Some Analyses on Mechanism to Decrease Seismic Force Applied to Buildings

by

Kiyoo Matsushita* and Masanori Izumi**

Synopsis

Recent studies[1)] show that the distribution of mass and rigidity is one of quite important factors for aseismic design of multi-story buildings. As an example of practical ways for obtaining the proper distribution, 'Double Basement Method' - a structural method to separate the basement of a building into two parts - are proposed in this paper for the earthquake resisting design of middle height buildings having 10 - 20 stories including base floors.

Analyses on earthquake response of idealized eighteen story buildings, to which this method is applied, are carried out by a digital electronic computer.

Most of the results are presented in the form of graphs showing the effect of rigidity and restoring force characteristics of the first story. The data will serve for the earthquake resistant design for this kind of buildings.

There is a plan to construct an eighteen story building with this method in Tokyo during 1965 - 66.

Notations

d_i = Interstory deflection between i th and i-1 th floor.
ℓ_i = Interstory height between i th and i-1 th floor.
m_i = Mass of i th floor.
y_i = Relative story deflection of i th floor to the base.
C_i = Damping coefficient of i th floor
K_i = Spring constant at i th floor
K_i' = Spring constant in non-linear range at i th floor
Q_i = Restoring force at i th floor
${}_sT$ = Undamped natural period of s th mode
${}_sU$ = Normal function of s th mode at i th floor
$\alpha(t)$ = Ground acceleration
ϕ_i = Shear strain at i th floor (d_i/ℓ_i)

Introduction

Two foundamental ways have been used in aseismic design of buildings; One is to make them rigid and strong so that they can resist against large earthquake forces and the other is to give them long natural periods in order to decrease earthquake forces applied to them.

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For low buildings, it is quite possible to give them enough strength, as the values of base shear force produced are not so large despite the large base shear coefficient.

Tall buildings, on the contrary, have long natural periods, and earthquake forces applied to them are small. Consequently, interstory deflections can remain in a limitation.

The problems are how to design middle height buildings having around 10 to 20 stories. They are not so tall enough as to make the natural period sufficiently long, and not so low to keep the values of shear force less than an economically allowable strength. It is not easy to make flexible buildings of middle height having long natural periods, because of necessity of heat and sound insulation, of protection for fire and, at the same time, of minimizing repair work for cracked finishing after middle size and strong earthquakes. Besides, most of the middle height buildings have basements, which make the distributions of mass and rigidity irregular and cause large values of earthquake response In order to solve this problem, there is such a way of thinking that security of human life is only what we should keep in mind for very severe earthquakes and buildings can be forsaken.

Therefore, elastic design is made for such strong earthquakes that may occur several times during their lives, and plastic design for probable severe earthquakes to keep the building only from collapse.

The methods presented in this paper belong to another thought, i.e., to make aseismic design for middle height buildings having basements through aseismic mechanism which enables the mass and rigidity distributions to be smooth and decrease earthquake forces applied to buildings.

Earthquake Response Related to Rigidity of Lower Stories in Buildings

Most of middle height buildings have basements, and the rigidity in lower part is much larger than that in upper stories, because of their thick R.C. retaining walls. Therefore, a smooth distribution of rigidity cannot be expected, and, consequently, their response to earthquake is apt to be irregular. (See Fig. 1 : Linear response of an ordinary eighteen-stories building including three basement floors and five story penthouse (${}_1T$ = 1.26 sec.) to El Centro 40S Earthquake is compared to an idealized building which has a smooth mass and rigidity distribution (${}_1T$ = 1.26 sec.)).

Computation is made by a digital electronic computer NEAC 2230, based on the following equation of shear vibration.

$$m_i\ddot{y}_i + C_i(y_i - y_{i-1}) - C_{i+1}(\dot{y}_{i+1} - \dot{y}_i) + K_i(y_i - y_{i-1}) - K_{i+1}(y_{i+1} - y_i)$$
$$= -m_i\alpha(t)$$

The fraction to critical damping is assumed as 0.05.

Double Basement Method

In order to avoid the above mentioned disadvantage, "Double Basement Method" is proposed in this paper.

Explanation of the Method

The base-floors of a building are structurally separated into two parts: Part I and Part II. Part I is made of R.C. (if necessary, with steel frames) as one rigid structure including retaining walls. Part I is structurally continuous to upper part, and not so rigid as Part I. (See Fig. 2 A, B, C and D Examples of Double Basement Method. A: Part II is surrounded by Part I in the plan, structurally separated, B: Flat slab construction is used for Part I, and through holes at the centre of the slabs, steel columns of Part II are built. C: Within the columns of Part I, steel columns of Part II are erected. D: For increasing the effect of damper, first ground floor will produce frictional force between the ground. It could also be made so that restoring characteristic may be changed.

Determination of Rigidity Distribution

Rigidity at base-floors can be determined freely adopting double basement method.

In the case, when strength of structural members are so sufficient that earthquake response may remain within elastic range, such rigidity distribution may be desirable as produce uniform values of $d_{i\ max}$ in earthquakere - sponse. If the story heights are different, the maximum shear strain $\phi_{i\ max}$ ($= d_{i\ max}/\ell_i$) instead of $d_{i\ max}$ should be uniform in order to minimize the damage of partition walls, finishing and other secondary structural elements. However, distribution of K_i thus determined depends to some extent on respective earthquakes. (See Fig. 3. Distributions of K_i and the values of $d_{i\ max}$ of buildings of ${}_1T = 1.26$ sec. produced in response to such earthquakes as El Centro 40S, Taft 52W, and Taft 52S, when their intensities are so modified that the maximum values will reach to 0.3g)

Consequently, for actural design, the type of earthquakes used for analyses may be chosen according to ground conditions of the site such as predominant natural periods of the ground, the shape of response specra at or near the site, etc.

In this paper, three earthquakes which response spectra are quite different are used as an example, and yet an K_i distribution which may be called as standard can be obtained as shown in Fig. 4. (Fig. 4 : An assumed standard K_i distribution and $d_{i\ max}$ obtained from linear response to the El Centro 40S, Taft 52W, and Taft 52S Earthquake. Fig. 5 : Undamped natural periods and normal functions of the standard model).

When a building can be built like what is shown in Fig. 2 A, it seems desirable to determine the distribution of K_i through the above mentioned steps in the stage of structural design.

For buildings belong to the types of Fig. 2 B, C and D, the same method can be applied. Besides, it may be also possible to make rigidity of columns at base-floors smaller by taking off beams, in the case when plan of the building is so made that large torsional motion will not occur.

Then, a building having flexible first story will be designed. The reason why the thought of 'Flexible first story' was not put into practice so often, may be the possibility of unstable motions. The flexible first story will cause a large value of d_i and produce a large bending moment combined with vertical load of upper stories, which may give a negative slope to elasto-plastic restoring force characteristics; If the stress is not exceed the yield value, then unstable response will not be observed as it does not concern to the negative slope. At present, it is quite possible to use structural materials having high yield points and strength, and the "flexible first story" construction could be built.

Computed Response of Building having Flexible First Story

Response of structure, which have the same K_i values in the upper fifteen stories as the standard model shown in Fig. 4 and different values of K_i for the three-story basement, to the El Centro 40S, Taft 52W and Taft 52S Earthquake are computed. (Fig. 6 : Models for buildings having flexible first stories. Fig. 7 A, B and C : Relation of $d_{i\ max}$ at each story and natural periods of buildings to the rigidity of the lowest story K_1, A - Response to El Centro 40S Earthquake, B - Response to Taft 52W Earthquake, C - Response to Taft 52S Earthquake. Fig. 8 : Undamped natural periods and normal functions of the standard model having flexible first story).

From the results, following items may be said.

1) In general, as K_1 increases, values of $d_{i\ max}$ except $d_{1\ max}$ increase.

2) How the values of d_i change depends on earthquakes. The Taft 52S Earthquake produces a relatively smooth curve, while the El Centro Earthquake makes a eminent peak when the natural period of the building is around 2 sec., as can be expected from the response specrum cruves for one-mass system.

3) In order to keep the value of $d_{1\ max}$ within some range and to obtain small values of $d_{i\ max}$ in upper stories such K_1 as make natural period around 1.4 sec. may be reasonable to the El Centro 40S and Taft 52S Earthquake. In this case d_1 (for 3 stories) is around or less than 5 cm and values of d_i except d_1 are 40% - 95% of those obtained from response for an uniform $d_{i\ max}$ distribution. (See Fig. 9)

4) This K_i, however, does not give so good effect to upper stories in the case of the Taft 52W Earthquake: d_{18} increases about 10% though d_4 decreases about 45%.

5) It is not so effective to apply 'flexible first story theory' to buildings which will be built in the site where earthquake waves of long periods could be predominent.

Restoring Force Characteristics

For buildings belong to the groups of Fig. 2 B, C and D have such a hardening-spring type restoring force characteristics as shown in Fig. 10., when the clearance between Part I and Part II is so adjusted, and soft materials are used as shock absorbing fillers.

This can act as a safty valve, for it prevents an unexpected large deflection at the flexible story, and saves the building from collapse, though cracks might be made in upper story in the case of very severe earthquakes. Fig. 11 A, B, C show the effect of restoring force characteristics of buildings (T = 1.43) having flexible first stories to the El Centro 40S, Taft 52W and Taft 52S Earthquake under such assumption that their maximum values reach to 0.40g.

Results obtained show that prefarable clearance is around 3 - 4 cm. (See Fig. 12)

Effect of Vertical Load

Stresses produced in the lower stories of a building subjected to large vertical load should not exceed their yield values in earthquake response. (See bibliography (2)). As for elastic range, the vertical load give a slight effect to the natural period and the response of the structures. (See Fig. 13).

Conclusive Remarks

Results of computation may deduce the following conclusions:

1) Proper values of the rigidity and smooth distribution of the mass remarkably decrease the values of earthquake response.

2) In order to obtain proper values of rigidity and mass distribution, structural separation of the base floors with double basement method is convenient.

3) In the case when only small torsional vibration might be produced in multi story buildings having basements, flexible first story may be adopted under this method.

4) When the ground condition is such that long periods are predominant in earthquake waves, flexible first story is not effective.

5) To erect the columns to support the multi stories within the columns which are rigidly connected to retain walls give prefarable effect to the restoring force characteristics in the case of severed earthquakes. This restoring force characteristics are adjustable according as the dimention of clearance between above mentioned columns.

6) In elastic vibration, effect of vertical load is not so large.

Bibliography

1) T. Hisada, K. Nakagawa and M. Izumi, "Earthquake Response of Tall Buildings, Part I and Part II", Occasional Report, Building Research Institute, Ministry of Construction, 1964.

2) T. Hisada, K. Nakagawa and M. Izumi, "Effect of Vertical Load to Earthquake Response of Buildings, Transactions of the Architectural Institute of Japan, No.89, 1963.

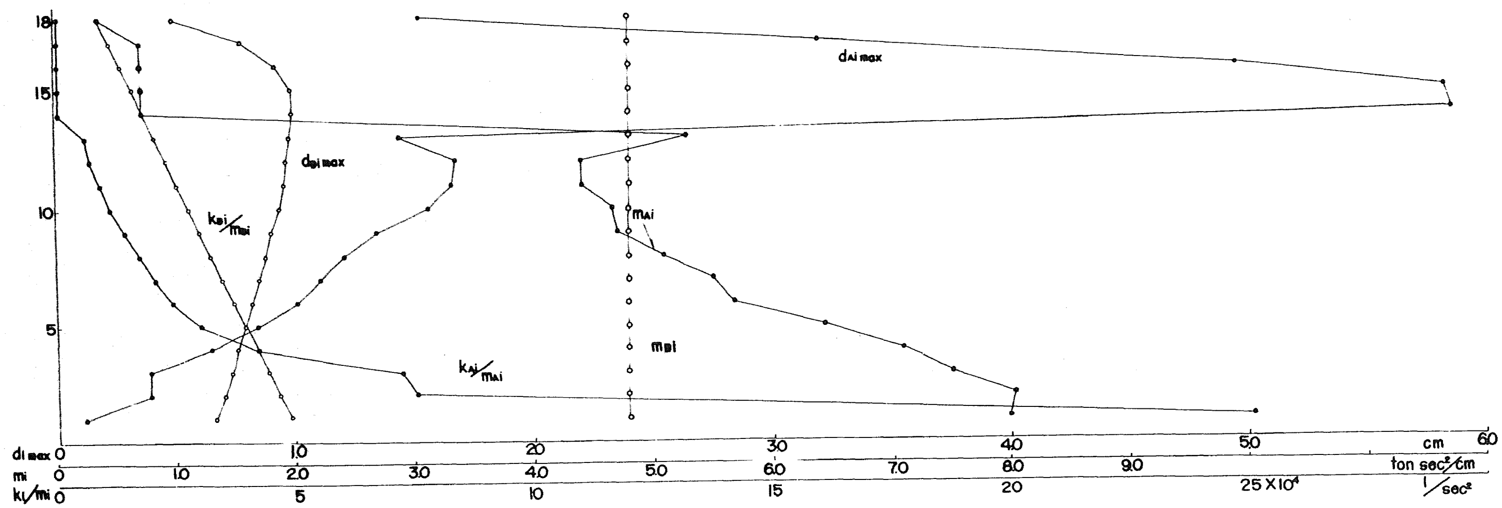
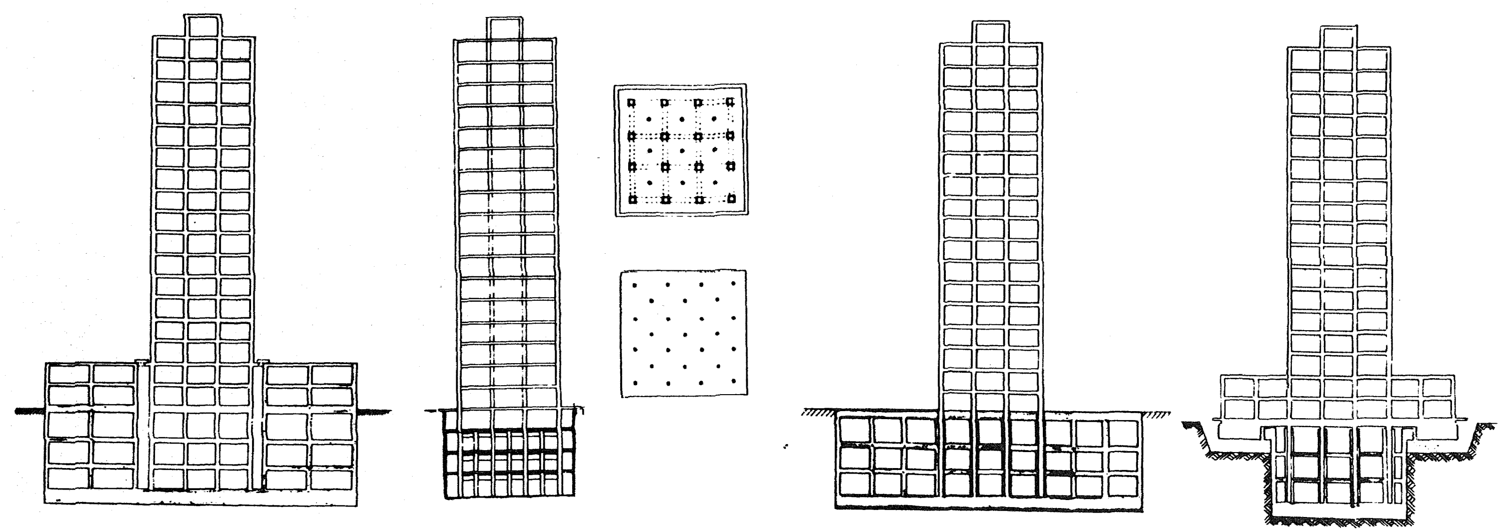


Fig. 1 Mass and Rigidity Distribution of Buildings and Response to the El Centro Earthquake. (Comparison of an ordinary building having irregular distributions with an idealized one having smooth distributions)



A = Part II is surrounded by Part I in the plan.

B = Flat slab con construction is used for Part I, and through holes at the centre of slab, steel columns of Part II are built

C = Within the columns of Part II are erected.

D = For increasing the effect of damper, first ground floor will produce frictional force between the ground.

Fig. 2 Examples of Double Basement Method

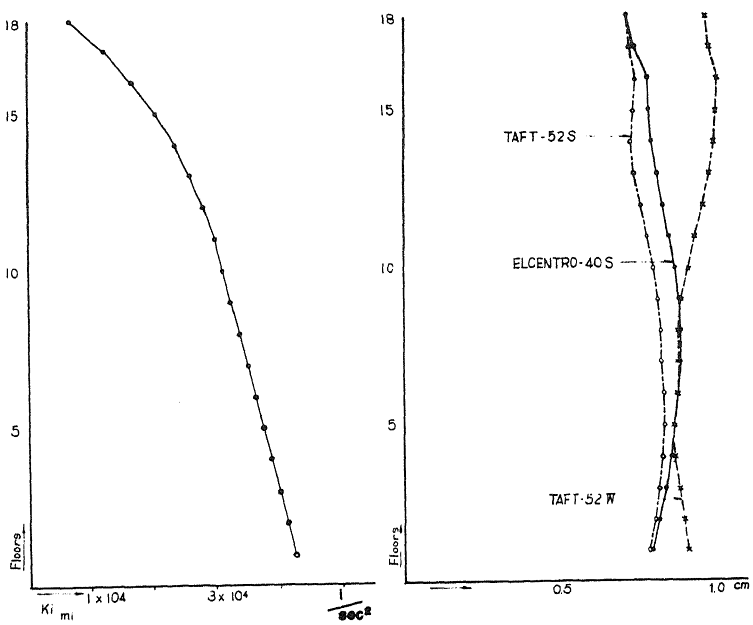


Fig. 3 Distribution of K_i and the Uniform Values of $d_{i\ max}$ of Buildings ($_1T$ = 1.26 sec.) in Response to El Centro 40, Taft 52W and Taft 52S.

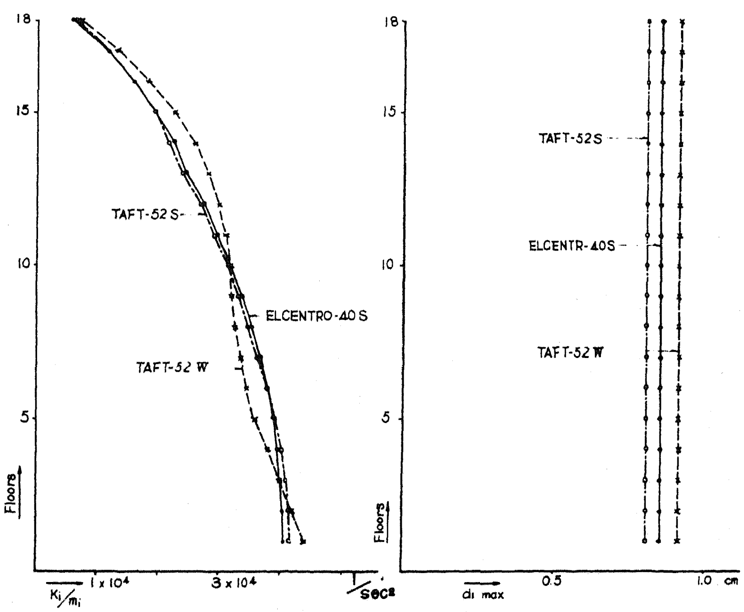


Fig. 4 An Assumed Standard K_i Distribution and $d_{i\ max}$ Obtained from Linear Response to El Centro 40S, Taft 52W, and Taft 52S Earthquakes.

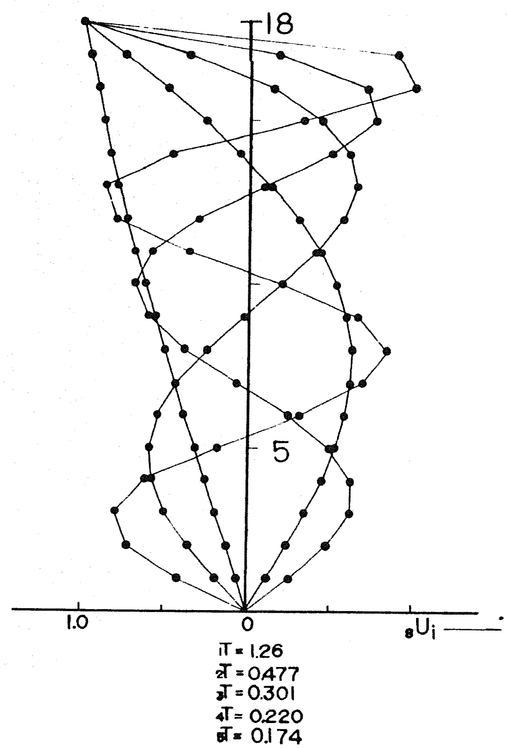


Fig. 5 Undamped Natural Periods and Normal Functions of the Standard Model.

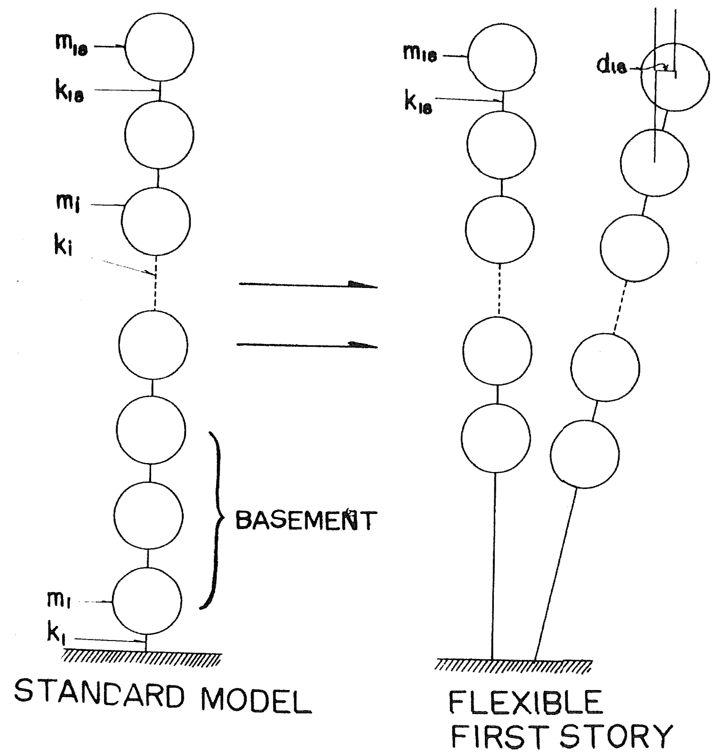


Fig. 6 Models for Buildings Having Flexible First Stories.

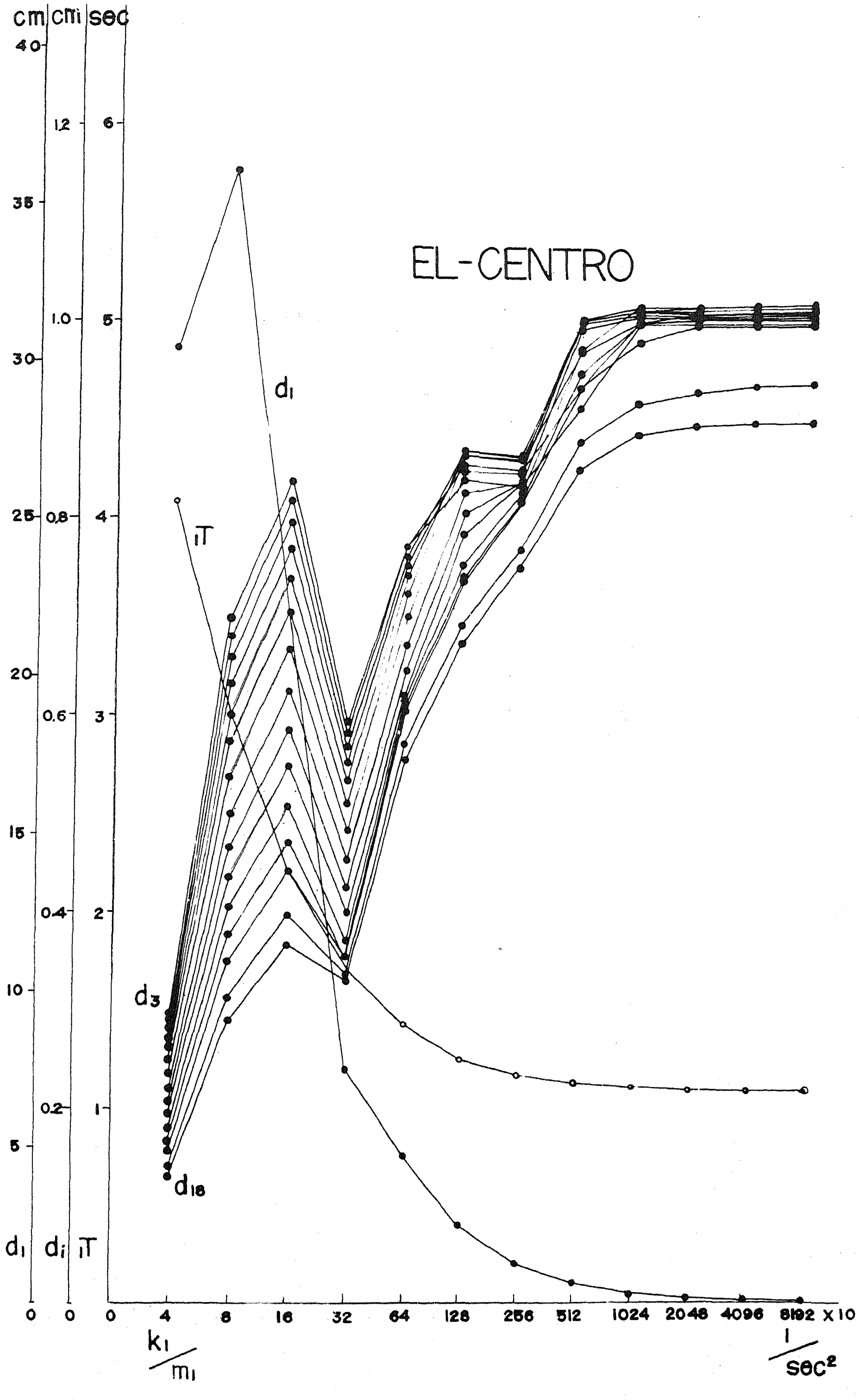


Fig. 7 Relation of $d_{i\ max}$ at Each Story and Natural Periods of Buildings to the Rigidity of the Lowest Story K_1
A : Response to El Centro 40S Earthquake

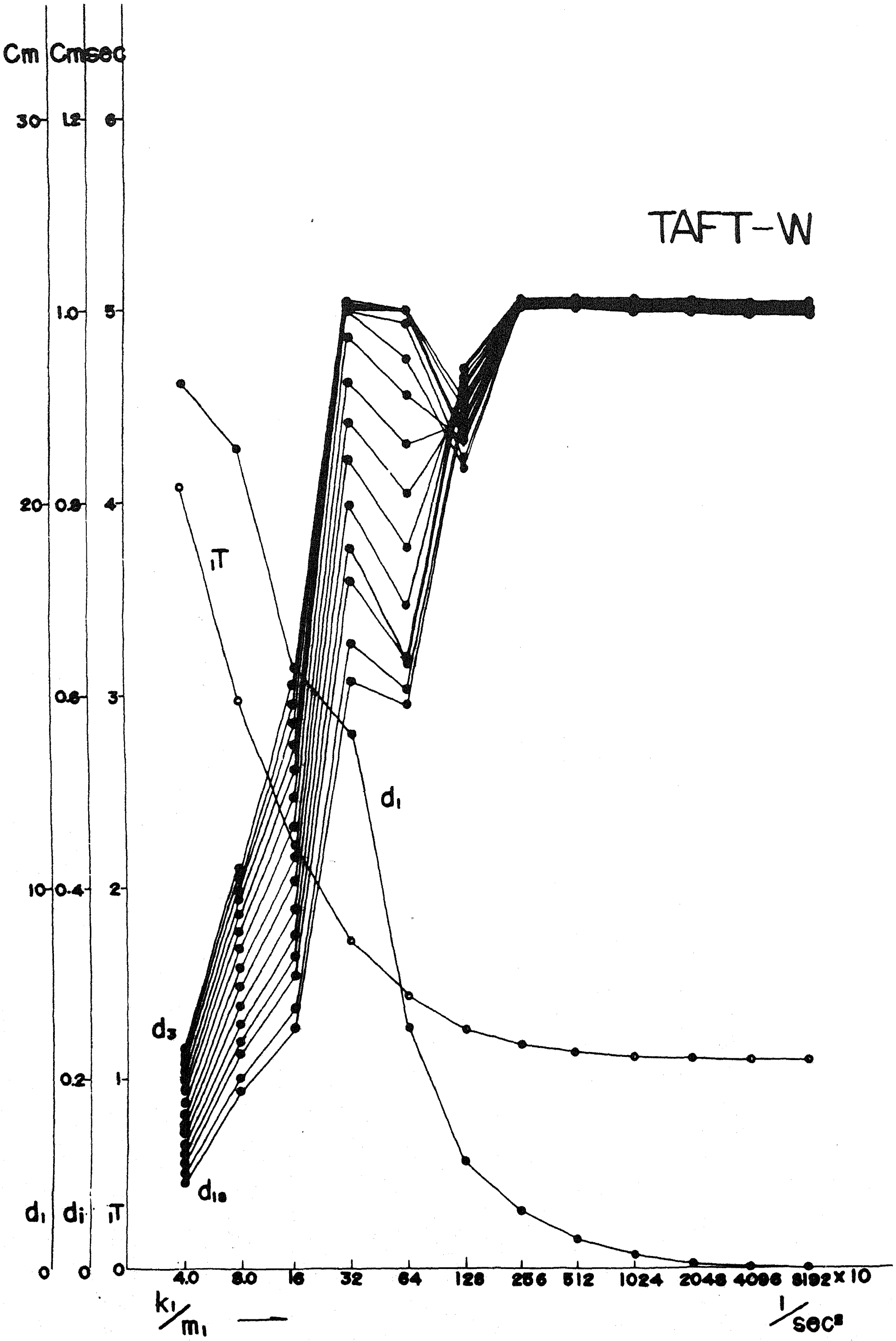


Fig. 7 Relation of $d_{i\,max}$ at Each Story and Natural Periods of Buildings to the Rigidity of the Lowest Story K_1
B : Response to Taft 52W Earthquake

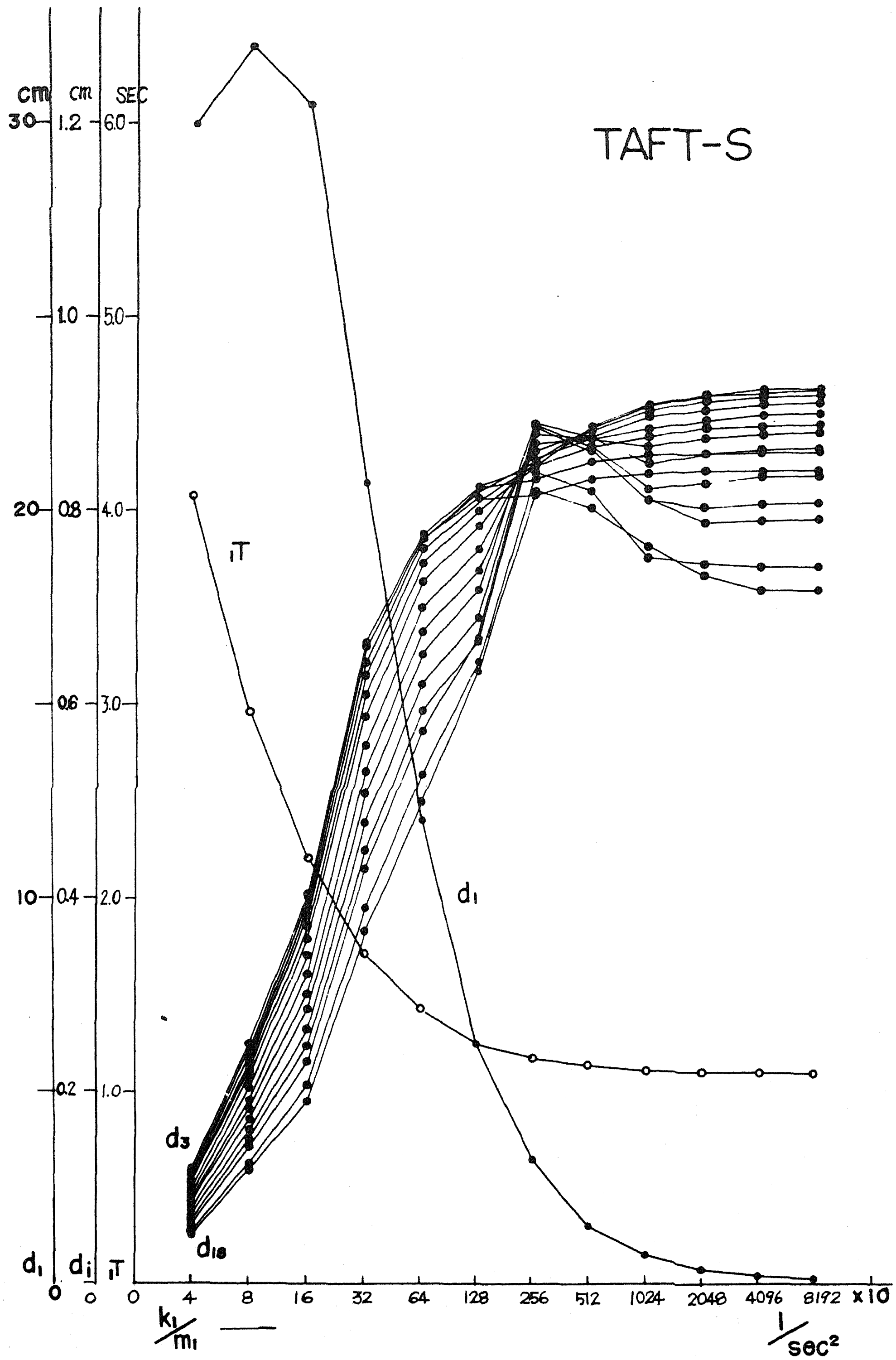


Fig. 7 Relation of $d_{i\ max}$ at Each Story and Natural Periods of Buildings to the Rigidity of the Lowest Story K_1
C : Response to Taft 52S Earthquake

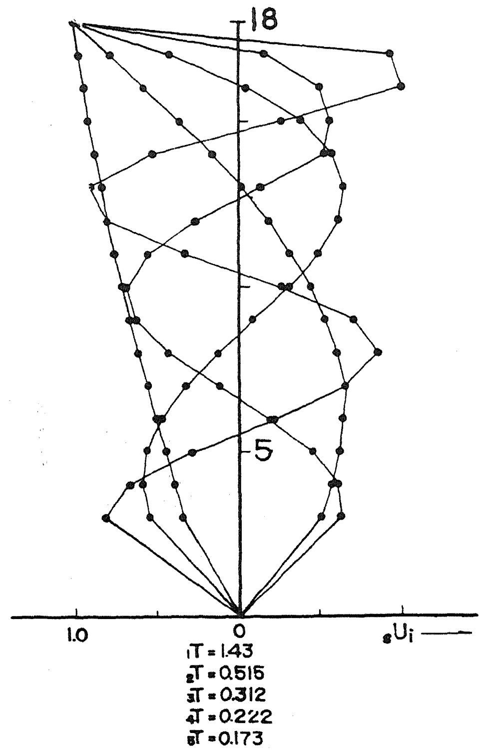


Fig. 8 Undamped Natural Periods and Normal Functions of the Standard Model Having Flexible First Story

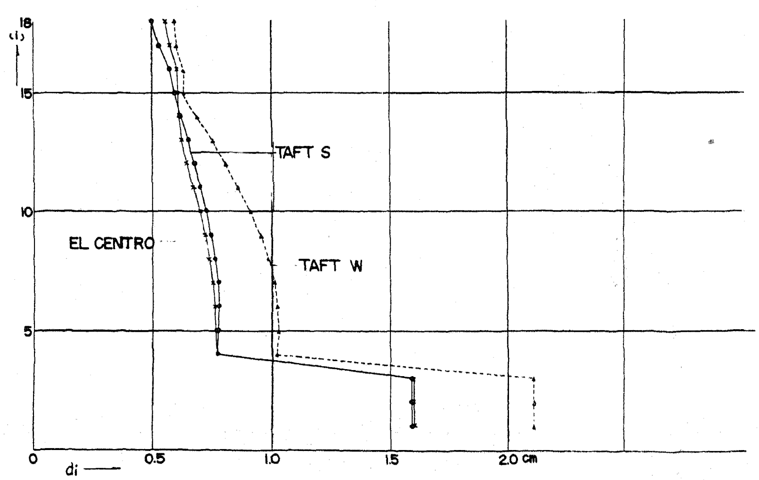


Fig. 9 Response of the Flexible First Story Model ($_1T$ = 1.43) to the El Centro, Taft W and Taft S Earthquake.

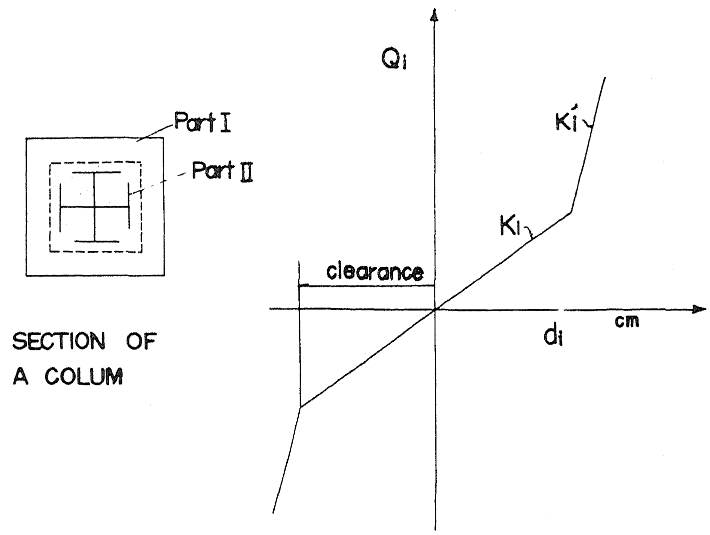


Fig. 10 Cross Section of Columns When Part I and Part II are Combined, and the Restoring Force Characteristics.

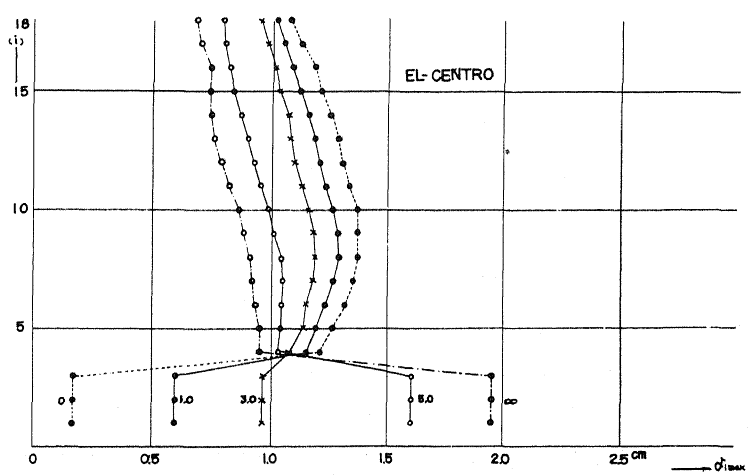


Fig. 11 Effect of Restoring Force Characteristics Adjusted by Clearance Length
A : Response to El Centro 40S Earthquake

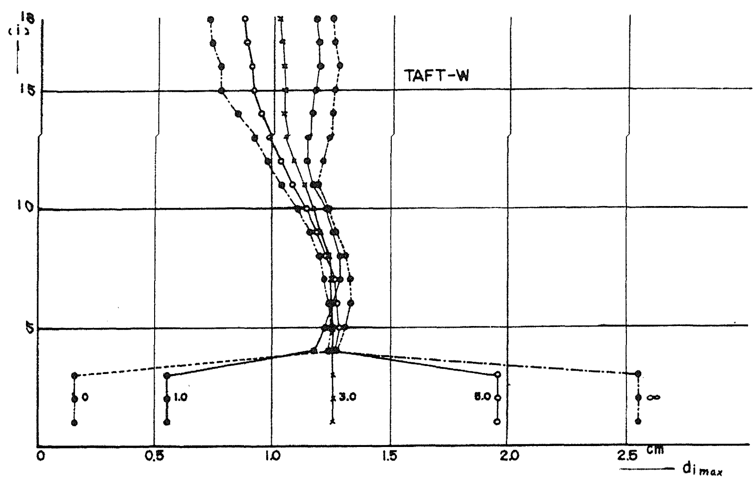


Fig. 11 Effect of Restoring Force Characteristics
Adjusted by Clearance Length
B : Response to Taft 52W Earthquake

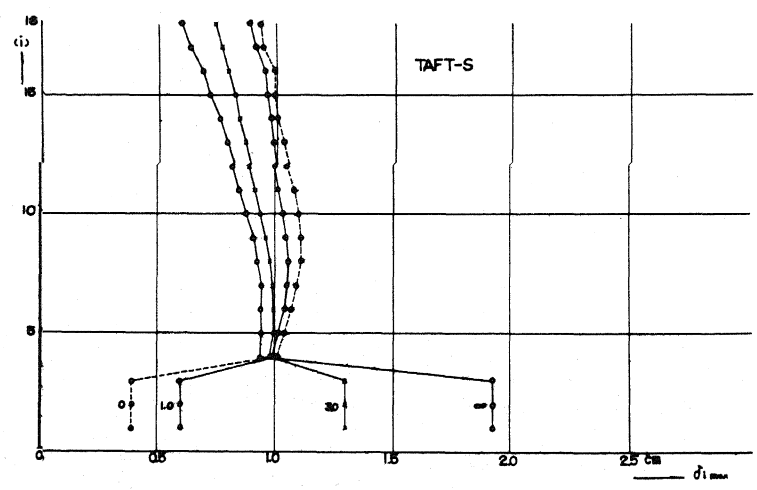


Fig. 11 Effect of Restoring Force Characteristics
Adjusted by Clearance Length
C : Response to Taft 52S Earthquake

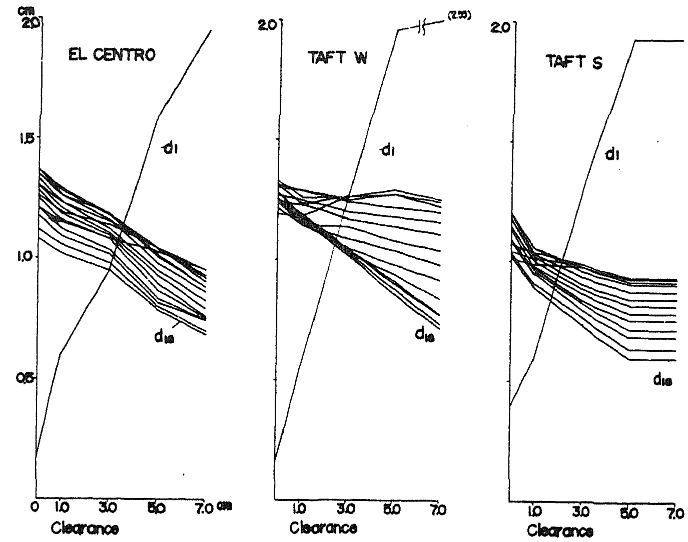


Fig. 12 Relation of Response to Clearance Length

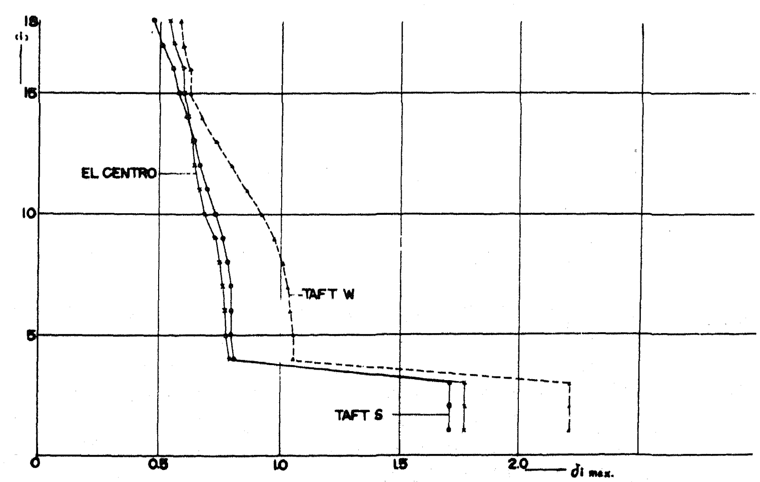


Fig. 13 Linear Response When Vertical Load Considered

SOME ANALYSES ON MECHANISM TO DECREASE SEISMIC FORCE APPLIED TO BUILDINGS

BY K. MATSUSHITA AND M. IZUMI

QUESTION BY: O.A. GLOGAU - NEW ZEALAND

For the case, Fig. 1, where tower and basement are connected what assumption do you make regarding the coupling of ground and building i.e. what portion of the earthquake enters through the foundation slab and what portion through the retaining walls? How do you support your assumption?

AUTHORS' REPLY: It is impossible to say the percentage of the force which enters through the base and the retaining walls of the ordinary structures. We feel that it should be solved in the future.

It is another merit of the separation of the structure mentioned in the paper that the analyses are clearly made because the earthquake force evidently enters from the base.

QUESTION BY: K.S. ZAVRIEV - U.S.S.R.

Is this applicable to both steel and reinforced concrete buildings or only steel-concrete structures?

AUTHORS' REPLY: This method is generally applicable to steel, R.C. and steel-concrete (steel framed R.C.) structures. As for the contact parts of each of the double constructions, it is preferable that these are constructed in steel.

QUESTION BY: R.W. BINDER - U.S.A.

What are the allowable interstorey displacement values used for wind compared with the 1/300 or 1/400 for seismic deflection? Is wind ofter the criteria in hurricane areas, i.e. predominating over seismic?

AUTHORS' REPLY: The shear force at the top storey of this building caused by wind pressure (calculated from the equation as $P = 1.2 \times 120 \sqrt[4]{h}$, where P is wind pressure in kg/m^2 and h is the height in metres above the ground level) is smaller than that caused by earthquakes. When the building is higher, the wind pressure will cause the maximum deformation.

QUESTION BY: C.M. STRACHAN - NEW ZEALAND

At the bottom of page 4 mention is made of a shock absorbing filler between Parts I and II. What type of filler is proposed?

AUTHORS' REPLY: Examples of fillers are rubber, asphalt compounds, foam concrete, or just sand. When the materials are inflammable, it is recommended to cover them with the mortar or steel plates for fire proofing.

As the fillers are easily repaired or replaced with new ones after a big earthquake, we feel it better to use them not only as shock absorbers but as energy absorbers after breakage by earthquake.

It can be said that this is a method to save the main structure from a violent earthquake by allowing for damage in predetermined parts, which can easily be repaired afterwards.

QUESTION BY: Y. OTSUKI - JAPAN

The idea is essentially the same as a floating foundation for a generating machine. The differences here are (1) For a machine the vibration comes from the floating mass (2) the mass is not a rigid mass compared to that of a generator machine.

In the aseismic performance of machinery, we have not had any complaints that the machine shook too much. This idea may only be good if the superstructure is very rigid. What was the difference of stiffness when fixed at base or when separated. Also in an isolated foundation a stopper is not harmless for the superstructure as it induces shock.

AUTHORS' REPLY: In this example the rigidity of the lowest three stories varies from about 1/1.4 to 1/3 of the maximum value of the upper part. Please see Fig. 10 and Fig. 13 of the supplementary paper.