EARTHQUAKE RESPONSE OF A BUILDING COLLIDED WITH A NEIGHBORING BUILDING

by
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SYNOPSIS

In this paper, the behavior caused by the collision of neighboring buildings during an earthquake motion shall be investigated. That is, the mechanism of the collision shall be simulated by the spring system, containing a dashpot, which is insterted between two model buildings and has some clearance between the spring and one model building (Fig.1(a)). And by this method the earthquake responses of some kinds of buildings shall be inquired.

INTRODUCTION

In Mexico Earthquake of 1957, damages due to the collision of neighboring buildings were observed[1], and since then, in order to avoid the collision, proper clear spacings between two neighboring buildings were provided[2]. On the other hand, in Japan, failures of the expansion joint of buildings were conspicuous in Niigata Earthquake of 1964 and in Tokachi-oki Earthquake of 1968. And as a principal cause of the damages in the expansion joint in Niigata Earthquake, the poor subsoil were considered[3], but almost no attention was being paid to the collision of neighboring buildings. It is, however, considered that severe damages of Misawa Commerce High School and Noheji Middle School at Tokachi-oki Earthquake were owing to the collision of separated portions at expansion joints[4]. But, up to present, there are no studies, both experimental and theoretical, on dynamic behavior of the collision of neighboring buildings. In this paper, earthquake response of buildings will be discussed concentrating on the collision of the neighboring buildings.

METHOD OF ANALYSIS

A dynamical model of building considered in this paper has a flexible floor system which consists of beams and slabs replaced by X-shaped bracing. Moreover it has a mass system, in which distributed masses are concentrated on each top of the columns[5]. The restoring force of the above-mentioned spring system inserted between two buildings acts as compressional force when the distance of the two buildings is shorter than the given distance (Fig.1). To simplify the description, we let the two model buildings have no damping and choose out of all mass points of them those mass points of the two buildings which collision occurs at, and then we number them so that the collision points of the two buildings may correspond. Then the equation of motion of the collision points is as follows:

$$\begin{bmatrix} M^1 & O \\ O & M^2 \end{bmatrix}\begin{bmatrix} X^1 \\ X^2 \end{bmatrix}+\begin{bmatrix} K^1+H & -H \\ -H & K^2+H \end{bmatrix}\begin{bmatrix} X^1 \\ X^2 \end{bmatrix}=-\begin{bmatrix} M^1 & O \\ O & M^2 \end{bmatrix}\begin{bmatrix} x^1 \\ x^2 \end{bmatrix}-\begin{bmatrix} K_f^1+H & -H \\ -H & K_f^2+H \end{bmatrix}\begin{bmatrix} x^1 \\ x^2 \end{bmatrix}+\begin{bmatrix} -H & O \\ O & -H \end{bmatrix}\begin{bmatrix} S \\ S \end{bmatrix} \qquad (1)$$

[M]: mass matrix. [K]: stiffness matrix. [K_f]: stiffness matrix of the floor.

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[X]: column vector of relative displacement to the ground displacement.
[x] : column vector of ground displacement. [S]: column vector of clear spacing.

$$[H] = \begin{bmatrix} k_1^{EJ}\sigma_1 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & \cdot & & & & \vdots \\ \vdots & & \cdot & & & 0 \\ \vdots & & & \cdot & & \\ 0 & \cdot & \cdot & \cdot & 0 & k_n^{EJ}\sigma_n \end{bmatrix} \qquad \sigma_i = \begin{cases} 0 & \text{if } (X_i^1+x_i^1)-(X_i^2+x_i^2)-s_i^{EJ} < 0 \\ 1 & \text{if } (X_i^1+x_i^1)-(X_i^2+x_i^2)-s_i^{EJ} \geqq 0 \end{cases}$$

k^{EJ}: spring constant of expansion joint. s^{EJ}: clear spacing of expansion joint.
Superscript 1, 2 shows the number of the buildings.

Expanding the equation (1), for all mass points of the two buildings we have the general equation of motion as follows:

$$[M][X] + [K][X] = [M][x] + [K_f][x] + [G][S] \tag{2}$$

$$[K] = \begin{bmatrix} K^1 & \\ & K^2 \end{bmatrix} + \begin{bmatrix} H & -H \\ -H & H \end{bmatrix} \qquad [G] = \begin{bmatrix} H & \\ & -H \end{bmatrix} \qquad [S] = \begin{bmatrix} S \\ S \end{bmatrix}$$

$[K_f]$ is transformed into the similar form of [K].
A numerical solution of the Equation (2) uses "Linear Acceleration Method". Compareing the numerical solution with the exact solution of collision of two one-mass system, it is found that the time interval of the numerical solution of collision vibration must be much shorter than the one of no collision vibration.

RESULTS OBTAINED

Because we do not have enough space to describe everything about the behavior of a building collied with a neighboring building, we will introduce a few typical examples.

In the case of a simple system of two buildings as shown in Fig. 1(a), which are subjected only by same ground motion up to the moment of collision, the relations between spring constant of expansion joint and collision period, velocity and displacement at the moment of separation, and coefficient of repulsion as the ratio of relative velocity of separation to that of collision are shown in Fig. 3. In the case of multi-storied buildings, the maximum displacements of the two buildings which have the fundamental periods of 0.4 sec. and of 0.32 sec. respectively, have bi-linear type relation between deflection and restoring force, and have coefficient of inner friction of 0.1 % are shown in Fig. 4. In the case of collision of two buildings on different levels as shown in Fig. 2(c), the relation between the knocked point of the taller column and the angle of bending of the broken column is shown in Fig. 5. Fig. 6 shows the maximum displacements of two one-storied buildings of the same L-shaped plan. One is collided at an expansion joint inserted vertically to one wing, and the other has no expansion joint.

CONCLUSION

As shown in Fig. 3, when the spring constant is small, the collsion period becomes long. On account of the displacement gap between the moments of collision and separation, the kinetic energy increases or decreases according as the potential energy decreases or increases, and it is sometimes observed that the

apparent coefficient of repulsion becomes greater than 1. It seems that this is the same effect as *the pushing of a swing*. When the spring constant becomes large, the collision period approaches π/ω , where ω shows the natural circular frequency of the mode of repulsion. Besides, when the viscous damping acts, the collision period approaches $\pi/\sqrt{1-h^2}\,\omega$ and the coefficient of repulsion approaches $e^{-\pi h/\sqrt{1-h^2}}$, where h shows the fraction of critical damping.

The maximum displacement by collision varies according to largeness of the clear spacing between two buildings. That is, it becomes large when the relative velocity at the moment of collision is large. If there is large difference in the scale of the two buildings, the deformation of the smaller one is greatly restricted by the deformation of the larger one. In the collision of the neighboring buildings whose floor levels are different from each other, a severe bending occurs at that part of a column hammered.

In the case of the multi-storied buildings, the first story suffers a very large deflection when every floor of the two buildings collide each other during the same collision period (see Fig. 4). This condition occurs easily when the buildings have a few stories and the spring constant of the members of expansion joint are small. Conversely, the displacement is comparatively small when the collision does not occur at all the floors. When the buildings are of multi-storiés and vibrate by the higher mode of natural vibration, the collision does not occur at all the floors and it seems to be probable that upper stories suffer a large deflection.

In the case of the building with an irregular-shaped plan which has complicated dynamic property, expansion joint must be constructed to divide the building into several regular-shaped plans with uniform dynamic property for the purpose of preventing unequal vibration. But when the clearance of expansion joint is small, the divided buildings collides each other and when the direction of the collision is not in agreement to the direction connecting gravity centers, they produce large torsional vibration.

ACKNOWLEDGEMENT

The writer is indebted to Prof. H. Kobayashi D. ENG. of Tokyo Institute of Technology for his guidance throughout these studies.

BIBLOGRAPHY

1) Fredrick S. Merritt, "Earthquake Revealed Defects in Design and Construction", Engineering News-Record, Aug. 15, 1957, 38-44.
2) "Provisions for Earthquake Resistant Design in the Federal District. MEXICO", Official 9 Feb. 1966.
3) "General Report on the Niigata Earthquake of 1964", Tokyo Electrical Engineering College Press, Mar. 1968.
4) "General Report on the Tokachi-oki Earthquake of 1971", Keigaku Publishing Co., Ltd., 1971.
5) K. Takeyama, "A study on the Earthquake Response of Space Structures by Digital Computers", Proceedings of 4WCEE, Vol. 2, A-3, 33-49.

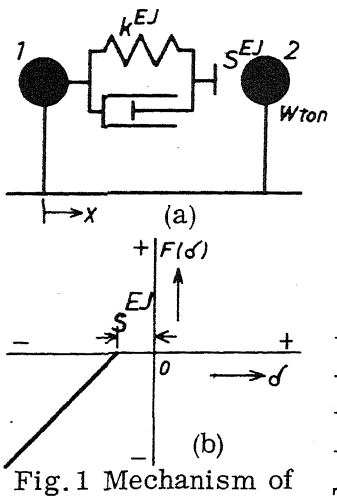


Fig. 1 Mechanism of collision

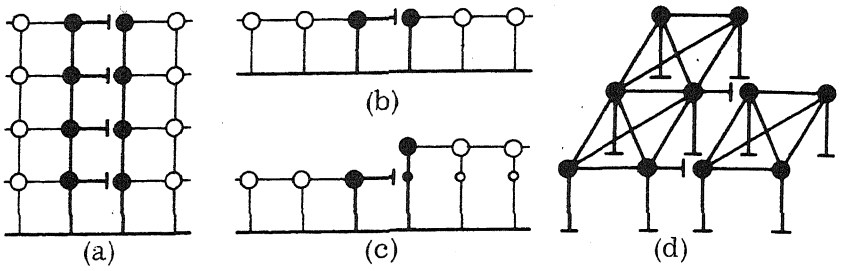
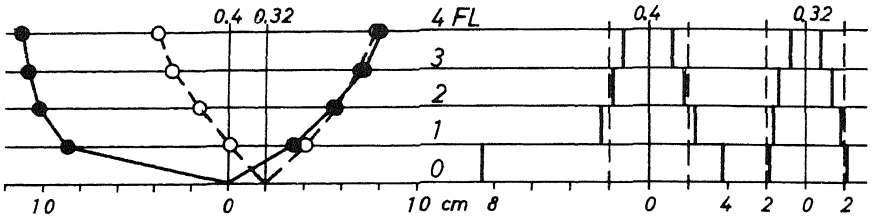


Fig. 2 Examples of model building



(a) Max. displacements (b) Story deflection

Fig. 4 An example of 4-storied building

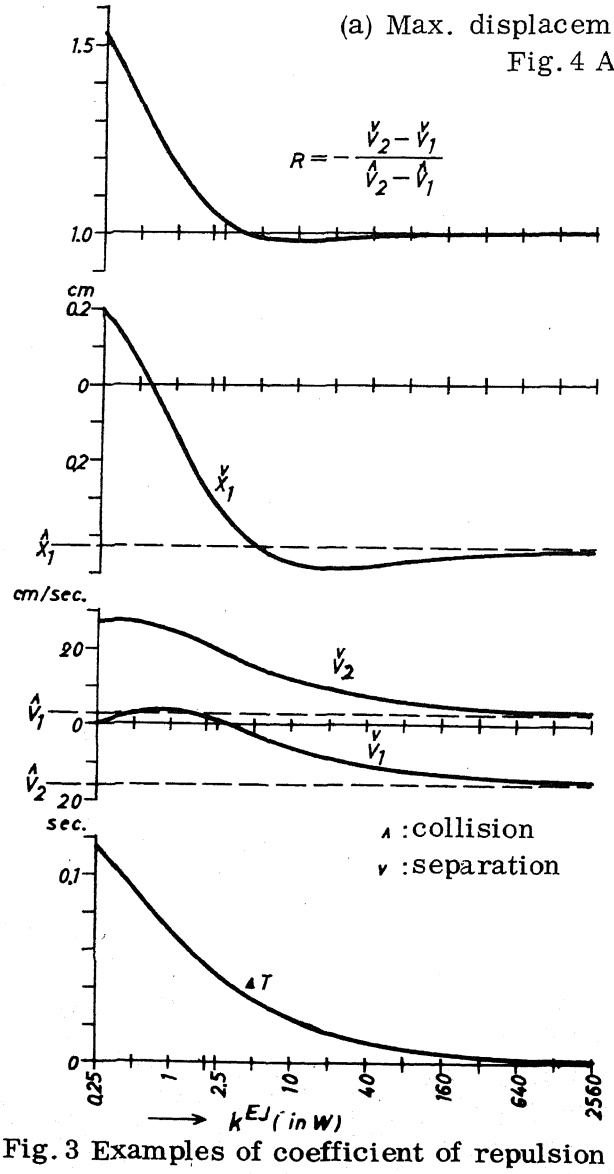


Fig. 3 Examples of coefficient of repulsion

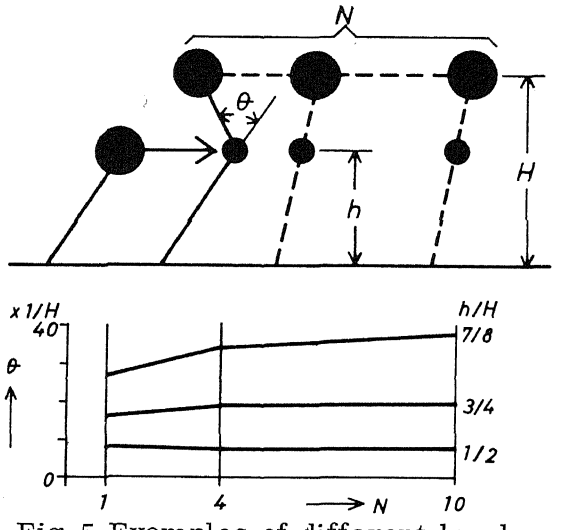


Fig. 5 Examples of different level collision

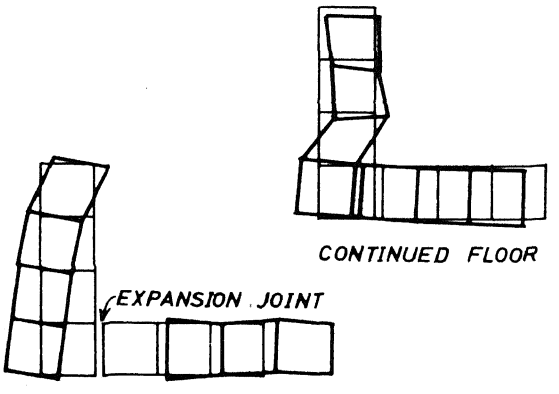


Fig. 6 Examples of L-shaped plan, max. displacement