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SONATINA-1 : A COMPUTER PROGRAM FOR SEISMIC RESPONSE ANALYSIS OF COLUMN IN HTGR CORE

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SONATINA-1: A Computer Program for Seismic Response Analysis of Column in HTGR Core

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An computer program SONATINA-1 for predicting the behavior of a prismatic high-temperature gas-cooled reactor (HTGR) core under seismic excitation has been developed. In this analytical method, blocks are treated as rigid bodies and are constrained by dowel pins which restrict relative horizontal movement but allow vertical and rocking motions. Coulomb friction between blocks and between dowel holes and pins is also considered. A spring dashpot model is used for the collision process between adjacent blocks and between blocks and boundary walls.

Analytical results are compared with experimental results and are found to be in good agreement. The computer program can be used to predict the behavior of the HTGR core under seismic excitation.

KEYWORD: Computer Program, HTGR-core-seismic, HTGR-core, Column-vibration, Seismic-response, Nonlinear Vibration, Core-structure, HTGR-fuel, Earthquake, Seismic, HTGR

SONATINA－1：高温ガス炉炉心コラムの地震応答解析計算プログラム

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ブロック型燃料の高温ガス炉炉心の地震応答計算プログラム SONATINA－1を開発した。計算モデルでは，ブロックは剛体とし，ダウェルは水平方向変位を拘束するがロッキング運動は妨げないものと考える。クーロン摩擦がブロック間およびダウェルピンと孔との間に生じるものとする。ブロック間およびブロックと境界との衝突は，バネーダッシュポットによってモデル化した。

計算値は実験値と比較して良い一致を示した。この計算プログラムを使用することによって高温ガス炉の炉心の地震挙動を調べることができる。

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1. Introduction

The high temperature gas-cooled reactor consists of several hundred fuel columns surrounded on their outer periphery by side permanent reflector blocks. Each fuel column contains 10 - 16 hexagonal blocks doweled together to ensure alignment of the coolant channels and the control rod channels. Gaps exist between columns allowing the blocks to collide each other during seismic excitation. It is necessary to analyze seismic behavior of the HTGR core for design purpose. Several computer programs have been developed for the purpose (1) - (8). The author has developed the computer program PRELUDE for one- and two-dimensional mathematical model. In the model, the element is treated the rigid body with one horizontal translational motion and is not considered rocking motion. The present mathematical model in the SONATINA-1, involves two translational motion, i.e. horizontal and vertical displacements, and one rotational at the center gravity. Blocks are treated as rigid bodies and are constrained by dowel pins which restrict relative horizontal movement but allow vertical and rocking motion. Coulomb friction between blocks and between dowel pins and sockets is also considered. A spring dashpot model is used for the collision process between adjacent blocks and between blocks and boundary. In the computer program, dowel forces and friction forces are also computed. At the termination of each run, a summary of maximum output valves is printed. The computer program has optional plotter capability which, if selected, vibration modes and time history response curves are depictted using the Calcomp plotting and COM (Computer Output Microfilming) machine.

2. Reactor Core Structure

Arrangement of experimental VHTR is set as in reactor plant of Fig.2.1. 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.2.2. Reactor core formed as 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.2.3 (the reactor core plan).

(1) Structure of reactor core

The core of experimental VHTR shown in Fig.2.2 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 shown in Fig.2.3 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.2.2 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.2.4 is pin-in-block type with 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 are 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.

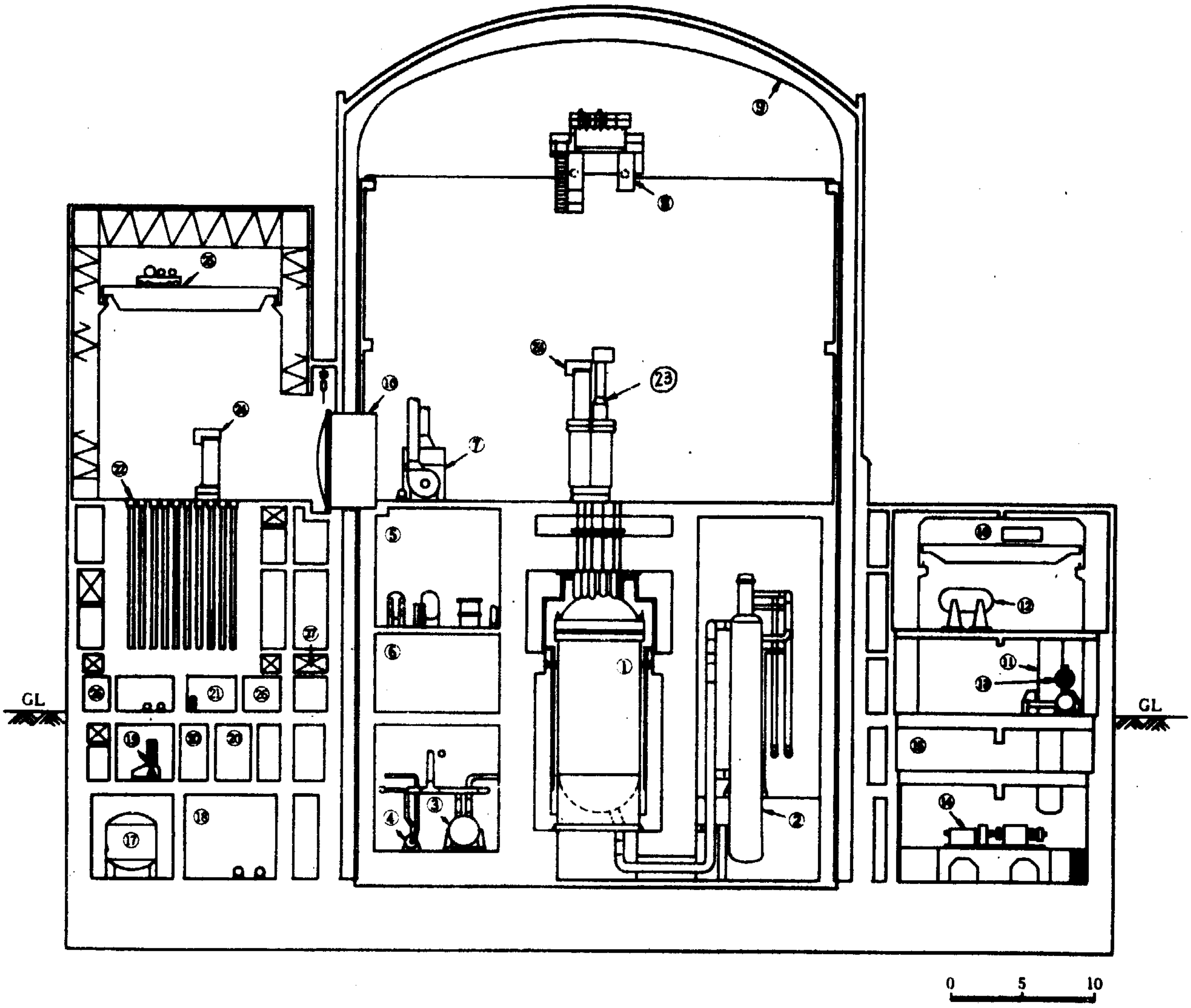
Orifice block in the upper top of column is made mutual key coupling in one region. Furthermore, upper part block in high temperature plenum in lower part of reactor core is also made mutual key coupling.

(3) Core side restraint mechanism

As shown in the core mechanism drawing of Fig.2.3, fixed reflector is directly coupled to core barrel through core restraint mechanism. This core side restraint mechanism is turnbuckle machinism 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).



1 Reactor vessel
2 Intermediate heat exchanger
3 Gas-circulator
4 Auxiliary gas-circulator
5 Primary helium purification system room
6 Auxiliary machinery room
7 Containment air-conditioner
8 Overhead crane
9 Containment
10 Air lock
11 Steam generator
12 Steam drum
13 Condenser
14 Helium circulator
15 Piping room
16 Overhead crane
17 Waste liquid tank
18 Floor drain room
19 Waste gas compressor
20 Waste gas filter
21 Storage vessel piping room
22 Fuel storage
23 Refueling machine
24 Fuel transfer cask
25 Overhead crane
26 Passage
27 Cable tray

Fig. 2.1 Section through VHTR Building (the First Conceptual Design)

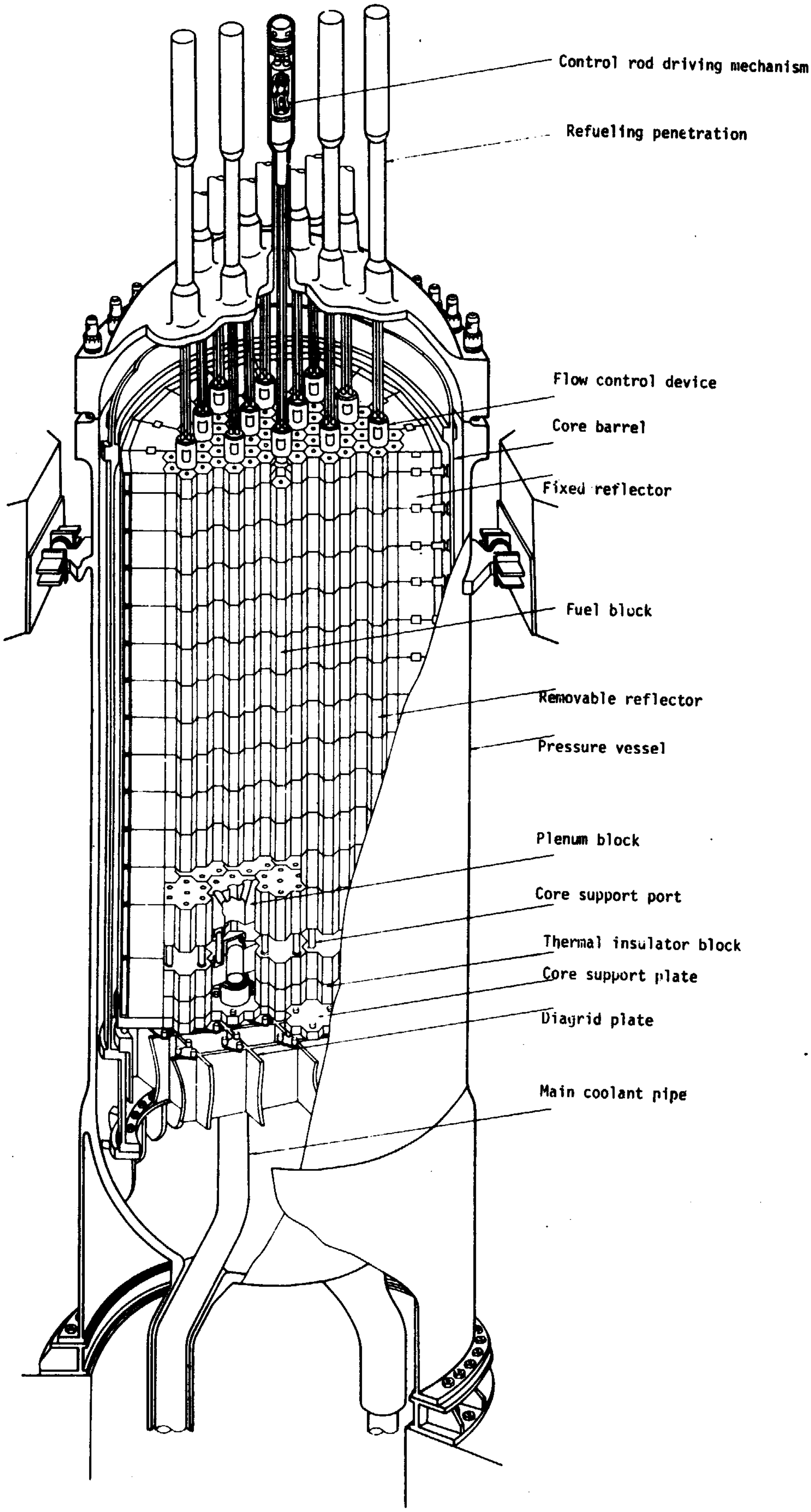


Fig.2.2 Reactor vertical view of VHTR

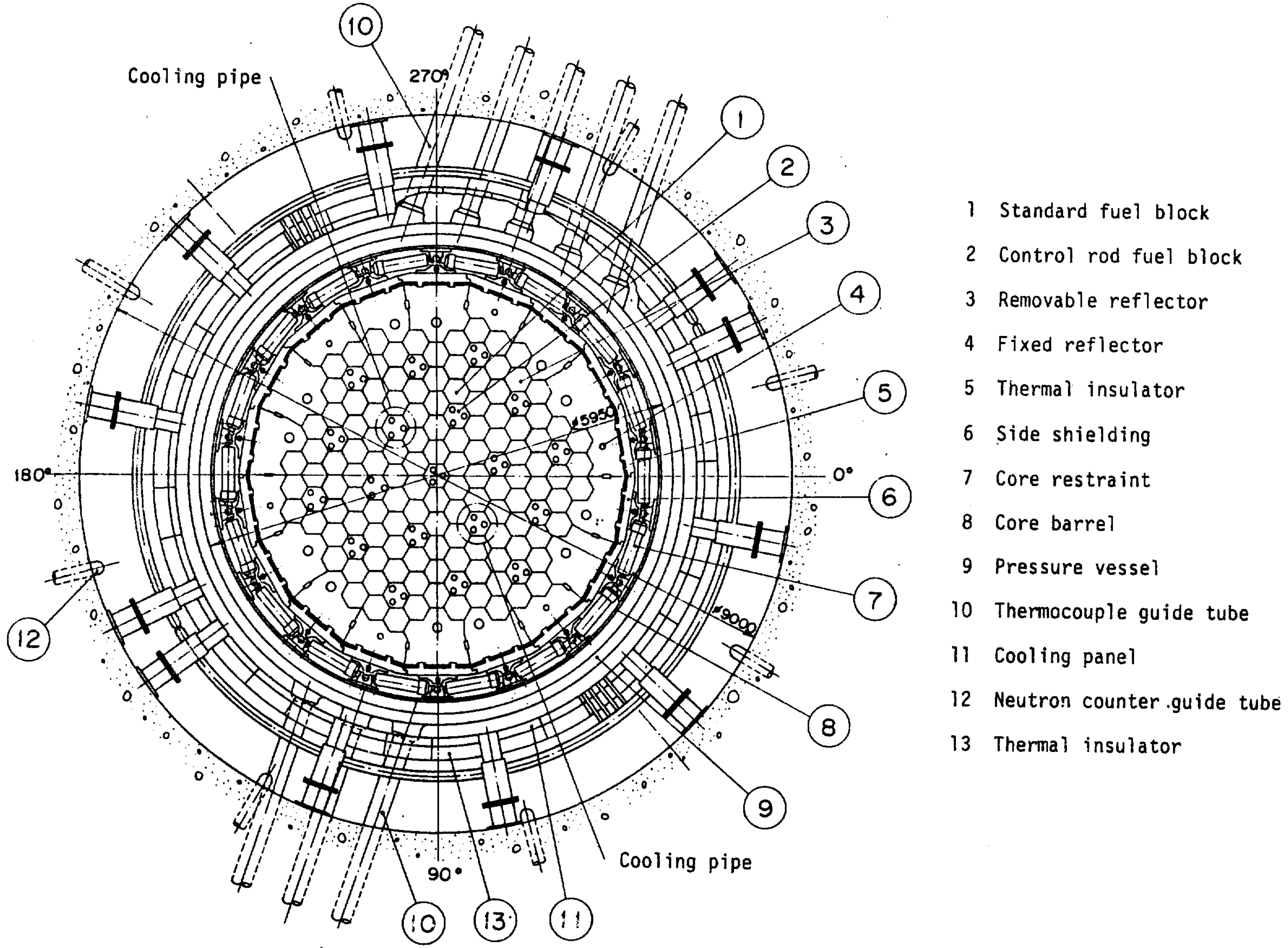


Fig.2.3 Reactor plane view of VHTR

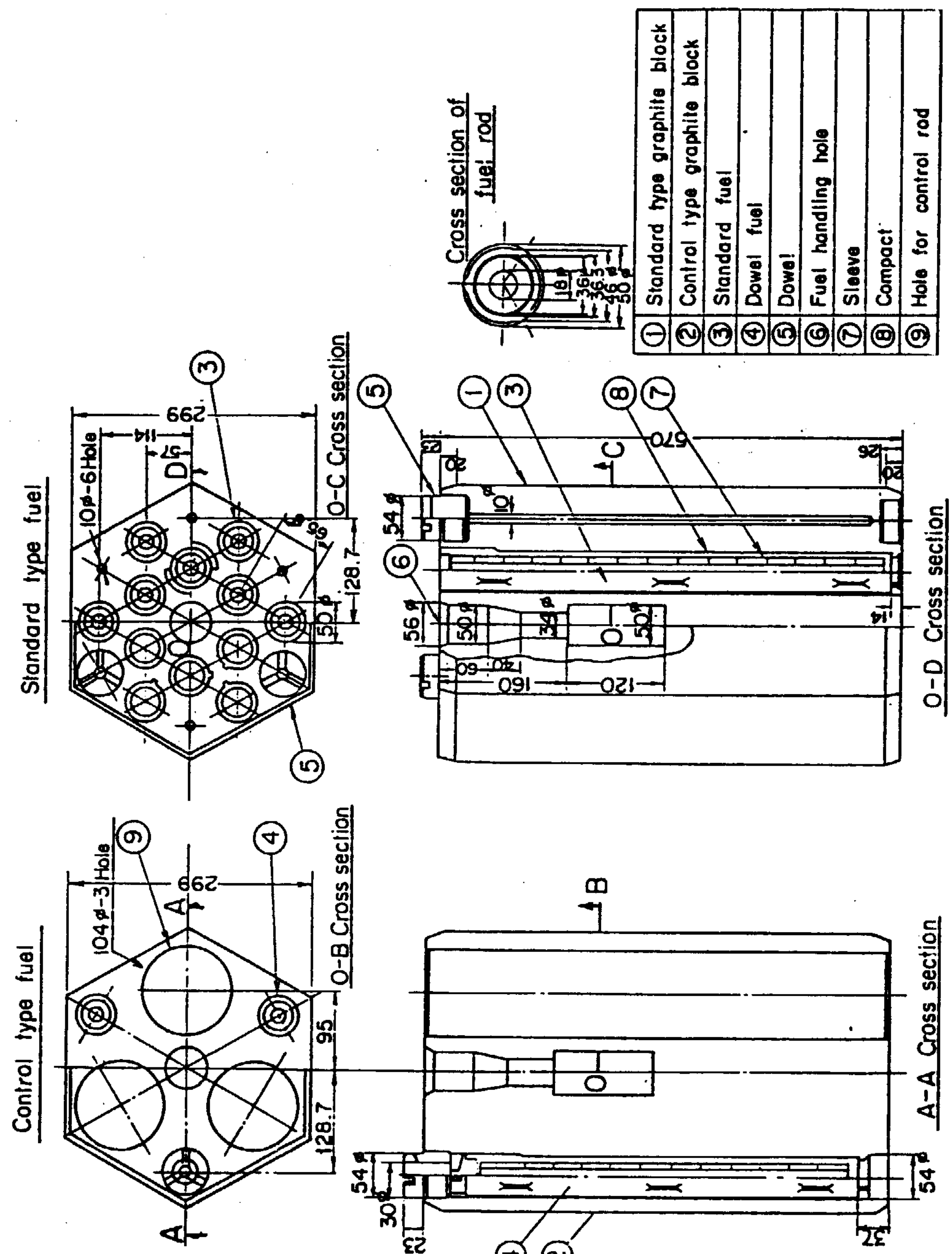


Fig.2.4 Fuel block

3. Calculation Equation

Nomenclature

a : block rocking spring half width

b : block geometric half width

C : damping coefficient

C^B : damping coefficient associated with ε

C^C : damping coefficient of displacement detector

C^D : damping coefficient associated with β

C^M : damping coefficient of impact plate support

C^V : damping coefficient associated with γ

d : distance of dowel from block center line

F^{BL} : horizontal collision force acting at the bottom of the left side

F^{BR} : horizontal collision force acting at the bottom of the right side

F^{DL} : dowel force acting at the left dowel

F^F : friction force acting at the horizontal interfaces between block

F^P : vertical gas pressure force acting at the block center

F^{TL} : horizontal collision force acting at the top of the left side

F^{TR} : horizontal collision force acting at the top of the right side

F^{VL} : vertical collision force acting at the left corner

F^{VR} : vertical collision force acting at the right corner

f(v) : prescribed function for the friction characteristics

g : gravity constant

h : block half height

I : block mass moment of inertia

K^B : spring constant associated with ε

K^D : spring constant associated with β

K^M : spring constant of impact plate support

K^V : spring constant associated with γ

m : block mass

n : total number of blocks in column

u : horizontal block displacement as the center gravity

u^B : impact plate displacement

u_O : boundary horizontal displacement

v : velocity

w : vertical block displacement at the center gravity

w_O : boundary vertical displacement

W^L : vertical forces due to block weight and pressure difference acting at lower part of the block

W^U : vertical forces due to block weight and pressure difference acting at upper part of the block

β : dowel spring deformation

γ : spring deformation of a spring-dashpot unit at interface between blocks

δ : initial gap between the block and boundary wall

δ_L : gap on the left side of dowel

δ_R : gap on the right side of dowel

ε : spring deformation of a spring-dashpot unit at between block and boundary impact plate

3.1 Equations Governing Motion

The forces involved in the analysis of a single vertical column of the HTGR core constrained within a rigid boundary are as shown in Figs.1(a) and 2.

Let the coordinate system be chosen as shown in Fig.1(b). Each block has two translational coordinates, u and w, and one rotational coordinate θ. Figure 1(b) shows the forces that act upon an individual block. The equations of motion for ith block of the single column may be written as:

$$m_i\ddot{u}_i = F_i^{TL} + F_i^{TR} + F_i^{BL} + F_i^{BR} + F_i^{F} + F_{i+1}^{F} + F_i^{DL} + F_i^{DR} + F_{i+1}^{DL} + F_{i+1}^{DR} + C_i^{C}\dot{u}_i, \quad (1)$$

$$m_i\ddot{w}_i = F_i^{VL} + F_i^{VR} + F_{i+1}^{VL} + F_{i+1}^{VR} + \mu F_i^{DL} + \mu F_i^{DR} + \mu F_{i+1}^{DL} + \mu F_{i+1}^{DR} + W_i^{U} + W_i^{L}, \quad (2)$$

$$\begin{aligned} I_i\ddot{\theta}_i = {} & M(F_i^{TL}) + M(F_i^{TR}) + M(F_i^{BL}) + M(F_i^{BR}) + M(F_i^{R}) \\ & + M(F_{i+1}^{F}) + M(F_i^{DL}) + M(F_i^{DR}) + M(F_{i+1}^{DL}) + (MF_{i+1}^{DR}) \\ & + M(F_i^{VL}) + M(F_i^{VR}) + M(F_{i+1}^{VL}) + M(F_{i+1}^{VR}) + M(\mu F_i^{DL}) \\ & + M(\mu F_i^{DR}) + M(\mu F_{i+1}^{DL}) + M(\mu F_{i+1}^{DR}) + M(W_i^{U}) + M(W_i^{L}), \end{aligned} \quad (3)$$

where, M(F) are moments caused by forces F. W^U and W^L are forces due to block weights and pressure differentials acting at the upper and lower part of block.

3.2 Friction Force between Blocks and Its Associated Moment

The friction force due to surface sliding is represented by a nonlinear Coulomb element. The equations for the friction force F_i^F and its associated moment $M(F_i^F)$ acting on the ith block, are as follows.

Defining α_i as $(\theta_i - \theta_{i-1})$, then, when $\alpha_i > 0$

$$\left.\begin{aligned} F_i^F &= -\mathrm{sign}(v_i)\ F(v_i), \\ M(F_i^F) &= F_i^F\ (-h_i\cos\theta_i - b_i\sin\theta_i), \end{aligned}\right\} \quad (4)$$

and for i-1th block

$$\left.\begin{aligned} F_{i-1}^F &= \mathrm{sign}(v_i)\ F(v_i), \\ M(F_{i-1}^F) &= F_{i-1}^F\ (h_{i-1}\cos\theta_{i-1} - b_{i-1}\sin\theta_{i-1}), \end{aligned}\right\} \quad (5)$$

where

$$v_i = \{\dot{u}_i - (h_i\cos\theta_i + b_i\sin\theta_i)\dot{\theta}_i\}$$

$$- \{\dot{u}_{i-1} + (h_{i-1}\cos\theta_{i-1} - b_{i-1}\sin\dot{\theta}_{i-1})\dot{\theta}_{i-1}\} \quad (6)$$

For $i = 1$

$$v_1 = \dot{u}_1 - (h_1\cos\theta_1 + b_1\sin\theta_1)\dot{\theta}_1 - \dot{u}_0, \quad (7)$$

where u_i and $\dot{u}_i$ are the horizontal displacement and velocity of the center of gravity of the ith block, respectively.

$\dot{u}_0$ is the horizontal velocity of the support floor.

If sign $(\alpha_i) \leqq 0$, then

$$\left.\begin{aligned} F_i^F &= -\mathrm{sign}(v_i)\ F(v_i), \\ M(F_i^F) &= F_i^F\ (-h_i\cos\theta_i + b_i\sin\theta_i), \end{aligned}\right\} \quad (8)$$

and for i-1th block

$$\left.\begin{aligned} F_{i-1}^F &= \mathrm{sign}(v_i)\ F(v_i), \\ M(F_{i-1}^F) &= F_{i-1}^F\ (h_{i-1}\cos\theta_{i-1} = b_{i-1}\sin\theta_{i-1}), \end{aligned}\right\} \quad (9)$$

where

$$v_i = \{\dot{u}_i - (h_i\cos\theta_i - b_i\sin\theta_i)\dot{\theta}_i\}$$
$$- \{\dot{u}_{i-1} + (h_{i-1}\cos\theta_{i-1} + b_i\sin\theta_{i-1})\dot{\theta}_{i-1}\} \quad (10)$$

For $i = 1$

$$v_i = \dot{u}_1 - (h_1\cos\theta_1 - b_1\sin\theta_1)\dot{\theta}_1 - \dot{u}_0, \quad (11)$$

where $\dot{u}_0$ is the horizontal velocity of the support floor. $F(v_i)$ is a prescribed function for the friction characteristics which is related to the vertical contact force and the coefficient of both dynamical and statical friction.

$$F(v_i) = F_i\ \{\mu_s + f(v_i) + f(v_i^2) + f(v_i^3)\}, \quad (12)$$

and, the functions $f(v_i, v_i^2, v_i^3)$ are related to kinematic coefficient of friction μ_k. The vertical contact forces are obtained by summing blocks weights $m_i g$ and the differential pressure of a unit block length, F_i^P.

$$F_i = \sum_{j=i}^{n} m_j g + F_i^P. \quad (13)$$

3.3 Vertical Impact Force and Its Associated Moment

The forces acting on the interface between the ith and i-1th block as a results of impact are derived in term of deformation of each spring-dashpot unit. When the gap is closing, the spring deformation γ_i and its time rate γ_i are

$$\gamma_i = \frac{1}{2}\{w_{i-1} - h_{i-1}(1-\cos\theta_{i-1}) - a_i\sin\theta_{i-1}\}$$
$$- \frac{1}{2}\{w_i + h_i(1-\cos\theta_i) - a_i\sin\theta_i\}, \quad (14)$$

$$\dot{\gamma}_i = \frac{1}{2}\{\dot{w}_{i-1} - (h_{i-1}\sin\theta_{i-1} + a_i\cos\theta_{i-1})\dot{\theta}_{i-1}\}$$
$$- \frac{1}{2}\{\dot{w}_i + (h_i\sin\theta_i - a_i\cos\theta_i)\dot{\theta}_i\} \quad (15)$$

For $i = 1$

$$\gamma_1 = \frac{1}{2}[w_0 - \{w_1 - h_1(1-\cos\theta_1) - a_1\sin\theta_1\}], \tag{16}$$

$$\dot{\gamma}_1 = \frac{1}{2}[\dot{w}_0 - \{\dot{w}_1 + (h_1\sin\theta_1 - a_1\cos\theta_1)\dot{\theta}_1\}], \tag{17}$$

where w_0 and $\dot{w}_0$ are the vertical displacement and velocity of the support floor, respectively. The vertical impact forces F_i^{VR} (or F_i^{VL}) and its associated moments $M(F_i^{VR})$ (or $M(F_i^{VL})$) acting on the ith block are as follows.

If $\gamma_i > 0$

$$\left.\begin{aligned} F_i^{VR} &= -K_i^V\gamma_i - C_i^V\dot{\gamma}_i \\ M(F_i^{VR}) &= -F_i^{VR}(h_i\sin\theta_i - a_i\cos\theta_i) \end{aligned}\right\} \tag{18}$$

For i-1th block

$$\left.\begin{aligned} F_{i-1}^{VR} &= K_i^V\gamma_i + C_i^V\dot{\gamma}_i, \\ M(F_{i-1}^{VR}) &= F_{i-1}^{VR}(h_{i-1}\sin\theta_{i-1} + a_i\cos\theta_{i-1}) \end{aligned}\right\} \tag{19}$$

When $\gamma_i \leqq 0$

$$\left.\begin{aligned} F_i^{VR} &= F_{i-1}^{VR} = 0, \\ M(F_i^{VR}) &= M(F_{i-1}^{VR}) = 0 \end{aligned}\right\} \tag{20}$$

Where K_i^V and C_i^V are the vertical spring and damping coefficients,respectively, for a single unit. In the more general formulation, these quantities may be represented by a polynominal function.

$$\left.\begin{aligned} K_i^V &= \sum_{j=0}^{m} K_{ij}^V\gamma_i^j, \\ C_i^V &= \sum_{j=0}^{m} C_{ij}^V\dot{\gamma}_i^j \end{aligned}\right\} \tag{21}$$

3.4 Boundary Wall Forces and Its Associated Moments

The forces acting on the ith block as a results of impact on the boundary walls are derived by deformation of each spring-dashpot unit which are located on the upper and lower, right and left-hand corners. During impact against the boundary wall on the upper right-hand corner the spring deformation ε_i and its time rate $\dot{\varepsilon}_i$ of ith block are

$$\varepsilon_i = u_i + h_i \sin\theta_i - b_i(1-\cos\theta_i) - u_i^B - \delta_i^B , \qquad (22)$$

$$\dot{\varepsilon}_i = \dot{u}_i + (h_i \cos\theta_i - b_i \sin\theta_i)\dot{\theta}_i - \dot{u}_i^B, \qquad (23)$$

where u_i^B is the lateral boundary displacement at the contact point and δ_i^B is the gap between the ith block and its boundary wall. The boundary wall impact force F_i^{TR} and its associated moment $M(F_i^{TR})$ acting on the ith block are as follows.

If $\varepsilon_i > 0$

$$\left.\begin{aligned} F_i^{TR} &= -\{K_i^B\, \varepsilon_i + C_i^B\, \dot{\varepsilon}_i\} \\ M(T_i^{TR}) &= F_i^{TR}(h_i \cos\theta_i - b_i \sin\theta_i), \end{aligned}\right\} \qquad (24)$$

where K_i^B and C_i^B are the boundary spring and damping coefficients, respectively and may be represented in the following general form.

$$\left.\begin{aligned} K_i^B &= \sum_{j=0}^{m} K_{ij}\, \varepsilon_i^j, \\ C_i^B &= \sum_{j=0}^{m} C_{ij}\, \dot{\varepsilon}_i^j \end{aligned}\right\} \qquad (25)$$

Similarly, on the upper left-hand corner

$$\varepsilon_i = -u_i - \{h_i \sin\theta_i + b_i(1-\cos\theta_i)\} + u_i^B - \delta_i^B, \qquad (26)$$

$$\dot{\varepsilon}_i = -\dot{u}_i - (h_i \cos\theta_i + b_i \sin\theta_i)\dot{\theta}_i + \dot{u}_i^B, \qquad (27)$$

if $\varepsilon_i > 0$

$$\left.\begin{aligned} F_i^{TL} &= K_i^B \ \varepsilon_i + C_i^B \ \dot{\varepsilon}_i, \\ M(F_i^{TL}) &= F_i^{TL} \ (h_i\cos\theta_i + b_i\sin\theta_i) \end{aligned}\right\} \quad (28)$$

On the lower right-hand corner

$$\varepsilon_i = u_i - \{h_i\sin\theta_i + b_i(1-\cos\theta_i)\} \ - u_i^B - \delta_i^B, \quad (29)$$

$$\dot{\varepsilon}_i = \dot{u}_i - (h_i\cos\theta_i + b_i\sin\theta_i)\dot{\theta}_i - \dot{u}_i^B, \quad (30)$$

if $\varepsilon_i > 0$

$$\left.\begin{aligned} F_i^{BR} &= \{K_i^B \ \varepsilon_i + C_i^B \ \dot{\varepsilon}_i\}, \\ M(F_i^{BR}) &= -F_i^{BR}(h_i\cos\theta_i + b_i\sin\theta_i) \end{aligned}\right\} \quad (31)$$

And the lower left-hand corner

$$\varepsilon_i = -u_i + \{h_i\sin\theta_i - b_i(1-\cos\theta_i)\} + u_i^B - \delta_i^B, \quad (32)$$

$$\dot{\varepsilon}_i = -\dot{u}_i + (h_i\cos\theta_i - b_i\sin\theta_i)\dot{\theta}_i + \dot{u}_i^B, \quad (33)$$

if $\varepsilon_i > 0$

$$\left.\begin{aligned} F_i^{BL} &= - K_i^B \ \varepsilon_i + C_i^B \ \dot{\varepsilon}_i, \\ M(F_i^{BL}) &= -F_i^{BL} \ (h_i\cos\theta_i - b_i\sin\theta_i) \end{aligned}\right\} \quad (34)$$

When $\varepsilon_i \leq 0$

$$\left.\begin{aligned} &F_i^{TR} = F_i^{TL} = F_i^{BR} = F_i^{BL} = 0, \\ &M(F_i^{TR}) = (M(F_i^{TL}) = M(F_i^{BR}) = M(F_i^{BL}) = 0 \end{aligned}\right\} \quad (35)$$

3.5 Dowel Forces in the Horizontal Direction and Its Associated Moments

The dowel forces in the horizontal direction are derived by the contact condition between dowel pins and mating holes. When a dowel pin and its mating hole are in contact, the dowel spring deformation β_i and its time rate $\dot{\beta}_i$ of ith block interface are

$$\beta_i = \{u_{i-1} + h_{i-1}\sin\theta_{i-1} - d_{i-1}(1-\cos\theta_{i-1})\} - \{u_i - h_i\sin\theta_i - d_i(1-\cos\theta_i)\} \mp \delta_{R,L}, \quad (36)$$

$$\dot{\beta}_i = \dot{u}_{i-1} + (h_{i-1}\cos\theta_{i-1} - d_{i-1}\sin\theta_{i-1})\dot{\theta}_{i-1} - \{\dot{u}_i - (h_i\cos\theta_i + d_i\sin\theta_i)\dot{\theta}_i\}, \quad (37)$$

For $i = 1$

$$\beta_1 = u_0 - \{u_1 - h_1\sin\theta_1 - d_1(1-\cos\theta_1)\} \mp \delta_{R,L}, \quad (38)$$

$$\dot{\beta}_1 = \dot{u}_0 - \{\dot{u}_1 - (h_1\cos\theta_1 + d_1\sin\theta_1)\dot{\theta}_1\}, \quad (39)$$

where δ_R and δ_L are the gap between dowel pin and hole on the right and left respectively. The dowel force F_i^{DR} and its associated moment $M(F_i^{DR})$ in horizontal direction acting on the ith right-hand dowel are as follows.

If $\beta_i > 0$ on the right gap and $\beta_i < 0$ on the left gap

$$\left.\begin{aligned} F_i^{DR} &= K_i^D\,\beta_i + C_i^D\,\dot{\beta}_i, \\ M(F_i^{DR}) &= -F_i^{DR}\,(h_i\cos\theta_i + d_i\sin\theta_i), \end{aligned}\right\} \quad (40)$$

for i-1th block

$$\left.\begin{aligned} F_{i-1}^{DR} &= -K_i^D\,\beta_i - C_i^D\,\dot{\beta}_i, \\ M(F_{i-1}^{DR}) &= F_{i-1}^{DR}\,(h_{i-1}\cos\theta_{i-1} - d_i\sin\theta_{i-1}) \end{aligned}\right\} \quad (41)$$

If $\beta_i < 0$ on the right gap and $\beta_i > 0$ on the left gap

$$\left.\begin{aligned} &F_i^{DR} = F_{i-1}^{DR} = 0, \\ &M(F_i^{DR}) = M(F_{i-1}^{DR}) = 0 \end{aligned}\right\} \quad (42)$$

where K_i^D and C_i^D are the dowel spring and damping coefficients, respectively and may be represented in the following general form.

$$\left.\begin{aligned} &K_i^D = \sum_{j=0}^{m} K_{ij}\ \beta_i^j \\ &C_i^D = \sum_{j=0}^{m} C_{ij}^D\ \dot{\beta}_i^j \end{aligned}\right\} \quad (43)$$

Similarly, the dowel forces F_i^{DL} and its associated moments $M(F_i^{DL})$ in the horizontal direction acting on the ith left-hand dowel are the same as equations (40) through (43) above.

3.6 Dowel Friction Forces in the Vertical Direction and Its Associated Moments

The dowel friction forces in the vertical direction are derived from the dowel forces and the friction factor. When dowel pin and mating hole are in sliding contact, the relative velocity between pin and hole on the ith block interface is

$$\begin{aligned} \omega_i = &\dot{w}_i + (h_i \sin\theta_i - d_i \cos\theta_i)\dot{\theta}_i \\ &- \{\dot{w}_{i-1} - (h_{i-1}\sin\theta_{i-1} + d_i \cos\theta_{i-1})\dot{\theta}_{i-1}\}, \end{aligned} \quad (44)$$

For $i = 1$

$$\omega_1 = \dot{w}_1 + (h_1 \sin\theta_1 - d_1 \cos\theta_1)\dot{\theta}_1 - \dot{w}_0 \quad (45)$$

The dowel friction force on the right-hand dowel in the vertical direction μF_i^{DR} and its associated moment $M(\mu F_i^{DR})$ for ith block are as follows.

$$\left.\begin{aligned} \mu F_i^{DR} &= -\text{sign}(\omega_i)\cdot|F_i^{DR}|\cdot f(\mu), \\ M(\mu F_i^{DR}) &= -\mu F_i^{DR}\ (h_i \sin\theta_i + d_i \cos\theta_i) \end{aligned}\right\} \quad (46)$$

for i-1th block

$$\left.\begin{aligned} F_{i-1}^{DR} &= \text{sign}\ (\omega_i)\cdot|F_i^{DR}|\cdot f(\mu) \\ M(\mu F_{i-1}^{DR}) &= -\mu F_{i-1}^{DR}\ (-h_{i-1}\sin\theta_{i-1} + d_i \cos\theta_{i-1}) \end{aligned}\right\} \quad (47)$$

where $f(\mu)$ is a function of the friction factors both static and kinenatic. Similarly, the friction force μF_i^{DL} on the left-hand side and its moment $M(\mu F_i^{DL})$ are as follows.

For the ith block

$$\left.\begin{aligned} \mu F_i^{DL} &= -\text{sign}(\omega_i)\cdot|F_i^{DL}|\cdot f(\mu) \\ M(\mu F_i^{DL}) &= -\mu F_i^{DL}\ (h_i \sin\theta_i + d_i \cos\theta_i) \end{aligned}\right\} \quad (48)$$

for the i-1th block

$$\left.\begin{aligned} \mu F_{i-1}^{DL} &= \text{sign}(\omega_i)\cdot|F_i^{DL}|\cdot f(\mu) \\ M(\mu F_{i-1}^{DL}) &= -\mu F_{i-1}^{DL}\ (-h_{i-1}\sin\theta_{i-1} + d_i \cos\theta_{i-1}), \end{aligned}\right\} \quad (49)$$

$$f(\mu) = f(\mu_k, \mu_s) \quad (50)$$

3.7 Moments Due to Block Weights and Pressure Difference

The moments acting on the ith block as a results of the blocks weight and pressure difference are as follows.

If $\alpha_{i+1} > 0$

$$M(W_i^U) = W_i^U\ (h_i \sin\theta_i + b_i \cos\theta_i) \quad (51)$$

If $\alpha_{i+1} = 0$

$$M(W_i^U) = W_i^U h_i \sin\theta_i \tag{52}$$

If $\alpha_{i+1} < 0$

$$M(W_i^U) = W_i^U (h_i \sin\theta_i - b_i \cos\theta_i) \tag{53}$$

Where

$$W_i^U = \sum_{j=i+1}^{n} W_j + F_i^P \tag{54}$$

Where $j = n$, $M(W_n^U) = 0$. Similarly,

If $\alpha_i > 0$

$$M(W_i^L) = W_i^L (h_i \sin\theta_i - b_i \cos\theta_i) \tag{55}$$

If $\alpha_i = 0$

$$M(W_i^L) = W_i^L h_i \sin\theta_i \tag{56}$$

If $\alpha_i < 0$

$$M(W_i^L) = W_i^L (h_i \sin\theta_i + b_i \cos\theta_i) \tag{57}$$

Where

$$W_i^L = \sum_{j=i}^{n} W_j + F_i^P \tag{58}$$

3.8. Equation of Motion for Impact Plate

For the ith impact plate on the right hand side, the equations of motion are as:

$$m_i^{BR} \ddot{u}_i^{BR} = -F_i^{MR} + F_i^{TR} + F_i^{BR} \tag{59}$$

where

$$F_i^{MR} = K_i^{MR} \psi_i + C_i^{MR} \dot{\psi}_i \tag{60}$$

and for the left impact plate

$$m_i^{BL}\, \ddot{u}_i^{BL} = F_i^{ML} - F_i^{TL} - F_i^{BL}, \tag{61}$$

where

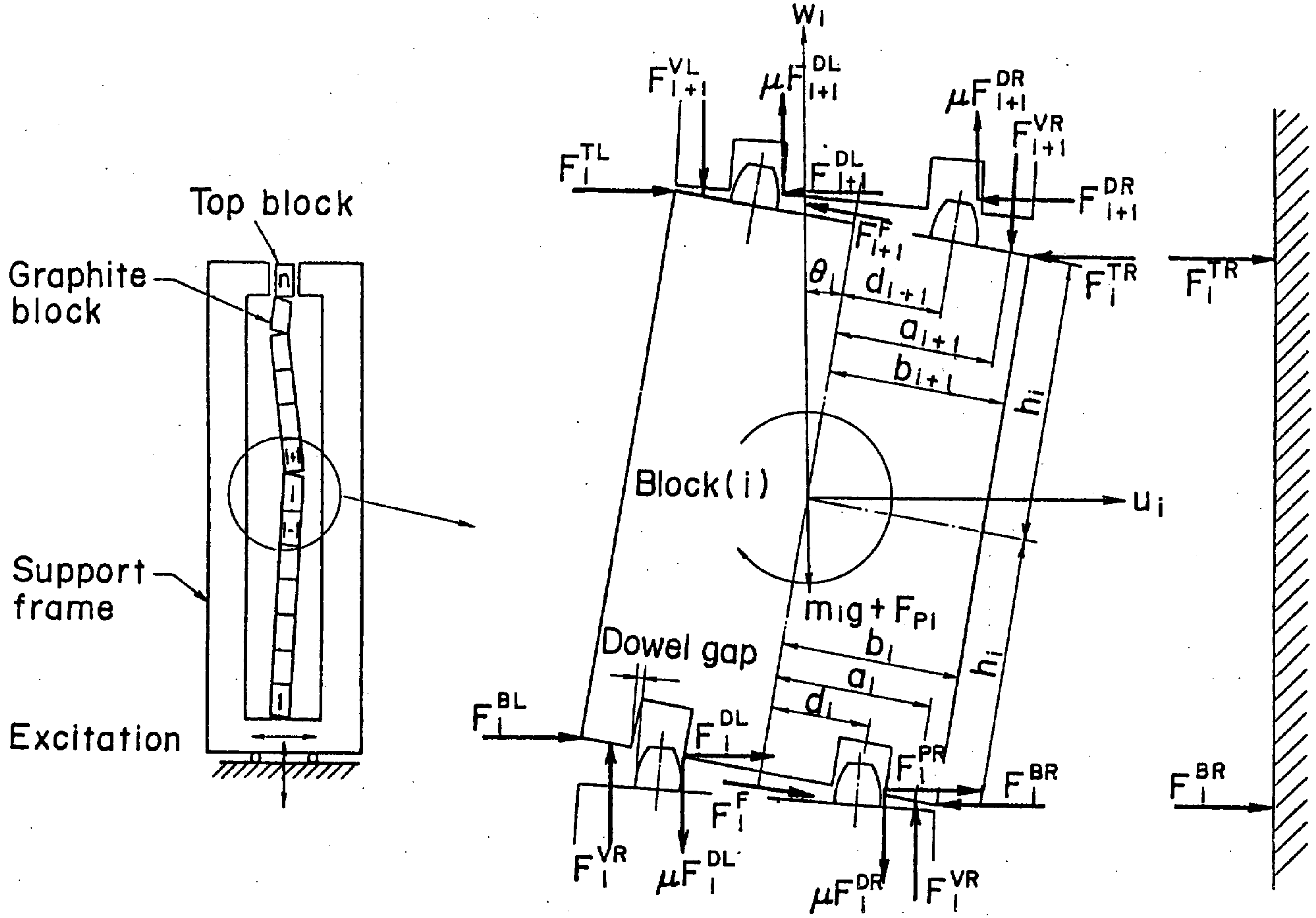
$$F_i^{ML} = K_i^{ML}\, \psi_i + C_i^{ML}\, \dot{\psi}_i, \tag{62}$$

$$\psi = u_b - u_i, \tag{63}$$

$$\left.\begin{aligned} K_i^M &= \sum_{j=0}^{m} K_{ij}^M\, \psi_j^j \\ C_i^M &= \sum_{j=0}^{m} C_{ij}^M\, \dot{\psi}^j \end{aligned}\right\} \tag{64}$$

3.9 Numerical Integration Method

The governing equations given in above can be numerically solved by using the fourth-order Runge-Kutta integration schemes.



(a) Column model (b) Forces acting on a fuel block

Fig.3.1 Column calculation model and forces acting on a fuel block

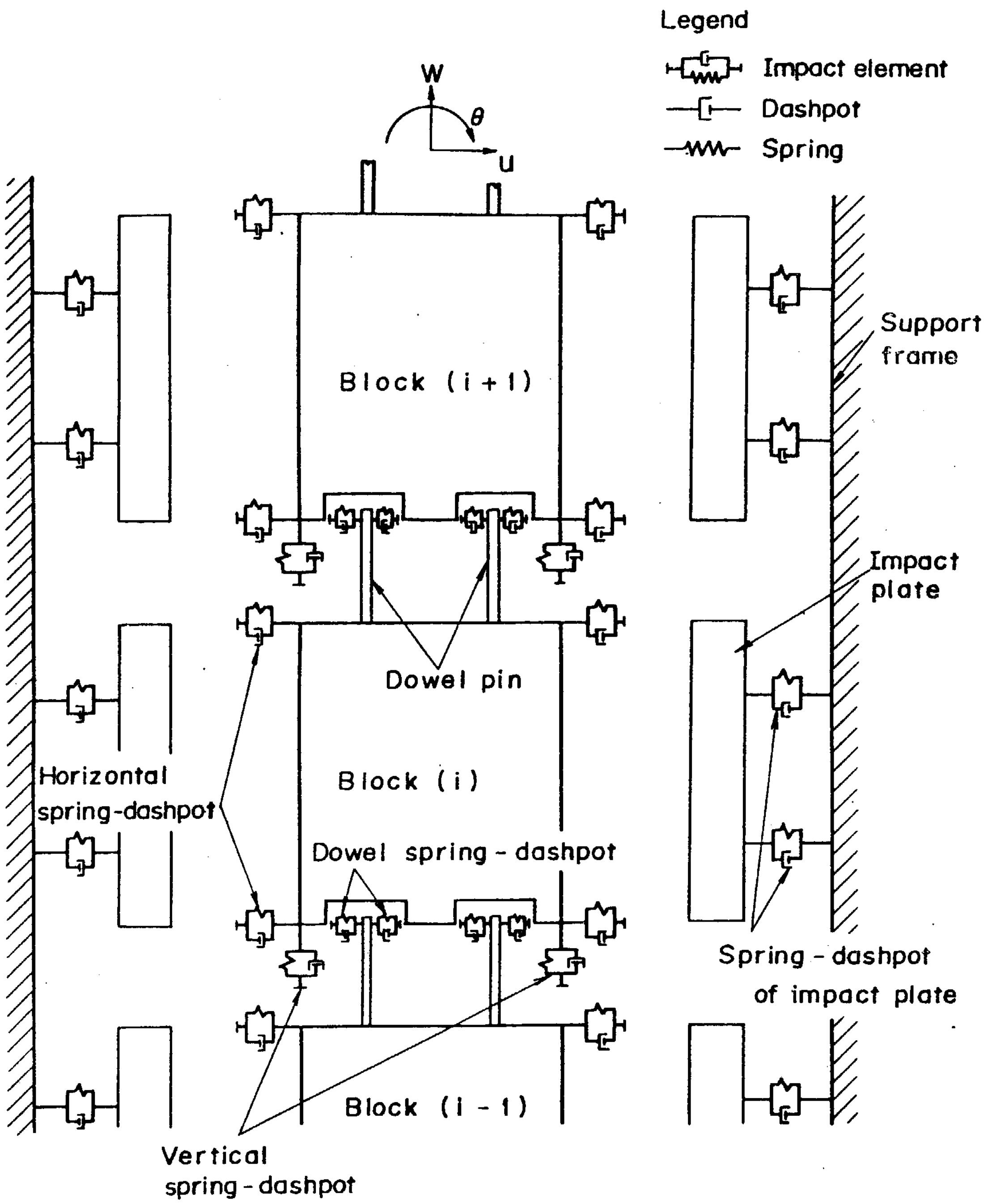


Fig.3.2 Idealized spring-dashpot model

4. Computer Program

The computer program SONATINA-1 performs the dynamic analysis of a single stacked column subjected to seismic excitation. The program is capable of solving nonlinear impact problems. The nolinearities may be due to gaps between block and boundary, and between dowel pin and socket, and Coutomb friction.

4.1 Program description

Computer program SONATINA-1 consists of 13 subroutine that are MAIN, JULY 31, FUN, MOMNT, FRIC, FUNBO, FUNUO, FUNWO, GCOS, SSIN, GREATT, PICT and DTVWST. Overall structure of SONATINA-1 is shown in Fig. 4.1. In the figure, line from one box to another indicates that the right routine is called by the left one. Function of subroutine is as follows.

MAIN	:	Initializes at start of run, controls the flow of program, and stores output.
JULY 31	:	Integrates system of differential equations using Runge-Kutta numerical method.
FUN	:	Sets up equations for given time.
MOMNT	:	Determines moment of block weight and gas pressure difference.
FRIC	:	Determines friction force.
FUNBO	:	Determines boundary displacement and velocity.
FUNUO	:	Determines base horizontal displacement and velocity.
FUNWO	:	Determines base vertical displacement and velocity.
GCOS	:	Determines value of cosine function.
SSIN	:	Determines value of sin function.
GREATT	:	Searches maximum value, and prints maximum value.
PICT	:	Plots vibration mode.
DTVWST	:	Stores displacement data for post processor SONPL1.

Macroscopic flow chart of SONATINA-1 is shown in Fig.4.2. SONATINA-1 has two post-processer that are SONPL1 and SONWV1. SONPL1 is used for column vibration mode plotting and SONWV1 for response curve plotting.

4.2 Description of input data

This section describes the input data required by SONATINA-1. Input data consists of job description, number of blocks, spring constants and damping coefficients, friction factor, gap between column and boundary, gap between dowel pin and socket, element geometry and weight, initial condition, seismic data, options for printout and plot interval, times for starting, ending and integral step and others. Input data forms are presented in Table 4.1.

Card 1

Problem initiation and title.

Card 2

Master control card.

Card 3

Initial value.

Card 4

Control card for geometry data.

Card 5

Geometry data.

Card 6 group

Card 6A

Friction factor and etc.

Card 6B

Spring constant and damping coefficient of dowel pin.

Card 6C

Spring constant and damping coefficient of vertical impact.

Card 6D

Spring constant and damping coefficient of boundary impact.

Card 6E

Gap between element and boundary data.

Card 7

Geometry and time data.

Card 8

Option data for print out.

Card 9

Impact data.

Card 10

Distance of vertical spring.

Card 11

Dowel data.

Card 12

Option for response curve plotting.

Card 13 group

Card 13A

Seismic data (Sinusoidal wave).

Card 13B

Option for seismic data (Sinusoidal wave).

Card 13C

Seismic data (Random wave).

Card 13D

Number of seismic data and time step of data, and seismic data displacement and velocity.

4.3 Description of output data

This section describes the output data from SONATINA-1. Printed output data consists of input data, time history data and output summary. The computer program SONATINA-1 has optional plotter capability which vibration modes and time history response curves are depictted using the Calcomp plotting and COM machine.

(1) Input data

Input data is printed in two formats. The first print format is exactly the same as it was read. Second, the program lists the data as interpreted by the code.

(2) Time history output

This time history data is printed every print interval. The following is a description of output data.

Time

TIME - Current value of time (sec).

Displacement

THETA - Angular displacement (rad).

U - Horizontal displacement.

W - Vertical displacement.

Velocity

D-THETA/D-T - Angular velocity (rad/s).

D-U /D-T - Horizontal velocity.

D-W /D-T - Vertical velocity.

Acceleration

D2THETA/D2T - Angular acceleration.

D2U /D2T - Horizontal acceleration.

D2W /D2T - Vertical acceleration.

Force and Moment

MOMENT BY GRAVITY - Moment by gravity.

FORCE BY FRICTION - Friction force between upper and lower block interface.

MOMENT BY FRICTION - Moment by friction force.

FORCE BY V. SPRING - Vertical impact force on the center of the block.

MOMENT BY V. SPRING - Moment by vertical impact force.

FORCE BY DOWEL - Dowel force.

MOMENT BY DOWEL - Moment by dowel force.

FORCE BY B. WALL - Boundary impact force on the center of the block.

MOMENT BY B. WALL - Moment by boundary impact force.

(3) Output summary

At the termination of a run, an output summary is printed which gives all of the maximum displacements, rotations, velocities, accelerations, forces, and moment. The following is a description of the output summary data.

Maximum displacement θ, u, w.

Maximum velocities $\dot{\theta}$, $\dot{u}$, $\dot{w}$.

Maximum acceleration $\ddot{\theta}$, $\ddot{u}$, $\ddot{w}$.

Maximum friction force.

Maximum friction force moment.

Maximum vertical impact force.

Maximum vertical impact moment.

Maximum dowel force.

Maximum dowel moment.

Maximum boundary impact force.

Maximum boundary impact moment.

Table 4.1 Input data cards for SONATINA-1

Column	Format	Variable	Description
Card 1 : Problem initiation and title card-one card.			
1-72	18A4	ITI	Title or job description. IF ITI(1) is blank, job stop.
Card 2 : Master control card-one card.			
1- 5	I5	NN	Number of block.
6-10	I5	NM	Number of different blocks.
11-15	I5	NB	Number of different length of vertical spring.
16-20	I5	ND	Number of different size dowels.
21-25	I5	NPR	Response curve plotting flag.
26-30	I5	KPR	Data stored interval for column vibration mode plotting. The code will store output every KPR integration step. If KPR is zero, data not stored. Data file No.51 is used for data store of column vibration mode plotting.
31-35	I5	NTW	Column vibration mode plotting flag.
36-40	I5	NSW	Dummy
41-45	I5	MPLOT	Data stored interval for response curve plotting. The code will store output every MPLOT integration step. If MPLOT is zero, data is not stored. Data file No.11 is used for data store of response curve plotting.
46-50	I5	NBND	Option for boundary structure. NBND = 0 : Boundary is elastic. NBND = 1 : Boundary is block.

Column	Format	Variable	Description
Card 3 : Initial value - NN cards.			
11-20	F10.0	X(1)	Initial rocking angle.
21-30	F10.0	X(2)	Initial rocking angular velocity.
31-40	F10.0	X(3)	Initial horizontal displacement.
41-50	F10.0	X(4)	Initial horizontal velocity.
51-60	F10.0	X(5)	Initial vertical displacement.
61-70	F10.0	X(6)	Initial vertical velocity.
As many cards as needs to initializes NN elements.			
Card 4 : Control card for geometry data - NN/6 cards.			
21-25	I5	IMT(1)	Element-1 definition.
26-30	I5	IMT(2)	Element-2 definition.
31-35	I5	IMT(3)	
⋮	⋮		
66-70	I5	IMT(10)	
Next card			
21-25	I5	IMT(11)	
26-30	I5	IMT(12)	
⋮	⋮		
Card 5 : Geometry data - NM cards.			
11-20	F10.0	HH	Block half height.
21-30	F10.0	EI	Block mass moment of inertia.
31-40	F10.0	EM	Block mass.
41-50	F10.0	WI	Block weight.
As many cards as needs to generate NM groups.			

Column	Format	Veriable	Description
Card 6 Group			
Card 6A : Friction factor etc. - one card.			
11-20	F10.0	F1	Static friction factor.
21-30	F10.0	F2	Related to dynamic friction factor. If static and dynamic friction factor is equal, F2 is zero.
31-40	F10.0	CXX	Damping coefficient of displacement detector.
41-50	F10.0	PPPP	Gas pressure force between upper and lower column.
Card 6B : Spring constant and damping coefficient of dowel pin-one card.			
11-20	F10.0	D1K	Spring constant of dowel pin.
21-30	F10.0	D2K	Spring constant.
31-40	F10.0	D3K	Spring constant.
41-50	F10.0	D1C	Damping coefficient of dowel pin.
51-60	F10.0	D2C	Damping coefficient.
61-70	F10.0	D3C	Damping coefficient.
Total spring constant $=$ D1K + D2K*β + D3K*β^2			
Total damping coeff. $=$ D1C + D2C*$\dot{\beta}$ + D3C*$\dot{\beta}^2$			
Card 6C : Spring constant and damping coefficient of vertical impact-one card.			
11-20	F10.0	V1K	Spring constant of vertical impact.
21-30	F10.0	V2K	Spring constant.
31-40	F10.0	V3K	Spring constant.
41-50	F10.0	V1C	Damping coefficient of vertical impact.
51-60	F10.0	V2C	Damping coefficient.

Column	Format	Veriable	Description
61-70	F10.0	V3C	Damping coefficient.

Total spring constant = $V1K + V2K*\gamma + V3K*\gamma^2$

Total damping coeff. = $V1C + V2C*\dot{\gamma} + V3C*\dot{\gamma}2$

Card 6D : Spring constant and damping coefficient of boundary impact-one card.

11-20	F10.0	B1K	Spring constant of boundary impact.
21-30	F10.0	B2K	Spring constant.
31-40	F10.0	B3K	Spring constant.
41-50	F10.0	B1C	Damping coefficient of boundary impact.
51-60	F10.0	B2C	Damping coefficient.
61-70	F10.0	B3C	Damping coefficient.

Total spring constant = $B1K + B2K*\varepsilon + B3K*\varepsilon$

Total damping coeff. = $B1C + B2C*\dot{\varepsilon} + B3C*\dot{\varepsilon}$

Card 6E : Gap between element and boundary data. - one card.

11-20	F10.0	DELB	Gap between element and boundary.
21-30	F10.0	WLC	Mass of left boundary.
31-40	F10.0	SLC	Spring constant between left boundary and frame.
41-50	F10.0	WRC	Mass of right boundary.
51-60	F10.0	SRC	Spring constant between right boundary and frame.

As many group cards 6 as needs to generate NN elements.

Card 7 : Geometry and time data-one card.

11-20	F10.0	BB	Block half width.
21-30	F10.0	DT	Integral time step.

Column	Format	Variable	Description
31-40	F10.0	TEND	Ending time.
41-50	F10.0	TINT	Starting time.
Card 8 : Option data for print out-one card.			
11-20	F10.0	T1T	Check print starting time in Ruge-Kutta scheme.
21-30	F10.0	T2T	Check print ending time in Runge-Kutta scheme.
31-40	F10.0	T1X	Check print starting time for calculation results.
41-50	F10.0	F2X	Check print ending time for calculation results.
Card 9 : Impact data-one card.			
11-20	F10.0	EE	Coefficient of restitution.
21-30	F10.0	TC	Contact time.
If momentum model is adopted, this data is necessary.			
Card 10: Distance of vertical spring-NB/6 cards.			
11-20	F10.0	XB(1)	Block rocking spring half width.
21-30	F10.0	XB(2)	- - - - - - - -
⋮	⋮		
Card 11: Dowel data-ND/2 cards.			
11-20	F10.0	XD(1)	Distance of dowel from block center line.
21-30	F10.0	DEL(1,1)	Gap on left side of dowel.
31-40	F10.0	DEL(2,1)	Gap on right side of dowel.
41-50	F10.0	XD(2)	

Column	Format	Variable	Description
51-60	F10.0	DEL(1,2)	
61-70	F10.0	DEL(2,2)	- - - - -
Next card.			
11-20	F10.0	XD(3)	- - - - -
21-30	F10.0	DEL(1,3)	- - - - -
31-40	F10.0	DEL(2,3)	- - - - -
⋮	⋮	⋮	
Card 12: Option for response curve plotting-one card.			
1-4	I4	IPLOT(1)	Rotation angle plot option.
3-8	I4	IPLOT(2)	Rotation angular velocity ploy option.
9-12	I4	IPLOT(3)	Rotation angular acceleration plot option.
13-16	I4	IPLOT(4)	Horizontal displacement plot option.
17-20	I4	IPLOT(5)	Horizontal velocity plot option.
21-24	I4	IPLOT(6)	Horizontal acceleration plot option.
25-28	I4	IPLOT(7)	Vertical displacement plot option.
29-32	I4	IPLOT(8)	Vertical velocity plot option.
33-36	I4	IPLOT(9)	Vertical acceleration plot option.
37-40	I4	IPLOT(10)	Moment by gravity plot option.
41-44	I4	IPLOT(11)	Friction force plot option.
45-48	I4	IPLOT(12)	Moment by friction force plot option.
49-52	I4	IPLOT(13)	Vertical impact force plot option.
53-56	I4	IPLOT(14)	Moment by vertical impact plot option.
57-60	I4	IPLOT(15)	Dowel force plot option.
61-64	I4	IPLOT(L6)	Moment by dowel force plot option.

Column	Format	Variable	Description
65-68	I4	IPLOT(17)	Boundary impact force plot option.
69-72	I4	IPLOT(18)	Moment by boundary impact plot option. IPLOT(I) = 0: Don't plotted. IPLOT(I) = Results are plotted.
Card 13 group			
Card 13A : Seismic data (Sinusoidal wave)-one card.			
11-20	F10.0	G	Amplitude of input wave. KIK = 0 : Displacement. KIK = 2 : Acceleration.
21-30	F10.0	W	Angular frequency. KIK = 0 : Radian/s. KIK = 2 : Hz.
31-40	F10.0	P	Phase shift. (radian).
Card 13B : Option for seismic data (Sinusoidal wave)-one card.			
10	I1	KIK	Option input wave data. (See card 13A).
Card 13C : Seismic data (Random wave)-one card.			
1-5	I5	KXK(1)	Option for horizontal data input.
6-10	I5	KXK(2)	Dummy.
11-15	I5	KXK(3)	Option for vertical data input.
21-30	F10.0	ALP	Maltiplication factor of displacement.
31-40	F10.0	BET	Maltiplication factor of velocity. KXK(I) = 0 : No-data. KXK(I) = 1 : Data input.
Card 13D : Number of seismic data and time step of data.			
1-4	I4	KXN(1,1)	Number of horizontal displacement data.
21-30	F10.0	DDT(1,1)	Time step.

Column	Format	Variable	Description
<u>Next cards</u>			
21-60	5F10.0	VX (1,1,KXN(1,1))	Horizontal displacement.
<u>Next cards</u>			
1-4	I4	KXN(1,2)	Number of horizontal velocity data.
21-30	F10.0	DDT(1,2)	Time step.
<u>Next cards</u>			
21-60	5F10.0	VD (1,2,KXN(1,2))	Horizontal velocity.
			If KXK(1) is zero, above four cards are not necessary.
<u>Next cards</u>			
1-4	I4	KXN(3,1)	Number of vertical displacement data.
21-30	F10.0	DDT(3,1)	Time step.
<u>Next cards</u>			
21-60	5F10.0	VX (3,1,KXN(3,1))	Vertical displacement.
<u>Next cards</u>			
1-4	I4	KXN(3,2)	Number of vertical velocity data.
21-30	F10.0	DDT(3,2)	Time step.
<u>Next cards</u>			
21-60	5F10.0	VX (3,2,KXN(3,2))	Vertical velocity.
			If KXK(3) is zero, above four cards are not necessary.

Table 4.2 Input data card for post-processor SONWV-1

Column	Format	Variable	Description
1-5	I5	M	Number of potting divide.
6-10	I5	IPLT2	Length of time axis, IPLT2 (mm/s).

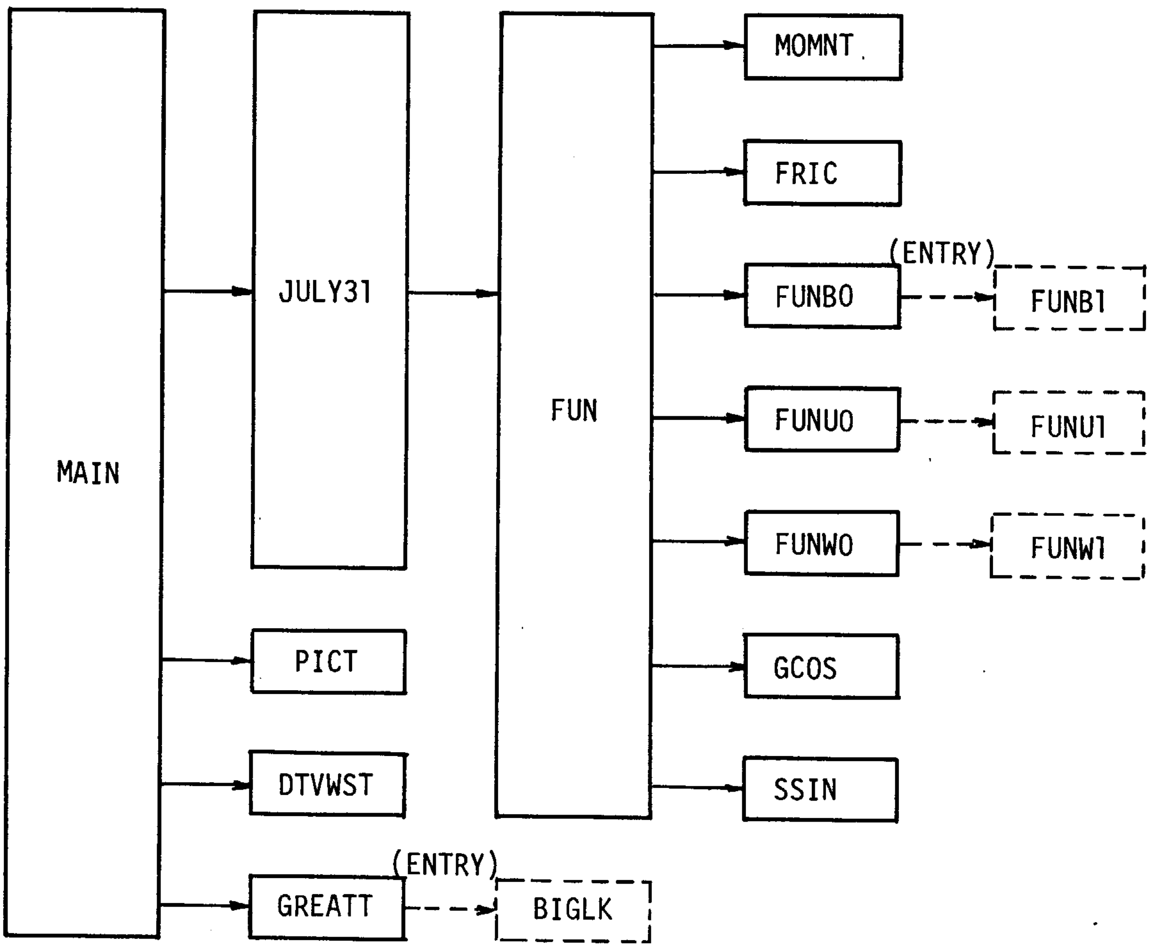


Fig. 4.1 Structure of SONATINA-1

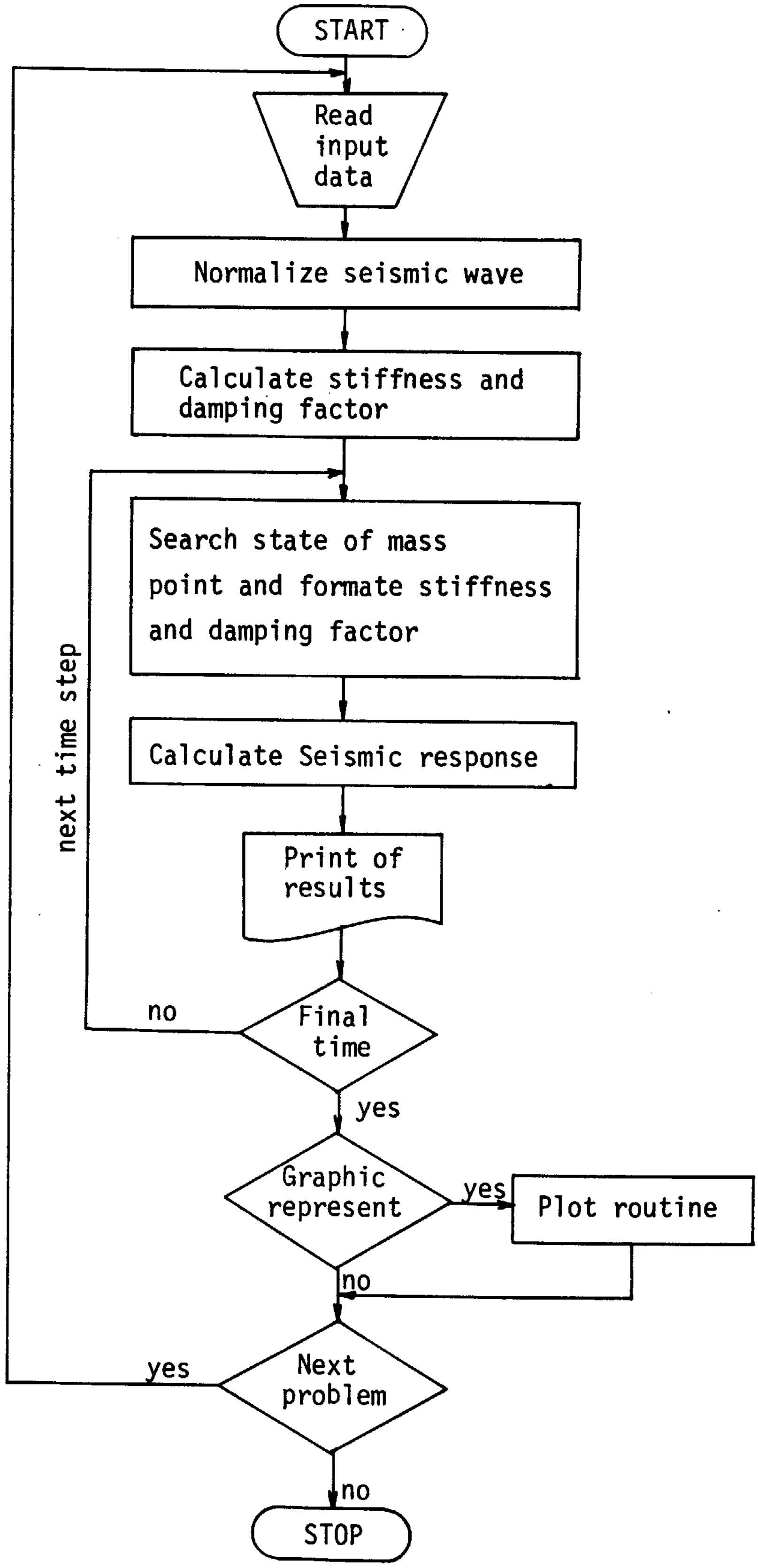


Fig. 4.2 Flow sheet of calculation

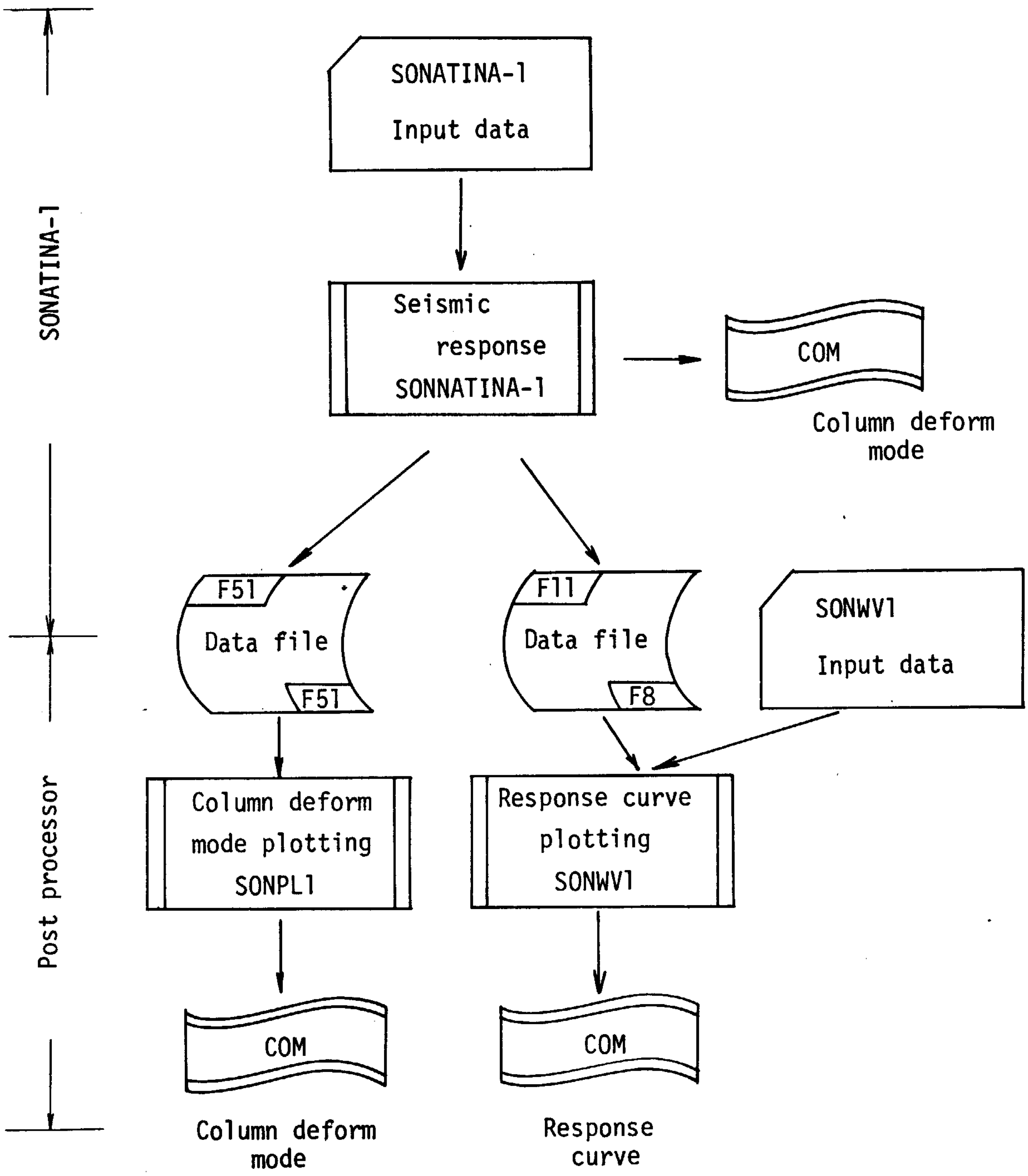


Fig. 4.3 Computer program SONATINA-1 and post-processor

5. Some Examples and Discussions

To demonstrate the performance of SONATINA-1, sevel examples were calculated and shown in this chapter. The results are also compared with experimental results. The geometry and weight of the block elements (shown in Table 5.1) in such a way that the system analyzed corresponds to a VHTR fuel column with dimension scaled by 1/2 and weight scaled by 1/8. Computation time interval is 10^{-4} seconds. The numerical results for both free-vibration problems are compared with experimental results.

5.1 Free vibration of a Single Column

Figure 5.1 shows a comparison of the calculation and experimental results of a single stacked column released from an initially displaced position. In the figure the time histories of the block displacement were plotted. For this free-vibration case there is good agreement between the experimental and analytical results. It is also seen that the oscillation periods are amplitude-dependent.

Through proper adjustment of the physical parameters in the analytical model, a close correlation between the analytical results and experimental data can be achieved for free-vibration problems. In the experiment the displacement was accurately measured by mean of differential transformer type displacement detector. In the analysis the damping coefficient of this detector was used to adjust the analytical data to experimental data.

5.2 Forced Vibration without Boundary Impact

The forced-vibration response of the one column under boundary excitation was also studied. The support floor was assumed to be connected with the boundary walls to form a rigid frame so that the movement of the walls is the same as that of the floor. Except at the top block, the side wall gap was large and as a results, no side wall impact occured. The column was excited by a sinusoidal floor motion at 3.5 Hz with 500 Gal maximum acceleration. The time histores of displacements of the blocks from both the experiment and analysis are shown in Fig.5.2. Figure 5.3 shows the column deflection as a function of input acceleration level for sinusoidal excitation along the horizontal axis. It can be seen from the figure that there is satisfactory agreement between the analytical and experimental results.

5.3 Forced Vibration with Boundary Impact

The forced vibration response of a single column impacting the boundary walls was studied for both sinusoidal and seismic wave input.

The blocks were subjected to impact loads due to periodic impingement against the walls. The column-to wall gap in the test was taken to be 15mm except at the top where a smaller gap of 0.5mm was used.

(1) Sinusoidal wave excitation

Figure 5.4 shows the time histories of displacements and impact forces of the column under 3.5 Hz at 500 Gal sinusoidal excitation. The results from analysis and experiment are compared. Figure 5.5 presents a sequential display of the motion of a 13-element column. The block were subjected to impact loads due to periodic impingement against the impact plates.

In the figure, it can be seen that the analytical results for both block displacements and impact forces are in good agreement with the experimental results.

Figure 5.7 (a) shows the distribution of the block impact forces along the column and compares analytical and experimental results. Analytical results show a favorable correlation with the results of the experiments.

(2) Random wave excitation

As the random input wave, the El Centro (1940 NS) modified by the structural response was applied to the VHTR core. Since the column model was 1/2 scale the time scale was reduced to $1/\sqrt{2}$ according to the law of similarity.

Figure 5.6 shows the time histories of the displacements and impact forces of the column when modified EL Centro wave of 500 Gal peak acceleration. Analytical and experimental results are compared. In the analytical results the large damping effect appears comparison with the experimental ones.

Figure 5.7 (b) shows the distribution of block impact forces along the column. Analytical results shows a favorable correlation with the results of the experiments.

Figure 5.8 shows the impact forces as a function of input acceleration level for sinusoidal and random excitation. Analytical results show a favourable correlation with the results of the experiments.

Table 5.1 Mass, moment of inertia, spring constant and damping coefficient

	Block No.1 - 12	Top block
a (cm)	2.5	
b (cm)	7.23	
d (cm)	5.2	
h (cm)	14.23	
I $(kg.sec^2/cm)$	0.524	1.36
m $(kg.sec^2/cm)$	0.00628	0.00918
m_B $(kg.sec^2/cm)$	0.00628	0.00918
δ_R, δ_L (cm)	0.025	
μ_k (-)	0.2	
μ_s (-)	0.2	
C^B (kg.sec /cm)	1.77	
C^C (kg.sec /cm)	0.02-0.12 (depend on column deflection)	
C^D (kg.sec /cm)	4.2	
C^M (kg.sec /cm)	1.77	
C^V (kg.sec /cm)	1.77	
K^B (kg/cm)	2.5×10^4	
K^D (kg/cm)	1.55×10^4	
K^M (kg/cm)	2.5×10^4	
K^V (kg/cm)	2.5×10^4	
P (kg/cm^2)	0.0	

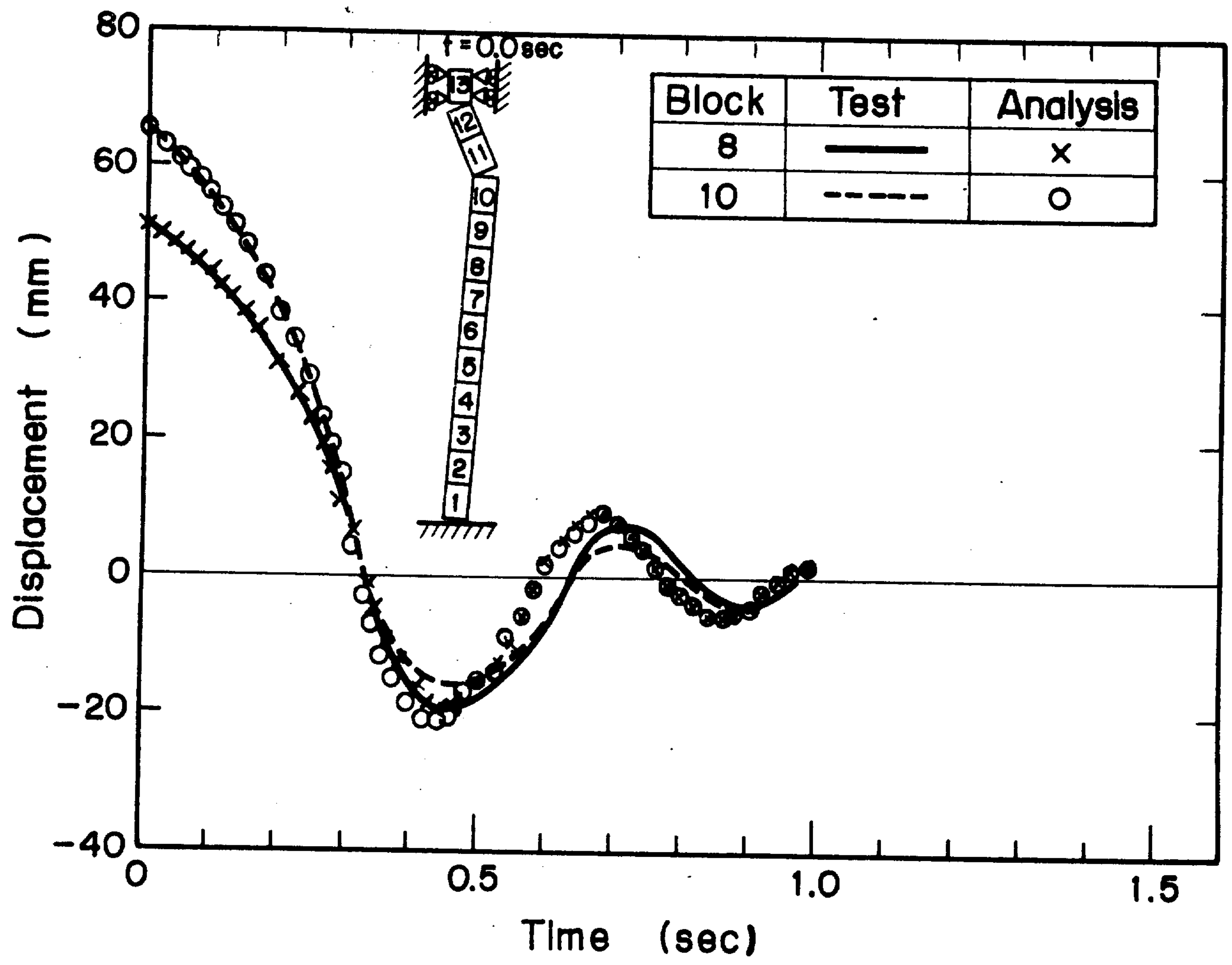
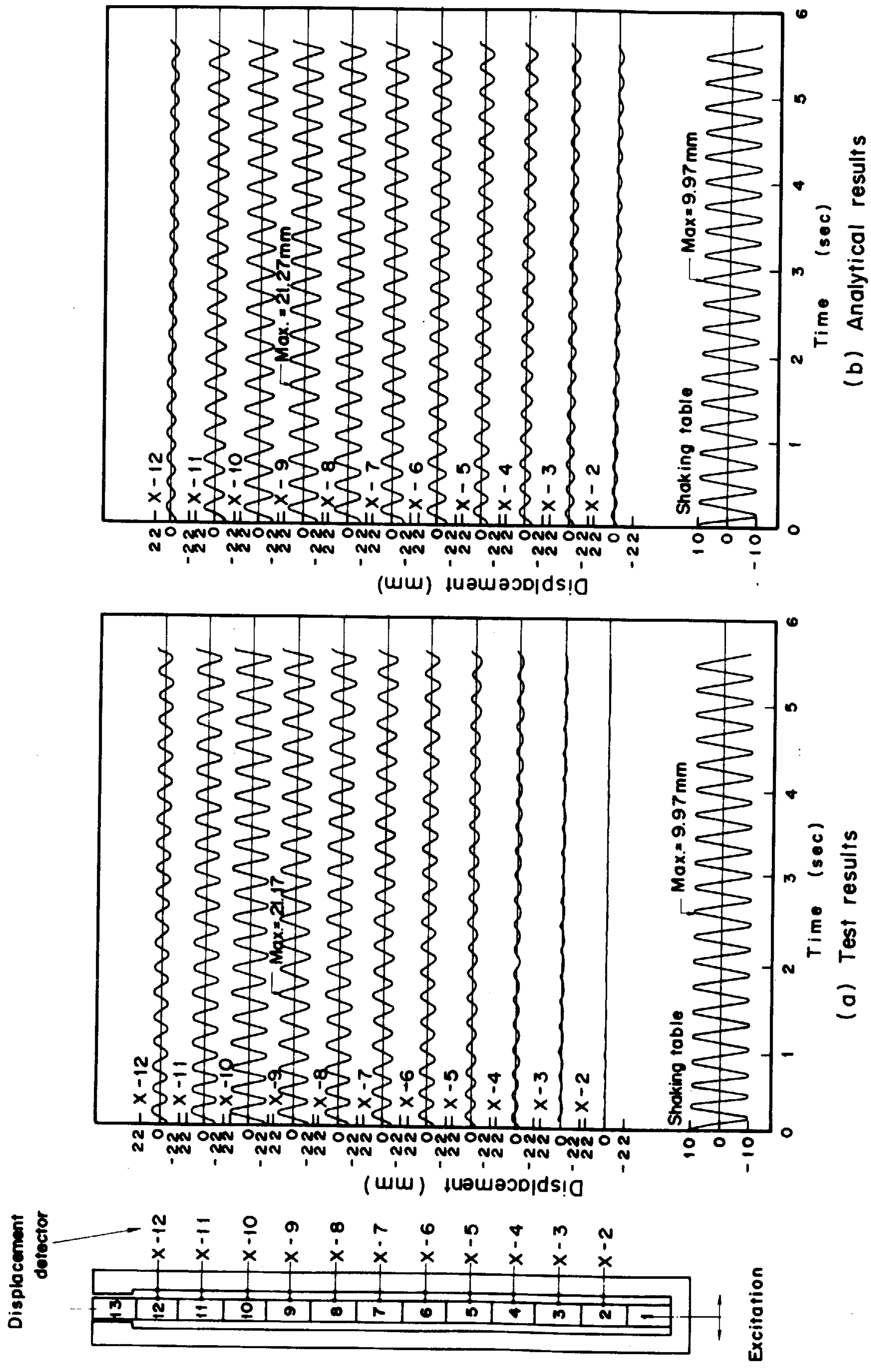


Fig.5.1 Column free vibration



(a) Test results

(b) Analytical results

Fig. 5.2 Comparison between test and analysis of displacement
(Input wave sinusoidal 3.5 Hz, max. acceleration 500 Gal)

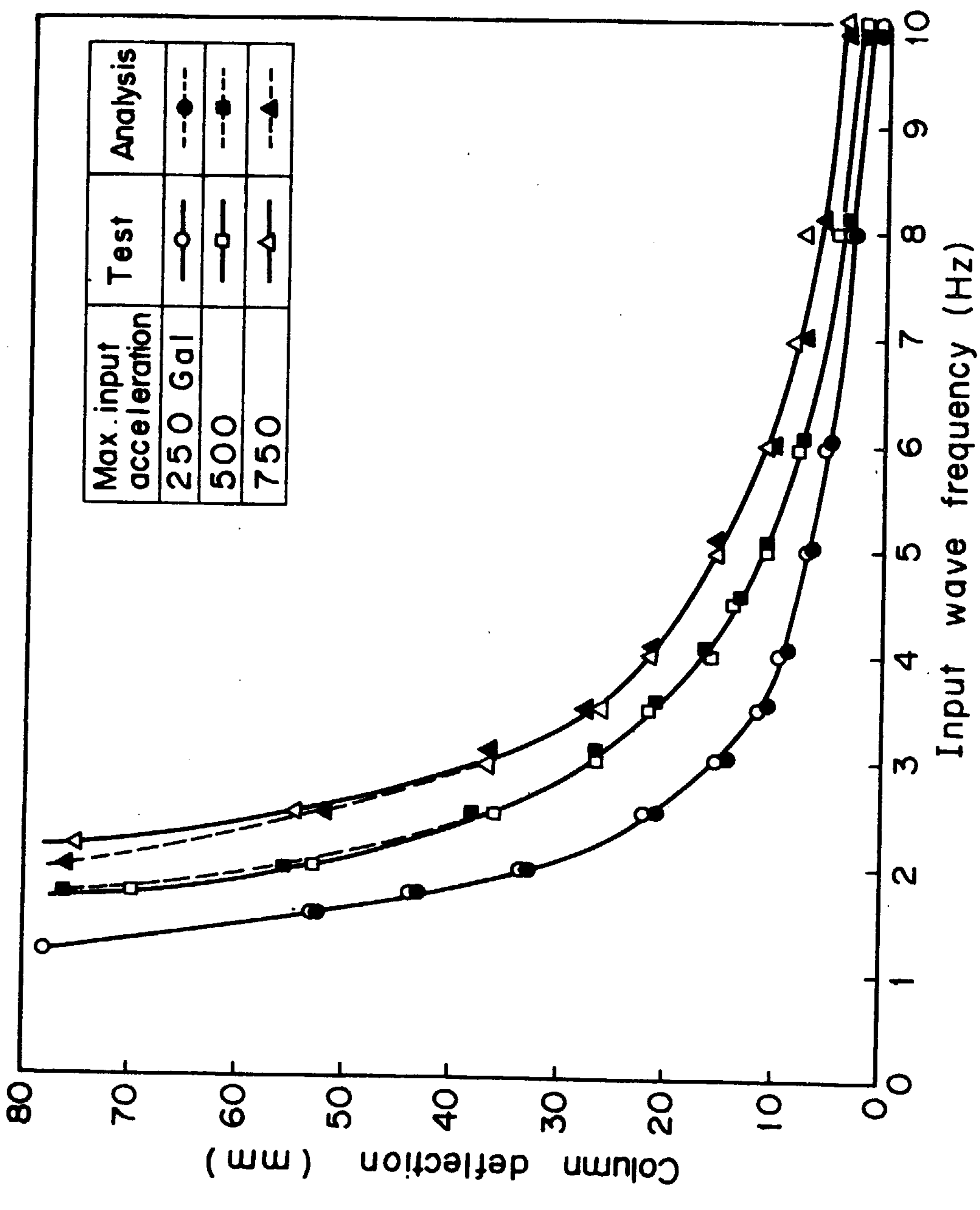
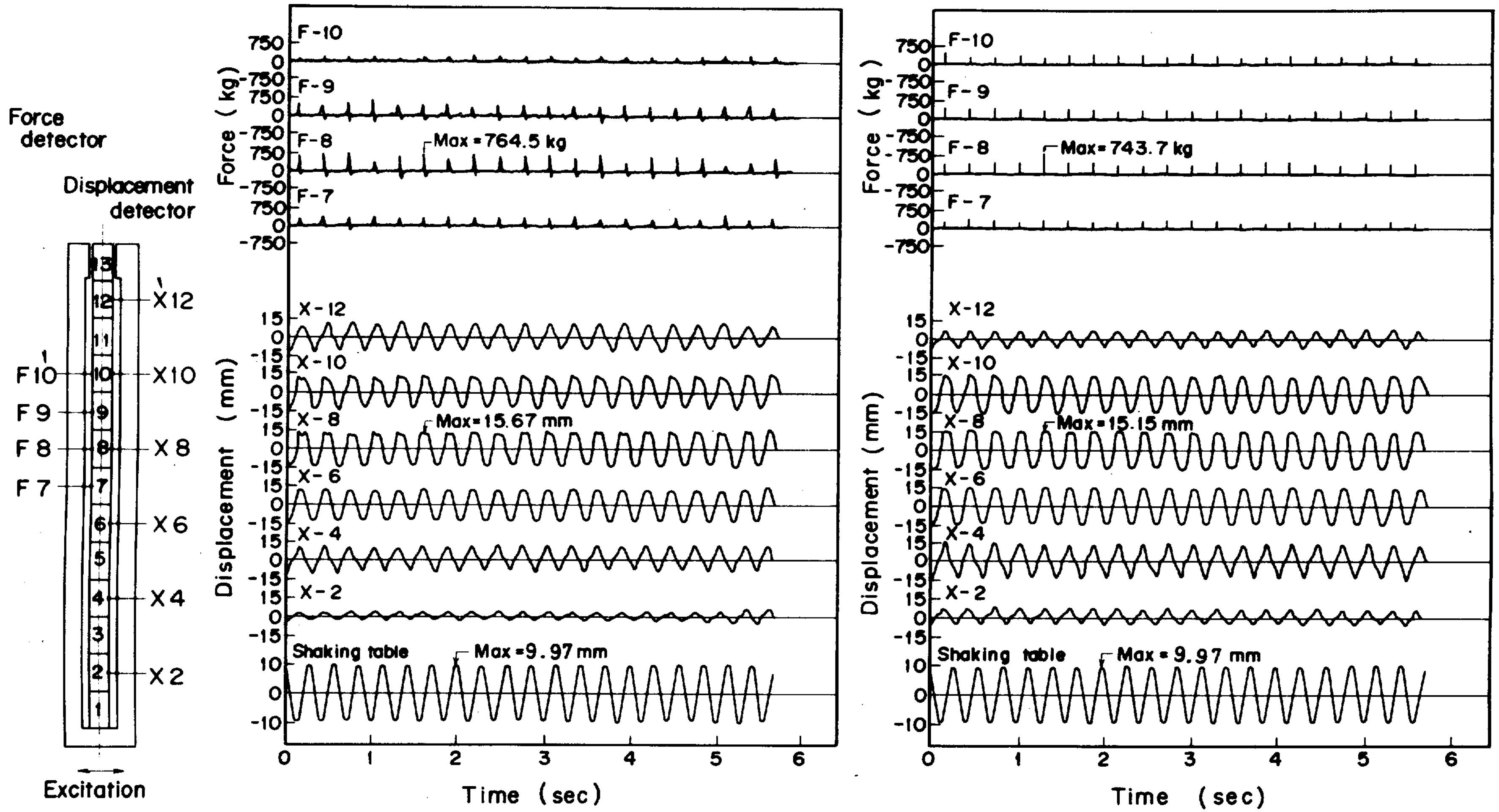


Fig.5.3 Column deflection vs. input wave frequency



(a) Test results (b) Analytical results

Fig.5.4 Comparison between test and analysis of displacement and impact force (Input wave sinusoidal 3.5 Hz, max. acceleration 500Gal)

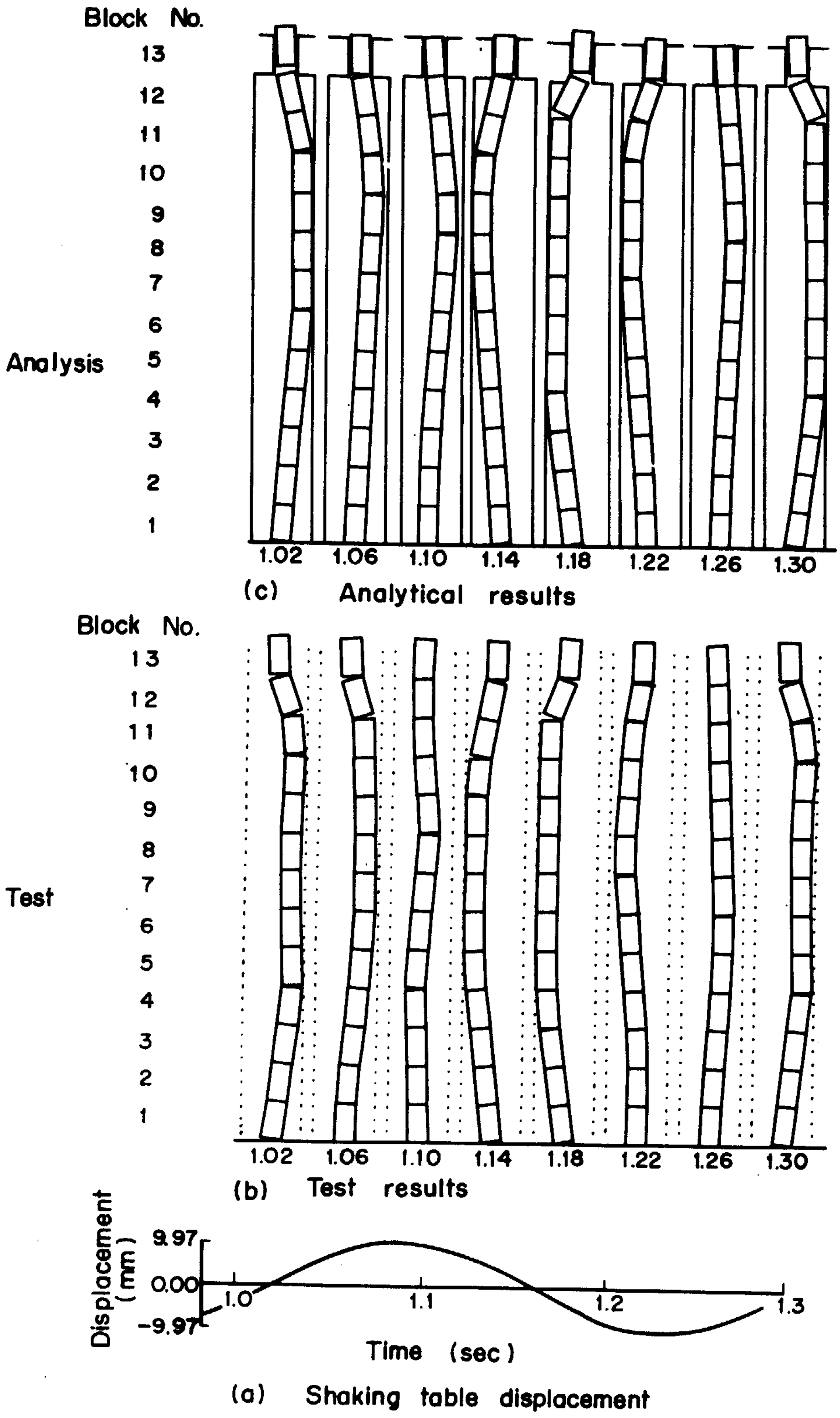


Fig.5.5 Comparison between test and analysis of columm vibration behavior

(Input wave sinusoidal 3.5 Hz, max. acceleration 500 Gal)

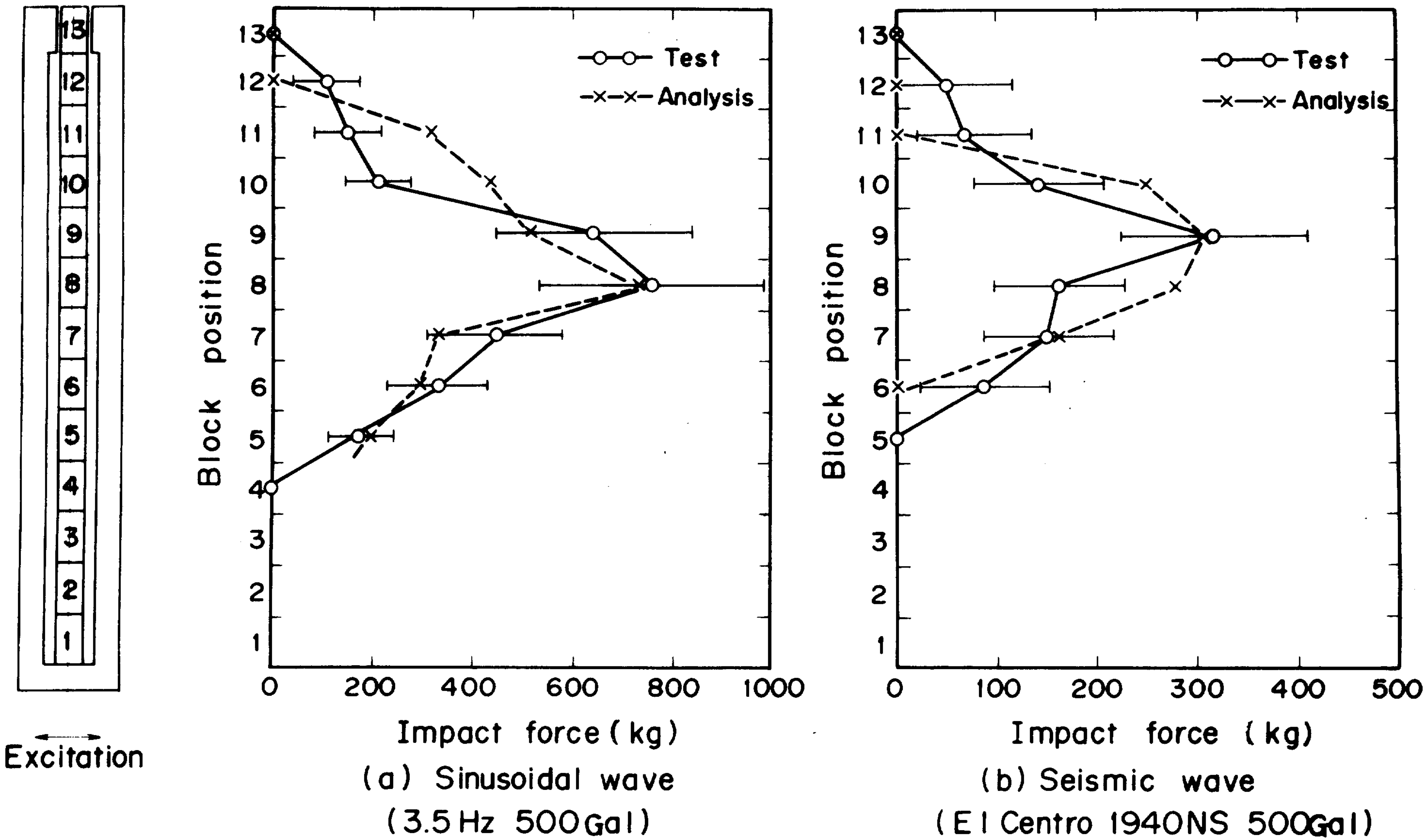


Fig.5.6 Comparison between test and analysis value of impact force distribution of block along column

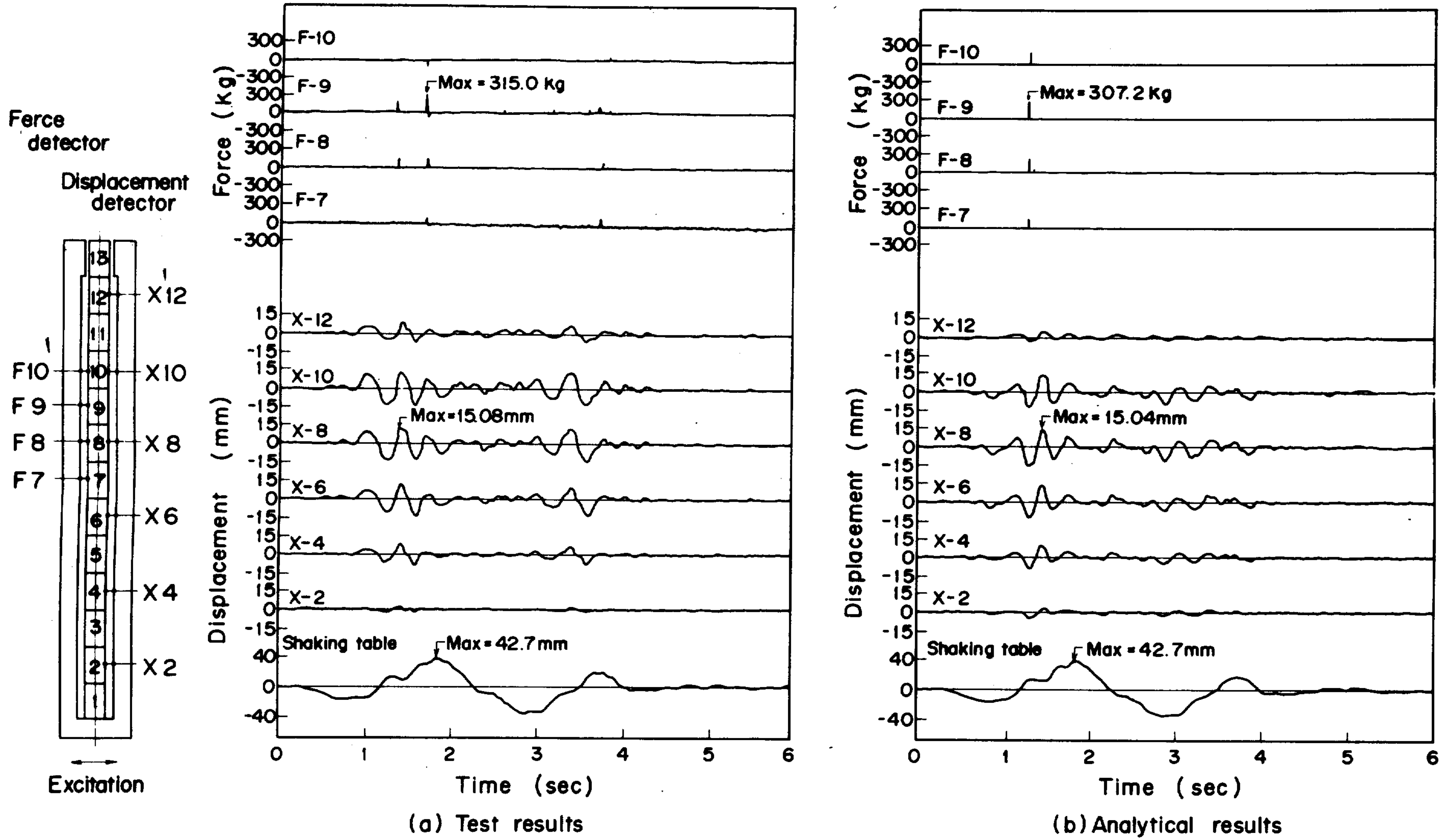
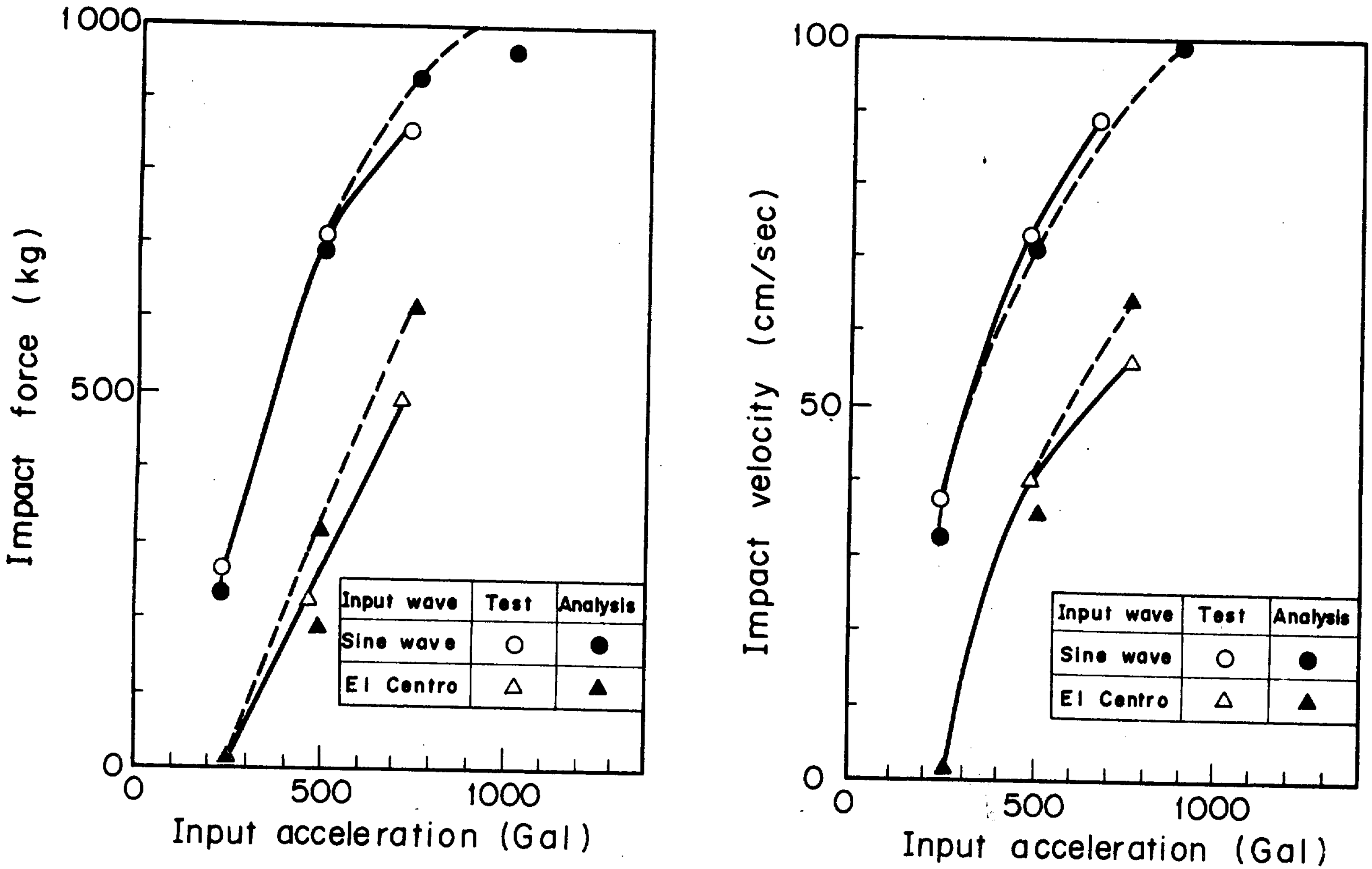


Fig.5.7 Comparison between test and analysis of displacement and impact force (Input wave El Centro 1940 NS, max. acceleration 500 Gal)



(a) Impact force (b) Impact velocity

Fig.5.8 Impact force and velocity vs. input acceleration

6. Concluding Remarks

The author has developed a computer program SONATINA-1 for simulation analysis of stacked block column of HTGR core. Several calculation results are compared with results obtained with vibration experiment. The following conclusions have been drawn:

(1) The calculation results were compared with experimental data for both the free and horizontal force vibration of a single column. Good agreement was obtained analytical and experimental results.

(2) Using this computer program, forces and moments can be computed. Especially dowel force and boundary impact force can be computed. And stresses of dowel pins and sockets can be evaluated from forces. This is important since the structural design of dowel pin and socket is often the most critical in a fuel block.

(3) The computer program is capable of being extended to the plane motion problem of a series of many interacting stacked block columns.

Acknowledgement

The author is indebted Mr. T. Nakazawa in Century Research Center, Ltd., Co. for help of making the computer program.

References

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Appendix A Sample problem input

Appendix B Sample problem output

Table A Sample problem input

```
....*....1....*....2....*....3....*....4....*....5....*....6....
   SIN WAVE  485 GAL  3.0 HZ     GAP = 1.5 CM
 13    2     2     2 1000                  10
  1
  2
  3
  4
  5
  6
  7
  8
  9
 10
 11
 12
 13
  1    1    1    1    1    1    1    1    1    1
  1    1    2
          14.28     0.524          6.28-3    6.15
          14.23     1.36           9.18-3    9.0
  1       0.2                 0.02
  1       15500.0   0.0       0.0       4.2       0.0       0.0
  1       25000.0   0.0       0.0       1.77      0.0       0.0
  1       25000.0   0.0       0.0       1.77      0.0       0.0
  1       1.5
  2       0.2                 0.02
  2       15500.0   0.0       0.0       4.2       0.0       0.0
  2       25000.0   0.0       0.0       1.77      0.0       0.0
  2       25000.0   0.0       0.0       1.77      0.0       0.0
  2       1.5
  3       0.2                 0.02
  3       15500.0   0.0       0.0       4.2       0.0       0.0
  3       25000.0   0.0       0.0       1.77      0.0       0.0
  3       25000.0   0.0       0.0       1.77      0.0       0.0
  3       1.5
  4       0.2                 0.02
  4       15500.0   0.0       0.0       4.2       0.0       0.0
  4       25000.0   0.0       0.0       1.77      0.0       0.0
  4       25000.0   0.0       0.0       1.77      0.0       0.0
  4       1.5
  5       0.2                 0.02
  5       15500.0   0.0       0.0       4.2       0.0       0.0
  5       25000.0   0.0       0.0       1.77      0.0       0.0
  5       25000.0   0.0       0.0       1.77      0.0       0.0
  5       1.5
  6       0.2                 0.02
  6       15500.0   0.0       0.0       4.2       0.0       0.0
  6       25000.0   0.0       0.0       1.77      0.0       0.0
  6       25000.0   0.0       0.0       1.77      0.0       0.0
  6       1.5
  7       0.2                 0.02
```

```
   7        15500.0    0.0        0.0        4.2        0.0        0.0
   7        25000.0    0.0        0.0        1.77       0.0        0.0
   7        25000.0    0.0        0.0        1.77       0.0        0.0
   7        1.5
   8        0.2                   0.02
   8        15500.0    0.0        0.0        4.2        0.0        0.0
   8        25000.0    0.0        0.0        1.77       0.0        0.0
   8        25000.0    0.0        0.0        1.77       0.0        0.0
   8        1.5
   9        0.2                   0.02
   9        15500.0    0.0        0.0        4.2        0.0        0.0
   9        25000.0    0.0        0.0        1.77       0.0        0.0
   9        25000.0    0.0        0.0        1.77       0.0        0.0
   9        1.5
  10        0.2                   0.02
  10        15500.0    0.0        0.0        4.2        0.0        0.0
  10        25000.0    0.0        0.0        1.77       0.0        0.0
  10        25000.0    0.0        0.0        1.77       0.0        0.0
  10        1.5
  11        0.2                   0.02
  11        15500.0    0.0        0.0        4.2        0.0        0.0
  11        25000.0    0.0        0.0        1.77       0.0        0.0
  11        25000.0    0.0        0.0        1.77       0.0        0.0
  11        1.5
  12        0.2                   0.02
  12        15500.0    0.0        0.0        4.2        0.0        0.0
  12        25000.0    0.0        0.0        1.77       0.0        0.0
  12        25000.0    0.0        0.0        1.77       0.0        0.0
  12        1.5
  13        0.2                   0.02
  13        15500.0    0.0        0.0        4.2        0.0        0.0
  13        25000.0    0.0        0.0        1.77       0.0        0.0
  13        25000.0    0.0        0.0        1.77       0.0        0.0
  13         0.05
            7.23       0.0001     1.0        0.0        0.1
            1.0        0.0        1.0        0.0
            0.0        0.0
            2.5       -2.5
            5.2        0.025      0.025     -5.2        0.025      0.025
   0    0   0     1    1    1
            0.542      18.849     0.0
   0
   0     0     0
....*....1....*....2....*....3....*....4....*....5....*....6....*.
```

Table B Sample problem output

SONATINA-1   SIN WAVE 195 GAL 3.0 HZ   GAP = 1.5 CM

INPUT DATA

1. CALCULATION SYSTEM

NO. OF MASS	13
TIME STEP	0.100000D-03
END TIME	0.100000D+01
PLOT START TIME	0.0
PLOT TIME STEP	0.100000D+00

2. DIMENSION

NO.	BLOCK HALF HEIGHT	BLOCK HALF WIDTH	VERTICAL SPRING DISTANCE LEFT SIDE	VERTICAL SPRING DISTANCE RIGHT SIDE	BOUNDARY GAP	DOWEL CENTER DISTANCE AND GAP LEFT SIDE LEFT GAP	LEFT SIDE DISTANCE	LEFT SIDE RIGHT GAP	RIGHT SIDE LEFT GAP	RIGHT SIDE DISTANCE	RIGHT SIDE RIGHT GAP
1	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
2	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
3	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
4	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
5	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
6	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
7	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
8	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
9	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
10	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
11	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
12	14.2300	7.2300	-2.5000	2.5000	1.5000	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250
13	14.2300	7.2300	-2.5000	2.5000	0.0500	0.0250	-5.2000	0.0250	0.0250	5.2000	0.0250

3. MASS

NO. OF MASS	MASS(KG.SEC**2/CM)	WEIGHT(KG)	ROTATION OF INERTIA
1	0.628000D-02	0.615000D+01	0.524000D+00
2	0.628000D-02	0.615000D+01	0.524000D+00
3	0.628000D-02	0.615000D+01	0.524000D+00
4	0.628000D-02	0.615000D+01	0.524000D+00
5	0.628000D-02	0.615000D+01	0.524000D+00
6	0.628000D-02	0.615000D+01	0.524000D+00
7	0.628000D-02	0.615000D+01	0.524000D+00
8	0.628000D-02	0.615000D+01	0.524000D+00
9	0.628000D-02	0.615000D+01	0.524000D+00
10	0.628000D-02	0.615000D+01	0.524000D+00
11	0.628000D-02	0.615000D+01	0.524000D+00
12	0.628000D-02	0.615000D+01	0.524000D+00
13	0.918000D-02	0.900000D+01	0.136000D+01

4. STIFFNESS

4.1 BLOCK

NO.	KV(1)	KV(2)	KV(3)
1	0.2500000D+05	0.0	0.0
2	0.2500000D+05	0.0	0.0
3	0.2500000D+05	0.0	0.0
4	0.2500000D+05	0.0	0.0
5	0.2500000D+05	0.0	0.0
6	0.2500000D+05	0.0	0.0
7	0.2500000D+05	0.0	0.0
8	0.2500000D+05	0.0	0.0
9	0.2500000D+05	0.0	0.0
10	0.2500000D+05	0.0	0.0
11	0.2500000D+05	0.0	0.0
12	0.2500000D+05	0.0	0.0
13	0.2500000D+05	0.0	0.0

4.2 DOWEL

NO.	KD(1)	KD(2)	KD(3)
1	0.1550000D+05	0.0	0.0
2	0.1550000D+05	0.0	0.0
3	0.1550000D+05	0.0	0.0
4	0.1550000D+05	0.0	0.0
5	0.1550000D+05	0.0	0.0
6	0.1550000D+05	0.0	0.0
7	0.1550000D+05	0.0	0.0
8	0.1550000D+05	0.0	0.0
9	0.1550000D+05	0.0	0.0
10	0.1550000D+05	0.0	0.0
11	0.1550000D+05	0.0	0.0
12	0.1550000D+05	0.0	0.0
13	0.1550000D+05	0.0	0.0

4.3 BOUNDARY

NO.	KB(1)	KB(2)	KB(3)
1	0.2500000D+05	0.0	0.0
2	0.2500000D+05	0.0	0.0
3	0.2500000D+05	0.0	0.0
4	0.2500000D+05	0.0	0.0
5	0.2500000D+05	0.0	0.0
6	0.2500000D+05	0.0	0.0
7	0.2500000D+05	0.0	0.0
8	0.2500000D+05	0.0	0.0
9	0.2500000D+05	0.0	0.0
10	0.2500000D+05	0.0	0.0
11	0.2500000D+05	0.0	0.0
12	0.2500000D+05	0.0	0.0
13	0.2500000D+05	0.0	0.0

5. DAMPING

5.1 BLOCK

NO.	CV(1)	CV(2)	CV(3)
1	0.1770000D+01	0.0	0.0
2	0.1770000D+01	0.0	0.0
3	0.1770000D+01	0.0	0.0
4	0.1770000D+01	0.0	0.0
5	0.1770000D+01	0.0	0.0
6	0.1770000D+01	0.0	0.0
7	0.1770000D+01	0.0	0.0
8	0.1770000D+01	0.0	0.0
9	0.1770000D+01	0.0	0.0
10	0.1770000D+01	0.0	0.0
11	0.1770000D+01	0.0	0.0
12	0.1770000D+01	0.0	0.0
13	0.1770000D+01	0.0	0.0

5.2 DOWEL

NO.	CD(1)	CD(2)	CD(3)
1	0.4200000D+01	0.0	0.0
2	0.4200000D+01	0.0	0.0
3	0.4200000D+01	0.0	0.0
4	0.4200000D+01	0.0	0.0
5	0.4200000D+01	0.0	0.0
6	0.4200000D+01	0.0	0.0
7	0.4200000D+01	0.0	0.0
8	0.4200000D+01	0.0	0.0
9	0.4200000D+01	0.0	0.0
10	0.4200000D+01	0.0	0.0
11	0.4200000D+01	0.0	0.0
12	0.4200000D+01	0.0	0.0
13	0.4200000D+01	0.0	0.0

5.3 BOUNDARY

NO.	CB(1)	CB(2)	CB(3)
1	0.1770000D+01	0.0	0.0
2	0.1770000D+01	0.0	0.0
3	0.1770000D+01	0.0	0.0
4	0.1770000D+01	0.0	0.0
5	0.1770000D+01	0.0	0.0
6	0.1770000D+01	0.0	0.0
7	0.1770000D+01	0.0	0.0
8	0.1770000D+01	0.0	0.0
9	0.1770000D+01	0.0	0.0
10	0.1770000D+01	0.0	0.0
11	0.1770000D+01	0.0	0.0
12	0.1770000D+01	0.0	0.0
13	0.1770000D+01	0.0	0.0

6. FRICTION

INTERFACE	F(1)	F(2)
1	0.1656000D+02	0.0
2	0.1533000D+02	0.0
3	0.1410000D+02	0.0
4	0.1287000D+02	0.0
5	0.1164000D+02	0.0
6	0.1041000D+02	0.0
7	0.9180000D+01	0.0
8	0.7950000D+01	0.0
9	0.6720000D+01	0.0
10	0.5490000D+01	0.0
11	0.4260000D+01	0.0
12	0.3030000D+01	0.0
13	0.1800000D+01	0.0

7. INITIAL STATE

NO.	THETA	D-THETA/D-T	U	D-U/D-T	W	D-W/D-T
1	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0

FOLLOWING DATA ARE WRITTEN ON PLOT-TAPE

0 - DISPLACEMENT

0 - VELOCITY

0 - ACCELERATION

A	0.543000D+00		
W	0.12849D+02		
P	0.0		
DIFDP	0.100000D-04		
CHECK	0.100000D+00		
BOUNDARY			0
E	0.0		
T0	0.0		
WAVE	0	0	0

CALCULATION RESULTS

TIME = 0.94978D-01 SEC

U,DU/DT,D2U/DT2 = 0.53020D+00 -0.22091D+01 -0.18335D+03
W,DW/DT,D2W/DT2 = 0.0 0.0 0.0

DISPLACEMENT

NO.	THETA	U	W	REFLECTOR COLUMN LEFT		RIGHT	
1	-0.393786D-03	0.546118D+00	-0.252606D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
2	0.931100D-03	0.550069D+00	-0.327034D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
3	0.465759D-03	0.562281D+00	-0.457770D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
4	0.710856D-03	0.555913D+00	-0.634357D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
5	0.262323D-03	0.547511D+00	-0.788841D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
6	0.292792D-03	0.531135D+00	-0.930811D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
7	0.561407D-03	0.520809D+00	-0.101946D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
8	0.156454D-03	0.511571D+00	-0.101367D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
9	0.334141D-03	0.496936D+00	-0.114364D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
10	-0.409820D-03	0.476526D+00	-0.109582D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
11	-0.135890D-03	0.489145D+00	-0.105076D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
12	-0.917664D-03	0.494624D+00	-0.907622D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
13	-0.594345D-03	0.489495D+00	-0.834525D-02	0.0	0.0	-0.989717D-01	-0.103091D-02

VELOCITY

NO.	D-THETA/D-T	D-U/D-T	D-W/D-T				
1	-0.155786D+00	-0.311491D+01	-0.294524D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
2	0.606251D+00	-0.780586D+00	-0.800702D+00	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
3	-0.132623D+01	0.249604D+01	0.174491D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
4	0.151895D+01	0.425205D+01	-0.188307D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
5	-0.114041D+01	0.996457D+01	-0.358093D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
6	0.112723D+01	0.819743D+01	-0.183788D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
7	-0.794761D+00	0.127860D+02	-0.231764D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
8	0.662160D+00	0.109036D+02	-0.461184D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
9	-0.493273D+00	0.127080D+02	-0.234930D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
10	0.388164D+00	0.112898D+02	-0.303491D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
11	-0.525029D+00	0.887475D+01	-0.250314D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
12	0.119265D+00	0.383418D+01	-0.330769D+01	-0.222796D+01	-0.222796D+01	-0.150000D+01	-0.150000D+01
13	0.248839D-01	-0.164056D+00	-0.167103D+01	-0.222796D+01	-0.222796D+01	-0.819762D-01	-0.180263D-01

ACCELERATION

NO.	D2THETA/DT2	D2U/DT2	D2W/DT2		
1	0.259159D+04	-0.506811D+04	0.137447D+04	0.0	0.0
2	-0.245509D+04	0.468879D+04	0.181199D+04	0.0	0.0
3	0.410881D+03	-0.430254D+04	-0.375736D+04	0.0	0.0
4	-0.397815D+03	0.312529D+04	0.498229D+03	0.0	0.0
5	0.238266D+03	-0.277867D+04	-0.418693D+03	0.0	0.0
6	0.132834D+04	0.309330D+04	0.288280D+04	0.0	0.0
7	-0.830406D+02	-0.238735D+03	-0.578434D+03	0.0	0.0
8	0.149132D+04	-0.230244D+03	-0.313938D+04	0.0	0.0
9	-0.814083D+02	-0.238672D+03	0.982726D+03	0.0	0.0
10	0.783097D+03	-0.158844D+04	0.147946D+04	0.0	0.0
11	-0.565925D+03	0.113256D+04	-0.182493D+04	0.0	0.0
12	0.393277D+03	-0.781319D+03	-0.851726D+02	0.0	0.0
13	-0.667297D+02	0.196305D+03	-0.980392D+03	0.0	0.0

CALCULATION RESULTS

TIME = 0.97796D+00 SEC

U,DU/DT,D2U/DT2 = -0.22088D+00 0.93499D+01 0.61452D+02
W,DW/DT,D2W/DT2 = 0.0 0.0 0.0

DISPLACEMENT

NO.	THETA	U	W	REFLECTOR COLUMN LEFT		RIGHT	
1	-0.144653D-02	-0.265164D+00	-0.232228D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
2	-0.341669D-02	-0.359916D+00	-0.349455D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
3	-0.383325D-02	-0.481253D+00	-0.627232D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
4	-0.384036D-02	-0.606171D+00	-0.816977D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
5	-0.372130D-02	-0.741193D+00	-0.922655D-02	0.0	0.0	-0.150000D+01	-0.150000D+01
6	-0.366773D-02	-0.871820D+00	-0.105987D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
7	-0.375573D-02	-0.996414D+00	-0.128347D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
8	-0.264142D-02	-0.111122D+01	-0.118739D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
9	-0.258255D-02	-0.121054D+01	-0.123869D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
10	0.246355D-02	-0.119483D+01	0.411479D-03	0.0	0.0	-0.150000D+01	-0.150000D+01
11	0.147722D-01	-0.924541D+00	0.266813D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
12	0.139446D-01	-0.490781D+00	0.270495D-01	0.0	0.0	-0.150000D+01	-0.150000D+01
13	0.256799D-02	-0.232753D+00	0.538841D-01	0.0	0.0	-0.277641D-01	-0.722830D-01

VELOCITY

NO.	D-THETA/D-T	D-U/D-T	D-W/D-T				
1	-0.600715D-01	0.901806D+01	0.101930D+01	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
2	-0.305030D+00	0.220661D+01	0.677021D+00	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
3	0.782202D-01	-0.550113D+00	0.101504D+00	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
4	-0.752093D+00	-0.751225D+01	0.740174D+00	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
5	0.726114D+00	-0.818938D+01	0.635837D+00	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
6	-0.734917D+00	-0.750724D+01	-0.227273D+01	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
7	0.239111D+00	-0.129756D+02	0.153014D+00	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
8	-0.478694D+00	-0.176985D+02	-0.926280D+00	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
9	0.524743D+00	-0.167374D+02	0.108807D+01	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
10	-0.204510D+00	-0.202640D+02	0.100124D+01	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
11	0.835815D+00	-0.114501D+02	0.301430D+01	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
12	0.469602D+00	0.708457D+01	0.553743D+01	0.935777D+01	0.935777D+01	-0.150000D+01	-0.150000D+01
13	0.153535D+00	0.126292D+02	0.420042D+01	0.935777D+01	0.935777D+01	-0.100419D+00	0.0

ACCELERATION

NO.	D2THETA/DT2	D2U/DT2	D2W/DT2		
1	-0.120214D+04	-0.116527D+04	-0.114441D+04	0.0	0.0
2	0.101695D+04	0.313512D+03	0.403145D+03	0.0	0.0
3	-0.237762D+04	0.832059D+04	0.287767D+04	0.0	0.0
4	-0.103935D+03	-0.645942D+04	0.238438D+04	0.0	0.0
5	0.234615D+02	-0.197121D+04	-0.412345D+04	0.0	0.0
6	-0.202126D+04	0.105052D+04	-0.292102D+04	0.0	0.0
7	0.798863D+03	0.240430D+03	0.322407D+04	0.0	0.0
8	-0.147623D+04	0.252514D+03	0.105878D+04	0.0	0.0
9	0.469716D+03	0.249277D+03	0.213799D+03	0.0	0.0
10	0.235473D+03	0.340559D+04	-0.247847D+04	0.0	0.0
11	0.170113D+03	-0.331761D+03	-0.109744D+04	0.0	0.0
12	0.375654D+03	-0.220783D+04	-0.986576D+03	0.0	0.0
13	0.482300D+02	0.166564D+03	0.132350D+03	0.0	0.0

CALCULATION RESULTS

MAXIMUM VALUES

DISPLACEMENT

MAX.	THETA	U	W
1	8.56656D-03	1.48620D-01	1.49614D-02
2	9.39958D-03	4.13897D-01	1.43189D-02
3	9.52403D-03	6.76858D-01	1.79901D-02
4	9.26791D-03	9.29829D-01	2.31013D-02
5	9.29212D-03	1.16736D+00	2.77510D-02
6	8.18841D-03	1.38614D+00	3.19684D-02
7	7.36005D-03	1.49204D+00	3.57049D-02
8	7.14820D-03	1.50260D+00	3.89065D-02
9	1.23926D-02	1.49717D+00	4.15743D-02
10	1.64577D-02	1.50082D+00	4.37307D-02
11	2.47559D-02	1.17822D+00	7.37606D-02
12	3.07871D-02	5.11504D-01	8.43807D-02
13	3.77926D-03	5.28535D-02	1.45513D-01
	3.07871D-02	1.50260D+00	1.45513D-01

VELOCITY

MAX.	D-THETA/D-T	D-U/D-T	D-W/D-T
1	1.73502D+00	1.86076D+01	4.48131D+00
2	1.69078D+00	1.88333D+01	4.03100D+00
3	1.67357D+00	2.21744D+01	4.68740D+00
4	1.62504D+00	2.40890D+01	4.19254D+00
5	1.57572D+00	2.78285D+01	5.87626D+00
6	1.39913D+00	3.42826D+01	5.37189D+00
7	1.27082D+00	3.68655D+01	7.10555D+00
8	1.98311D+00	3.78053D+01	6.82072D+00
9	2.24429D+00	4.21212D+01	7.99710D+00
10	1.83531D+00	3.57830D+01	9.39813D+00
11	1.38066D+00	3.00397D+01	6.11834D+00
12	1.40571D+00	2.43412D+01	7.38172D+00
13	8.52718D-01	1.80313D+01	7.65776D+00
	2.24429D+00	4.21212D+01	9.39813D+00

ACCELERATION

MAX.	D2THETA/DT2	D2U/DT2	D2W/DT2
1	7.21295D+03	3.40076D+04	1.08792D+04
2	4.16590D+03	1.80375D+04	6.85508D+03
3	3.91636D+03	2.07279D+04	9.24135D+03
4	3.72882D+03	2.03236D+04	1.10350D+04
5	3.46307D+03	2.02160D+04	1.06098D+04
6	3.08655D+03	1.98532D+04	9.87074D+03
7	3.30667D+03	2.00525D+04	8.34548D+03
8	4.28055D+03	2.81706D+04	1.01494D+04
9	6.24583D+03	3.88236D+04	1.73948D+04
10	5.08777D+03	4.46430D+04	1.75216D+04
11	3.01913D+03	3.04973D+04	9.30524D+03
12	5.69731D+03	3.48025D+04	8.20903D+03
13	2.22785D+03	2.49098D+04	5.95036D+03
	7.21295D+03	4.46430D+04	1.75216D+04

CALCULATION RESULTS

MAXIMUM VALUES

FORCE AND MOMENT

MAX. NO.	MOMENT BY GRAVITY	FORCE BY FRICTION	MOMENT BY FRICTION	FORCE BY V.SPRING	MOMENT BY V.SPRING	FORCE BY DOWEL	MOMENT BY DOWEL	FORCE BY B.WALL	MOMENT BY B.WALL
1	1.15307D+03	3.18900D+01	4.55740D+02	7.44711D+01	3.25986D+02	1.61757D+02	2.55640D+03	0.0	0.0
2	1.08142D+03	2.94200D+01	4.20769D+02	4.91999D+01	3.82203D+02	8.37217D+01	1.37374D+03	0.0	0.0
3	9.92364D+02	2.69700D+01	3.85622D+02	5.36315D+01	4.13632D+02	1.03162D+02	1.46799D+03	0.0	0.0
4	9.01319D+02	2.45100D+01	3.50405D+02	7.54499D+01	4.22661D+02	1.03162D+02	1.46796D+03	0.0	0.0
5	8.09781D+02	2.20500D+01	3.15229D+02	7.27798D+01	2.77818D+02	1.05009D+02	1.49426D+03	0.0	0.0
6	7.17919D+02	1.95900D+01	2.79915D+02	6.81382D+01	4.04099D+02	1.05009D+02	1.49427D+03	0.0	0.0
7	6.27679D+02	1.71300D+01	2.44665D+02	5.55596D+01	2.72827D+02	1.08508D+02	1.54405D+03	7.30165D+01	1.03611D+03
8	5.34251D+02	1.46700D+01	2.09504D+02	6.98882D+01	2.48161D+02	1.57116D+02	2.23579D+03	1.71870D+02	2.43667D+03
9	4.45011D+02	1.22100D+01	1.74829D+02	1.03089D+02	3.62297D+02	1.57118D+02	2.23577D+03	2.42697D+02	3.45161D+03
10	3.60768D+02	9.75000D+00	1.39884D+02	1.16188D+02	2.72407D+02	1.08243D+02	1.54020D+03	2.24985D+02	3.18103D+03
11	2.71762D+02	7.29000D+00	1.05010D+02	5.22869D+01	2.28236D+02	9.43276D+01	1.33413D+03	1.46572D+02	2.05898D+03
12	1.75817D+02	4.83000D+00	6.97732D+01	5.73200D+01	2.09207D+02	2.12599D+02	3.03947D+03	0.0	0.0
13	6.55535D+01	1.80000D+00	2.56614D+01	6.36243D+01	1.62253D+02	2.12599D+02	3.03951D+03	1.95342D+02	2.68087D+03
	1.15307D+03	3.18900D+01	4.55740D+02	1.16188D+02	4.22661D+02	2.13599D+02	3.03951D+03	2.42697D+02	3.45161D+03

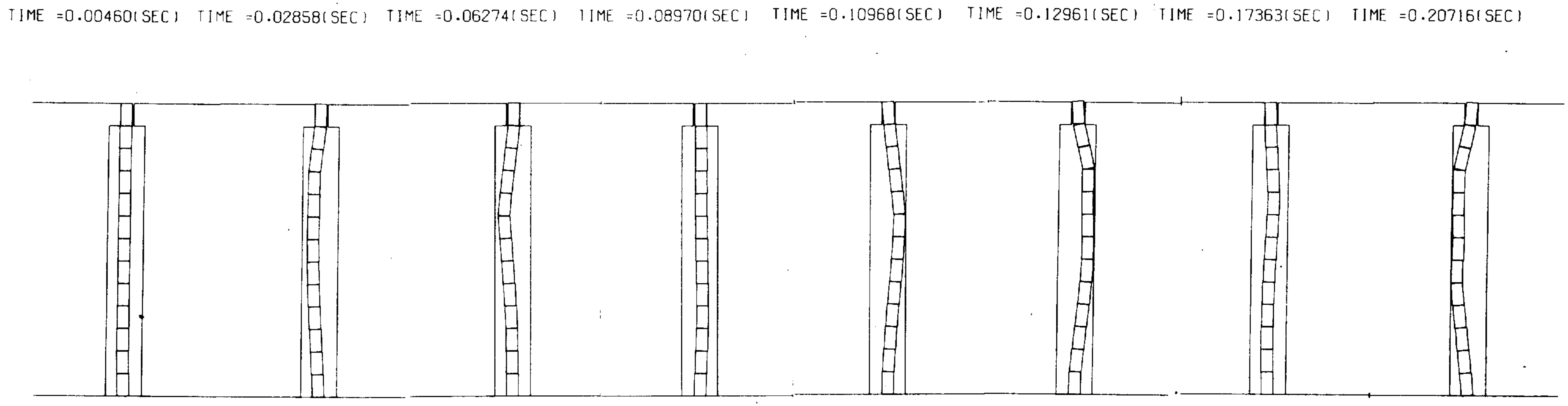

Fig. B.1 Output of SONPL-1 (Column vibration mode)

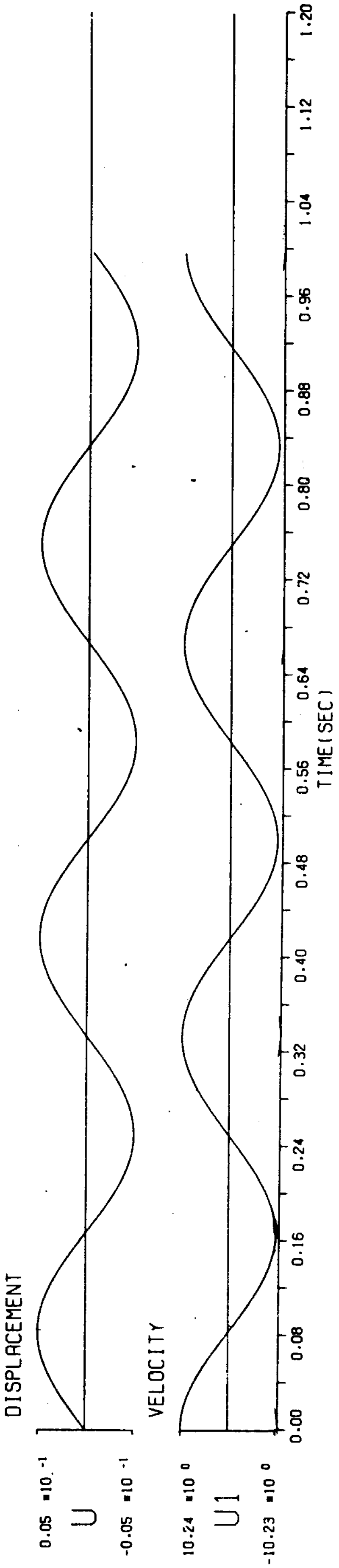

Fig. B.2(a) Output of SONWV-1 (Input wave)

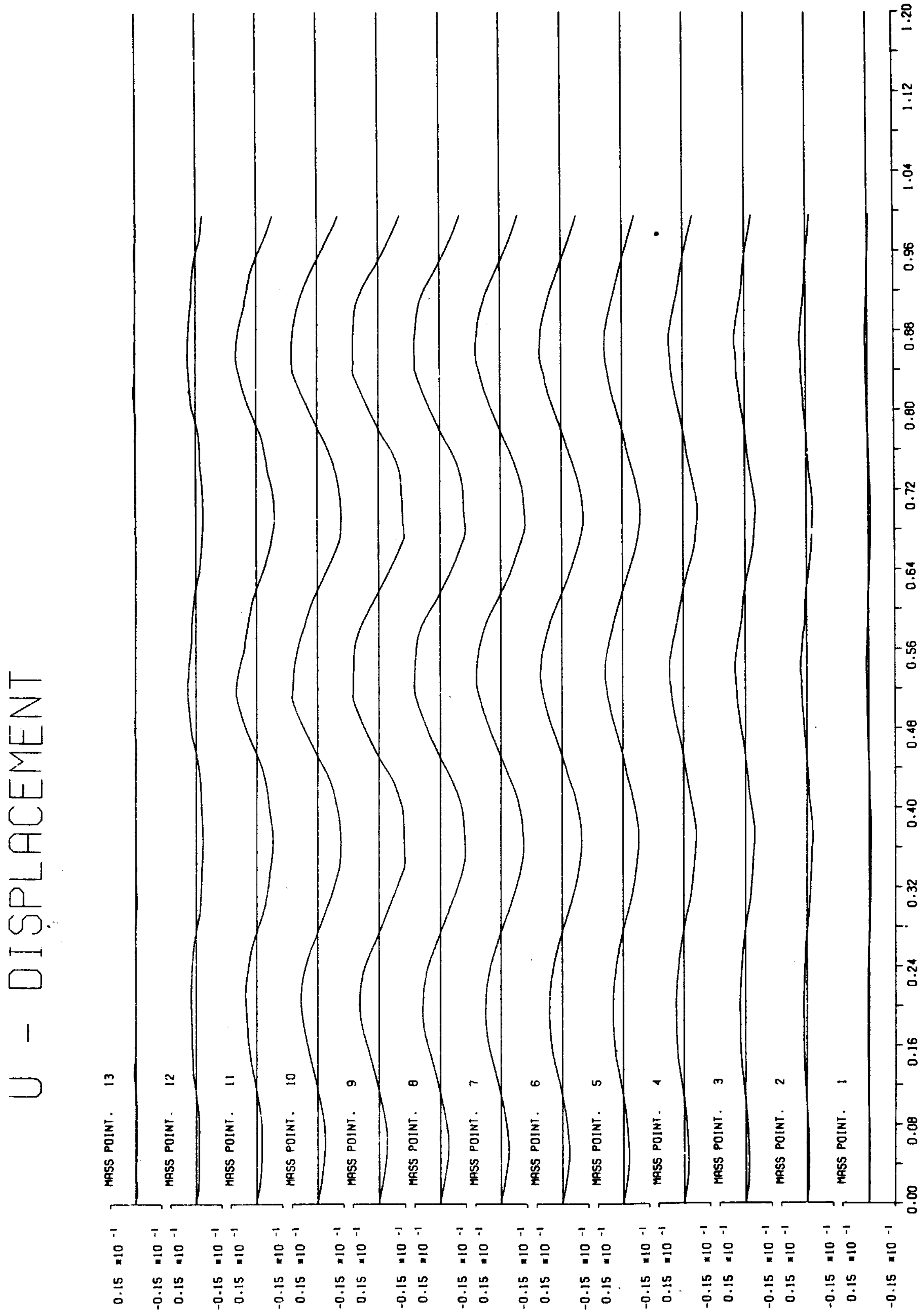

Fig.B.2(b) Output of SONWV-1 (U-displacement)

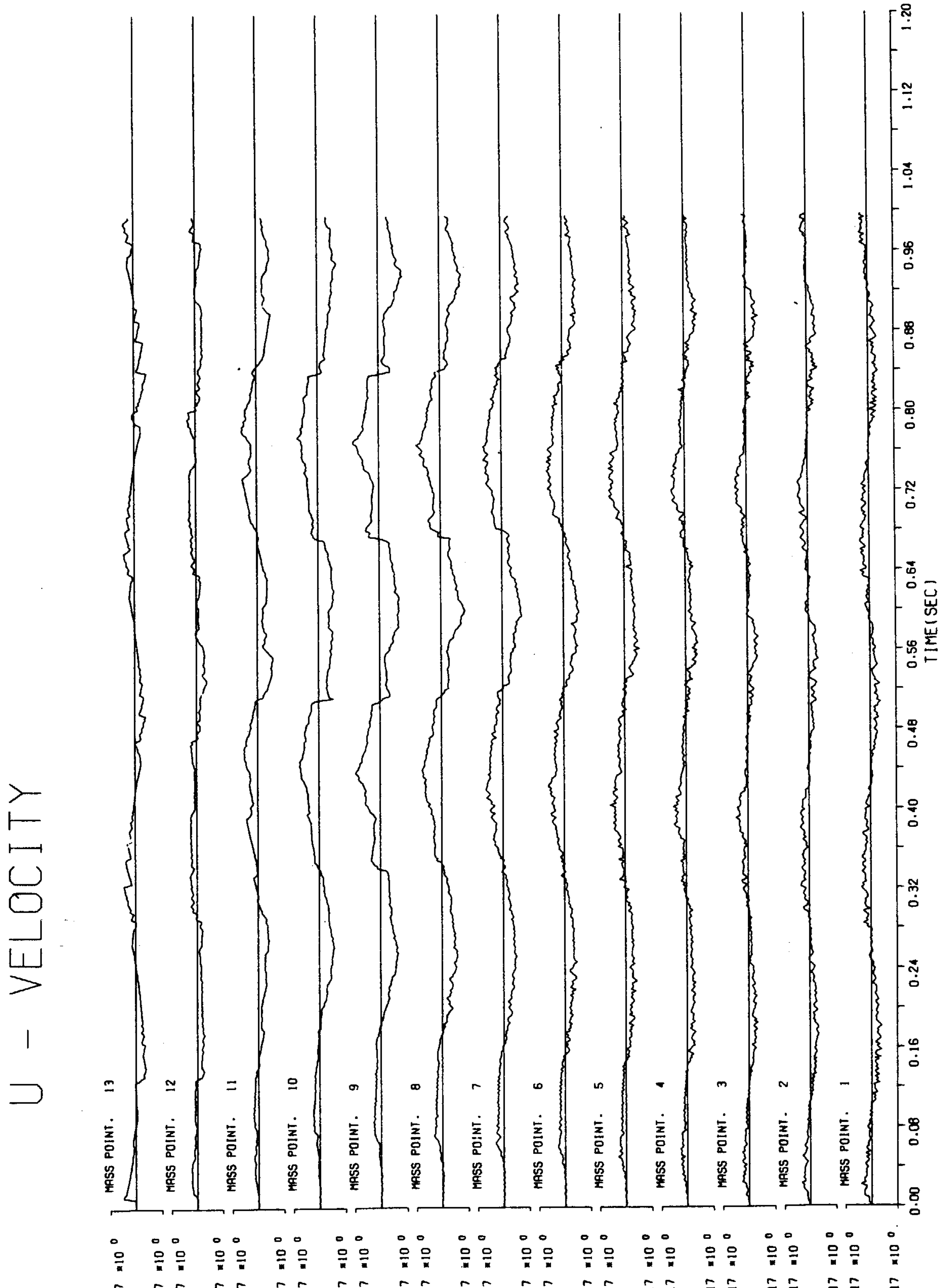

Fig.B.2(c) Output of SONWV-1 (U-velocity)

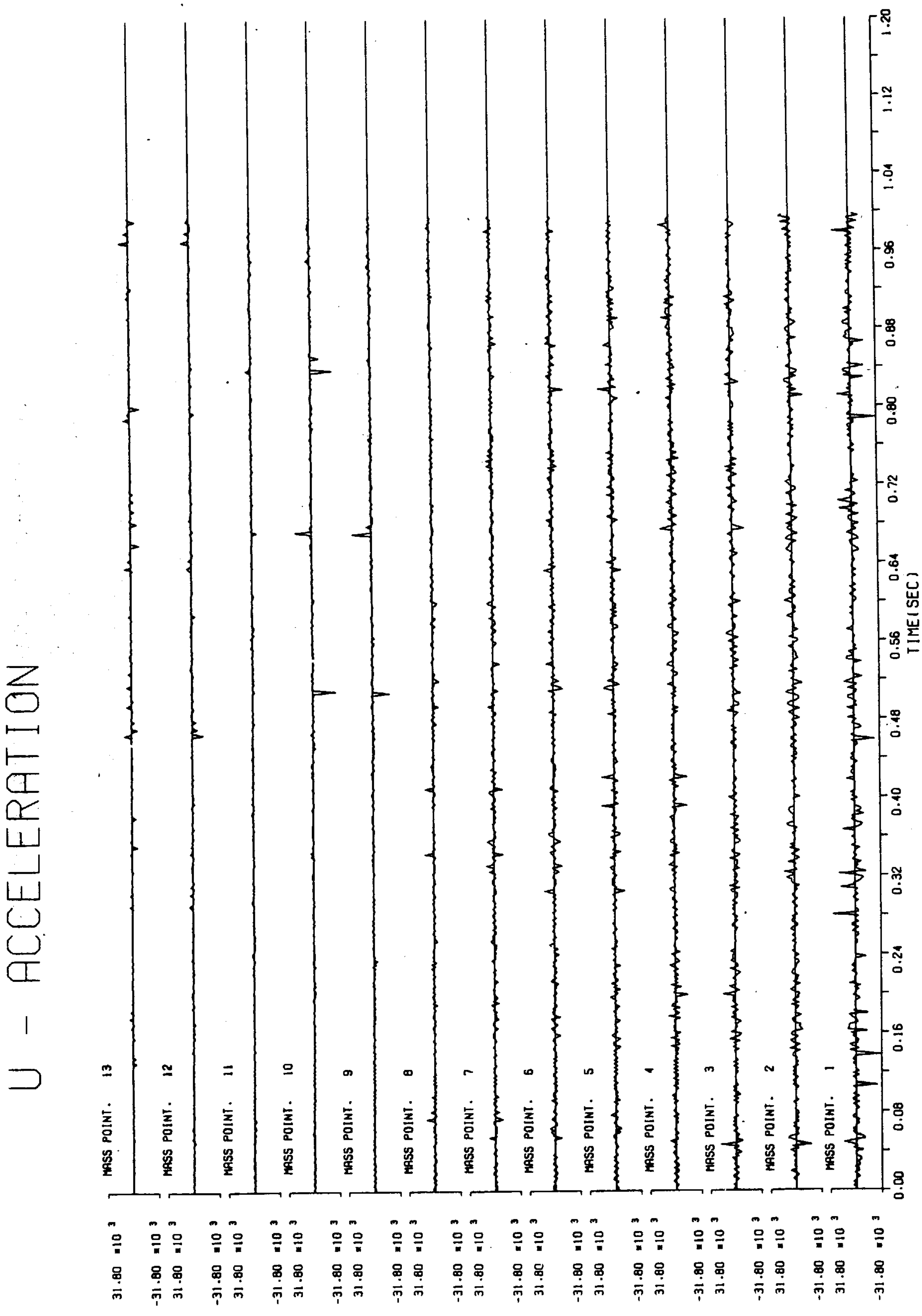

Fig.B.2(d) Output of SONWV-1 (U-acceleration)