A STUDY ON THE EARTHQUAKE RESPONSE OF SPACE STRUCTURES BY DIGITAL COMPUTERS

by
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ABSTRACT

A method for calculating the earthquake response, the normal modes and associated natural periods by new analytical model of multistoried buildings, considering horizontal distribution of mass and stiffness, floor deformation, building shape, etc., are described and illustrated. For the seismic design, the author studied fundamental problems of buildings with deformable floor, the effect of the horizontal length of buildings, the effect of the plan shape of buildings, the effect of the stiffness distribution of the floor and the columns and the effect of the traveling velocity of earthquake motion, by examples.

INTRODUCTION

We have carried out many studies on the dynamical analysis on the building due to earthquake motion by using the multi-mass models which mass is concentrated at each floor portion equal to the total mass of each story, and whose stiffness is equivalent to the total stiffness of each story, by rigid floor. However, in actual buildings, whose horizontal dimensions become large, the floor must be deformable. This fact-is quite important thing for the seismic design of structures.

In many earthquake damages of buildings, the author has found the great difference among the damage of columns of the story by their horizontal positions, particularly the difference is the greatest in the buildings with irregular combined plan. The vibration problems of this type of building can not be considered by the use of the usual analytical model. Therefore, the author has established a new analytical model which have deformable floor systems.[I]

In this case, the floor system of building which consists of beams and slabs, is replaced by the truss type framing, such as ordinary replacement of the walled frame by the truss type framing. At the same time we have many studies on replacement of the wall panel by the X shape diagonal bracing by TANABASHI[8], ONITAKE[9], MATSUI[10], ODAKA[11] and others.

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(I) The vibrational analysis of the buildings considering floor deformations were studies, however, the general property of the buildings with floor deformation have not been obtained yet. [1]-[7]

On the other hand, YAMADA[(12)] shows that many experimental results of horizontal floor deformation and seismic wall deformation are explained to be in good agreement with the results calculated by the following expression (beam theory) :

$$\delta = \left(\frac{H^3}{3\alpha EJ} + \frac{KH}{\beta GA}\right)Q \qquad \text{(single paneled frame)} \qquad (A)$$

δ : deflection
Q : shearing force
H : length of the shear span
E : Young's modulus
G : modulus of rigidity
J : moment inertia of cross section
A : cross sectional area
K : coefficient of shear deformation by cross section
α, β : coefficient of correction

$\alpha \fallingdotseq 1$, $\beta \fallingdotseq 0.5$ (in floor)

The deformation of single truss frame with X shape diagonal bracing is

$$\delta = \left(\frac{H^3}{2A_bEL^2} + \frac{(L^2+H^2)^{\frac{3}{2}}}{2A_dEL^2}\right)Q \qquad (B)$$

A_b : area of cross section of frame
A_d : area of cross section of bracing
L : length of span

In both expression, the first term denotes the bending deflection and the second term denotes shear deflection. Equating to both second terms, equivalent area of the diagonal bracing for the panel is obtained as follows.

$$A_d = \frac{1+\left(\frac{L}{H}\right)^2}{4(1-\nu)\frac{K}{\beta}\frac{L}{H}}td = \eta\ td \qquad (C)$$

t : thickness of panel
d : diagonal length of frame

The value of η calculated by using this expression and other expressions are shown in Fig. 1 by the ratio of H/L.

There are great difference among these value η. This fact is important. More experimental studies should be done. In this paper, however, the property of horizontal deformation is more interested than the accuracy of quantity η, because floor deformations of buildings due to earthquake motion were not yet reasonably estimated.

The author used following computers in this study

OKITAC 5090 OKI DENKI JAPAN

Main core memory : 4000 words

Magnetic tape : 2 channels

(CONPUTATION CENTER OF KOBE UNIVERSITY)

FACOM 222 FUJI TSUSHINKI JAPAN

Main core memory : 4000 words

Magnetic tape : 2 channels

(CONPUTATION CENTER, TOKYO INSTITUE OF TECHNOLOGY)

HITAC 5020 HITACHI JAPAN

Main core memory : 65000 words

(COMPUTER CENTER, UNIVERSITY OF TOKYO)

EQUATION OF MOTION OF THE MOLTI-STORIED BUILDING

In this paper, the objective of analysis is limited to the ordinary space frame structure, which is assumed to be multi-mass system.

Assumptions are as follows :

Assumption 1 All masses of the floor portion of each columns of each stories are concentrated to one mass system. (See Fig. 2)

Assumption 2 Each floor of the building is the truss type framing constructed with beams and the X-shape diagonal bracing such as equivalent to floor slabs regarding these horizontal deformation. (See Fig. 2)

Assumption 3 Each column of the lowest story of the building is fixed at the foundation to the rigid layer.

Assumption 4 Relation of relative displacement of each member of this floor truss to their restoring force is only extensional mode. Relation of story displacement of the columns to their restoring force is only shear type flexural mode.

Assumption 5 Damping of structure is of viscous type, and value of the damping force is the following expression.

$$\gamma \cdot K \cdot \frac{d\delta}{dt}$$

δ : relative displacement of structural member

K : stiffness of structural member

γ : coefficient of damping

Assumption 6 To consider only two horizontal components, which are parallel to the frame of structure.

Assumption 7 Earthquake motion applied to this multiple degree-of-freedom structures is supposed to have two horizontal components and some difference of transmitting time of ground motion for each basement of the building by the velocity of propagation of earthquake waves.

Selecting the certain Cartesian coordinates (o, x, y, z), z axis is vertical direction, x and y axes are parallel to floor framing, for the multiple degree-of-freedom system. (See Fig. 3) The relations between positions of particles on the same horizontal floor level are independent of z coordinate. Therefore, the relative displacement between i-th particle and j-th particle in r-th floor level is

$$\delta^{r}_{i,j} = (X^{r}_{j} - X^{r}_{i}) \cos \theta_{i,j} + (Y^{r}_{j} - Y^{r}_{i}) \sin \theta_{i,j} \tag{1}$$

X, Y : displacements in x and y direction of particle.
Superscript r denotes r-th floor, subscript i or j denotes i or j-th particle and subscript i, j denotes member of floor framing, from i-th particle to j-th particle.

Considering neither expansion nor contraction of columns, story deflection of column are also independent of z coordinate. Then the relative displacements in x and y directions between i-th particle on r-th floor level and i-th particle on (r-1)-th floor level are

$$\delta_{ix}^{r,r+1} = X_i^{r+1} - X_i^r \qquad (2)$$

$$\delta_{iy}^{r,r+1} = Y_i^{r+1} - Y_i^r$$

where superscript r, r+1 denotes the member of story, from r-th floor level to (r+1)-th floor level and subcript ix and iy denote the positions and the directions of the value.

Then the equilibrium of motion at i-th particle of r-th floor level is as follows

$$M_i^r \cdot \ddot{X}_i^r + C_{ix}^{r-1,r} \cdot \dot{\delta}_{ix}^{r-1,r} + F(\delta_{ix}^{r-1,r}) - C_{ix}^{r,r+1} \cdot \dot{\delta}_{ix}^{r,r+1} - F(\delta_{ix}^{r,r+1})$$

$$- \sum_{j=1}^{n} \left\{ C_{i,j}^r \cdot \dot{\delta}_{i,j}^r + F(\delta_{i,j}^r) \right\} \cos\theta_{i,j} = 0$$

$$M_i^r \cdot \ddot{Y}_i^r + C_{iy}^{r-1,r} \cdot \dot{\delta}_{iy}^{r-1,r} + F(\delta_{iy}^{r-1,r}) - C_{iy}^{r,r-1} \cdot \dot{\delta}_{iy}^{r,r-1} - F(\delta_{iy}^{r,r-1}) \qquad (3)$$

$$- \sum_{j=1}^{n} \left\{ C_{i,j}^r \cdot \dot{\delta}_{i,j}^r + F(\delta_{i,j}^r) \right\} \sin\theta_{i,j} = 0$$

M_i^r : mass of i-th particle on r-th floor level
C : damping force depending on relative displacement
$F(\delta)$: restoring force depending on relative displacement
$\sum_{j=1}^{n}$: summation of values for all j-th particles which are connected with i-th particle

Considering the hysteresis of structural member, which is of bilinear type with yielding point, restoring force expressed as follows

$$F(\delta) = K^{(s)} + f^{(s)} \qquad (4)$$

$K^{(s)}$: stiffness of structural member which is the slope of the force-deflection curve at the stage S
$f^{(s)}$: solid friction at the stage S

Substituting Eqs. (1), (2), (4) into Eq. (3) and assembling the equations for all particles, the equation of motion of the multiple degree-of-freedom system have the matrix form as follows

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} + \{f\} = \{0\} \qquad (5)$$

[M]: mass matrix
[K]: stiffness matrix

$[C]$: damping matrix
$\{f\}$: column solid friction vector
$\{U\}$: column displacement vector

where

$$[M] = \begin{bmatrix} \ddots & & \\ & [M^r] & \\ & & [M^r] \\ & & & \ddots \end{bmatrix}, \quad [M^r] = \begin{bmatrix} M_i^r & \\ & \ddots \end{bmatrix} \qquad [K] = [K_f] + [K_s]$$

$$= \begin{bmatrix} \ddots & & \\ & [K_f^r] & \\ & & \ddots \end{bmatrix} + \begin{bmatrix} & -[K_s^{r,r+1}] & [K_s^{r,r+1}] + [K_s^{r-1,r}] & -[K_s^{r-1,r}] & \end{bmatrix},$$

$$\begin{Bmatrix} \{\bar{X}^r\} \\ \{\bar{Y}^r\} \end{Bmatrix} = [K_f^r] \begin{Bmatrix} \{X^r\} \\ \{Y^r\} \end{Bmatrix} = \begin{bmatrix} [K_{xx}^r] & [K_{xy}^r] \\ [K_{yx}^r] & [K_{yy}^r] \end{bmatrix} \begin{Bmatrix} \{X^r\} \\ \{Y^r\} \end{Bmatrix}, \quad [K_s^{r,r-1}] = \begin{bmatrix} \ddots & \\ & K^{(s)r,r-1} \ddots \end{bmatrix},$$

$$\{f\} = \{f_f\} + \{f_s\} = \begin{Bmatrix} \vdots \\ \{f_f^r\} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \{f_s^r\} \\ \vdots \end{Bmatrix} = \begin{Bmatrix} \vdots \\ \sum_{j=1}^{n} f_{i,j}^r \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ f_i^{r,r+1} + f_i^{r-1,r} \\ \vdots \end{Bmatrix},$$

$$\{U\} = \begin{Bmatrix} \{X^r\} \\ \{Y^r\} \end{Bmatrix}, \quad \{\dot{U}\} = \frac{d}{dt}\{U\}, \quad \{\ddot{U}\} = \frac{d^2}{dt^2}\{U\}, \qquad [C] = \gamma[K].$$

$[K_f]$: stiffness matrix of floor framing, diagonal partitioned matrix
$[K_s]$: stiffness matrix of vertical members, tridiagonal partitioned matrix
$[K_f^r]$: stiffness matrix of floor framing of r-th floor level
$[K_s^{r,r+1}]$: stiffness materix of one story, which is r-th floor level to (r + 1)-th floor level

Let the column displacement vector to be in the form

$$\{U^r\} = \{U^o\} + \{u^r\}$$

$\{U^o\}$: column ground displacement vector
$\{u^r\}$: column relative dispacement vector of r-th floor level to the ground level

expression (5) is converted to expression (6)

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} + \{f\} = -[M]\{\ddot{U}^o\} - [C_f]\{\dot{U}^o\} - [K_f]\{U^o\}$$

Eliminating the equation (7) that gives ordinary shear type motion from expression (6), expression (8) that is equlibrium condition of floor deformation is obtained as follows

$$[M]\{\ddot{u}\} + [C_s]\{\dot{u}\} + [K_s]\{u\} + \{f_s\} = -[M]\{\ddot{U}^o\} \quad (7)$$

$$[C_f]\{\dot{u}\} + [K_f]\{u\} + \{f_f\} = -[C_f]\{\dot{U}^o\} - [K_f]\{U^o\} \quad (8)$$

NATURAL MODES AND ASSOCIATED NATURAL PERIODS

The free-vibration equation for an undamped linear system, appears as

$$[M]\{\ddot{u}\} + [K]\{u\} = 0 \quad (9)$$

from Eq. (6) when the excitation $[M]\{\ddot{U}^o\} + [C_f]\{\dot{U}^o\} + [K_f]\{U^o\}$, the friction $\{f\}$ and the damping $[C]$ vanish. If a solution for $\{u\}$ is assumed to be in the form

$$\{u\} = \text{Re}\{U \; e^{i\omega t}\} \quad (10)$$

where $\{U\}$ is a column vector of unknown amplitude, ω is an unknown frequency, i is the square root of -1 and Re{ } signifies "the real part of. By substituting into Eq. (9), it is found that $\{U\}$ and ω should satisfy the following algebraic equation

$$[K]\{U\} = \omega^2[M]\{U\} \quad (11)$$

This algebraic problem is the well-known the matrix eigen value problem. Then the frequency equation is

$$\det([K] - \omega^2[M]) = 0 \quad (12)$$

As examples, the author calculates for following four types of building, such as

1. Building with relatively narrow and long plan
2. Building with irregular plan, that is of box, channel and L shapes
3. Building with various stiffness distribution of seismic elements, such as column and wall, on the same story
4. Building with various horizontal rigidty of floor framing

To calculate these examples, the "power method" was used for the numerical analysis.

BUILDING WITH RELATIVELY NARROW AND LONG PLAN

For the effect of horizontal dimension of building to free vibration, the natural modes and asociated natural periods of one storied buildings with relatively narrow and long rectangular plan and with uniform stiffness distribution and uniform mass distribution are calculated

These examples are

narrow side length	long side length
1 span	4 span
1 span	8 span
1 span	24 span

weight of mass	w ton
stiffness of column	w ton/cm
stiffness of member of floor	20w ton/cm

Natural modes of vibration shows periodical floor deformation which divided into two types of floor deformation such as bending type and expansion type. Natural periods are shown for their ratio to the period of equivalent one mass system. Relation of half wave length of floor deformation to their ratio of the period to equivalent one mass system are shown in Fig. 4.

BUILDING WITH IRREGULAR PLAN

shape of plan

L - type	both length of wing portion is four span
⊏- type	both length of wing portion is four span and central portion is three span
□- type	length of each four side is three span

weight of mass	w ton	(uniform distribution)
stiffness of column	w ton/cm(	")
stiffness of member of floor	20w ton/cm(	")

Natural modes and the ratio of the associated natural periods to the period of equivalent one mass system, are shown in Fig. 5. Relation of wave length through the wings for floor deformation of these natural modes and associated periods are good agreement to those of the buildings with relatively narrow and long rectangular plan.

STIFFNESS DISTRIBUTION IN THE SAME STORY

For the effect of the distribution of the seismic wall, six types of one-storied building are calculated. The standard building in these examples have no walls, uniform mass distribution, and stiffness distribution on the same story and for the same floor framing. Other five buildings have eight panels of walls whose total stiffness are three times as long as total story stiffness of the standard building mentioned above, and these distributions are shown in Fig. 6.

weight of mass	w ton
stiffness of column	w ton/cm
stiffness of wall	75 w/8 ton/cm
stiffness of member of floor	20 w ton/cm

In Fig. 6, natural modes are shown by diagram and associated natural periods are shown in the diagram for their ratios to the fundamental period of translation of standard building. The fundamental periods of five buildings with eight walls for each floor deformation such as translation, rotation, bending and expansion are shown again in Fig. 7. The fundamental periods of translation mode of every buildings are longer than those of the building with rigid floor. In the case of the concentrated wall distribution near the symmetrical axes of the building in both x and y direction, the periods of rotation mode become longer than those of translation mode.

HORIZONTAL RIGIDITY OF FLOOR FRAMING

For the effect of the buildings with various types of floor such as rigid slab, prefabricated slab and no slab, four types of building are calculated. Four types of building have the same mass distribution and stiffness distribution on the same story which have uniform stiffness distribution of column system and have one wall on the one side gable end. (See Fig. 10)

Building No.	K_b / K_c	K_d / K_c
1131	12	24
1132	1.2	2.4
1133	0.12	0.24
1134	12	0.24

K_b : stiffness of beam of floor framing

K_d : stiffness of diagonal bracing of floor framing

K_c : mean stiffness in the story

The calculated periods are shown for the ratio to that of equivalent one mass system. Each five natural modes and associated periods for both bending mode and expansional mode are shown in Fig. 8, and also the effect of the horizontal rigidity to the periods are shown in Fig. 9.

EARTHQUAKE RESPONSE

"Linear acceleration method" is used as a numerical analysis of Eq. (6) with an electric digital computer. The Eq. (3) is written as Eq. (13) for i-th particle of r-th floor level at time t.

$$
{}_xA^{o,r}_{i,t}\,(M^r_i + \alpha^{r,r+1}_{ix} + \alpha^{r-1,r}_{ix} + \sum_{j=1}^{n} \alpha^r_{i,j}\cos^2\theta_{i,j}) - \alpha^{r,r+1}_{ix}\cdot{}_xA^{o,r+1}_{i,t}
- \alpha^{r-1,r}_{ix}\,{}_xA^{o,r-1}_{i,t} - \sum_{j=1}^{n}\alpha^r_{i,j}\cdot{}_xA^{o,r}_{j,t}\cos^2\theta_{i,j} + {}_yA^{o,r}_{i,t}\sum_{j=1}^{n}\alpha^r_{i,j}\sin\theta_{i,j}\cos\theta_{i,j}
- \sum_{j=1}^{n}{}_yA^{o,r}_{j,t}\cdot\alpha^r_{i,j}\sin\theta_{i,j}\cos\theta_{i,j} = -M^r_i\cdot{}_xA^o_{i,t} + {}_xA^{r,r+1}_{i,t-1}\cdot\beta^{r,r+1}_{ix} + {}_xV^{r,r+1}_{i,t-1}
\cdot\gamma^{r,r+1}_{ix} + {}_xD^{r,r+1}_{i,t-1}\cdot K^{r,r+1}_{ix} + f^{r,r+1}_{ix} - {}_xA^{r-1,r}_{i,t-1}\cdot\beta^{r-1,r}_{ix} - {}_xV^{r-1,r}_{i,t-1}\cdot\gamma^{r-1,r}_{ix}
- {}_xD^{r-1,r}_{i,t-1}K^{r-1,r}_{ix} - f^{r-1,r}_{ix} + \sum_{j=1}^{n}\Big\{({}_xA^o_{i,j,t}\cdot\alpha^r_{i,j} + {}_xA^r_{i,j,t-1}\cdot\beta^r_{i,j}
+ {}_xV^r_{i,j,t-1}\cdot\gamma^r_{i,j} + {}_xD^r_{i,j,t-1}\cdot K^r_{i,j})\cos\theta_{i,j} + ({}_yA^o_{i,j,t}\cdot\alpha^r_{i,j} + {}_yA^r_{i,j,t-1}
\cdot\beta^r_{i,j} + {}_yV^r_{i,j,t-1}\cdot\gamma^r_{i,j} + {}_yD^r_{i,j,t-1}\cdot K^r_{i,j})\sin\theta_{i,j} + f^r_{i,j}\Big\}\cos\theta_{i,j} \quad ,
$$

$$
{}_yA^{o,r}_{i,t}\,(M^r_i + \alpha^{r,r+1}_{iy} + \alpha^{r-1,r}_{iy} + \sum_{j=1}^{n}\alpha^r_{i,j}\sin^2\theta_{i,j}) - \alpha^{r,r+1}_{iy}\cdot{}_yA^{o,r+1}_{i,t}
$$

$$- \alpha^{r-1,r}_{ix} \cdot {}_xA^{o,r-1}_{i,t} - \sum_{j=1}^{n} \alpha^{r}_{i,j} \cdot {}_yA^{o,r}_{j,t} \sin^2\theta_{i,j} + {}_xA^{o,r}_{i,t} \sum_{j=1}^{n} \alpha^{r}_{i,j} \sin\theta_{i,j} \cos\theta_{i,j}$$

$$- \sum_{j=1}^{n} {}_xA^{o,r}_{j,t} \cdot \alpha^{r}_{i,j} \sin\theta_{i,j} \cos\theta_{i,j} = -M^{r}_{iy} A^{o}_{i,t} + {}_yA^{r,r+1}_{i,t-1} \cdot \beta^{r,r+1}_{iy} + {}_yV^{r,r+1}_{i,t-1}$$

$$\cdot \gamma^{r,r+1}_{iy} + {}_yD^{r,r+1}_{i,t-1} \cdot K^{r,r+1}_{iy} + f^{r,r+1}_{iy} - {}_yA^{r-1,r}_{i,t-1} \cdot \beta^{r-1,r}_{iy} - {}_yV^{r-1,r}_{i,t-1} \cdot \gamma^{r-1,r}_{iy}$$

$$- {}_yD^{r-1,r}_{i,t-1} \cdot K^{r-1,r}_{iy} - f^{r-1,r}_{iy} + \sum_{j=1}^{n} \Big\{ ({}_xA^{o}_{i,j,t} \cdot \alpha^{r}_{i,j} + {}_xA^{r}_{i,j,t-1} \cdot \beta^{r}_{i,j}$$

$$+ {}_xV^{r}_{i,j,t-1} \cdot \gamma^{r}_{i,j} + {}_xD^{r}_{i,j,t-1} \cdot K^{r}_{i,j}) \cos\theta_{i,j} + ({}_yA^{o}_{i,j,t} \cdot \alpha^{r}_{i,j} + {}_yA^{r}_{i,j,t-1}$$

$$\cdot \beta^{r}_{i,j} + {}_yV^{r}_{i,j,t-1} \cdot \gamma^{r}_{i,j} + {}_yD^{r}_{i,j,t-1} \cdot K^{r}_{i,j}) \sin\theta_{i,j} + f^{r}_{i,j} \Big\} \sin\theta_{i,j} \quad . \qquad (13)$$

where

$$\alpha = C\,\Delta T/2 - K\Delta T^2/6$$
$$\beta = C\,\Delta T/2 - K\Delta T^2/3$$
$$\gamma = C - K\Delta T$$
$$A^{a,b}_{c,t} = A^{b}_{c,t} - A^{a}_{c,t} = A^{o,b}_{c,t} - A^{o,a}_{c,t}$$
$$A^{c}_{a,b,t} = A^{c}_{b,t} - A^{c}_{a,t} = (A^{o,c}_{b,t} - A^{o,c}_{a,t}) - (A^{o}_{b,t} - A^{o}_{a,t})$$
$$A^{o}_{a,b,t} = A^{o}_{b,t} - A^{o}_{a,t}$$

A : acceleration
V : velocity
D : displacement
ΔT : time increment

superscripts a, b, c :	a, b and c-th floor level
superscripts o :	ground level (basement)
formerly subscript x, y :	x and y direction
subscripts a, b, c :	a, b and c-th particle
subscript t, t - 1 :	t and (t - 1)-th time

The value V and the value D have the same arrangement as value A. Then combination of two superscripts denotes relative values for A, V and D, or members of the story for K, f, α, β, γ and also combination of two subscripts with exception subscript t and t - 1 denotes relative values for A, V and D or members of floor framing for K, f, α, β, γ.

In these expression the values with subscript t - 1 are given at the previous step, M, θ, C/K, Δ T are constants, and A^{o}__ t is given by input data at t. Then stiffness K and friction f are assumed to take constant values during small interval ΔT. And so unknown values are

$xA^{o,r}_{i,t}$, $yA^{o,r}_{i,t}$, $xA^{o,r}_{j,t}$, $yA^{o,r}_{j,t}$, $xA^{o,r-1}_{i,t}$, $yA^{o,r-1}_{i,t}$, $xA^{o,r-1}_{i,t}$, $yA^{o,r-1}_{i,t}$

only . The number of unknown value is 2N, that is twice the total number of particle, and there are same number of equation, so unknown value $A_{\_\,\_,\,t}$ are given as the solution of this algebraic equation at each step. Velocity V and displacement D are given by the following expression

$$V_{\_\,\_,\,t} = (A_{\_\,\_,\,t} + A_{\_\,\_,\,t-1})\,\Delta T/2 + V_{\_\,\_,\,t-1}$$

$$D_{\_\,\_,\,t} = (A_{\_\,\_,\,t}/6 + A_{\_\,\_,\,t-1}/3)\,\Delta T^2 + V_{\_\,\_,\,t-1}\,\Delta T + D_{\_\,\_,\,t-1}$$

In next step these value $A_{\_\,\_,\,t}$, $V_{\_\,\_,\,t}$, $D_{\_\,\_,\,t}$ are used for $A_{\_\,\_,\,t-1}$, $V_{\_\,\_,\,t-1}$, $D_{\_\,\_,\,t-1}$, these solution are obtained step by step.

As examples, the author calculates the one-storied buildings with small horizontal extent, for reasons of the limited capacity of the computer and the limited time for the calculation.

These buildings, which are presented in this paper, have the same plan-shape, total mass and total stiffness of story. However the various stiffness distribution on the story and for the floor framing, two mass distribution and four types of velocity of propagation of earthquake waves are considered.

Each distribution of the buildings calculated are shown in Fig. 10. In the number of four figures for the building, first figure denotes type of mass distribution, second figure denotes type of stiffness distribution in x-direction of story, third figure denotes stiffness distribution in y-direction of story and fourth figure denotes type of stiffness distribution of floor framing.

In these examples, earthquake motions used for calculation are EL centro May 18, 1940 N-S component (in x-direction of the building) and E-W component (in y-direction of the building) only, and its direction of propagation is that of 30 degree anticlockwise to x axis, and its period of duration is three seconds for reason of the calculation time.

Maximum values of relative displacement of all structural members obtained by this calculation, are shown in Fig. 11, 12, 13, 14.

STIFFNESS DISTRIBUTION IN THE SAME STORY

In Fig. 11, the buildings with symmetrical distributions in both x and y directions, such as No. 1111, 1121, 1211, show the same maximum value of the story deflection and in the case of the building with unsymmetrical distribution of mass and story stiffness, and with no eccentricity between both centers of gravity and story rigidity, such as No. 2141, story deflections are similar to those of the buildings with uniform distribution, but in the case of the building with eccentricity between both centers of gravity and story rigidity, such as No. 1131 and 2111, story deflections are different from those of the case of no eccentricity by the effect of rotational motion.

However, maximum values of relative displacements of members of floor framing in the case of the buildings with non uniform stiffness distribution of story show the larger deflection than those of the building with uniform distribution.

STIFFNESS DISTRIBUTION IN THE SAME FLOOR

Fig. 12 shows that the rigidity of floor framing gives large influence to the relative displacement of structural members of the buildings subjected to earthquake motion.

In the case of these examples, when the stiffness of the members of the floor framing is more than ten times as much as the mean value of the stiffness of columns, the floor system of its building can be regarded as the rigid floor in the horizontal direction.

EARTHQUAKE MOTION

Fig. 13 shows that the effect of the difference of earthquake motion for each basements to relative displacements of structural member is unnegligibly large.

In these examples, only transmitting time of earthquake motion is considered. Regarding earthquake motion for each basement of the building, not only the transmitting time but also the pattern of earthquake waves should be considered.

OTHERS

This study does not give any conclusions on the plastic deformation of floor framing of the building yet, however Fig. 14 shows that the plastic deformation of the story differs for each column.

CONCLUSION

By this study, the author obtains the following things.

In the case that the building is not large, the stiffness of the members of floor framing is more than ten times as much as the mean stiffness of columns, the floor system of its building can be regarded as the rigid floor in the horizontal direction.

In case of the building with relatively narrow and long rectangular plan whose dimension of long side is large sufficiently, or with irregular combined plan, whose total length is large sufficiently, and in case of the building with small stiffness for its floor framing, the floor deformation due to earthquake motion should be considered in its seismic design.

The effect of the unbalanced stiffness destribution of the story of the building increases the member stress of the floor framing not only for a portion of unbalanced stiffness but also for a portion far from unbalanced portion.

The difference of earthquake motion for each basement, whose transmitting time is considered only, is influence to the result of the deformation of the building, therefore acceleration records of earthquake must be more accurate for its horizontal extent.

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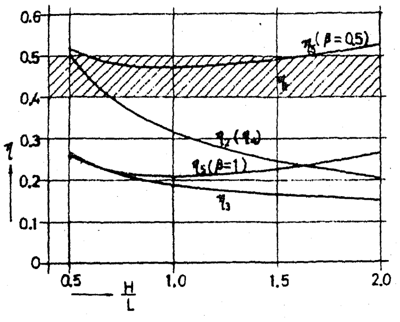

Fig. 1 Realation η for the replacement of the panel to the diagonal bracing and value H/L which is panel ratio of dimension.
η_1 ; TANABASHI (8),
η_2 ; ONITAKE (9),
η_3 ; MATSUI(10),
η_4 ; ODAKA(11),
η_5 ; Eq. (C).

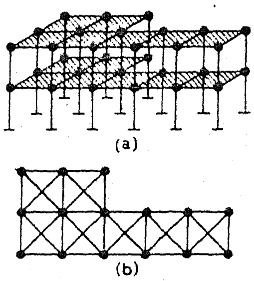

Fig. 2 (a) Model of space structure.
(b) Truss type framing of the floor.

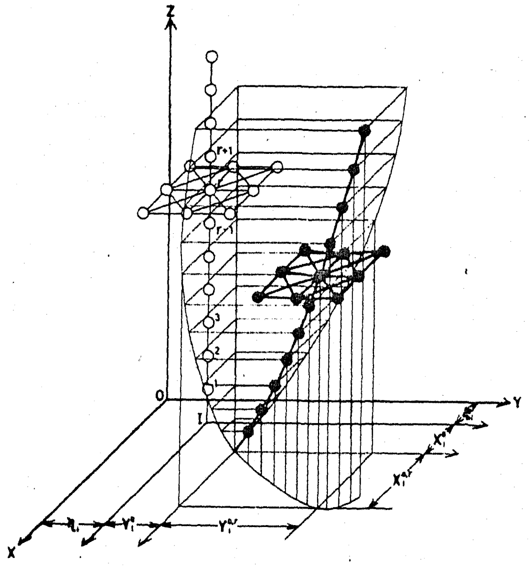

Fig. 3 Coordinates, displacements and relative displacements.

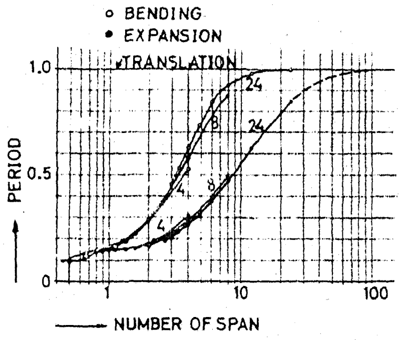

Fig. 4 Relation of period and floor deformation of the buildings with relatively narrow and long rectangular plan.

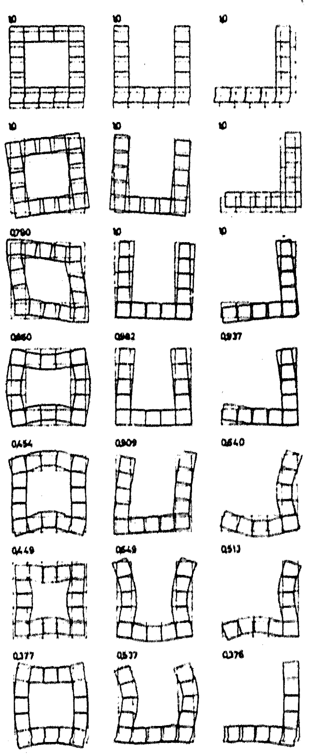

Fig. 5 Examples of natural modes and associated natural periods of the buildings with irregular plan.

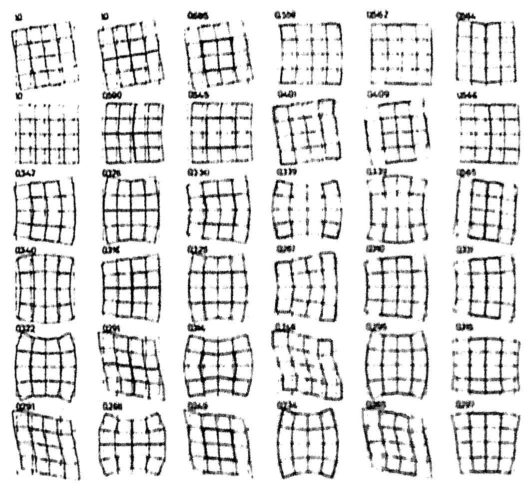

Fig. 6 Examples of natural modes and associated natural periods of the buildings with various eight walls.

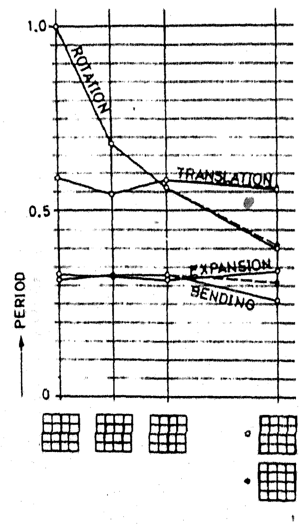

Fig. 7 Fundamental periods of each modes of the buildings with various eight walls.

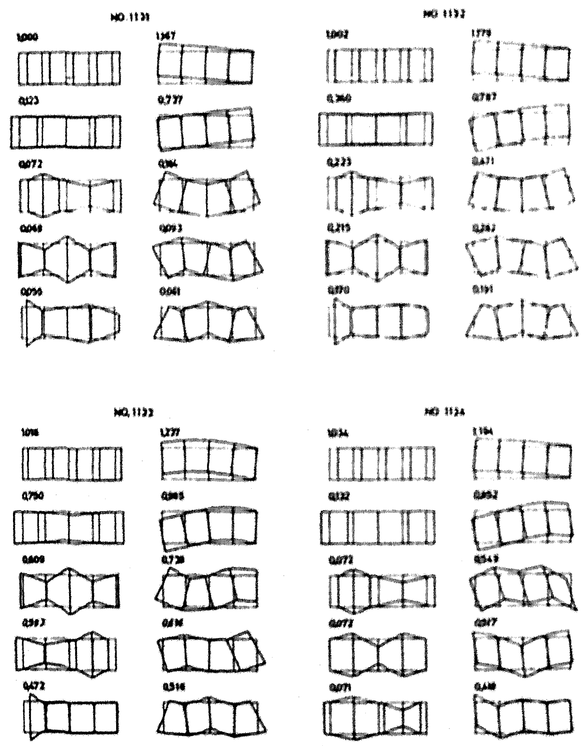

Fig. 8 Examples of natural modes and associated natural periods of the building with various floor rigidy.

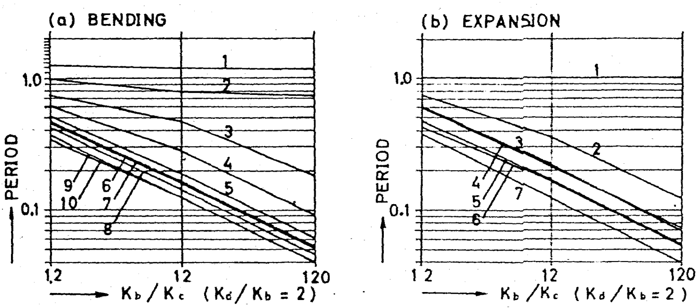

Fig. 9 Relation of natural periods and floor rigidities for each mode.

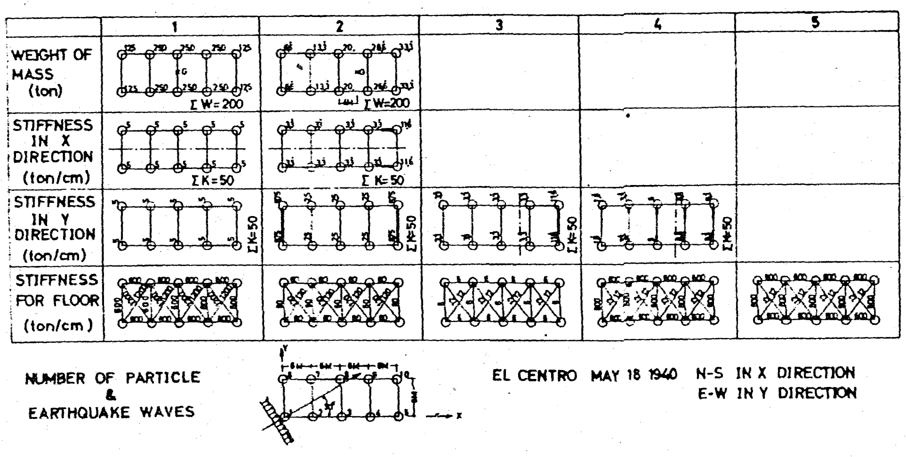

Fig. 10 Distribution of mass and stiffness of the building calculated the earthquake response.

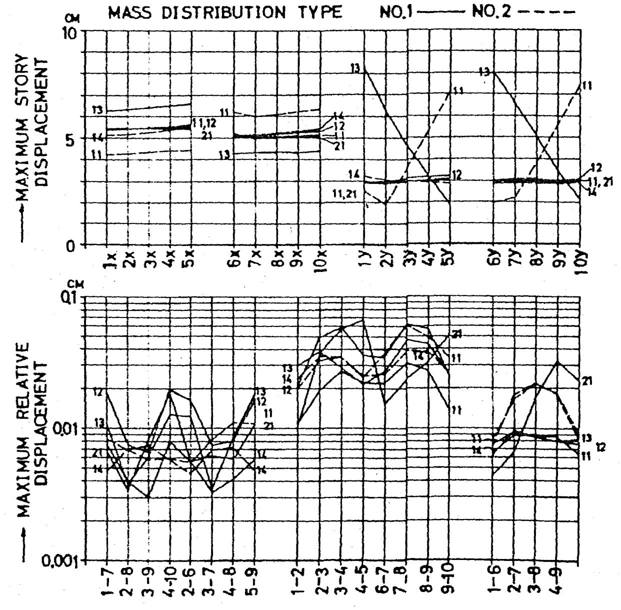

Fig. 11 Maximum relative displacement of the all structural members of the buildings whose No. 1111, 1121, 1131, 1211, 2111, 2141. In the diagram, number of two figures are shown, first figure denotes stiffness distribution in x direction which is second figure of the building No. , second figures denotes stiffness distribution in y direction which is third figure of the building No..

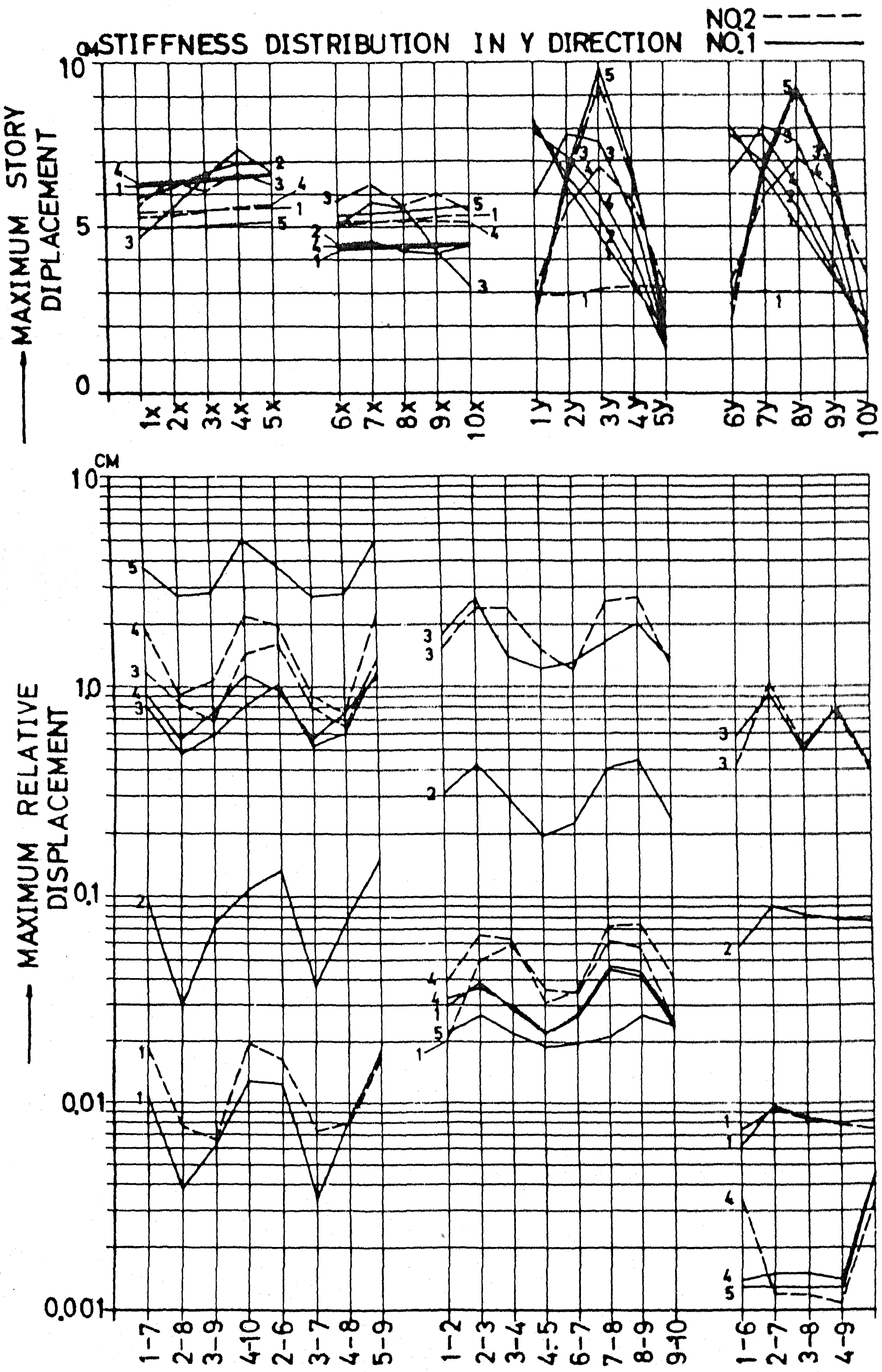

Fig. 12 Maximum relative displacement of the all structural members of the building No. 1121, 1123, 1124, 1131, 1132, 1133, 1134, 1135. The figure, in the diagram, denotes the fourth figure of the building No..

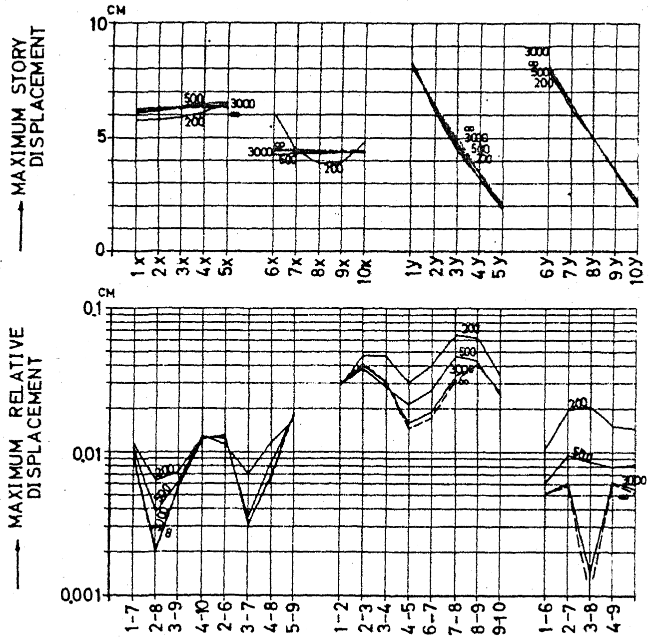

Fig. 13 Maximum relative displacement of the all structural members of the building No. 1131 for the four types of velocity of propagation of the same earthquake waves. The number in the diagram denotes this velocity in m/sec..

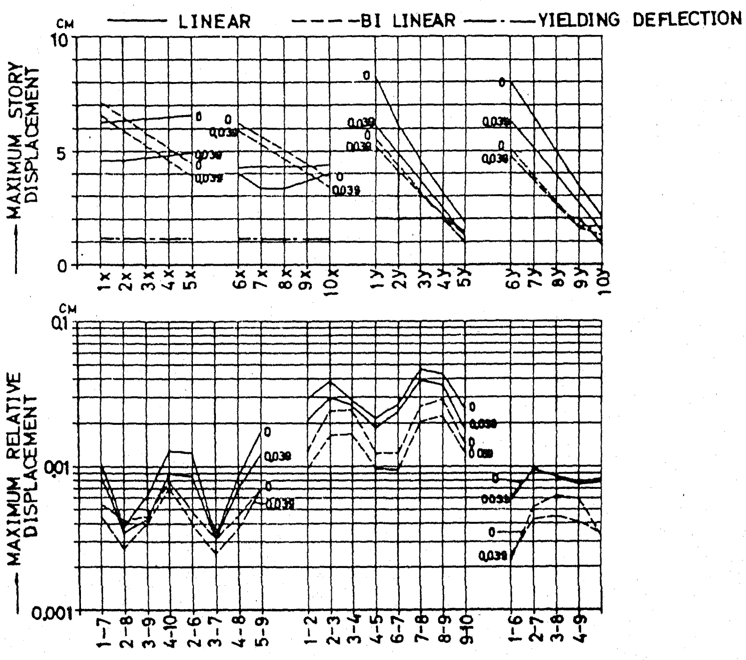

Fig. 14 Maximum relative displacement of the all structural members of the building No. 1131. Examples for the effects of the building with bi-linear force-deflection curve and with damping. Number 0.039 (=h), in the diagram, denotes C/K = 0.005.