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RESEARCH AND DEVELOPMENT OF PERFORMANCE-BASED SEISMIC DESIGN THEORY

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SUMMARY

The current structure seismic design method is force-based, and played an important role in building seismic design. But it does have some shortcomings. The theory of performance-based seismic design (PBSD) was suggested firstly by the American scientists and engineers in the beginning of 1990s. The Japanese and European scholars in earthquake engineering field took great interest in it and devoted to it at all of the standpoints. The PBSD theory stemmed from displacement-based seismic design(DBSD) which is supposed by Moehle [4] in Berkley University in California. It is based on the structure analysis and is a revolution in development of seismic theory. It includes all aspects of design and has important meanings. The background of the occurrence, the development, the basic idea, the main properties of the theory and the present research are summarized in this paper. Its importance to improve the seismic design theory is pointed out, too, finally.

INTRODUCTION

The theory of performance-base seismic design (PBSD) was suggested firstly by the American scientists and engineers in the beginning of 1990s. The Japanese and European scholars in earthquake engineering field took great interest in it and devoted to it at all of the standpoints. In recent years, many researchers in China discussed the theory. Mr. Ya-yong wang suggested that the Chinese seismic design code would follow the trend of world and that the study of the theory would be integrated with the national condition of China. The background of the occurrence, the development, the basic idea, the main properties of the theory and the present research are summarized in this paper. Its importance to improve the seismic design theory is pointed out, too, finally.

BACKGROUND

Analysis And Considerate Damage To Earthquake

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The design ideology of two or three levels is adopted in many seismic design codes of the world presently. That is to say that the fortification levels are “ to resist minor earthquake without damage, to resist moderate earthquake with restoration and to resist major earthquake without collapse “, which the seismic codes and regulations are based on. Some of the buildings designed with these codes whose basic aim is to keep lives do survive earthquakes, but the direct and indirect economic losses caused by major even moderate or minor earthquakes cannot be controlled effectively. The damages and losses often go beyond the predictions of the designers and the degree of them oversteps the bounds that the society and the owners can bear. For example, over 5500 people died or were injured in great Kobe earthquake whose magnitude is M7.1, in 1995, and the economic losses came up to 100 billon dollars. The restoration and rebuilding after the earthquake took about two years and nearly 100 billon dollars were consumed. [1]

The losses indicate that with the development of economy and the increasing population density, it will be more serious, and it make researchers realize that the old seismic codes have some shortcomings in seismic concepts, meeting the requirements of society and some other aspects. In fact, the society and the people have many different levels of demands. How to improve the current seismic concept, in order to make the seismic performances of structures meet the prediction requirements in and after the future earthquakes, is an important task lying before the earthquake engineers and structure engineers in 21 century, and is the basement of the PBSD theory.

Shortcomings Of Current Seismic Code

The current structure seismic design method is force-based, i.e., the forces and displacements under minor earthquake are calculated with elastic method; the combined forces obtained are used to design sections of elements. At the same time, in order to prevent the damages of non-structural elements, the displacement checks are needed in the servebility stage. The energy-consuming capacity and ductility of structure are mainly acquired by detailing. This method of structure seismic design achieved the advanced level in the world in 1980s, and played an important role in building seismic design. But it does have some shortcomings:

1. The current design method is strength or force-based. But after the surrey and analysis of the damages caused by most earthquakes, it shows that the factor that controls the damage is velocity or displacement instead of force in certain episode of earthquake [3].

2. In current code, the earthquake action is determined according to the response spectrum and characterizes the zonation of earthquake magnitude. The variations of different regions are reflected by intensity and field soil mechanics. The randomness of the earthquake and structure response is neglected.

3. By the statistical analysis of seismographic records, survey of earthquake damage and theoretical analysis [2], it proves that the long period components ($T>3s$) exist in ground motion. For structure with nature period longer than 3s, the response to earthquake is controlled by velocity or displacement instead of acceleration.

   A minimal limitation is set by the code when the earthquake action of this type of structures is considered. This is not good enough in term of the theoretical and statistical results. It also shows that the component of the ground motion spectrum is rich near to the epicenter when the strong earthquake happens. Seen from the greater peak value accelerations, even there is good prediction of the earthquake hazard, the earthquake catastrophe inevitably takes place unexpectedly because of the poor estimation of the near-field earthquake effect. In addition, structure response spectrum curves with various damp ratios are not available in present seismic code.

4. There is discontinuousness among the specification of different types of sits soil. In order to make the type of site soil accord with reality when the structure analysis is conducted, regulation and improvement are needed to reduce the jumping phenomenon.
5. The bi-direction torsion earthquake action is neglected or seldom considered in seismic verification calculation. In fact, many damages are caused by structure torsion in essence. Therefore, more attention should be paid to the structure torsional effect.

6. The main contains of the deformation verification in code are to calculate the structure displacement response under given horizontal earthquake and to compare it with the allowable deformation that the structure can take function well. According to the existing research results [3], there are some dissatisfactions about it: 1) the determination foundation the allowable inter-story angle displacement is unimpressive enough in the elastic inter-story displacement verification under minor earthquake. The maximum allowable elastic angle displacement tends to a large value and hardly meets the fortify requirement of the first level; 2) the nominal inter-story displacement directly adopted to calculate the elastic inter-story displacement is not suitable for tall buildings (especially super rise buildings) because the deformation of such structures is bending deflection mainly; 3) the allowable elastic inter-story angle displacement is not available for frame-shear wall system, frame-barrel system, shear wall system and so on; 4) all deformation components cannot be considered totally in the time-history response analysis of frame structure system. The restore force model adopted simulates the bending deformation mainly. The result calculated theoretically is much away from that the structure response because the slip of longitude reinforcement in nodal and shear deformation resulted from the shearing stiffness degradation in plastic zone are not embodied.

Appearance Of PBSD

The PBSD theory stemmed from displacement-based seismic design (DBSD) which is supposed by Moehle [4] in Berkley University in California. The new concept of seismic design was used to bridge design firstly. DBSD method needs the analysis of structures to make the plastic deformation capacity reach the requirement under certain earthquake action, i.e., the controlling of the interstory angle displacement under major earthquake. So, the core idea of the method is to control the displacement and interstory displacement level. It is the foundation of the PBSD method based on.

ASPECTS OF PBSD

Basic Performance Levels

Based on the analysis of structure response, structure performance is divided into different levels according to the different fortification classes in PBSD. The designer can choose the reasonable performance level and suitable detailing method properly by the owner.

The basic performance levels include three aspects [6]: applicability, damage control, and personnel security. Personnel security is the lowest performance requirement when the structure subjects to the greatest probable earthquake action; applicability means that the serious damage can be avoided and structures can be retrofitted as quickly as it can be when the frequent earthquakes appen, damage control is that the economic losses and impact on society are in acceptable range when the major earthquakes take place and this fortification level can be chosen freely by the owner themselves.

Basic Contains Of Design Theory

The theory of PBSD contains three aspects: fortification levels of earthquake, seismic performances of structure, design methods of structure.

The essence of PBSD is to control the seismic function of structures under future probable earthquakes. The fortification levels of earthquakes mean that the magnitude of earthquake action applied on structures. For the fortification levels of earthquakes relate directly to the seismic capacity of structures in the future, the choice of them is an important aspect in PBSD. Vision 2000 declared that the theory of PBSD could control all of the fortification levels of probable earthquake spectra. To attain the goal, it needs to choose the earthquake wave spectra corresponded to different levels of motion parameters according to the various return periods of earthquakes. These concrete parameters embody the fortification levels. Table 1 is the suggested classes of earthquakes.

Table 1. Classes Of Fortification Earthquakes In Vision 2000

Classes of fortification earthquake	Return period	Exceedance probability
Frequent earthquake	43 years	50% in 30 years
Accidental earthquake	72years	50% in 50 years
Seldom earthquake	475 years	10% in 50 years
Rare earthquake	970 years	10% in 100 years

The seismic performance is related to the earthquake action. Though the choice of ground motion parameters related to the earthquake classes, the damage degree can be controlled in an acceptable range. In addition, the peak ground acceleration, frequency spectrum and duration are factors of ground motion characteristics and important parameters affecting the structure response. Near-field earthquake affection also has great impacts on it. The estimation of different classes of earthquakes can be done by some methods described in reference [7]. So, the future seismic code should adopt two parameters to interpret fortification levels, which are, ground motion and classes of earthquake.

The performance levels are the greatest degree of structures under certain class of earthquakes. The results of damage of structure and non-structure elements are described be damage degree, structure function and life safety. For different level of performance, the factors should embody the type of structure system, vertical and longitude bearing elements, performance level, structure deformation, equipment and decoration, people' s requirements and so on, and they should be described quantitatively for ease of design and estimation. Table 2 is the description of performance levels.

Table 2. Performance levels and descriptions

Damage degree	Structure function and live safety
Nearly perfect	Function is good and usage is not affected; life is safety
Minor damage	Structure is applicable after slightly repair.
Moderate damage	Function is destroyed and cannot be repaired in short and moderate time.
Serious damage	Structure cannot be repaired, but life remains safe.
collapse	Structure cannot be repaired and there are casualties.

The structure seismic fortification aims are the expected performance levels corresponding to the earthquake classes. The American scholars suggested that the aims can be divided into three levels: basic aim, important aim and special aim. The basic aim is the lowest standard for common buildings, the important aim for important buildings such as hospital, school, public security, firehouse, communication building and so on and the special aim for very important buildings such as nuclear material-contained building. The specification of code is the lowest requirement and a high target can be chosen be the designer according to the owner. The relationships among fortification levels, earthquake classes and target performances can be seen in fig 1.

The current Chinese seismic code adopts three-level fortification and two-stage seismic design method, and it contains some concept of PBSD at some point [2]. The programs are that a complete train of thought is not developed; some parameters are not described quantitatively and operationality is lack.

The current code pays much attention to the damage of main structures because of the important relationship to human lives, but the losses caused by non-structural damage, equipment damage and so on are seldom considered. With the economic development, such losses are becoming larger. With the achievement of multi-level fortification target, PBSD method can minimize the losses. The concrete design method of PBSD is still unperfect and further study is needed.

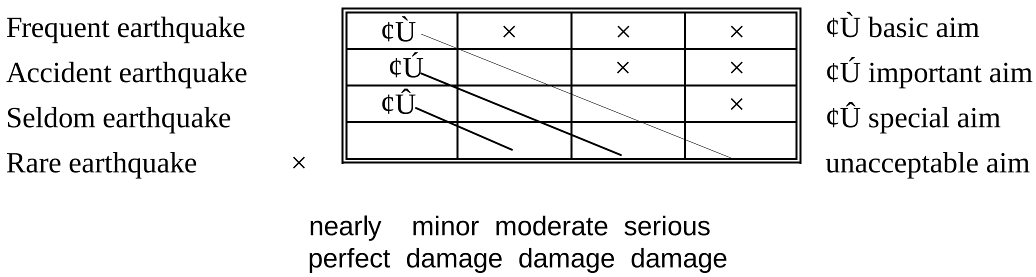

Fig. 1Relationship among fortification levels, earthquake classes and target performance

CURRENT RESEARCH

Summarization Of Current Research

After the appearance of PBSD, the design system is a research task in United State, Japan, New Zealand and many other countries. Many organizations and associations are founded to study the method. The main current researches about it in earthquake engineering field and structure engineering field are listed bellow:

1. three performance levels. They are life safety level, structure damage level and application function level. The life safety level requires that no story collapse happens under earthquake action; the structure damage level requires that damage which may threaten the structural safety will not happen and application function level requires that deformation that affects the normal function will not happen.

2. three seismic fortification levels. the highest level, the level that structure may suffer an earthquake risk in its life-span and the level that structure may suffer several earthquake risks in its life-span. Each level is corresponding to the performance level.

3. calculation and analysis of structures. elastic analysis method and serviceability limit state, elastic-plastic analysis method and damage limit state, equivalent linearity response spectrum analysis method and allowable deformation limit state which ensures the structure function. Each analysis method and limit state correspond to performance level and earthquake fortification level.

4. structural safety. The above characteristic parameters are used to estimate the critical deformation, yield point, the allowable value that the equipment can work properly. The limit deformation and/or energy may be used to predict the structural safety.

Some outcomes are available through a number of researches [9]. For example, a set of rational function levels is defined, and some quantitative parameters such as bending, shear, and axial deformation of beams and columns, even plastic performances of the connections of them are available. The target performances are determined according to the function and importance of structures. The PBSD seismic design method follows the conventional structure design system, and the difference is the emphasis on the displacement properties and nonlinear inelastic static analysis of structures. Below are two design methods used by PBSD theory.

Capacity Spectrum Method

Capacity spectrum method was suggested firstly by Freeman [10] in 1975 and improved later. Its essence is to overlay the earthquake response spectrum curve and the structure capacity spectrum curve to predict the response properties of structure under given earthquake. The response spectrum is the linear elastic response spectrum of SDOF system under given earthquake input. The capacity spectrum is the converted acceleration displacement curve of equivalent SDOF system after the pushover analysis to the structure. The concrete steps can be seen in reference [11].

Displacement Influence Factor Method

The method is used to determine the maximum expectation displacement in structure static analysis. The displacement is defined as target displacement δ_t:

$$\delta_t = c_0 c_1 c_2 c_3 s_a \frac{T_e}{4\pi^2} G$$

here, c_0 is the ratio of displacement of equivalent SDOF system to roof displacement of structure; c_1 is the ratio of the maximum nonlinear expectation displacement to linear displacement; c_2 is an influence factor to the maximum displacement response by shape of hysteretic hoops; c_3 is an influence factor by P-Δ effect; S_a is spectrum response acceleration with real nature period and damp, and T_e is the nature period of structure.

The key point of the method is to simplify the MDOF system into SDOF system, but further study of abstraction method and accuracy is needed, this method is only used to predict the whole performance, and the performance of structure elements cannot be embodied.

MAIN PROPERTIES OF PBSD

Although theory of PBSD has different concept and design methods comparing with traditional design, it does not repel to the mature part and available experiences of old theory. It has the following properties:

1. multi-level characteristic. Though similar to old theory that minor, moderate and major earthquake can be used to describe the earthquake classes, it is believed that the target performance levels include two aspects of life safety and economic losses. In design, the analysis should be synthesized and the most suitable economic performance should be chosen.

2. completeness characteristic. Target performance is not necessarily chosen according to code; the reality demands, requirement of owner, invest capacity and so on are considered. The seismic capacity is the result of given target performance instead of seismic verification after design.

3. flexibility. Though some important allowable minimal values are set, the designers have much flexibility; they can choose the target performance, detailing, new material, new technique and so on.

FORSEE RESEARCH AND APPLICATION

The theory of PBSD is not mature yet. Farther researches are needed before it is used extensively.

1. To the earthquake risk, transition from intensity to zonation according to ground motion parameters is required. The meanings of minor, moderate and major earthquake should be defined clearly. In China, the new mapping is finished on the basis of earthquake action factor $K = \alpha / g$ and characteristic period T_g.

2. To the structure performance, the obscure meanings of non-damage, repairable and no collapse and so on should be verified. The target performance levels should be defined quantitatively.

3. To the response spectrum used in design, long period component, near- field effect and duration of earthquake should attract attention, and velocity spectrum, displacement spectrum, energy spectrum and/or capacity spectrum may substitute the acceleration spectrum in design.

4. To the design method, the linearity method of transmitting from MDOF to equivalent SDOF system should be improved or completed to make PBSD applicable.

5. To the standard of damage and function destroyed, the probability norm may be more suitable, and the subentry factor method used to describe limit state may be modified.

CONCLUSION

The theory of PBSD is based on the structure analysis and is a revolution in development of seismic theory. It includes all aspects of design and has important meanings. With the quicken of economic globalization and the increment of international invest and commerce, disputes always exist because of the difference performance characteristics caused by the different codes. But all of those and be avoided when the PBSD method is used. From the trend of code revision [5, 8, 12, 13] in the world, it can be said that the PBSD theory is the most popular choice.

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