COLLAPSE OF BUILDING WITH EXPANSION JOINTS THROUGH COLLISION CAUSED BY EARTHQUAKE MOTION

Akira Wada (I)
Yozo Shinozaki (II)
Noriyoshi Nakamura (II)
Presenting Author: Akira Wada

SUMMARY

According to reports on damage of building due to earthquake in the last 20 years, it seems that in many cases, collapse of building is brought about when collision occurs in a structure having expansion joints. When earthquake hits a building with expansion joints, collision occurs and the actual horizontal force produced is greater than that usually calculated in aseismatic calculation. This paper clarifies how to analyze a collision behaviour between adjoining buildings, and indicates that this phenomena is one of the main reasons for collapse of building.

INTRODUCTION

Investigations into past earthquake damage have shown that the pounding together of adjoining buildings in an earthquake has apparently made damage worse in several cases, including those in which the Misawa Commercial High School Building (Photo 1) was hit by the 1968 Tokachi-oki earthquake, the Kuju Lakeside Hotel, by the 1975 Oita earthquake and those of the Mt. Mckinley Building in Alaska, Olive View Hospital in Los Angeles (Photo 2), and Gran Hotel in Managua. Some damaged building fell down completely.

In order to study the effects of pounding, including collapse due to it, the fact that the horizontal component of force occuring to support gravity while the vertical members of the building are inclined is of the same order as the inertial force caused by the earthquake is considered In other words, it is considered that vibration which will not cause the collapse of a separate building can help bring about the collapse of buildings pounding together. Each time pounding occurs the buildings receive horizontal impact forces in the same direction; force to the right is exerted on the building on the right and force to the left, on the building on the left. Because of this, the buildings

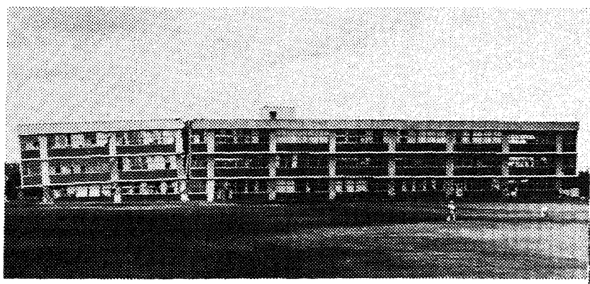


Photo.1 The Misawa Commercial High School

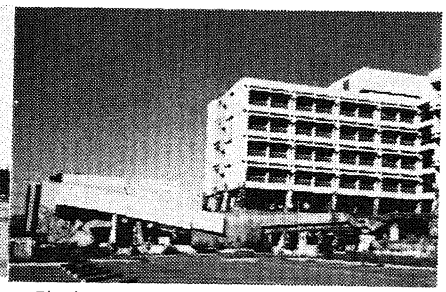


Photo.2 Olive View Hospital

(Courtesy of Dr. Hiroyoshi Kobayashi, Professor of Tokyo Institute of Technology)

(I) Dr.Eng., Assoc.Professor, Tokyo Institute of Technology, Tokyo, Japan
(II) Graduates, Tokyo Institute of Technology, Tokyo, Japan

slid in the opposite directions from vibration centering on the point of origin, are susceptible to the effects of gravity, and fall down while vibrating and sliding in one direction.

In spite of the above-mentioned cases of past damage, existing Japanese aseismic codes give no definite guidelines on the problem of adjoining buildings pounding together.

COLLISION SPRING

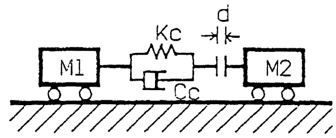


Fig.1

Let us assume there is a collision spring between two masses as shown in Fig.1. The spring is assumed to have restoring force characteristics such that only when the relative distance between the masses becomes smaller than the initial distance (d), the spring contracts and generates force enables us to consider the phenomenon of pounding within the framework of an ordinary response analysis. In the present analysis we assumed that this collision spring corresponds to the axial stiffness of the floors and the beams in each story. The value can be approximated by simple calculation, and is about 5000 t/cm when two square reinforced concrete floor slabs are assumed.

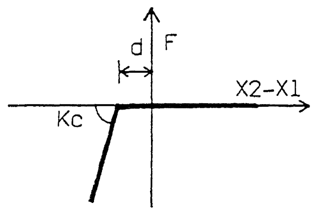


Fig.2

RESPONSE ANALYSIS CONSIDERING EFFECTS OF GRAVITY

Conventional shear models only give an equation of motion in which the effects of gravity are not considered, as follows (see Fig.3).

$$M\,\ddot{x}(t) + C\,\dot{x}(t) + P(t) + M\,\ddot{x}_0(t) = 0 \qquad \text{..........} \quad (1)$$

under elastic conditions

$$P(t) = K\,x(t) \qquad \text{..........} \quad (2)$$

under elasto-plastic condition

$$P(t) = K'\,\Delta x(t) + P(t-\Delta t) \qquad \text{... ... ..} \quad (3)$$

In order to take the effects of gravity into account, however, here we consider one mass vibration model in the form of an upside-down pendulum provided with a moment resisting spring as shown in Fig.4. This makes it possible to set up an equation of motion to enable follow-up until collapse, without taking the displacement ($x = R\cdot\Theta$) of the mass to be infinitesimal.

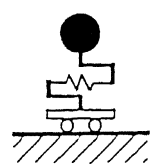


Fig.3

$$\begin{aligned} &M\,\ddot{x}(t) + C\,\dot{x}(t) + P(t) \\ &+ M\,\ddot{x}_0(t)\cos\{\,x(t)/R\,\} \\ &- M\,g\,\sin\{\,x(t)/R\,\} \\ &= 0 \qquad \text{..........} \quad (4) \end{aligned}$$

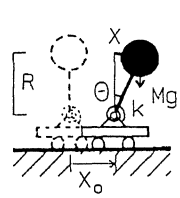


Fig.4

For this equation, too, P(t) of Eq.(2) or (3) may be used.

K in these equations represents a spring constant given by $K = k / R^2$ (k denotes the constant of the moment resisting spring). We can solve this problem by using the linear acceleration method.
The equation of motion at $t = t + \Delta t$ is as follows.

$$M \ddot{x}(t+\Delta t) + C \dot{x}(t+\Delta t) + K x(t+\Delta t) + M \ddot{x}_0(t+\Delta t) \cos\{ x(t+\Delta t) / R \} - M g \sin\{ x(t+\Delta t) / R \} = 0 \cdots\cdots \quad (5)$$

Applying the linear acceleration method gives the following equations.

$$\dot{x}(t+\Delta t) = \dot{x}(t) + \{ \ddot{x}(t) + \ddot{x}(t+\Delta t) \} \Delta t / 2 \quad \cdots\cdots\cdots \quad (6)$$

$$x(t+\Delta t) = x(t) + \dot{x}(t) \Delta t + \ddot{x}(t) (\Delta t)^2 / 2 + \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / 6 \quad \cdots\cdots\cdots \quad (7)$$

When the term $x(t) + \dot{x}(t) \Delta t + \ddot{x}(t) (\Delta t)^2/2$ is replaced with $R \cdot S(t)$ to make the later development easier to understand, Eq.(8) is obtained and cosine and sine terms in Eq.(5) are expressed by Eq.(9) and (10), respectively.

$$x(t+\Delta t) = R \cdot S(t) + \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / 6 \quad \cdots\cdots\cdots\cdots \quad (8)$$

$$\begin{aligned} \cos\{ x(t+\Delta t) / R \} &= \cos\{ S(t) + \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / (6 R) \} \\ &= \cos S(t) \cos\{ \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / (6 R) \} \\ &\quad - \sin S(t) \sin\{ \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / (6 R) \} \cdots\cdots \quad (9) \end{aligned}$$

$$\begin{aligned} \sin\{ x(t+\Delta t) / R \} &= \sin\{ S(t) + \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / (6 R) \} \\ &= \sin S(t) \cos\{ \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / (6 R) \} \\ &\quad + \cos S(t) \sin\{ \Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / (6 R) \} \cdots\cdots \quad (10) \end{aligned}$$

Here, considering the term $\Delta\ddot{x}(t+\Delta t) (\Delta t)^2 / (6 R)$ to be negligible small. We can arrange the equation of motion at $t = t + \Delta t$ as follows.

$$\begin{aligned} & C\{ \dot{x}(t) + \ddot{x}(t) \Delta t / 2 \} + P(t) + K(t+\Delta t)\{ \dot{x}(t) \Delta t + \ddot{x}(t) (\Delta t)^2 / 3 \} \\ & + M \ddot{x}_0(t+\Delta t)\{ \cos S(t) + \sin S(t) \ddot{x}(t) (\Delta t)^2 / (6 R) \} \\ & - M g \{ \sin S(t) - \cos S(t) \ddot{x}(t) (\Delta t)^2 / (6R) \} \\ & = \{ - M - C \Delta t / 2 - K(t+\Delta t) (\Delta t)^2 / 6 + M \ddot{x}_0(t+\Delta t) \sin S(t) (\Delta t)^2 / (6 R) \\ & \quad + M g \cos S(t) (\Delta t)^2 / (6 R) \} \ddot{x}(t+\Delta t) \quad \cdots\cdots\cdots \quad (11) \end{aligned}$$

Therefore, use of Eq.(11) enables us to obtain acceleration at $t + \Delta t$ from the displacement, velocity and acceleration at t , and Eq.(6) and (7) to obtain displacement and velocity at $t + \Delta t$. By repeating this procedure we can obtain advanced response. In this paper we have used a Δt value of 1/1000 sec. for computation.

SPECTRUM-TYPE RESPONSE OF ELASTO-PLASTIC ONE MASS SYSTEM CONSIDERING THE EFFECTS OF GRAVITY

In this analysis the structure is assumed to have restoring force characteristics of the elastic full-plastic model. As an evaluation of the input earthquake wave in this case, the amount of elasto-plastic response of one mass system can be shown by spectrum-type representation as in the case of elastic response. Figs.5 and 6 give spectrum representaions of the elasto-plastic response of the one mass system due to the earthquake wave of El Centro NS 1940 (Max 319.19 gal) used for the present analysis. When g is 980 gal with the coefficient of yield shear force (α_y) value of 0.1 or 0.2 , however, the response absolute amount assumes a very large value, causing falling down in some case. Also, with smaller radius of gyration R the effect of the α_y becomes extremely conspicuous. Thus, considering the effects of gravity g , is important in the study of large displacement dynamic analysis.

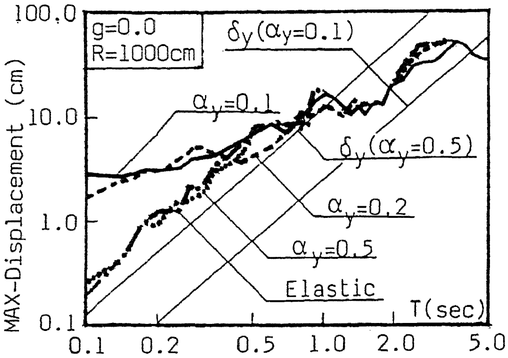


Fig.5 Elasto-Plastic Response

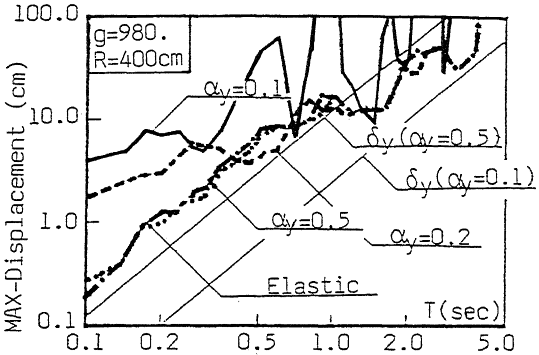


Fig.6 Elasto-Plastic Response

METHOD OF ANALYSIS IN CONSIDERATION OF COLLISION

Independent equation of motion for two masses system can be set up as follows from the Eq.(4) mentioned above.

$$M_1\ddot{x}_1 + C_1\dot{x}_1 + P_1 + M_1\ddot{x}_0\cos\{x_1/R_1\} - M_1 g\sin\{x_1/R_1\} = 0 \quad \text{.......... (12)}$$

$$M_2\ddot{x}_2 + C_2\dot{x}_2 + P_2 + M_2\ddot{x}_0\cos\{x_2/R_2\} - M_2 g\sin\{x_2/R_2\} = 0 \quad \text{.......... (13)}$$

Interlocking between the two masses for P in the above equations occurs during the time they are colliding. When the constant of the collision spring is denoted by Kc , the initial distance between the masses is denoted by d , the center of gravity heights of mass 1 and mass 2 respectively , by R_1 and R_2 , and the height of the point where the collision occurs by R_3 . P_1 and P_2 are given in Eqs.(14) and (15), respectively (see Fig.7). They enable us to consider the interlocking occuring between the two masses.

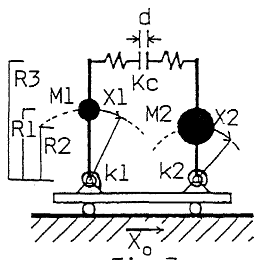
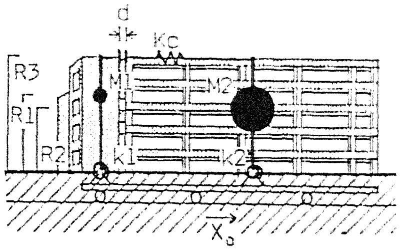


Fig.7

$$P_1 = K_1x_1 + Kc\{x_1(R_3/R_1)^2 - x_2(R_3^2/R_1R_2) - d\} \quad \text{.......... (14)}$$

$$P_2 = K_2x_2 + Kc\{x_2(R_3/R_2)^2 - x_1(R_3^2/R_1R_2) + d\} \quad \text{.......... (15)}$$

EXAMPLE I

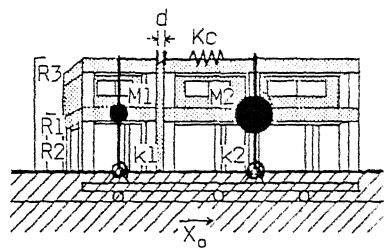


M1:100t M2:4000t
T1:0.5s T2:0.42s Kc:5000t/cm
h1:0.03 h2:0.03 hc:0.0
R1:13.0m R2:11.0m R3:20.0m

Fig.8 Building (I)

When an expansion joint is unintentionally used to connect a stairway tower to a main building, for instance, the former, with a much smaller weight than the latter, will be affected badly by their pounding together. In the past, stairway towers and attached escape stairs have often been damaged.

In this example shown in Fig.8 we have taken a five-storied stairway tower and its main building in a weight ratio of 1 : 40 as our model and made a comparison of the vibrational characteristics in a case in which they pounding each other in an earthquake, and in one in which no such pounding occurs. Fig.9 shows the acceleration of El Centro 1940 NS (Max 319.19 gal) used in this computation. Unlike the case in Fig.10 where the initial distance between two masses is amply large, the case in Fig.11 (line a) , where there is only 10 cm of initial distance of them shows suddenly increasing displacement after pounding, which finally results in gradual falling down due to the effects of gravity. Fig.11 (line b) shows the results of similar calculation when the effects of gravity are not considered. In this case falling down did not occur.



M1:1000t M2:5000t
T1:0.42s T2:0.35s Kc:5000t/cm
h1:0.03 h2:0.03 hc:0.0
R1:4.0m R2:4.0m R3:8.0m

Fig.12 Building (II)

EXAMPLE II

The complete collapse of a story has been noted among cases of earthquake damage to buildings in the past, in which pounding worsened damage in our opinion: the Kuju Lakeside Hotel Building and the city hall of the Mutsu Municipal Office hit by the Tokachi-oki earthquake in Japan, Namely, the idea is that the combination of the occurrence of a small R value in elasto-plastic response, which tends to increase the effects of gravity as mentioned above, and pounding, gave rise to these tragic collapse. This example, uses the height of a story as the radius of gyration R to model the failure of one story. Fig.12 shows the analysis model of the example II. In this analysis, we used the same earthquake for example I.

Fig.13 shows the time histories of displacements at collision points of each mass when initial distance is large and coefficient of yield shear is 0.2. In this case, pounding did not occur.

When the initial distance is 6 cm and coefficients of yield shear are 0.1, 0.2 and 0.3 , the pounding effects have been occured and Fig.14 shows time histories of this analysis results. It is noted that pounding causes a large increase in displacement in the repelled direction, unlike in situations in which pounding does not occur. Fig.15 shows the results of a comparison of vibrational characteristics when the initial distance between two masses and the coefficient of yield shear are used as parameters. With an increase in the initial distance between two masses, there is no pounding and no increase in displacement. When two masses become extremely close on the other hand, the number of times pounding occurs greatly increases, although displacement does not increase so much that a collapse occurs.

CONCLUSION

The simple analysis done so far has led us conclude that pounding greatly increases displacement, the impact of which causes the falling down or collapse of a building or buildings. It must also be emphasized that the effects of gravity are very influential in a situation involving a large amplitude, such as the one analyzed this time, and this gravity effect is the main cause of collapse of a building.

This analysis, based on one mass system, is not sufficient for following up the behavior of an actual structure, but we think that it at least shows that the possibility of large deformation caused by pounding is strong.

There are many groups of tower-like buildings (Photo 3) and apartment houses close together divided by expansion joints (Photo 4) built in area where housing density is high in Japan. Although the possibily of the pounding of such buildings is indeed likely, many structural designers usually draw up aseimatic designs without considering pounding. When building thus pound one another, large impact forces not forseen in the design stage occur and may result in a tragic situation.

ACKNOWLEDGEMENTS

We would like to express our sincere thanks to Dr. Hiroyoshi Kobayashi and Dr. Seiji Kokusho, professors of the Tokyo Institute of Technology, who gave us the chance to begin this research as well as very useful advice.

REFERENCES

1 Kazuhiko Takeyama : Earthquake Response of a Building Collided with a Neighboring Building, Proceedings of the Fifth World Conference on Earthquake Engineering, Vol.2, p.2211 (1973.9)

2. Shizuo Ban : Collision of Two Adjacent Buildings due to Earthquake Excitation, Transactions of the Architectural Institute of Japan, Vol.221, p.1 (1974.7)

3. Christopher Arnold and Robert Reitherman : 'The Adjacency Problem' Building Configuration and Seismic Design, John Wiley & Sons, Inc. , 1982.

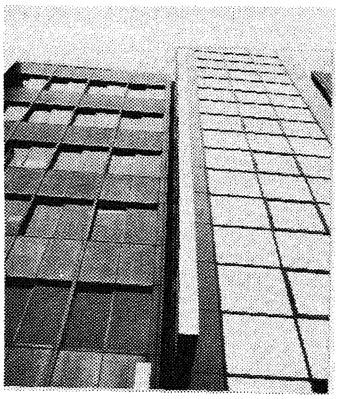


Photo.3 Group of Tower-like Buildings

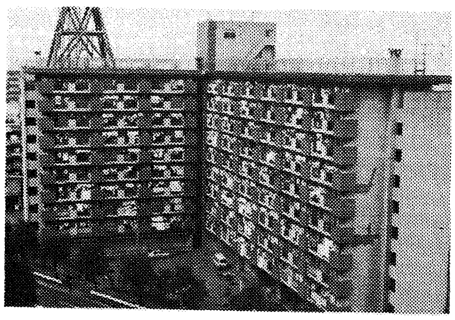


Photo.4
Apartment House divided by expansion joints

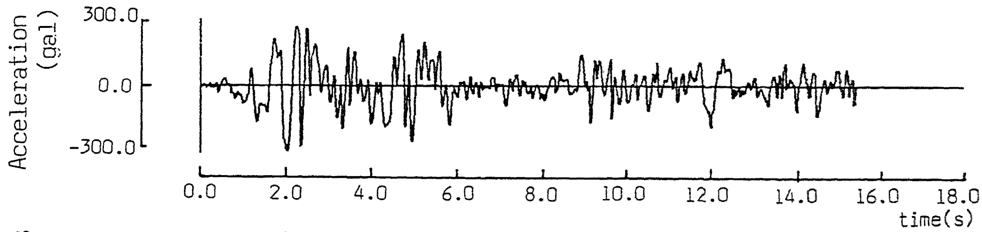


Fig.9 Time Histories of Input Earthquake Wave
(EL CENTRO 1940 NS MaxAcc=319.19 gal)

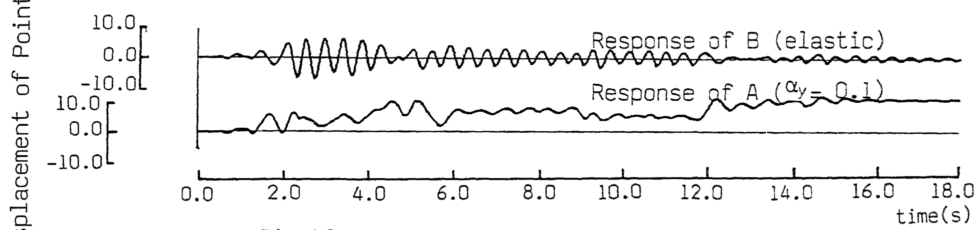


Fig.10 Time Histories of Response without Collision

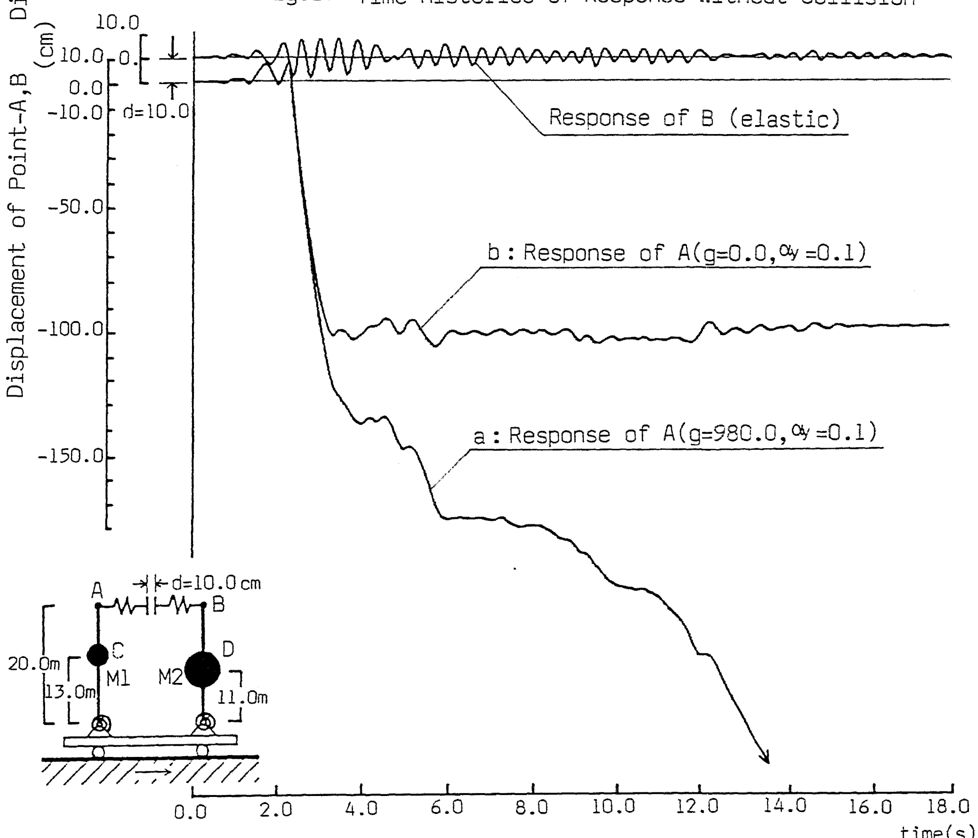


Fig.11 Time Histories of Collision Response

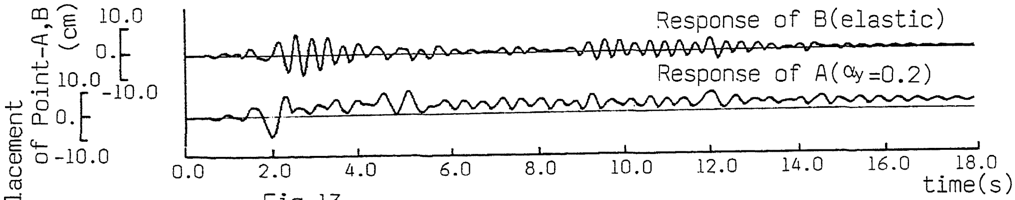


Fig.13
Time Histories of Response without Collision

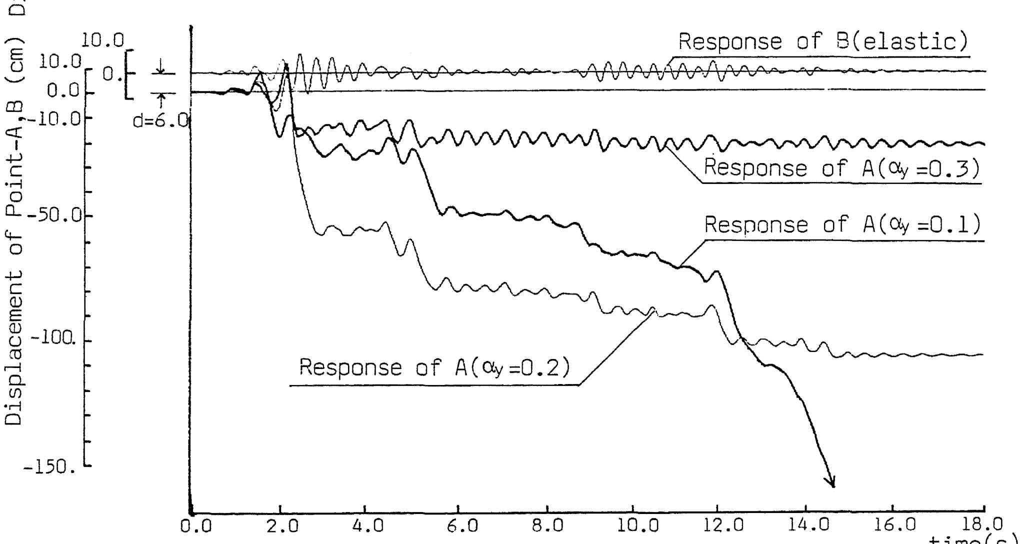


Fig.14 Time Histories of Collision Response

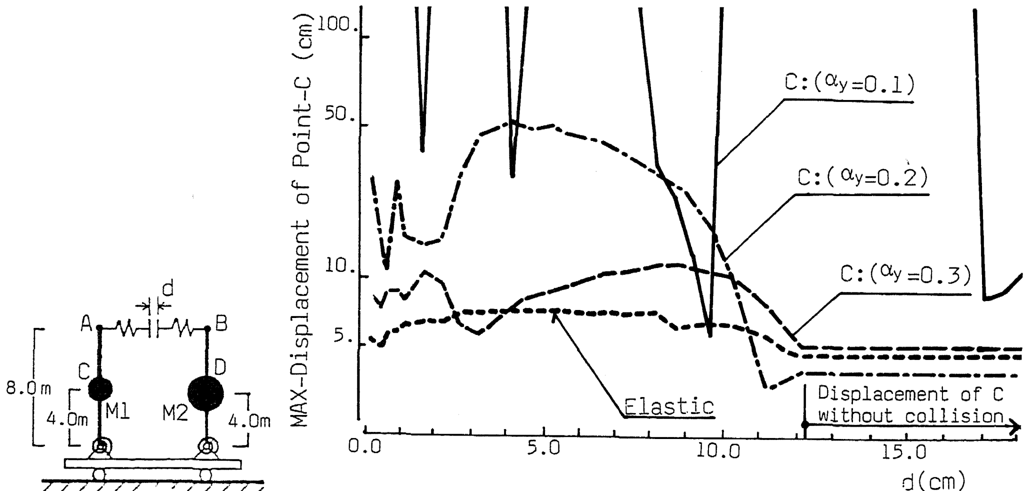


Fig.15 Comparision of MAX-Displacement of Point-C vs. Various Initial Distances