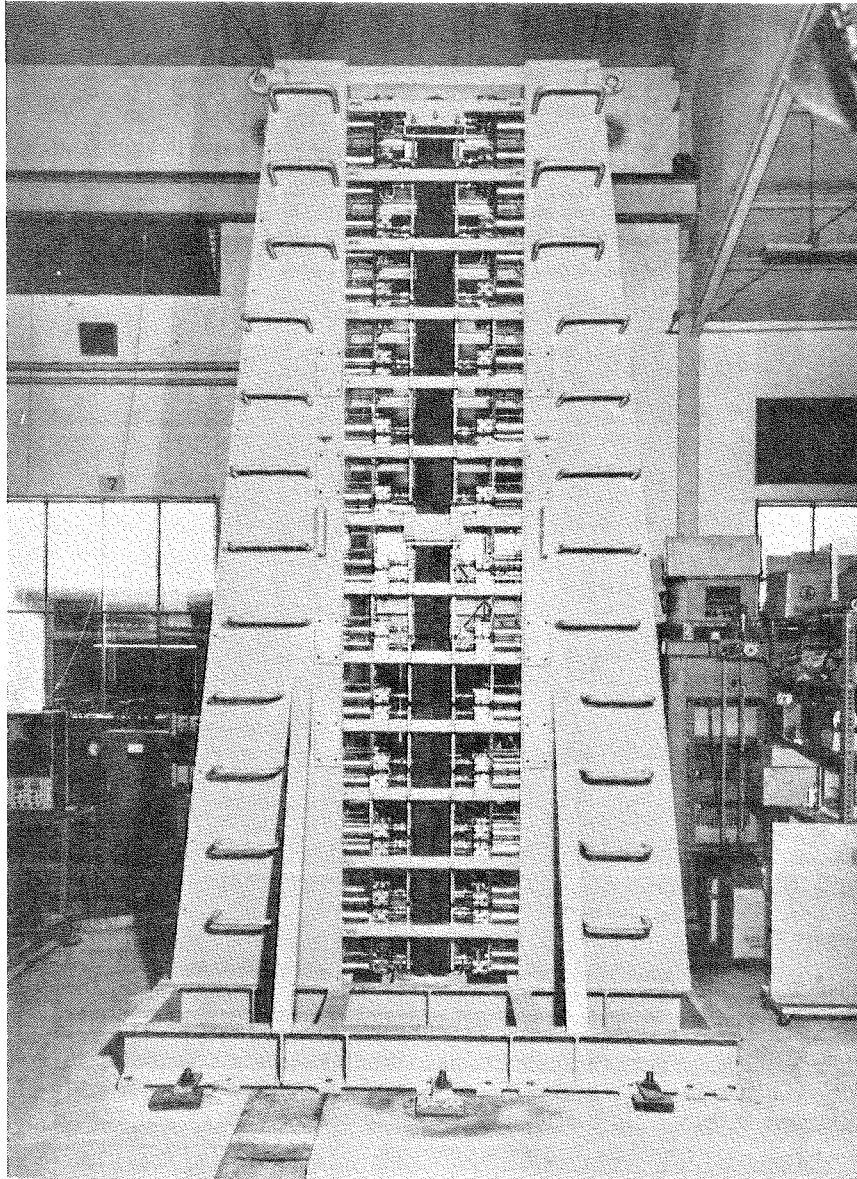


Fig. 5b Test apparatus for one stacked column vibration test

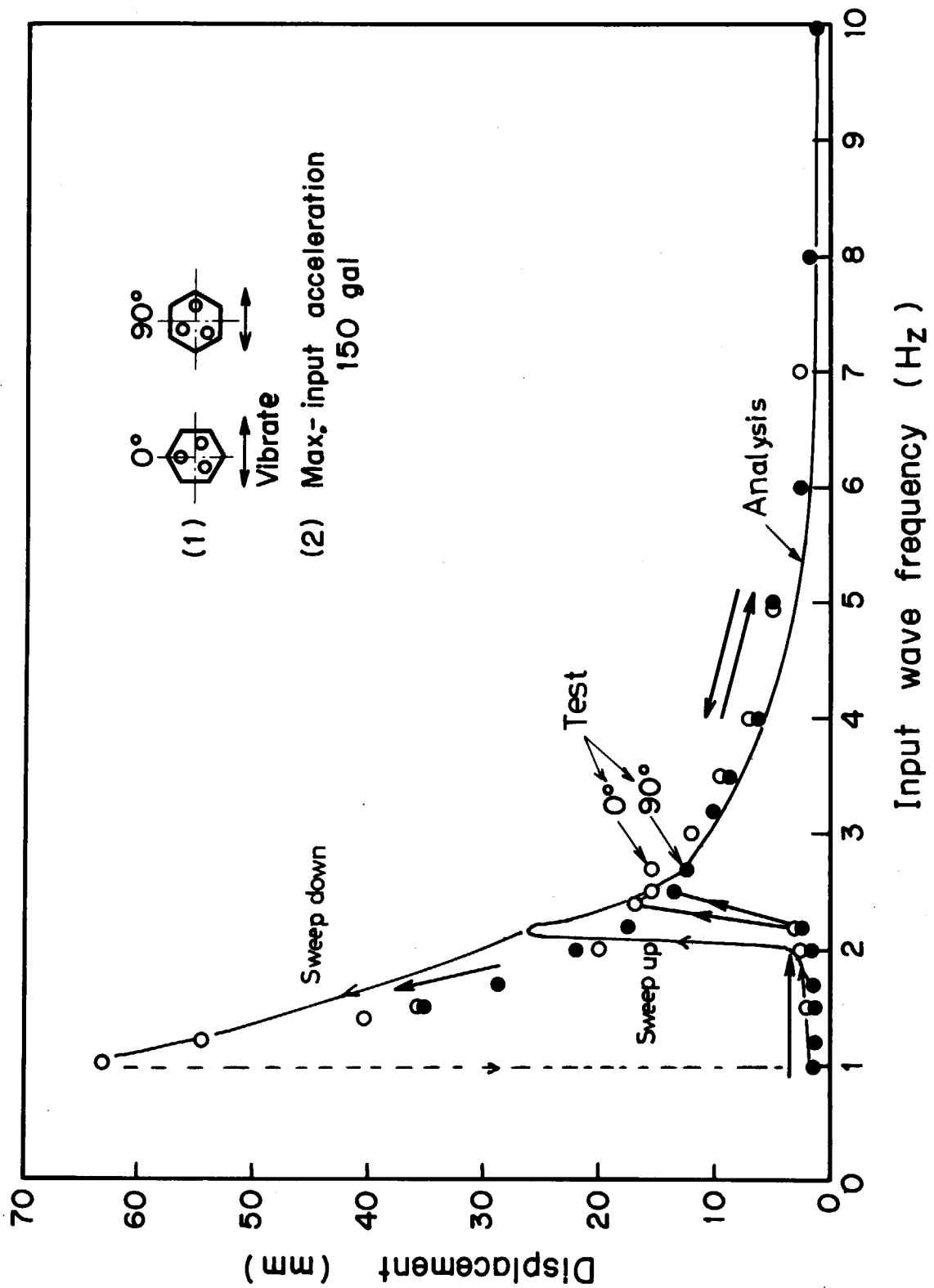


Fig. 6 Effect of vibrated direction of block on response

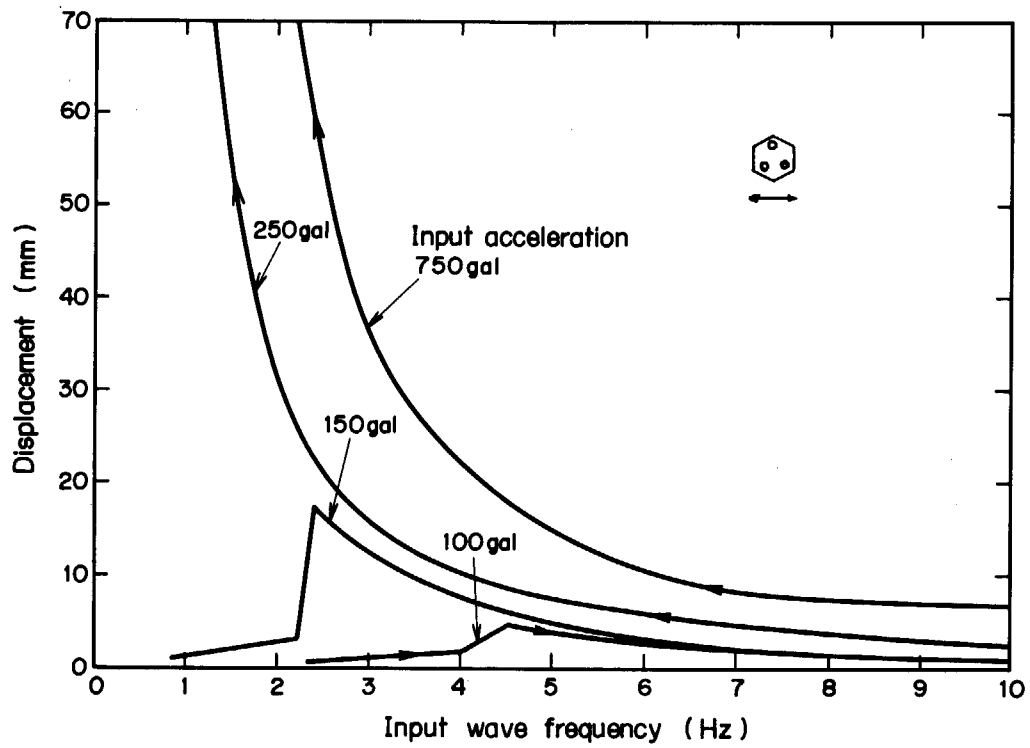


Fig. 7a Effect of input wave frequency and acceleration on response displacement

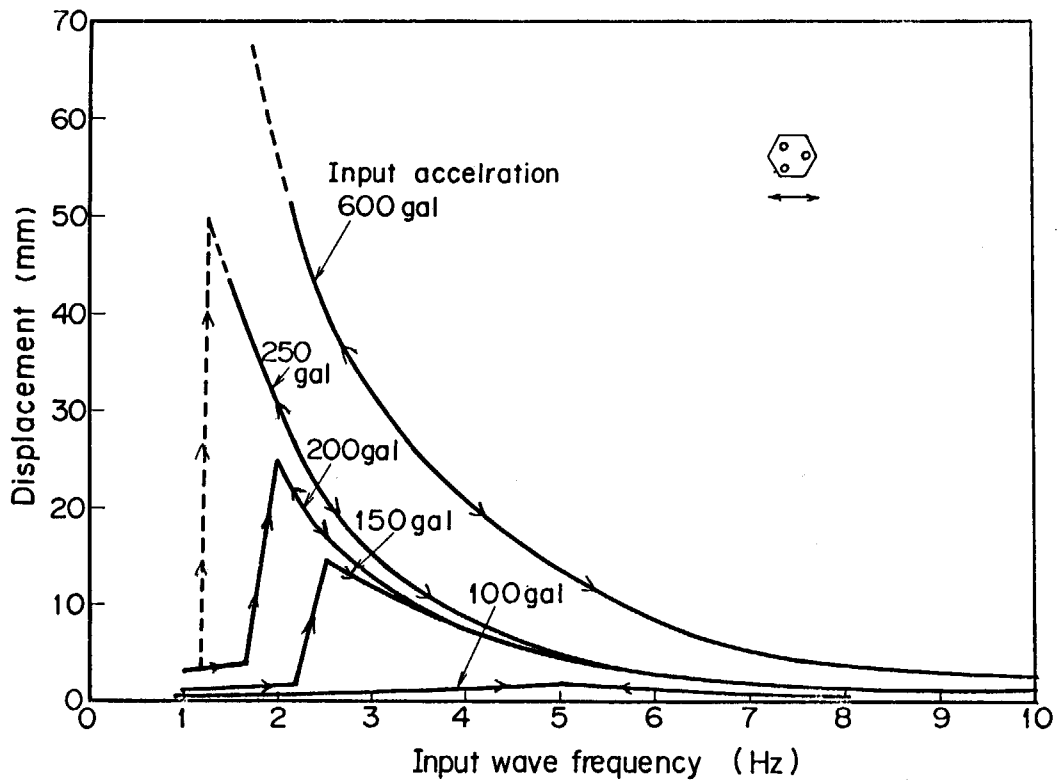


Fig. 7b Effect of input wave frequency and acceleration on response displacement

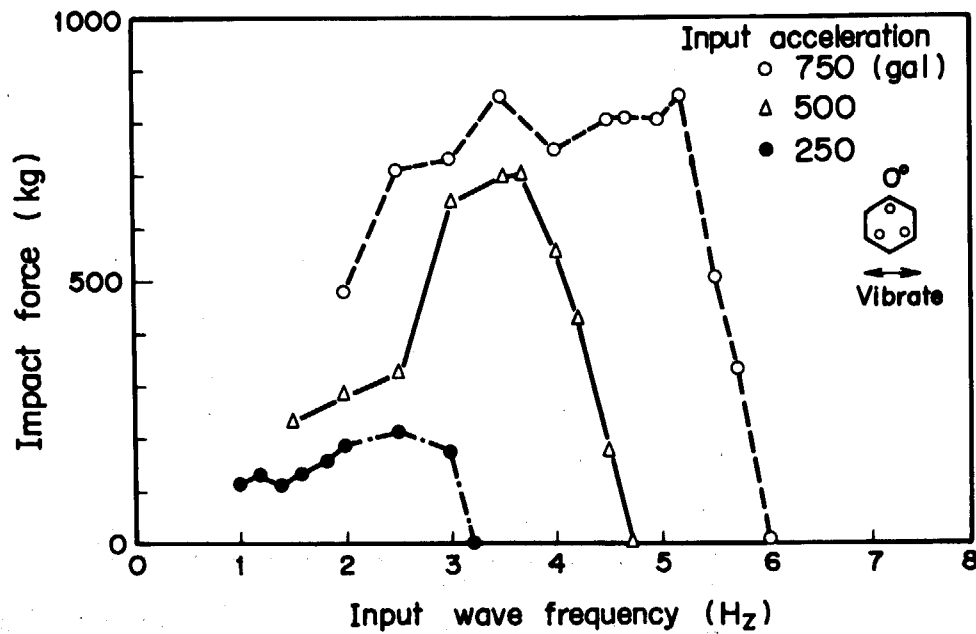


Fig. 8 Effect of input wave frequency and acceleration level on impact force
(Gap width 15 mm, Block impact direction 0°)

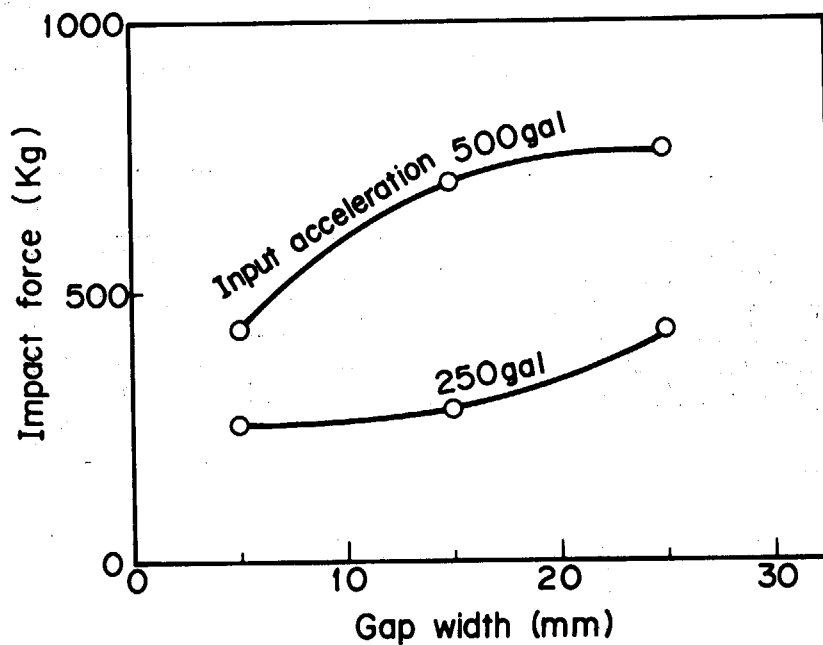


Fig. 9 Effect of gap width and input acceleration on impact force

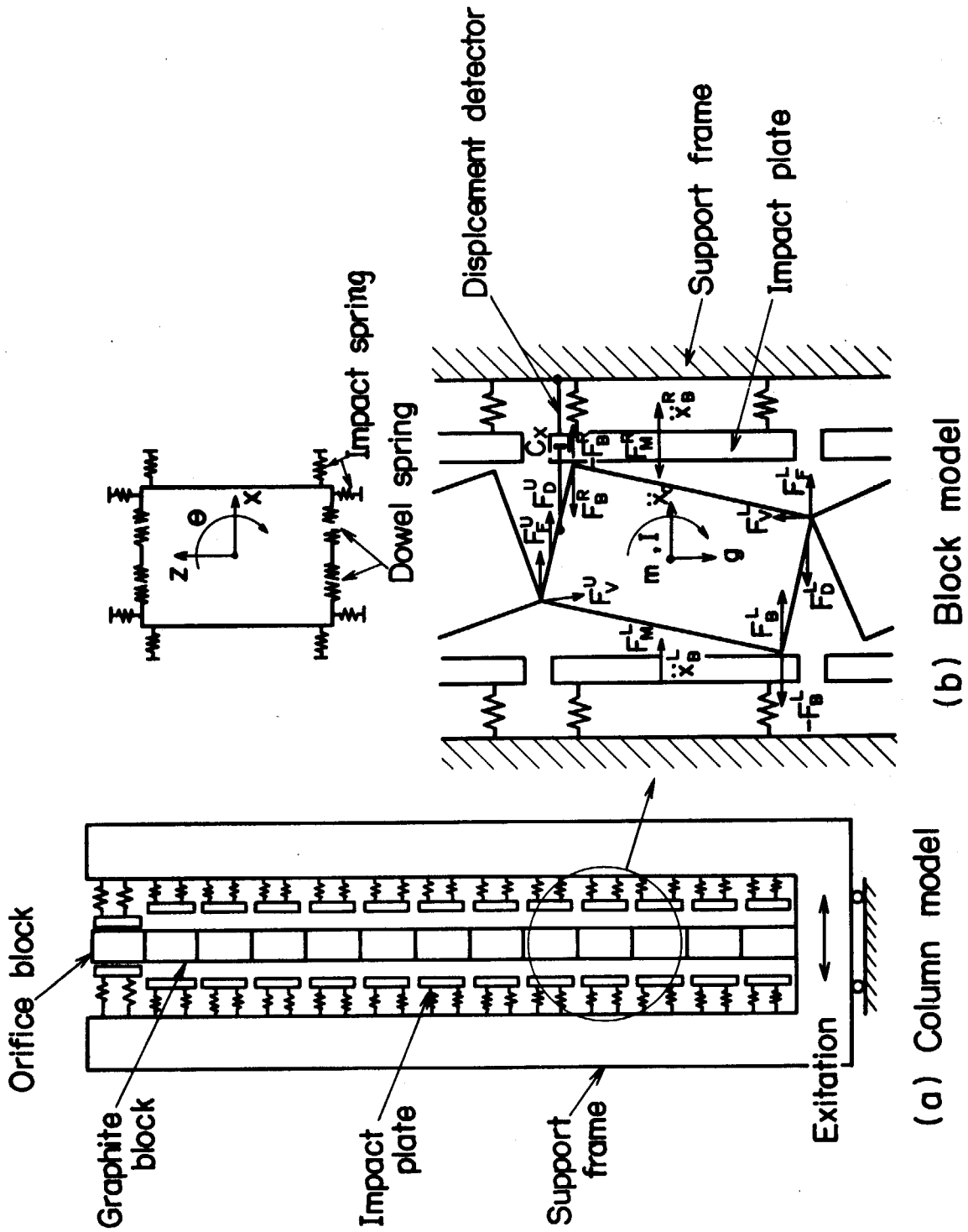


Fig. 10 Analytical model

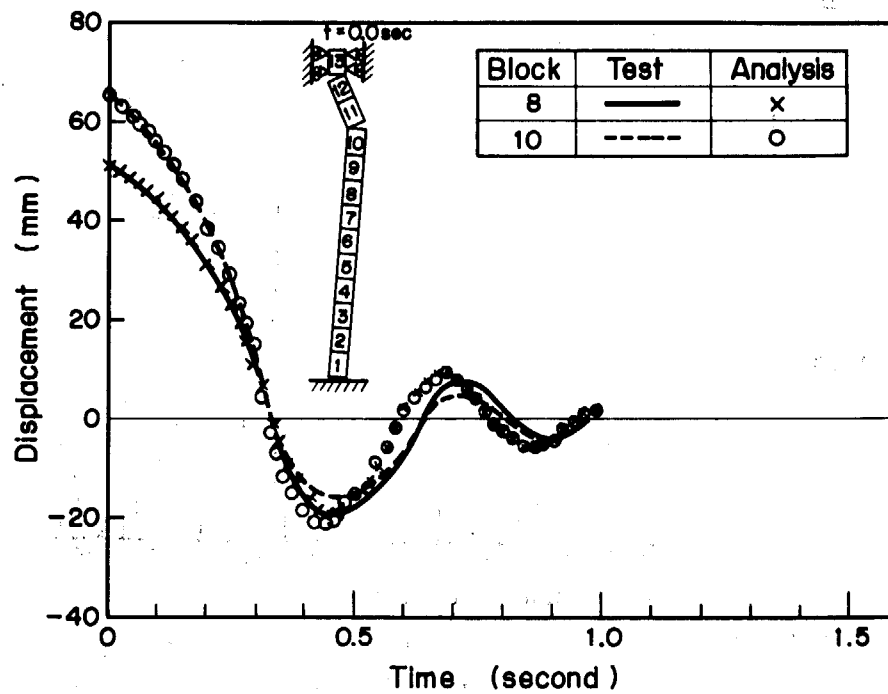
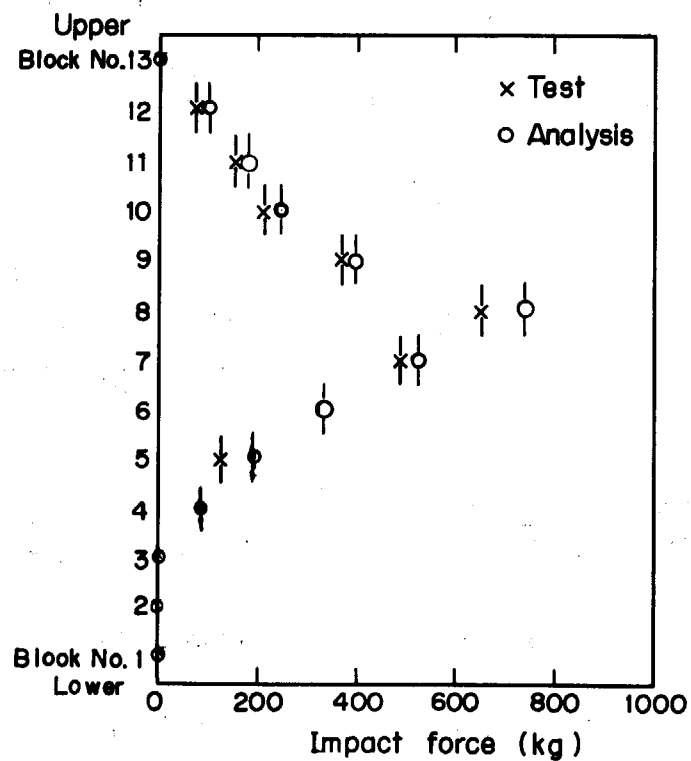


Fig. 11 Column free vibration

Fig. 12 Impact force profile along column
(Sinusoidal wave 3.5 Hz, 500gal)

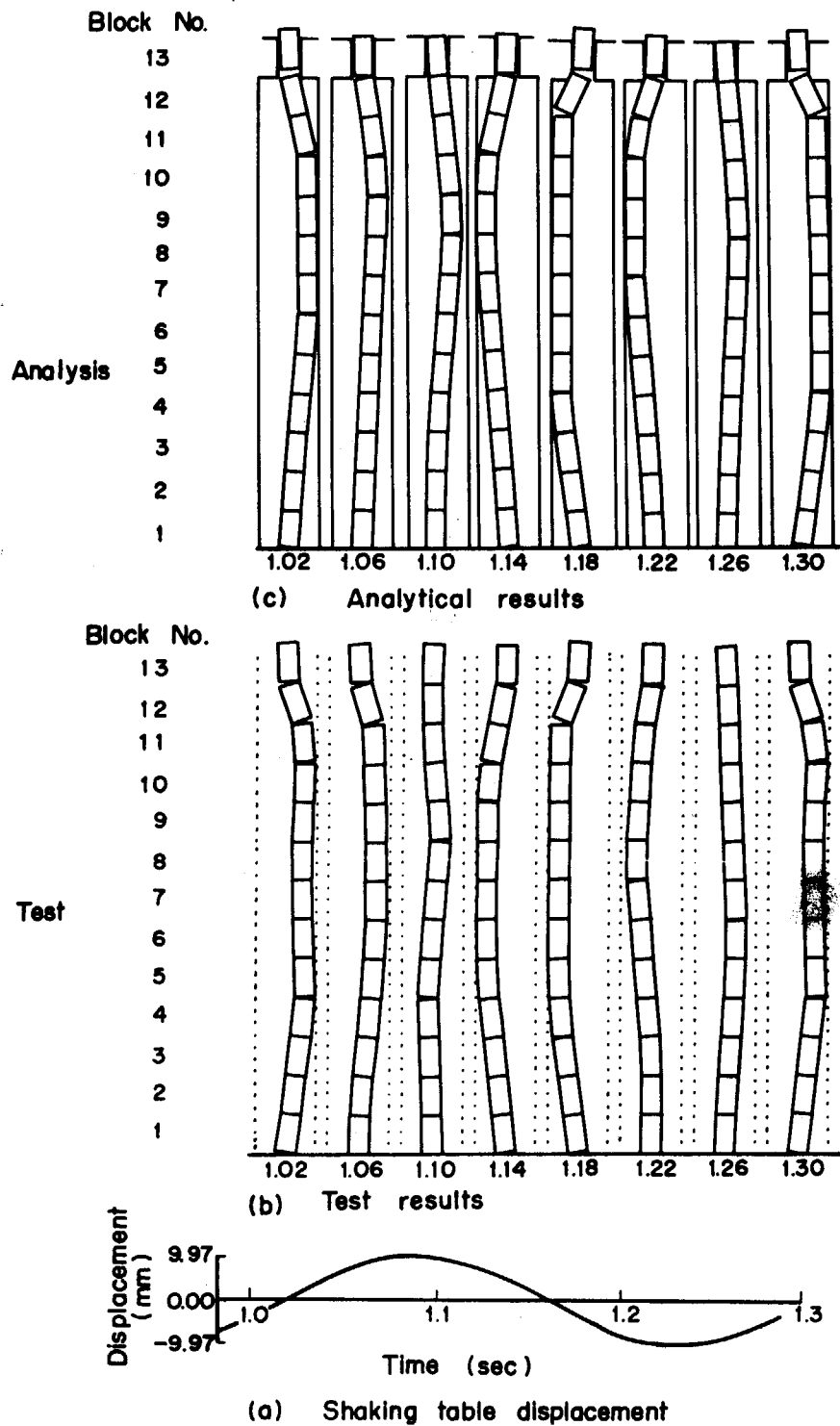


Fig. 13 Comparison between test and analysis
of column vibration behavior
(Input wave sinusoidal 3.5 Hz, max.)
(acceleration 500 gal)