DEFLECTION CONTROLLED ELASTIC RESPONSE OF BUILDINGS AND METHODS TO DECREASE THE EFFECT OF EARTHQUAKE FORCES APPLIED TO BUILDINGS.

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SYNOPSIS

This paper is prepared as supplementary data to our oral presentation.* The figures in this paper are the same as the slides used in the oral presentation.

The authors feel that a building design based on deformation is as important as that based on stress or strength. As it costs much to make building details which can follow large deflections without any deterioration of qualities such as fire-protection, sound proofing etc., it is desirable that the interstory deflections produced in earthquake responses remain within a limitation. Allowable interstory deflections used in this paper are 1/300 of interstory heights. As this limitation causes large story shear coefficients in low and middle-height buildings, some practical structural methods used to decrease the story shear coefficient are presented in the latter half of the paper, one of which is applied to a building which will be erected in Tokyo in 1965-67.

Structural Design of Tall Buildings in Japan

The height limitation of buildings was eliminated from the Japanese Building Code in 1963 to make possible more effective use of the land and improvement of city conditions. Since then new recommendations concerning structural design of tall buildings have been prepared by the Architectural Institute of Japan (A.I.J.). Also many tall buildings have been designed by various construction companies some of which have already been completed while others are now under construction.

According to the recommendation, the fundamental natural period of a building is assumed, first of all, from the number of building stories, then base shear coefficient is calculated from the period, the distribution of the story shear coefficients is assumed, sections of structural members are decided and dynamic calculations are made. When the results of the response calculation are not desirable, some correction will be given to the sections of the structural members, and then same steps in calculation will be repeated until good results are obtained.

As the base shear coefficient recommended by A.I.J. is proportional to the value of the inverted fundamental natural period (I/T), we can make it smaller by choosing a longer period. It causes, however, large interstory deflections and results to those undesirable phenomena as the difficulty of

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* On the request of Prof. E. Rosenblueth, Reporter of Session IV.

design of details which can follow to a large deflection, increase of bending moment at the lower columns by vertical loads, producing 'negative slope' restoring force characteristics in the plastic range, and giving an unstable feeling to the people in the building. (See the 1st slide or Fig. 1).

Allowable Interstory Deflections of Buildings

In many cases, finishing of structural members are used for fire-protection, so it should not be broken by strong earthquakes. If we use details which can follow to a large deflection, it may cost much. If we adopt ordinary methods for details, deflection of 1/300 rad. might be the maximum allowable shear strain. As the interstory heights of buildings are around 3.6 meters, they correspond to interstory deflections of 1.2cm. The A.I.J., recommendation presents the values of deflections related to the frequency of occurrence, as shown in the upper part of the 2nd slide or Fig. 2.

Control of Deflection in Response

Through many analyses of earthquake response of tall buildings by electronic computers, it becomes clear that the response of the building is adjustable by choosing proper values of rigidities. In other words, the maximum interstory deflections, ductility factors, and base shear coefficients can be equal to given values within some ranges, provided that input earthquake data, masses, damping ratios, and restoring force characteristics of the building are fixed.

This enables us to design on a basis of limiting deflections as well as stresses.

Conditions Used for the Calculations in this Paper

Since the intensity and frequency characteristics of future earthquakes cannot be predicted with any degree of accuracy, we used the 1940 El Centro Earthquake and the 1952 Taft Earthquake adjusted to a maximum acceleration level of 0.33 g. By applying these two earthquakes, the peculiarity of an earthquake might be diminished to some extent. The many earthquakes are used, the more generalized the calculated results will be.

As for the given conditions, uniform mass distribution and uniform interstory deflections of 1.2 cm are used, and calculations of elastic response are made under an assumption that damping ratio is 5%. (See the lower part of 2nd slide or Fig. 2).

Calculated Rigidities which Produce the Maximum Interstory Deflection of 1.2 cm in Elastic Response

The 3rd slide or Fig. 3 shows the calculated results; the values of rigidity of buildings which produce the maximum deflection equal to 1.2cm.

in the elastic response to both the El Centro and Taft Earthquakes. The numbers of stories of buildings are 10 to 40.

It is clear that the distribution of rigidities (Spring Constant/mass; K_i/m_i) makes a family of curves which are nearly parabolic in shape.

Programming to Obtain the Rigidities of Deflection Uniformly Controlled Systems

Calculations of rigidities are made by electronic computers and the flow-chart of the program is shown in 4th slide, or Fig. 4. For the response calculation, step by step method is used, where iteration and Gauss method are combined.

The values of rigidities (K_i) and damping coefficients (C_i) are calculated after the values of masses and earthquake data are given to the computer. The first values of rigidities are calculated based on assumptions that the base shear coefficient is proportional to the inverted fundamental natural period (1/T) and that the first mode vibration is predominant in the response. Therefore the initially used rigidity distribution is proportional to a parabolic curve given in the form of ($=(n+i)(n-i+1)/2$ where n is the number of stories and i shows a floor number counted from the base). In a response calculation, interstory deflections are chequed in every time-step, and only when an absolute value of a newly calculated deflection is larger than the old value of the corresponding floor, the old value is replaced by the new one in the memory of the computer. The maximum interstory deflections thus obtained are not erraced when a response calculation to an earthquake is completed, and a new calculation to another earthquake is started after initial conditions are given. The maximum deflections finally obtained (d_i-max) are the maximum values produced in the response calculations to a group of earthquakes, and they are compared with the given values of deflections (d_i-given). If they do not coincide with the corresponding given values, the values of K_i and C_i are corrected automatically, the values of d_i-max are erased from the memory and calculations are restarted and repeated until the values of d_i-max converge to d_i-given.

Rigidities and the Maximum Interstory Deflection of Initially Assumed Systems

In the 5th slide or Fig. 5, initially used values of rigidities (a family of parabolic curves) and finally obtained values are plotted with their maximum interstory deflections obtained in response calculation. It seems that the initially used values are not so different from the final results except for the 40 story buildings, in which the fundamental natural period just accords a peak of the response spectrum curve of the El Centro Earthquake.

The 6th slide or Fig. 6 shows an example of comparison of responses of 20-storied buildings such as initially assumed system, the system of uniformly controlled deflection to both El Centro and Taft Earthquakes and that to either of the two earthquakes. It shows that the rigidities of upper part is determined by the El Centro Earthquake, and the lower part by the Taft Earthquake.

The 7th slide or Fig. 7 shows the base shear coefficients and fundamental natural periods of the 'deflection uniformly controlled systems'. They appear to be separated into three groups which may be the result of the characteristics of the two earthquakes used. When the shear force response spectrum of an earthquake has peaks, the rigidities which satisfy the given conditions could be obtained on both sides of the peaks. In this program, the larger rigidities were used. For reference, shear force response spectrum curves of the El Centro and Taft Earthquakes are also plotted.

The story shear coefficients of low and middle height buildings (10 - 15 stories) are relatively large, and in the latter half, structural methods to solve this problem will be discussed.

Comparison of Result of Response of Deflection Control System with that of Others

Even in an elastic response, the calculate results are usually not so desirable in the system in which only stress analyses are made. At the discontinuous points such as discontinuities in the mass distribution, rigidity distribution, and strength distribution (in elasto-plastic response only), the response produces abrupt changes in story displacements. The 8th slide or Fig. 8 shows an example of comparisons made between a deflection controlled system and an ordinary one. This illustrates that the deformation-design is quite important in order to make a good structural design.

Methods to Obtain Smooth Rigidity Distribution

Most multi-story buildings are provided with basements which have very large rigidities compared to the rigidities of the super structures due to the presence of very thick retaining walls. In such a case it is better to separate the structure into two parts; a tall flexible structure having a smooth rigidity distribution and a low rigid structure including retaining walls. (See the picture in the left part of the 9th slide or Fig. 9).

Methods to Decrease Earthquake Force Applied to a Building

When the plan area of the basement structure is slightly larger than that of the super structure, then the separation of structure can be made not in the plan but in the vertical section as shown in the right side of 9th slide or Fig. 9. We call it as "Double Column Method" or "Double Frame Method". This method enables us to have another deflection control system in order to decrease the effect earthquake force applied to a building.

From the deflection control system, it is evident, that story shear coefficients of buildings of lower and middle height are large, as the fundamental periods are short. If we use the combination of different structural materials and methods in a building, we can extend the adjustable range in the response. For instance, the lower part of the tall structure in Double Frame Method can be made of high strength steel and allowable deflection can be increased, while other parts are made of relatively rigid reinforced concrete (R.C.). By applying it, the lower part of the tall structure works as a filter of short-length waves of earthquakes and the response of upper part decreases. The low and rigid structure including the retaining walls can work as a stopper for the unexpected large deflection of the flexible steel frame part, so it works as a kind of safety-valve. The stress of the stopper increases when the tall part touches it, but the additional stress is not so large as to exceed the strength of thick walls.

The clearance between flexible and rigid structures should be filled with soft materials in order to absorb impacts.

The 10th slide or Fig. 10 shows the deflection-response of the various systems. It is clear that response of the systems having flexible lower parts are remarkably small compared to the deflection uniformly controlled system and rigidity parabolically distributed system. When the clearances between flexible and rigid structures are smaller than the allowable deflection of the flexible part, the response of the upper part is almost within the range made by uniform deflection and 'flexible lower' systems.

The 11th slide or Fig. 11 shows other methods to obtain the same merits as the double frame method. Left part of slide shows the flexible columns erected within the columns of rigid structure and right one shows the same kind of system improved for increasing the damping effect.

The 12th slide or Fig. 12 shows the sectional elevation of the building which is now being designed at Matsushita's Lab. The central part shows the tall and flexible structure having the flexible lower part. The surrounding parts are used as stoppers. Some sections of columns are compared with those of a deflection uniformly controlled system, showing that reasonable designs can be made through improved systems.

The 13th slide or Fig. 13 shows the values used and calculated for the preliminary structural design of the building.

A comparison is made in the deflections (shear strain and interstory deflection) and story shear coefficients of the deflection uniformly controlled system. Since the interstory heights of this building are not uniform, shear strains were held constant with height rather than interstory deflections.

Concluding Remarks

The following items could be said from the data shown in this paper.

1) It is desirable and possible to make a building design based on the deformation as well as the stress and strength.

2) As for the rigidity of a tall building, a parabolic distribution may be recommendable, for the maximum deformations in earthquake responses may form a not so bad distribution.
When the values of rigidities are kept a little larger than calculated ones, deflection could remain within the allowance to different earthquakes of the same intensity, though the story shear coefficients used to the stress-design will be increased a little.

3) Combining the different structural materials and methods, it is possible to decrease earthquake-effects to buildings. Authors feel, however, this method is not applicable when the ground conditions are particular and the earthquake characteristics would not likely be similar to the El Centro or Taft Earthquakes. Therefore, it is desirable to study the characteristics of the more frequently occurring small earthquakes and microtremors behaviour before starting the structural design of the building.

4) Considering the effect of vertical load which might give a negative slope to the restoring characteristic curve in the plastic range, elastic designs at the lower part of buildings are preferable. The stoppers in the improved structural methods will prevent large deflections of the lower part, will provide a restoring force and will keep the lower part within the elastic range.

Content

Controlled deflections in structural design of tall bldgs. and Examples of methods to decrease earthquake force applied to bldgs.

Steps of Stuctural Design of Tall Bldgs. in General.

1. Assume the fundamental natural period (T) from the number of stories.
2. The value of base shear & story shear coef. are decided from T.
3. Sections of members are decided.
4. Spring consts. (Ki) are calculated from the sections.
5. Dynamic calculation is made by electronic computers.
6. If the results of response calculation are not preferable, correct the sections and repeat calculations.

If Large Interstory Deflections Allowed.

1. Small base shear coef.
2. Ordinary structural details cannot follow the deflection.
3. Difficulty in noise & heat insurance, and fire proof.
4. Uncomfortable feeling. etc.

—Fig. 1—

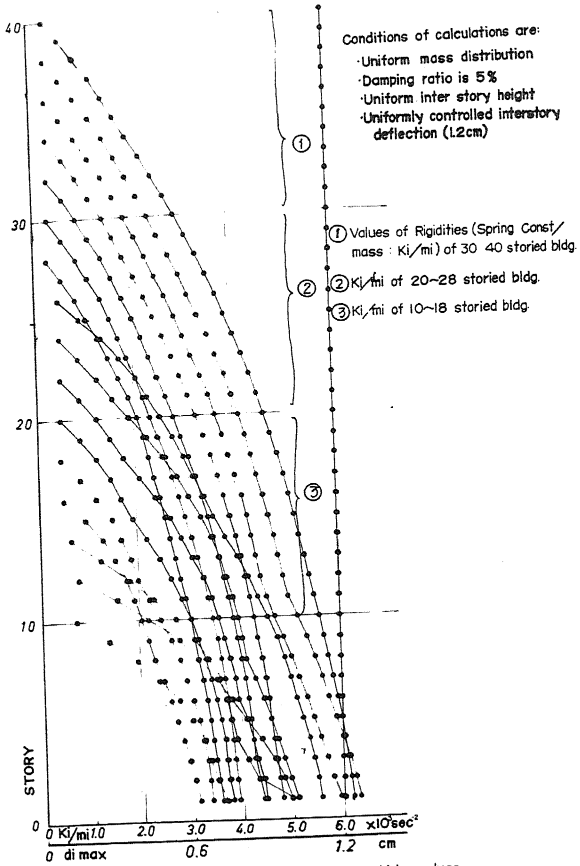
Limitation of Inter story Deflection	Frequency of Occurrence	Loss of Lives	Injury	Property Loss
1/400	Sometimes	Non	Non	Non
1/300	Once in a While	Non	Non	Non or Slight
1/150	Very Seldom	Non	Non or Very Slight	No Care

Recommendation of A.I.J. about the Limitation of Inter story Deflection

1. Elastic Response to the El Centro (1940) and Taft (1952) Earthquakes (Max. Accelertion, 0.33g or Amplified to 0.33g)
2. Controled Shear Strain (or Interstory Deflection)

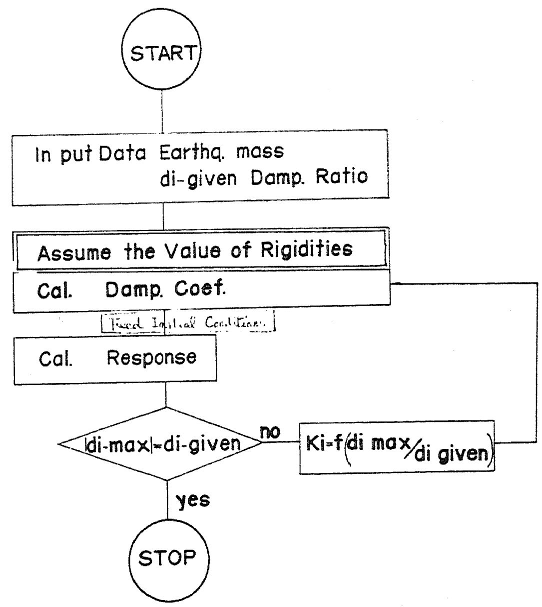
Conditions of Calculation

—Fig.2—



Values of Rigidities of Bldgs. of 10~40 Stories which produce the max. interstory deflections equal to 1.2cm in the elastic response to either El Centro or Taft Earthq.

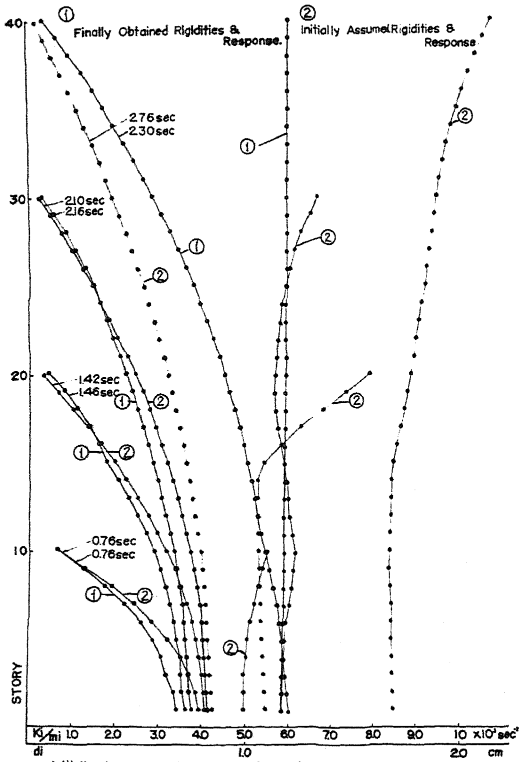
—Fig. 3—



Flow Chart of Programming

An parabolic distrib. of Rigidities is used for the first trial, based on those assumptions as base shear coef. $\propto \frac{a}{T}$ and 1st mode vib. is predominant.

—Fig. 4—



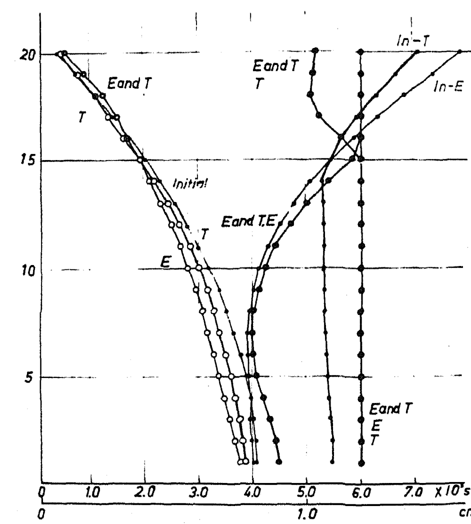
Initially Assumed Values of Rigidities & the Response when di-given is 1.2cm. For the comparison final results are also plotted.

—Fig.5—

Blue lines show the initally assumed rigidities (a parabolic curve) & the responses to each of the El Centro & Taft Earthqs.

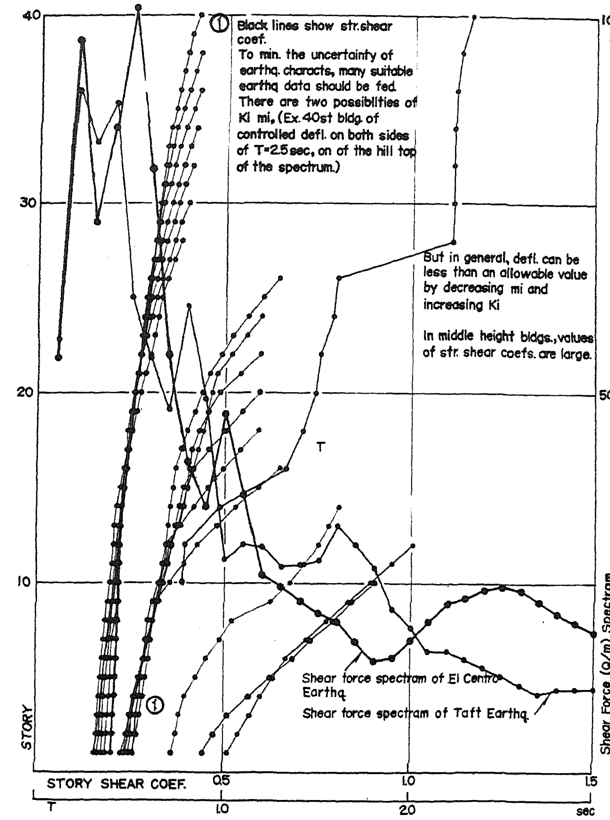
Black lines show the rigidities which produce uniform interstory deflection in the response to one of the El Centro & Taft Earthqs. In the El Centro Earthq. response, the top part accords to the red line.

Red lines show the finally obtained Ki/mi and the max. deflection respons to one of two earthqs. and to both of them.



Comparison of Rigidities and Responses in 20 Storied Bldg.

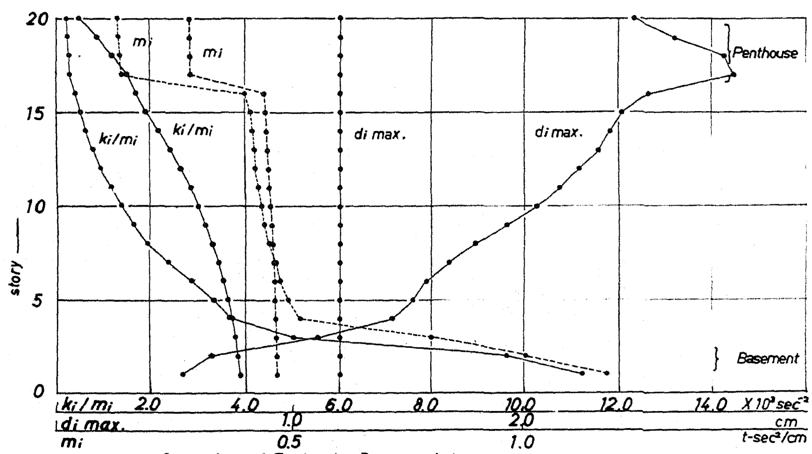
—Fig.6—



Story Shear Coefs. & Fundamental Natural periods (T) of Defl. Controlled Bldgs. of 10 40 Strs.

—Fig.7—

When structural design only for the static stress (or strength) is made, preferable interstory deflections in earthq. response can hardly be obtained in general case. Design for deformation is so recommendable.

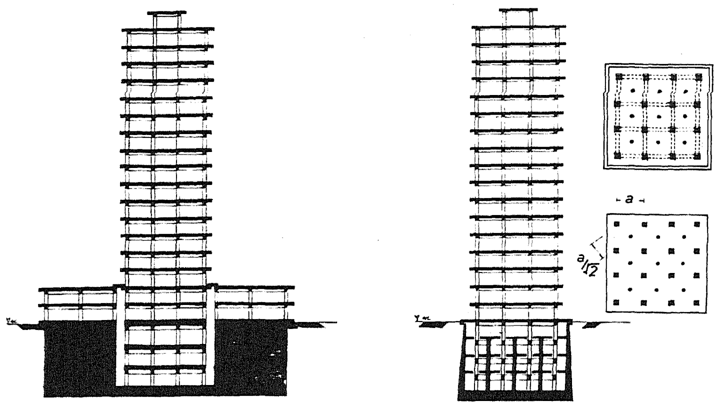


Comparison of Earthquake Response between Deflection Controled Bldg. and Non-Controled One.

—Fig.8—

The most of bldgs. of tall and middle height have base floors, and rigidity of base floors is very large, because of thick retaining walls. In order to obtain a smooth distribution of rigidities, seperate the structure into two parts. Red part is a low and rigid structure including retaining walls, and the other is a tall and flexible structure having a good rigidity distribution.

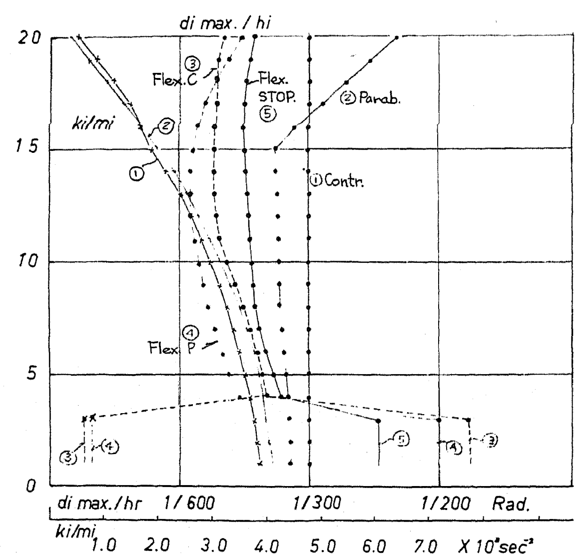
When the area of the basement is not so larger than the area of the tall part, the seperation of the structure will be made not in the plan, but in the vertical section of the bldg. We call it as 'Double Column Method' in which inter-column distance becomes only about 30 % lesser.



—Fig.9— *Structural Methods Available when Adjust the Rigidity-distribution*

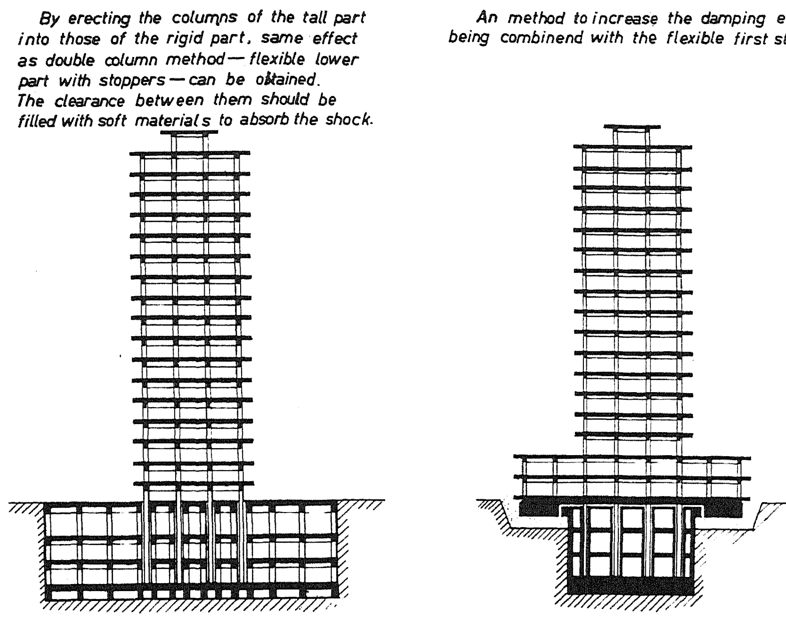
These contains the possibility of a new structual method — a structure combined different structural materials and details. An example is a bldg. which lower part is made of steel and flexible, and the upper part, made of R. C. and rigid. Besides, red coloured rigid structures in the slide work as stoppers which prevent undesirably large deflections.

The black line① and blue line② show the response of systems having controlled and parabolic ki/mi distribution The black dotted line and the blue dotted line show the responses of structures having flexible lower parts.③.④ The red line⑤ shows the response of a flexible-lower story structure (shown in black dotted line) having a clearance of 4.0 cm between the stopper-structure.



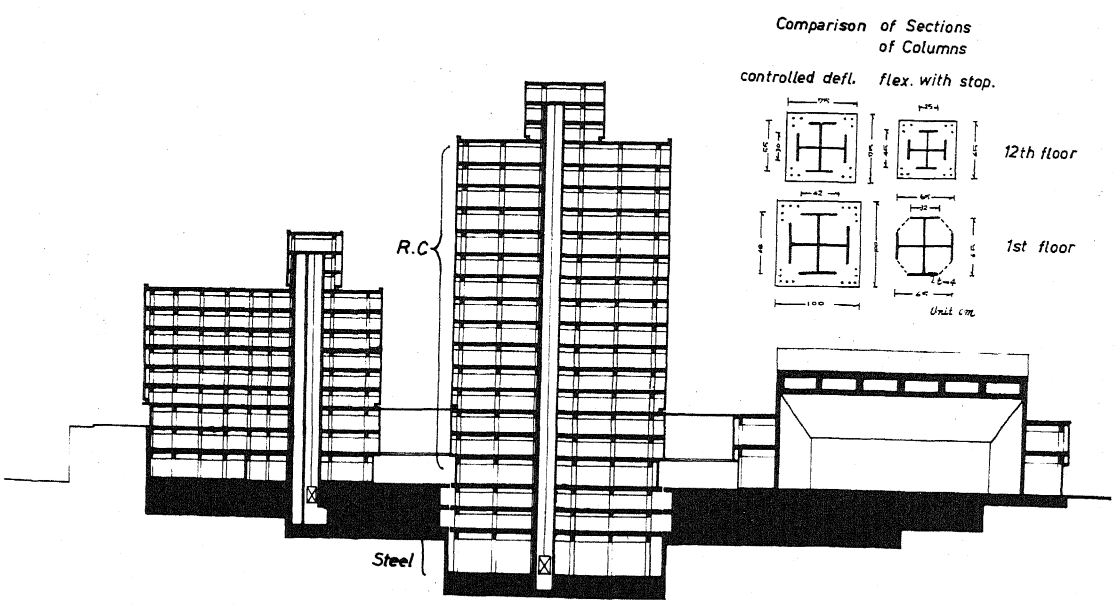
Comparison of Responses of Various Methods

—Fig.10—



Other Practical Methods

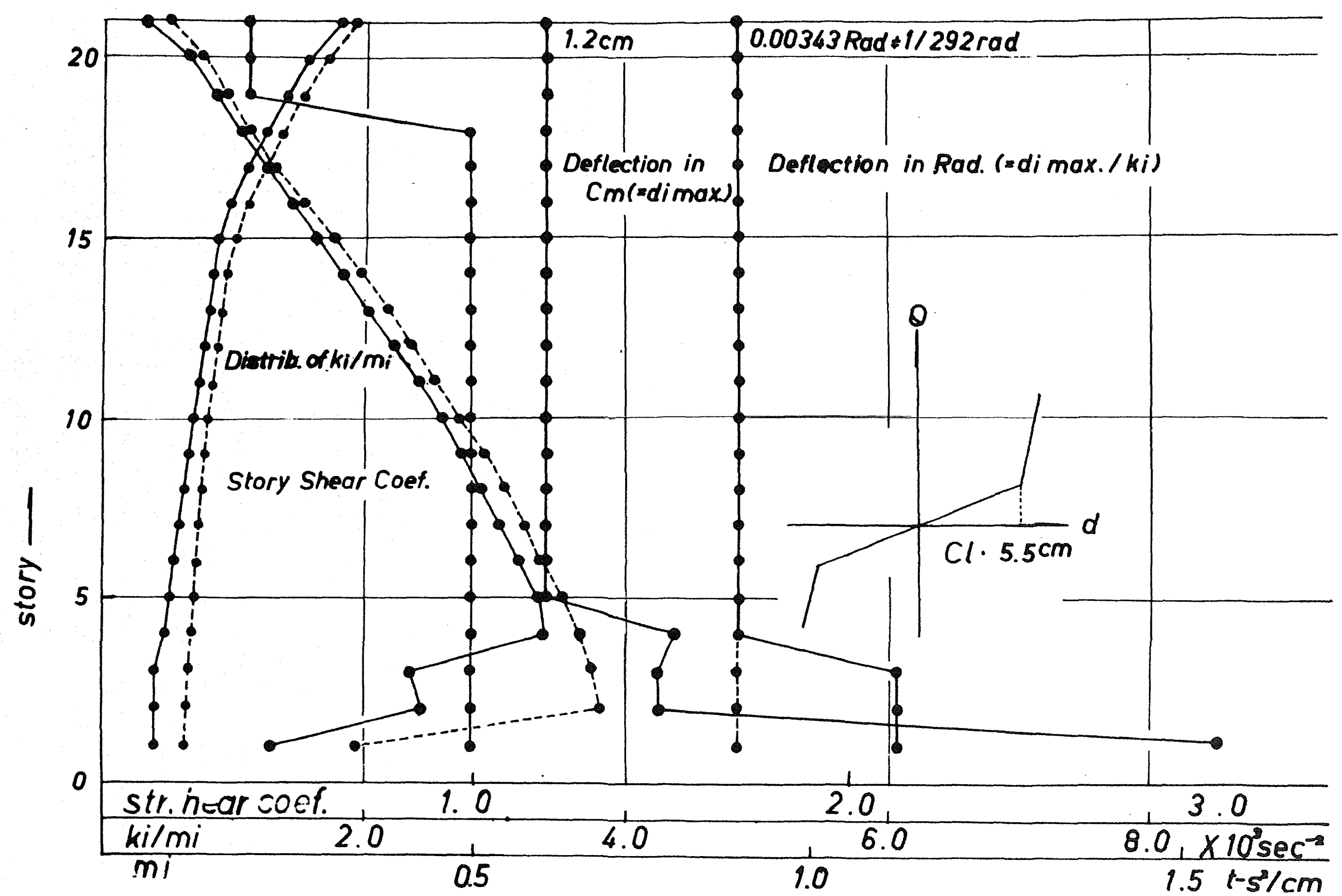
—Fig.11—



An Building, Having Flexible Lower Stories & Stoppers, Is Designed. It Is to Be Constructed in Tokyo in 1965 ~ 1967.

—Fig.12—

Dotted lines show the valves obtained from an uniformly controlled shear strain system Other lines show the values calculated and used in the fundamental Structural design of the building, having flexible lower stories with stoppers.



Mass, Regidity, Interstory Deflection and Shear Strain Distributions of a Bldg. under Designing. ($\alpha max. = 0.3g$)

— Fig.13 —