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Practical Use of Dynamic Response Analysis in Seismic Design

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1. Introduction

The behavior of a structure during an earthquake is a dynamic action in fact. Dynamic analysis using computers has developed for these thirty years to clarify this action and has realized nuclear power plants and tall buildings in seismically active land Japan. The progress of dynamic analysis technologies played a leading role to revise Building Standard Law in 1981. Nowadays, these technologies also contribute to implement large space structures, base isolated structures and tall buildings made of reinforced concrete.

Actually, dynamic analysis is essential for the design of these advanced structures, but we find that dynamic analysis is not usually used for ordinary structural design. The main reasons are considered to be the following three.

a) Difficulties in making precise input data

b) Difficulties in evaluating results due to large amount of output

c) More time and labor required than static analysis

It is considered to be very difficult to complete the detail design only by dynamic analysis. The results of dynamic analysis depend much on the choice of input earthquake ground motion and on analytical modeling itself.

The situation mentioned above is the current state of ordinary building design. On the other hand, the way of substituting static analysis for dynamic analysis is studied by authorities, in order to make the regulation and recommendation of seismic design. In these cases, many prepositions and assumptions are necessary for replacing dynamic analysis with static analysis. These limitations narrow the applicable range of static design procedure.

In design circumstances, EWS and PC are widely used and software programs of analysis are well arranged. Response analysis which could not be performed without big host computers thirty years ago, can be performed easily by personal computers now. We present this paper in order to appeal that dynamic analysis should be general and practical technologies to increase design flexibility.

2. Practical Seismic Design in Japan

Seismic design methods for structures in Japan are classified as below, according to the height of a building. This classification was set when Building Standard Law was revised in 1981.

a) Equal or lower than 30m (regular shape)
Static design (elastic design and simplified plastic design)

b) Equal or lower than 30m (irregular shape)
Static design (elastic design and complicated plastic design)

c) Over 30m up to 45m
Static design (elastic design and complicated plastic design)

d) Over 45m up to 60m
Static design (elastic design and complicated plastic design) and
Response analysis (Level 1 and Level 2)

e) Over 60m / reinforced concrete
Static design (elastic design and complicated plastic design) and
Response analysis (Level 1 and Level 2)

f) Over 60m / steel
Static design (elastic design) and
Response analysis (Level 1 and Level 2)

Modal superposition method is sometimes applied to find the external force distribution of static design, but the response analyses listed above are mostly time history response analyses.

A base shear coefficient for elastic design is 0.2*Z*Rt and that for plastic design is 1.0*Z*Rt*Ds. Acceleration ground motions recorded in past earthquakes are used for response analysis. As an input level, the maximum amplitude of the acceleration is scaled using the maximum velocity obtained from the integration of acceleration records. For buildings in Tokyo, Level 1 is set to be Vmax=25cm/sec, and Level 2 is set to be Vmax=50cm/sec. These values correspond to 250cm/sec^2 and 500cm/sec^2 of the maximum acceleration respectively in El Centro 1940 NS earthquake ground motion.

In ordinary design of a steel frame structure, the response analysis of Level 1 is linear and elastic, and the response analysis of Level 2 is nonlinear considering elasto-plastic characteristic. For a reinforced concrete structure, due to the possible cracking in level 1, nonlinear analysis is performed for both levels.

In steel frame structural design, there is a movement to accomplish rational design by accepting the plastic deformation of certain seismic members such as braces in Level 1. In this case, nonlinear analysis is also performed for Level 1.

3. Aims of Analysis

The aims of analysis are to grasp the response when an external turbulence effects a building. Structural design is performed by finding out the response and comparing it with the design criteria.

Analysis methods are classified by static or dynamic, linear or nonlinear. 'Nonlinear' is subdivided into material nonlinear, geometrical nonlinear and the case combining both. Linear static analysis is usually applied in general structural design, and the most advanced analytical method is the dynamic analysis considering both material and geometrical nonlinearity.

Table 1 Analysis Methods in Seismic Design

		Static	Dynamic
Linear		-A- (simple)	-E-
Nonlinear	material	-B-	-F-
	geometrical	-C-	-G-
	both	-D-	-H- (complex)

There are various analysis methods for Seismic Design as shown in Table 1. According to each method from -A- to -H-, a different external turbulence and modeling method are adopted, and different criteria are defined. Simple calculation makes it easy to grasp the whole behavior of a building, but more assumptions for modeling are necessary and they limit the application range. Complicated calculation captures delicate behaviors and has wide application, but requires more input data.

In Japan, as mentioned in 2, to a building whose height is equal or lower than 45m, [-A-static +linear] and [-B-static +Material Nonlinear] are applied. To a building over 45m, in addition to these static methods, [-E- dynamic +linear] and [-F-dynamic + Material Nonlinear] are applied.

The behavior of a building during an earthquake is actually dynamic, but the seismic design of an ordinary building is based mainly on static calculation. In static seismic designs listed here, dynamic action is assumed to be replaced by static calculation. Although this replacement enables to substitute simple calculation for advanced and complicated calculation, the applicable range becomes limited and the number of assumptions increases. The development of technologies is impeded when design is systematized by simple structural models, simple external force definitions, simple calculations and strict criteria to judge the results. We recommend that advanced analysis such as dynamic analysis should be used effectively depending on the situation and the appropriate criteria should be defined according to the analysis. This approach shall increase the flexibility of design.

4. Mathematical Models for Practical Dynamic Analysis

The most simple model is a multiple mass and spring model with equivalent shear stiffness. In tall building design, when the total bending deformation caused by the column expansion and contraction can not be neglected, the property of the building is replaced with one bending shear pole model and a bending deformation component substitutes for an elastic model and a shear deformation component for an elasto-plastic model.

In early days, the load-displacement relationship of these models was calculated by simplified methods. Recently, the relationship is often calculated by non-linear static analysis in which a frame is subjected to incrementally increased external force whose distribution shape is the same as the design shear force. These results are often modeled by tri-linear type.

Hysteresis rule, the relationship appeared in a frame subjected to repeated load, is modeled by Normal tri-linear or Degrading or Takeda model. Researchers try to coincide the analytical results to the experimental results.

When a building has an irregular shape and has a problem in its torsional vibration, equivalent shear type models or bending pole models are assembled three-dimensionally and the torsional vibration analysis is performed occasionally.

Since about ten years ago, with the appearance of super computers, engineers began to use the response analysis method which could treat elasto-plastic property of individual member of a structural frame. A two-dimensional frame is generally analyzed, but recently a three-dimensional frame can be analyzed with the improvement of computer technologies. Thus free shaped tall buildings can be designed.

Vibration equation is composed of a mass matrix term, a damping matrix term and a stiffness matrix term. A mass matrix has no serious problem. A stiffness matrix is as explained before. Here we mention how to make a damping matrix and specify a damping factor.

The basic idea of common method is that a damping matrix is made to be proportional to a stiffness matrix and the damping effect becomes proportional to the frequency. As a damping factor, 0.02 is usually specified to a steel structure and 0.03 ~ 0.05 to a reinforced concrete structure. For a steel structure, the elastic stiffness matrix of initial stage is used for the matrix which is the basis of a damping matrix. For a reinforced concrete structure, because of the reduction of stiffness due to crack occurrence, the current stiffness matrix at each time step is

adopted considering crack influence. In case of a hybrid structure or a soil-structure interaction model, the damping effect is estimated independently for different materials.

The set-up of a damping matrix has yet many unknown points, but above mentioned method became so common that researchers are discouraged to pursue the truth of damping estimation. We have to reconsider this critical issue.

5. Evaluation of Response Results

The time history and the maximum value of story shear force and overturning moment are derived from the response analysis of a mass and spring model. The distribution of the maximum story shear force and the overturning moment are obtained by plotting these data in height direction. The distribution of story shear force in static design is made by enveloping these data. Additionally, as the results of response analysis, we can get the time history and the maximum value of the deformation, velocity and acceleration of each mass. These values have not been used in conventional design, because these values do not relate directly to the structural safety. We should pay more attention to the velocity and acceleration which directly influence comfortable living conditions and the damage of interior contents.

The structural safety depends on the values corresponding to the story shear force and the deformation of a frame such as story deflection angle, residual deformation angle and ductility factor. The results of response analysis of level 1 and level 2 are evaluated by the following criteria.

Table 2 Design criteria for story deformation

	Level 1	Level 2
Story deformation angle	1/200	1/100
Ductility factor	1.0	2.0

When analysis is performed based on the property of a frame, the stress and deformation of each member are calculated. In this case, the following criteria are usually adopted to confirm the design.

Table 3 Design criteria for member deformation

	Level 1	Level 2
Ductility factor of rotational angle at a beam end	1.0	4.0
Ductility factor of rotational angle at a column end	1.0	2.0

The limit deformability of a structure is actually two times larger than the criteria of level 2 (1/100, 2.0, 4.0, 2.0). With this redundancy, the uncertainty in dynamic analysis application is supplemented. Recently, some seismologists propose that input earthquake ground motion should be larger than level 2. For this severe input, we could use the all deformability of structural members with relaxing the criteria of level 2 to (1/50, 4.0, 8.0, 4.0). This analysis requires high numerical analysis technologies, because the nonlinearity becomes higher than level 2.

The cycles of plastic deformation have more dominant influence on the earthquake damage of a structure than the maximum displacement and the maximum shear force which occurs once during an earthquake duration. This means that the cumulative ductility factor and the plastic strain energy accumulated in members are more suitable to indicate the earthquake

structural damage. These cumulative values are easily obtained from the time history which is the result of dynamic analysis.

In case of a mass-spring model, the cumulative ductility factor and the plastic strain energy accumulated can be calculated for each story. The earthquake input energy subjected to a structure can be calculated by adding the summation of plastic strain energy and the total energy absorbed by damping terms.

In case of a frame model, the cumulative ductility factor and the plastic strain energy accumulated can be calculated for each member. The earthquake input energy subjected to a structure can be calculated by the same way as a mass-spring model.

These cumulative values are rational index, because the method using the accumulation of the results throughout the duration is more realistic than the method using only the maximum values. The idea of this cumulative method is progressing as a research, but a few structural engineers use this method in actual design.

6. Useful Knowledge Acquired from Dynamic Analysis

There are plenty of design knowledge and many data obtained by performing response analysis. Aside from using these data for actual design assessment, dynamic analysis is of great help to clarify the dynamic behavior and to give incentive education to young engineers.

As mentioned in 2., in response analysis of level 1, the force subjected to a structure is proportional to the deformation due to the linear elasticity of a model. In case of a mass-spring model, the results to be focused on are the story shear force and story deformation. In case of a frame model, the results to be focused on are the axial force, shear force and bending moment of members and the frame deformation.

In response analysis of level 2, when a structure exceeds the elastic limit, the force subjected to a structure is not proportional to the deformation due to non-linearity of force-deformation relationship. Two important results are the deformation in the part where plastic deformation is acceptable, and the force caused in the part where plastic deformation is unacceptable.

The followings are useful design information acquired from the response analysis using a mass-spring model.

a) The deformation distribution of the whole structure.
   Whipping effects and others are found.

b) The distribution of the maximum story shear force.
   Used for the decision of shear force distribution in static design.

c) The distribution of the maximum overturning moment.
   The value derived from static calculation based on the design shear force are overestimated.

d) Plastic deformation concentrated on the story with less stiffness or strength.
   Used for the decision of proper stiffness or strength distribution.

e) The change of behavior corresponding to input magnitude.

f) Examination of the effects and behavior of dynamic control systems.
   The performance of tuned mass system, active control system, viscous dampers and friction dampers can be checked.

g) Grasping the behavior after large plastic deformation.
   Collapse phenomenon due to one side shift of plastic deformation can be pursued.

The followings are useful design information acquired from the response analysis using a frame model.

a) Dynamically changing of column axial force
In static design, the maximum column axial force due to lateral force is overestimated, because all upper beams are assumed to be yielded. In dynamic analysis, reasonable values can be derived, because the axial force is calculated for each time step.

b) Bending moment distribution on columns
In static design, the bending moment of a beam is equally divided into upper and lower columns, because the structural deformation mode is close to the primary simple mode. In dynamic analysis, a structure vibrates in various modes which varies every moment and the division rate of the beam moment changes a lot. Additionally, as the column is subjected to forced deformation, the maximum bending moment of a column in dynamic analysis becomes larger than that in static analysis.

c) Dynamic concentration of member force
We can clarify the dynamic change of the force caused in the members where plastic deformation is not acceptable. These values are generally larger than the values of static analysis.

d) Smooth deformation distribution compared to a mass and spring model
In case of a mass and spring model, large story deformation tends to concentrate on the story with less stiffness or strength. But in case of a frame model, the member with redundant strength makes other stories deform and reduces the plastic deformation in the stories with weak strength.

e) Detail examination on the effect and behavior of dynamic control systems
We can examine the performance of tuned mass system, active control system, viscous dampers and friction dampers more accurately compared to Mass and spring model.

7. Problems in Time Domain Analysis

Although dynamic analysis has many advantages, there are still some problems in its practical use. The problems exist in each stage of choosing input earthquake ground motion, modeling a structure and evaluating the results. We list the problems below, but these could be solved depending on the attitude of structural engineers.

a) It is an illusion that the large amount of calculation always clarifies the real behavior.

b) Some engineers misunderstand that design means analysis itself.

c) Young structural engineers sometimes use dynamic analysis without careful consideration.

d) The peak and bottom of spectra of input earthquake ground motion have a great influence on the response results.

e) The modeling of load-displacement relationship of a structure has a serious influence on response results.
For example, the secondary or tertiary stiffness of a tri-linear model, etc.

f) A little change of input brings different results.

g) Depending on the situation, the expected results can be obtained by manipulating input data.

h) In static design, given external force is always transmitted into certain parts of a structure, therefore the results can be checked by the equilibrium condition. Contrarily, in dynamic analysis, the results can not be strictly checked, therefore the mistake of input can not be found easily.

8. The method to evaluate the responses by the total input energy

According to limit state design seismic theory of Prof. H. Akiyama, the total input energy is the most appropriate value to scale the earthquake impact on a structure. When the level of earthquake ground motion is specified, the total input energy depends only on the primary natural period and the weight of the structure. The total input energy is not severely influenced by the dynamic characteristics of the structure. Thus the total input energy is the most rational index to evaluate the results of earthquake response analysis.

According to this theory, seismic design means "how the total input energy is distributed among the whole structure?". When this total input energy is widely distributed to many places or members, the damage of one part becomes smaller. On the other hand, when the total input energy is distributed to limited places or members, the damage of one part becomes larger. To give a typical example, 'the weak beam and strong column system' is adopted in an ordinary structure and the input energy is designed to be distributed among the overall structure. In a base isolated structure, input energy is designed to be concentrated on an isolated interface and a super-structure is not responsible for bearing the energy.

As mentioned in 5., this energy is absorbed by the damping and the structural plastic strain energy. The plastic strain energy is determined by the number of cycles and the strength and the strain amplitude of parts which are plastically deformed. When the strength is small, the plastic strain becomes large, and when the strength is large, the plastic strain becomes small.

The total input energy is calculated from the results of response analysis and the following items can be derived.

a) Input level of response analysis can be judged by the summation of the total input energy to the structure.

b) The structural balance is checked by observing the state of stored energy distribution.

We suggest that the summation of total input energy and its distribution state should become critical points in evaluation of response results, in addition to the input earthquake ground motion, the stress and deformation as the structural response.

9. Conclusions

This paper introduces Japanese current state of dynamic analysis in practical seismic design, especially the evaluation of mathematical models and the response results. We also mention useful knowledge acquired from dynamic analysis, the problems in Time Domain Analysis and the method to evaluate the responses using the total input energy. Present seismic design is composed of static calculations and the criteria for these results. But we are sure that dynamic analysis is more appropriate than static analysis to certificate the seismic performance of a structure as a final product. Especially, dynamic analysis is essential to verify the seismic performance of newly developed structures such as vibration controlled structures and base isolated structures. In future, not only for special structures but also for ordinary structures, new design system composed of seismic response analysis and its proper evaluating method will become useful to raise design flexibility.

The next generation of sophisticated design system will be based on performance based design. To place dynamic analysis properly in this design system, we should create the rational theory and establish the methodology for the specification of input earthquake ground motion, for the modeling method of a structure and for the evaluation method of the results.

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