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# TORSIONAL RESPONSE ANALYSES OF BUILDINGS SUBJECTED TO BI-DIRECTIONAL GROUND MOTIONS

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## ABSTRACT

Two horizontal strong motion components, orthogonal to each other, are applied to a building with eccentricity simultaneously. The building response behavior is discussed using simple models and , a real damaged building of Hachinohe Library is also presented. The most unfavourable condition of the response behavior is presented when the maximum response direction of the earthquake, related to the 1st mode, is adjusted in accordance with the vibration direction of the building. It is necessary to consider the direction of the seismic input and the direction of the building vibration in the aseismic design of buildings.

## KEYWORDS

torsional response; bi-directional ground motions; vibration direction; response direction; eccentricity; inelastic dynamic analyses; seismic input direction.

## INTRODUCTION

Most of the failure conditions are caused by the effects of torsional vibration excited by earthquake ground motions from observations of damaged buildings. In fact, it is not common the existance of buildings without eccentricities of either stiffness or mass. Thus, it is evident the importance to make the vibration behavior for torsional response clearer in order to diminish the damage of buildings.

In this study two horizontal strong motion components, orthogonal to each other, are applied simultaneously to a building with eccentricity. The response behavior of different buildings is discussed using simple models and, a real damaged building, the Hachinohe Library, is also presented.

## 2-DIMENSIONAL RESPONSE SPECTRA

Three strong motion records of EL CENTRO ( max. peak acceleration of NS-342 gal, EW-210 gal), TAFT (max. peak acceleration of NS-153 gal,EW-176 gal), and HACHINOHE (max. peak acceleration

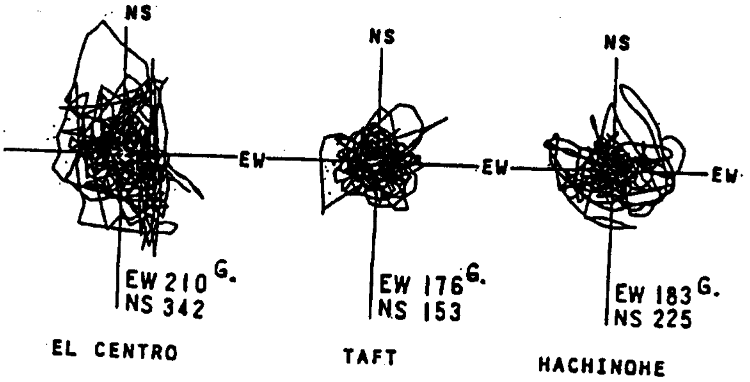


Fig.1 Orbit of Acceleration Strong-Motion Records

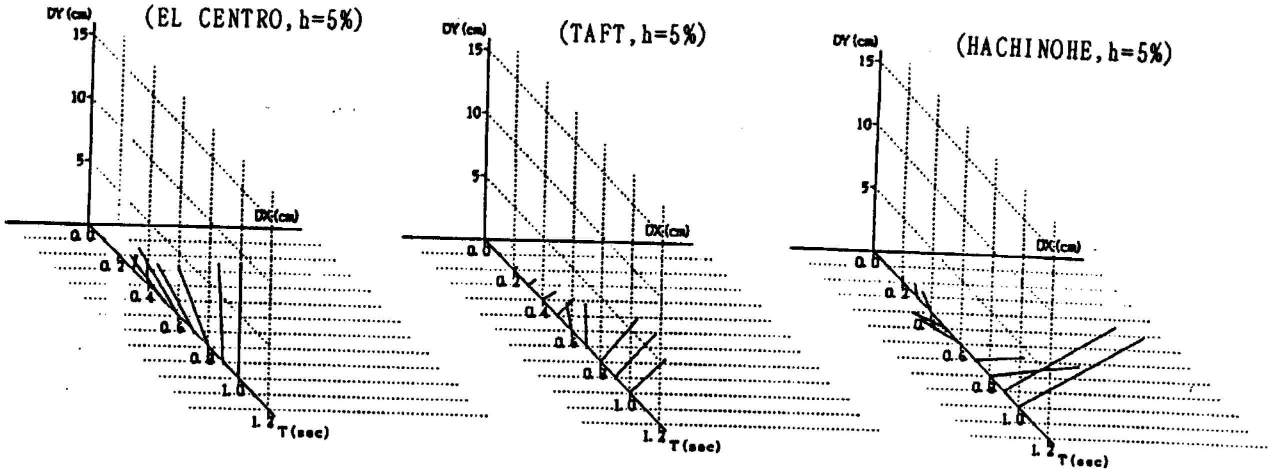


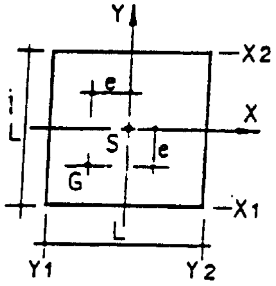
Fig.2 2-Dimensional Response Spectra

of NS-225 gal, EW-183 gal), are used for the analyses. Fig. 1 shows the orbit of acceleration of these three strong motion records at 20 seconds.

One-mass vibration system with 3-degrees of freedom is used. Earthquake waves,EW-component in X-axis and NS-component in Y-axis, are applied to the vibration system simultaneously. The stiffness of the models are the same in both directions, the mass is not eccentrical. The response characteristics for these three earthquake motions are analysed as shown in Fig.2 (these are namely 2-dimensional displacement response spectra). The 2-dimensional response spectra show the maximum displacement response from the periods 0.1 Sec. to 1.0 Sec., where it is possible to observe that they have different response directions. Even for one building natural period, the response direction is not the same when earthquake inputs are different.

## NATURAL VIBRATION BEHAVIOR

Fig.3 shows the basic model of the structure. Three type of models are used. The first is a model M1e having maldistribution of mass for both directions, in which the eccentrical distance of X-direction and Y-direction is the same, and the natural period of the building

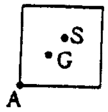
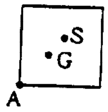
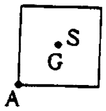


G : Center of Gravity

S : Center of Rigidity

Fig.3 Basic Model of Structure

Table 1 Natural Periods and vibration Direction

| Model | Mode | Period (sec.) | Vibration Direction θ |
|---|---|---|---|
| M1e  | 1 | 0.36 | −45.00 |
| | 2 | 0.30 | 45.00 |
| | 3 | 0.26 | −45.00 |
| M2e  | 1 | 0.51 | −5.32 |
| | 2 | 0.38 | 63.60 |
| | 3 | 0.28 | −86.08 |
| M2  | 1 | 0.50 | 0.00 |
| | 2 | 0.36 | 90.00 |
| | 3 | 0.30 | 90.00 |

without eccentricity is 0.3 Sec. for both directions. The second is the model M2e having maldistribution of mass on both directions, in which the eccentrical distance of X-direction and Y-direction is the same, and the natural period of the building without eccentricity is 0.5 Sec. at X-direction, 0.3 Sec. at Y-direction. The third is the model M2, that is equal to the model M2e without maldistribution of mass or stiffness.

Table 1 shows the natural periods and the predominant vibration directions of each mode, the vibration direction θ of each mode is decided by the participation factors excited along X and Y directions respectively. The vibration directions of M1e are: -45° for the 1st and 3rd modes: 45° for the 2nd mode. For M2e are: -5.32° for the 1st mode: 63.6° for the 2nd mode: -86.08° for the 3rd mode.And for M2 are: 0° and 90° which coincide with the geometrical axis.

## SEISMIC INPUT DIRECTION

Two horizontal strong motion components, orthogonal to each other, are applied to a one-mass vibration system model without eccentricity, in which the period of mass is relative to the 1st mode period of the analysis models mentioned above. The earthquake waves are applied simultaneously for EW-component in X-direction, and NS-component in Y-direction. The maximum response directions related to the 1st mode are shown in Table 2. A larger building response is obtained when adjusting the earthquake input direction to be coincident with the vibration direction of the building.

### Torsional Response Analysis

The directions of seismic input used in the analyses of torsional response changed from 0° ~ 180° . The damping coefficient for the 1st mode is 0.05. Fig.4~Fig.6 show the maximum

Table 2 Max. Response Direction Related to The 1st Mode

| Model | EL CENTRO | TAFT | HACHINOHE |
|---|---|---|---|
| M1e | -67.11<br>22.11 | 64.16<br>-109.16 (70.84) | -47.49<br>2.49 |
| M2e | -56.07<br>50.75 | 40.38<br>-45.70 (134.40) | -21.69<br>16.37 |
| M2 | -53.53<br>53.53 | 44.36<br>-44.36 (135.64) | -22.50<br>22.50 |

* The lower numerals show the direction of seismic input adjusted to the vibration direction of building

response displacements of point A for each model. As shown in Fig.4. The response value is larger when the seismic input of EL CENTRO-EW component is applied in 22.11° with X-axis, and EL CENTRO-NS is applied in 112.11° with X-axis. In the case of TAFT strong motion record: The response value is maximum when EW-component is applied in 70.84° , NS-component is applied in 160.84° . In the case of HACHINOHE strong motion record: The response value is maximum when EW-component is applied in 2.49° , NS-component is applied in 92.49° . These seismic input directions are in accordance with the adjusted directions related to the 1st mode vibration direction of the building as mentioned above. Models M2e and M2 present the same phenomenon as shown in Fig.5 and Fig.6.

Further discussions for inelastic torsional response analyses are carried out using the model M1e. It is subdivided in three cases called Pe1, Pe2 and Pe3 respectively, according to the distribution of the seismic capacity as shown in Table 3. The yield shear coefficient of building is 0.4. The hysteresis model of each frame iss assumed to be degrading tri-linear as shown in Fig.7. Pe1 type has the same seismic capacity for each frame. In the case of Pe2 type, the seismic capacity ratio for X1-frame is 1.4, and for X2-frame is 0.6. In the case of Pe3 type, the seismic capacity ratio for X1-frame is 0.6,and for X2-frame is 1.4. Fig.8 shows the inelastic response results when subjecting them to the two horizontal components of EL CENTRO wave, for the input direction range 0° ~180° . The response results of Pe1 type with the same seismic capacity show the same phenomenon as the elastic model M1e,the response value is greater than in other directions when the input direction is adjusted to the 1st mode vibration direction (EW- 22.11° ,NS- 112.11° ). In the case of Pe2 type , the X2-frame with lower capacity progresses to the plastic zone firstly,then the center of stiffness moves close to the center of mass decreasing the distance of eccentricity, thus the effects of torsion vibration become smaller. Therefore the maximum response direction is not always coincident with the 1st mode vibration direction. In the case of Pe3 type,with lower capacity in the easier drifting X1-frame which progresses faster to the inelastic zone, the building eccentricity increases and, the torsional vibration effect becomes larger and, the effect of seismic input direction is remarkable.

## CASE OF THE DAMAGED BUILDING HACHINOHE LIBRARY

The building Hachinohe Library was damaged in the Tokachioki Earthquake 1968. The plan of the building is shown in Fig.9. There are five spans along the X-axis, and three spans along the Y-axis. There is a Reinforced Concrete wall 12 cm. thick between frames 5 and 6. The building is damaged by the effects of torsional vibration during the earthquake due to the existance

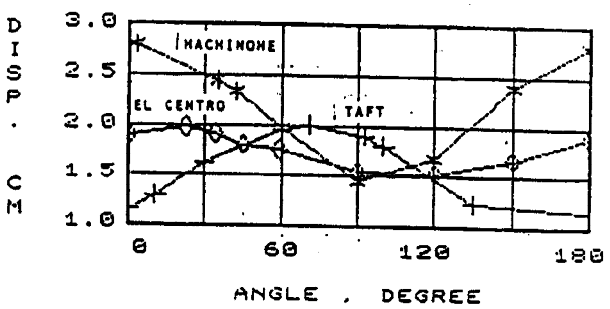


Fig.4 Max. Response Dis. of M1e

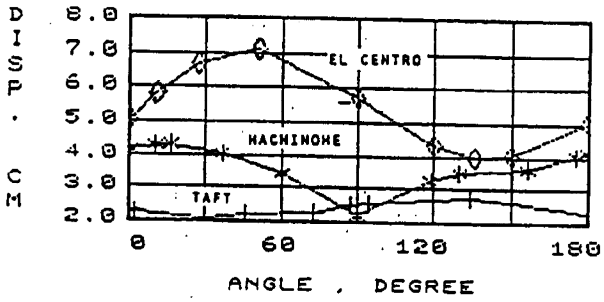


Fig.5 Max. Response Dis. of M2e

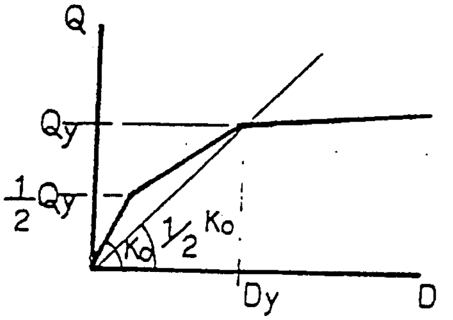


Fig.7 Hysteresis Rule of Each Frame

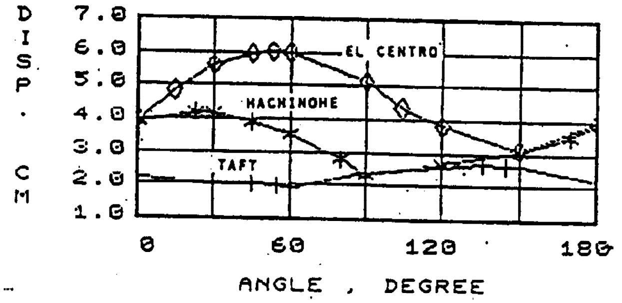


Fig.6 Max. Response Dis. of M2

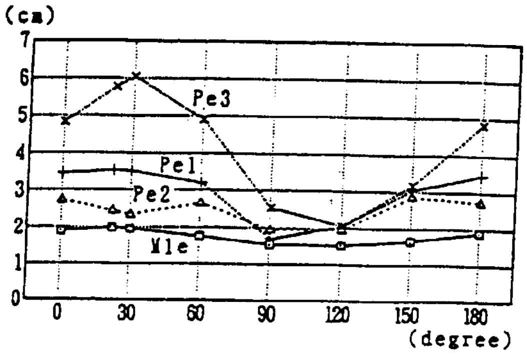
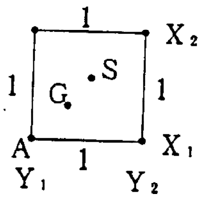


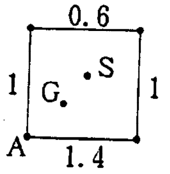
Fig.8 Max. Response Displacements (h=5%)

Table 3 Seismic Capacity Distribution of M1e

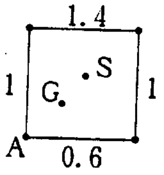
Distribution of The Seismic Capacity



(Pe1)



(Pe2)



(Pe3)

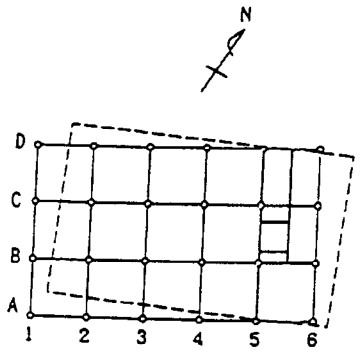


Fig.9 Plan of The Hachinohe Library

Table 4 Natural Periods and Vibration Direction of The Hachinohe Library

| Mode | Period (sec.) | Participation Factor $\beta_x$ | $\beta_y$ | Vibration Direction $\theta$ |
|---|---|---|---|---|
| 1 | 0.332 | -0.154 | -0.628 | 76.2 (256.2) |
| 2 | 0.296 | 0.944 | -0.107 | 173.5 ( -6.5) |
| 3 | 0.122 | 0.006 | 0.714 | 89.5 |

Table 5 Response Direction and Input Direction

| Strong-Motion Records | HACHINOHE (EW,NS) |
|---|---|
| Input Direction | EW=0° , NS=90° |
| Max. Response Direction | −60.4° |
| Vibration Direction of Building | 76.2° |
| Adjusted Input Direction | EW=136.6°,NS=226.6° |

of this wall. This is confirmed by investigations after the earthquake.

The main theme of this study is the seismic input direction, besides the damage phenomena are also discussed. The hysteresis curve of each frame of the building is derived using the step-by-step incremental static analysis method , simplifying this nonlinear relationship to a degrading tri-linear model.

The natural periods, participation factors and vibration directions of each mode are shown in Table 4 . The vibration mode shapes are shown in Fig.10. The 2nd mode is a motion predominant in the X-direction, when an excitation is applied in the X-direction. The 1st mode is a predominant torsional motion coupled with the 3rd mode, when an excitation is applied in Y-direction. The larger deflection side of the 1st mode is the west-side,and of the 3rd mode is the east-side.

Two horizontal components of Hachinohe strong motion record, with a peak acceleration of 225 gal in NS-component and a peak acceleration of 183gal in EW-component,are used. The inelastic torsional response analyses is carried out obtaining response direction and maximum displacement as shown in Table 5 and Fig.11. The 1st mode vibration direction of this building is 76.2° , the direction of the earthquake maximum response displacement related to the 1st mode period (T=0.33Sec.) is -60.4° ; then 136.6° is obtained adjusting the direction of the seismic input to the vibration direction of the building. Also the seismic input direction is changed from 0° ~180° for the response analyses. Unfortunately the building geometry and location was such that when applying the EW-component in 136.6° and NS-component in 226.6° , this was excited in the most unfavorable direction. As a reference, EL CENTRO ground motion

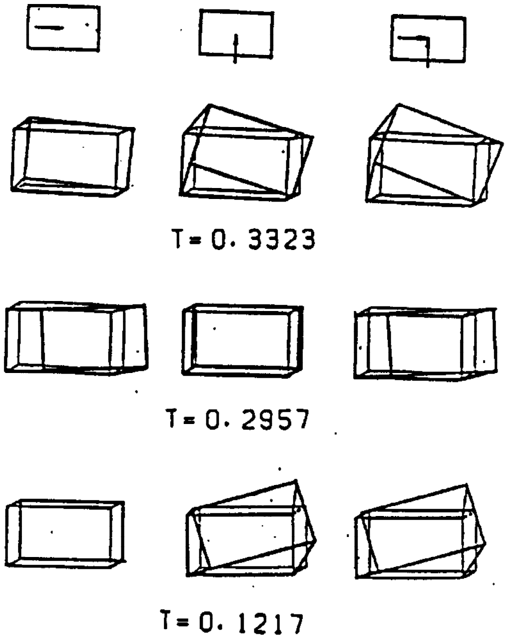


Fig.10 Vibration Modes ($\beta u$)

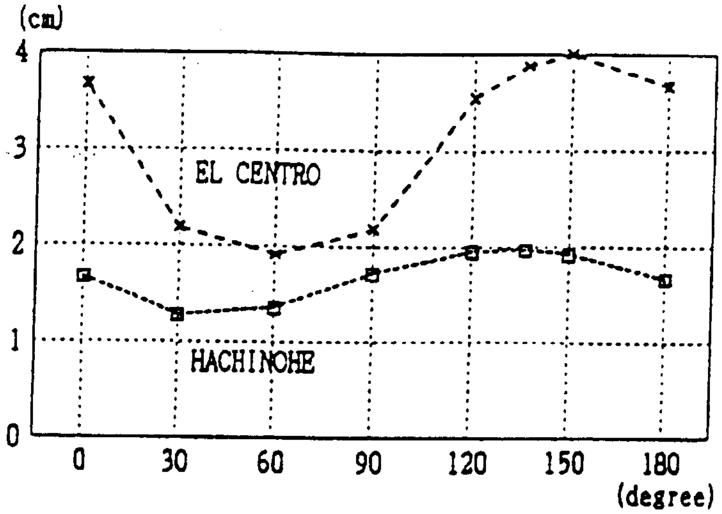


Fig.11 Max. Response Displacements (h=3%)

is used to carry out the response analysis and to show the results in the same figure.

## CONCLUSIONS

The existance of buildings without eccentricities of stiffness or mass is seldom. The effects of eccentricity on the building response behaviors are remarkable. It is important to have the vibration behaviors of the building and the earthquake characteristics clearer in order to diminish the damage of buildings.

The present study tries to investigate both the response direction and the vibration direction and, their effect on the building response. Unfavourable conditions of the response behaviors are presented, when the maximum response direction of earthquake related to the 1st mode of the building is adjusted, in accordance with the vibration direction of the building.

It can be concluded, that it is necessary to consider the direction of the seismic input and the direction of the building vibration in the aseismic design of buildings. This study has led to some important conclusions regarding to problems of seismic input in design.

## ACKNOWLEDGEMENT

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