Performance-based Seismic Design Principles and Objectives of Shanghai Tower

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Summary

Since both of the height and irregularity of Shanghai Tower are far beyond the current Chinese code specification, non-prescriptive performance-based seismic design (PBSD) approach is required to be employed in the seismic design of this super tall building. PBSD principles and objectives of this building are presented here. The seismic performance objectives selected for Shanghai Tower are as follows: fully operational under frequent earthquakes, operational under basic earthquakes, and life safety under rare earthquakes. The design criteria for structural components and systems consistent with the above performance objectives are established. The individual requirements of loading-carrying capacity and deformation demands on different types of structural components under different earthquake level are put forward in order to accomplish predefined performance objectives. The requirements on seismic performance analysis and evaluation are presented at last.

Keywords: *performance-based seismic design; super tall building; performance objective; performance evaluation.*

1. Introduction

As a result of rapid economic growth and urbanization, many tall buildings have been constructed in Mainland China in recent twenty years. Owing to the wide variety of social requirement for commercial or aesthetic purposes, the limited availability of land, and the preference for centralized services, the height of tall buildings has grown taller, and the configuration as well as structural system has become more complex in recent years, resulting in a large number of code-exceeding tall buildings. The uniqueness in these structures beyond the scope of current design codes brings new challenges to engineers, since the structural behaviour of complex tall building is difficult to predict and evaluate. The current design codes typically provide minimum requirements for the design of code-compliant structures to ensure safety of life and property. As the code-exceeding buildings are concerned, although the use of alternate method which is non-prescriptive is permitted, the procedures and requirements of such non-prescriptive design have not been well defined. Usually, the details of design are required to work out in each case.

In Mainland China in recent years, the application of PBSD approach has been highly recommended in the design of tall buildings with irregularity or height beyond the code specification in engineering practice in order to control the seismic damage and economic losses, promote the implementation of the advanced technology in construction, and meet the diverse needs and objectives of the owners, users and society. However, it has not been reached the agreement on generalized PBSD methodologies for tall buildings beyond the scope of design codes in engineering practice. For each project, a seismic peer review panel shall be convened and provide an independent, objective, and technical review of those aspects of the structural design of the building that relate to seismic performance.

In general PBSD methodologies developed up to now could be classified into two types, indirect PBSD and direct PBSD. For indirect PBSD, after the conceptual design phase traditional forced-based analysis is conducted to quantify the forces or stresses induced and initial design of structural components and systems is conducted at first, then the deformation or seismic damage is estimated and checked against pre-established limit, and the design should be modified until the pre-defined performance objectives could be achieved[1]. It can be easily applied and especially adequate to irregular structural form in current practice. The direct PBSD approach starts directly by predetermined displacement or damage index consistent with the design performance level, proportions the structure and then conducts the response analysis. The direct displacement-based seismic design is one of the most suitable procedures which can easily be incorporated into PBSD philosophy[2]. Although the direct displacement-based seismic design procedure appears promising, it has not been mature enough to be applied directly to various structures, and it is appropriate mainly to regular structures[3].

In this paper the general PBSD approach incorporating the experience gained from previous practice and current design codes applied in Mainland China is summarized first for code-exceeding tall buildings. Then following this method, PBSD principles and objectives of Shanghai Tower are introduced. The 124-story Shanghai Tower is located in Lujiazui Financial and Trade District, Shanghai, China, which will be occupied for office and hotel uses. The total building height is 632 m while the total structural height is 580 m. It is classified as a code-exceeding tall building since both of the total structural height and the irregularity exceed the limit specified in the Chinese seismic design code. According to the advice provided by the seismic peer review panel, performance-based seismic design and analysis were conducted. The PBSD principles and objectives of this building are presented here.

2. General Methodologies for PBSD of Code-exceeding Tall Buildings

Different from the seismic design of ordinary code-compliant tall buildings, the most important task for seismic design of code-exceeding tall buildings is to demonstrate that the desired seismic safety and performance objectives can be assured in spite of the existence of unfavourable code-exceeding conditions by taking effective measures to counteract the negative impacts exerted by the code-exceeding conditions. The key components and potential weak positions related to the code-exceeding conditions should be identified and consequently additionally strengthened so that they no longer fail first or suffer severe damage. The common design philosophy, such as weak beam and strong column, weak flexural strength and strong shear strength, and weak member and strong joint, is also employed to adjust the strength and then the reinforcement of the structural component. Good understanding of structural behaviour under the earthquake is prerequisite to accomplish this task. Good engineering practice and judgement are vital in some cases. Sufficient evidence for the rationality of the structural solutions and realization of the pre-defined seismic performance objectives should be provided by comprehensive analytical studies and/or testing.

The design criteria should be established corresponding to the desired performance objectives. These minimum acceptance criteria ascertain that the performance objective could be accomplished. In particular, the identified key components and potential weak positions, and the corresponding limit values of responses should be addressed so as to enhance their seismic performance. The criteria are usually set in terms of limit values of stresses, load-carrying capacity, deformation such as strain, plastic rotation, inter-story drift ratio, etc.

The PBSD procedure consists of two design phases. In the first phase, after the preliminary design is completed with the basic configuration and structural layout selected, the code-exceeding conditions are identified, and the seismic performance objectives are determined accordingly. Furthermore, the key structural components which are crucial to the seismic safety of overall structure are identified and laid particular emphasis. The design criteria are established to achieve the desired performance objectives. Different performance requirements are proposed for different types of structural components. The seismic effects under the frequent earthquake and the effects of other actions are determined on the basis of linear-elastic behaviour. The dimensions and reinforcement of structural members are derived by using the conventional strength-based design code. The general method for determining the seismic effects is the modal response spectrum analysis using elastic design spectra.

In the second phase, the seismic performance of the target building is evaluated by comprehensive numerical analysis. For tall buildings which greatly exceed the height limit or have very complex or unique as well as innovative structural system without design experience and referential bases, structural testing on the joint, member, or full structural model is highly recommended to conduct in order to study the structural behaviour and check the seismic performance directly. If the pre-defined seismic performance objectives can not be satisfied, design iteration should be done until satisfied. The flowchart of the general PBSD procedure is shown in Fig.1.

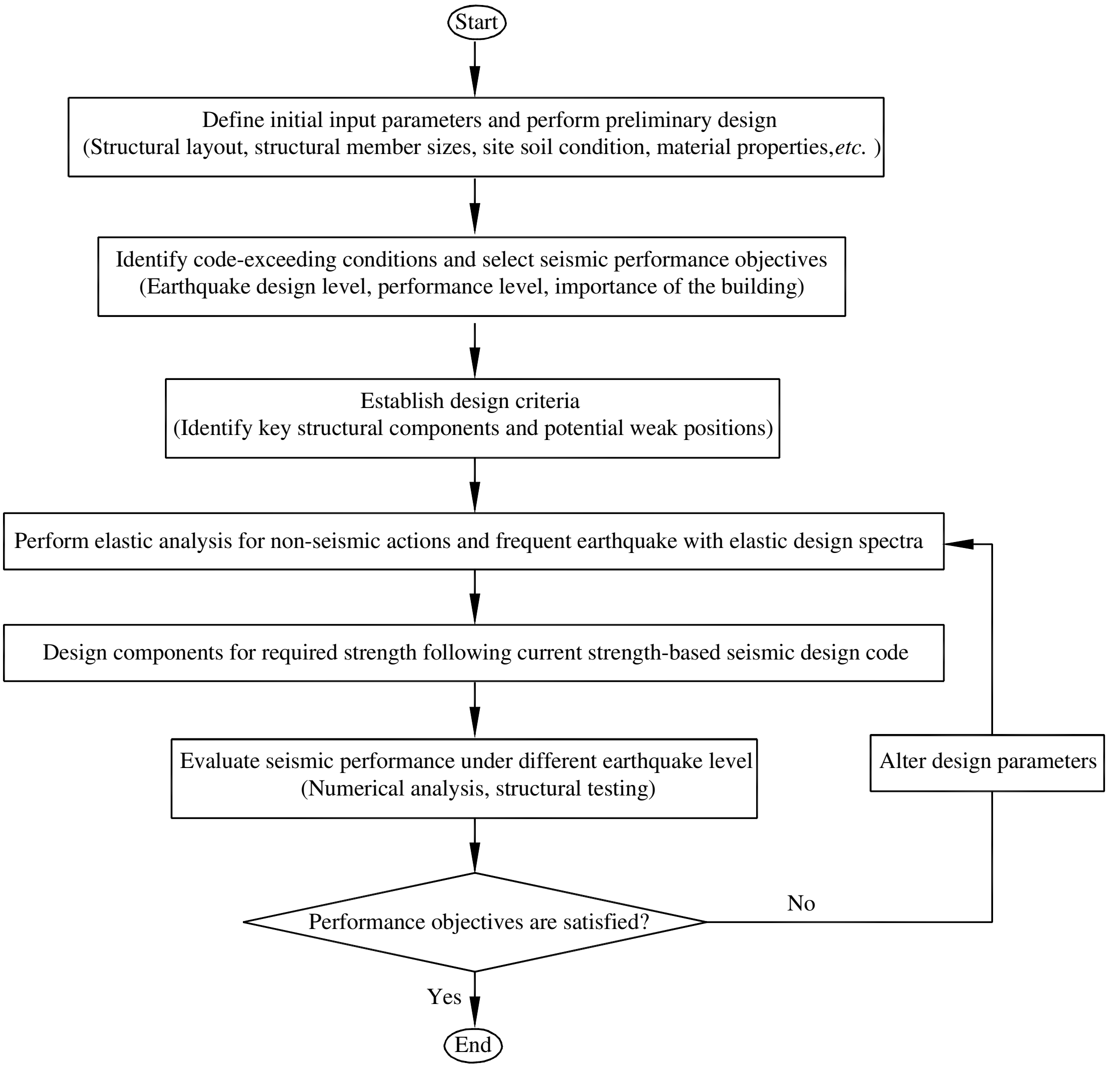
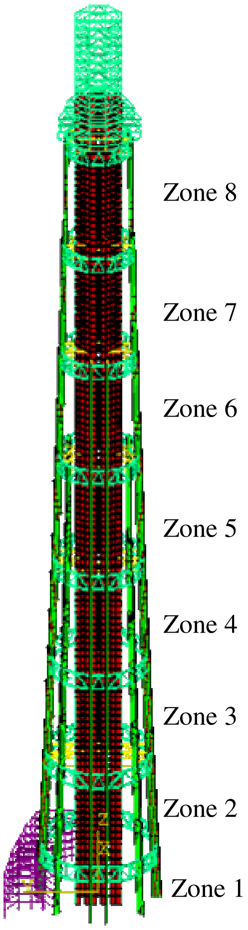


Fig. 1: Flowchart of performance-based seismic design procedure

3. Structural Description of Shanghai Tower

The steel-concrete composite superstructure of Shanghai Tower, divided into eight zones in vertical direction, resists lateral loads with a central reinforced concrete shear wall core interconnected with composite mega-frame through six two-story high outrigger trusses, as shown in Fig.2. Gravity loads are resisted by steel-concrete composite floor system. The square-shaped core is 30 m deep with flanges varying in thickness from 1.2 m at the bottom to 0.5 m at the top, and with web from 0.9 m at the bottom to 0.5 m at the top. Due to the requirement of building function, from zone 5 the four corners of core are removed and the left core is cruciform. The mega-frame consists of eight mega-columns, four corner columns, and eight circular two-story high belt trusses distributed rough evenly in eight zones. The stories containing the belt trusses are regarded as stiffened stories. The structural plan layout of 19F (normal story) and 22F (stiffened story) is shown Figs.3 and 4 respectively. The eight mega-columns rise to the top of zone 8 while the four corner columns ends at the top of zone 5. The mega-columns vary in cross-section from 5.3 m by 3.7 m at the bottom to 2.4 m by 1.9 m at the top. The belt trusses also act as transfer members transmitting the vertical loads on the floors between two adjacent strengthened stories to mega-columns. In each zone two parallel circular trusses are set to enhance the torsional resistance. All the trusses are composed of H-shaped steel members. The amount and location of outrigger trusses are optimized. Six outrigger trusses are determined to be distributed in zones 2, 4, 5, 6, 7, 8 respectively. The outrigger trusses provide additional seismic defence as well as considerable lateral stiffness to reduce the inter-story drift. The layout of all main components in the stiffened stories is shown in Fig.5. Twenty-one one-story high radial trusses are installed in the stiffened stories to transmit the vertical loads from outer curtain walls and floors to belt trusses. The plan layout of radial trusses is shown in Fig.6.



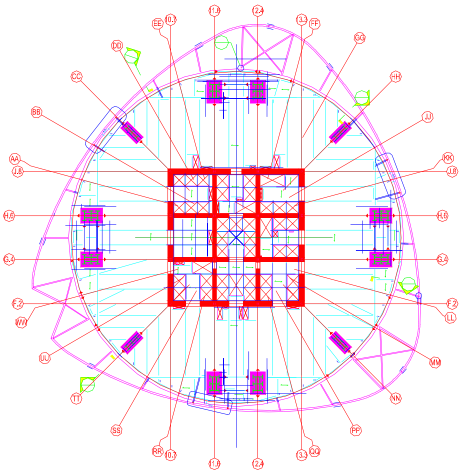


Fig. 3: Plan layout of 19F

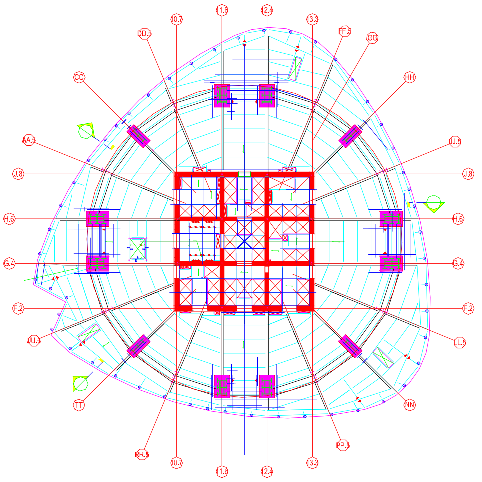
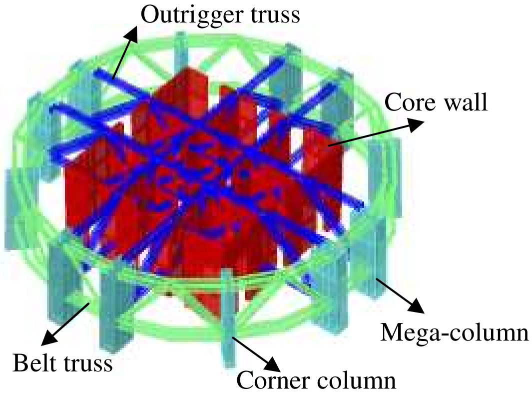


Fig. 4: Plan layout of 22F



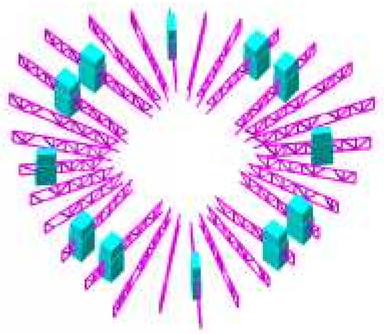


Fig. 2: Perspective view of main structure *Fig. 5: Main components in stiffened stories* *Fig. 6: Plan layout of radial trusses*

The following items are identified as code-exceeding: (1) the total structural height of 580 m exceeds the limit of 190 m stipulated for composite frame-RC core tube structures; (2) the elevation irregularity including several stiffened and transfer stories exceeds the code limit; (3) the overhanging length of 14 m of the radial truss in the stiffened stories exceeds the limit of 4 m and 10% of total span[4].

4. Earthquake Ground Motions

Three levels of seismic hazard, minor or frequent earthquake with the exceeding probability of 63.2% in 50 years (50 year return period), moderate or basic earthquake with the exceeding probability of 10% in 50 years (475 year return period), and strong or rare earthquake with the exceeding probability of 2% in 50 years (2475 year return period), are considered here according to current Chinese seismic design code[5]. The seismic protection intensity of Shanghai is seven. The peak ground acceleration (PGA) of frequent earthquake, basic earthquake, and rare earthquake with intensity 7 is 35, 100, and 200 gal respectively.

To evaluate the seismic performance of the structure by time history analysis, appropriate earthquake ground motions should be selected as the seismic excitation. The rules of selecting are as follows: (1) the site soil condition of the recorded motions is similar to that of the construction site which is classified as type Ⅳ (soft soil); (2) the effective duration is between five and ten times of the fundamental vibration period which is about 9 s; (3) the total base shear obtained from time history analysis using each set of motions should be not less than 65% of that from modal response spectrum analysis using the design spectrum, and the average base shear obtained by using all the ground motions should be not less than 80% of that from modal response spectrum analysis. The damping ratio is taken as 4% for frequent and basic earthquake, and 5% for rare earthquake. Seven sets of three-dimensional earthquake records including five sets of natural motions and two sets of artificial motions are selected accordingly. Five sets of natural earthquake records are from 1971 San Fernando earthquake, 1968 Borrego Mountain Earthquake, and 1985 Mexico Earthquake. The comparison between the design spectrum and the spectrum of one horizontal component of individual motions is shown in Fig.7.

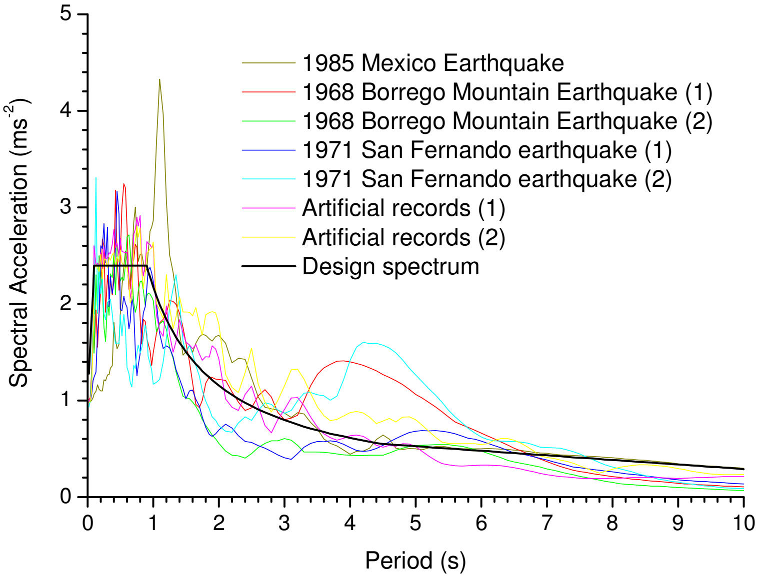


Fig. 7: Design Spectrum and spectra of selected earthquakes

5. Performance Objectives and Design Criteria

Seismic performance objectives are defined as the coupling of expected performance levels with expected levels of seismic ground motions. Due to both of the height and irregularity of Shanghai Tower far beyond the code specification, the enhanced seismic performance objectives compared with ordinary buildings are adopted according to the advice of the seismic peer review panel, expressed as follows: fully operational under frequent earthquakes, operational under basic earthquakes, and life safety under rare earthquakes. Core walls, mega-columns, outrigger trusses, belt trusses, and the crown at the top are identified as key structural members crucial to the seismic safety of the overall structure. The following stories are identified as the potential weak stories: the low stories located in zones 1 and 2, the stiffened stories, and the stories one story lower or higher than the stiffened stories. The design criteria for structural components and systems consistent with the above performance objectives are established as follows, setting individual requirements on inter-story drift ratio, and loading-carrying capacity and performance level on different types of structural components under each earthquake level.

Under frequent earthquakes, all structural components perform elastically. The inter-story drift ratio of the bottom story and other stories should not be larger than 1/2000 and 1/500 respectively.

Under basic earthquakes, the structure performs rough elastically. The dynamic properties after the earthquake are almost same as the initial state. The following components should keep elastic: mega-columns, the parts of core walls including the low part located in zones 1 and 2, the part located in the stiffened stories, and the part in the adjacent stories one story lower or higher than the stiffened stories, belt trusses, the crown, and all the joints connecting the key members. The following components should be prevented from yielding: the parts other than those mentioned above in core walls and outrigger trusses. The inter-story drift ratio should not be larger than 1/200.

Under rare earthquakes, the structural is moderately damaged. The local collapse as well as overall collapse should be prevented. The failure of the joints connecting the key members should be avoided. Shear failure should be prevented for mega-columns and core walls. The performance level of the above-mentioned low part of core walls and mega-columns is immediate occupancy, and that of left part should not exceed life safety. The performance level of outrigger trusses and the crown should not exceed life safety. Yielding of the steel bars or steel plates in outrigger trusses, the crown, and the part other than the lower of mega-columns and core walls is permitted, but the stress of the steel is not allowed to reach the ultimate strength. The performance level of belt trusses is immediate occupancy. The belt trusses and all the joints connecting the key members should be prevented from yielding. The performance level of the other components should not exceed collapse prevention. The falling of any components is prohibited. The inter-story drift ratio should not be larger than 1/100.

6. Seismic Performance Evaluation

After the basic configuration and structural layout are selected, the seismic effects under the frequent earthquake and the effects of other actions are calculated by modal response spectrum analysis using elastic design spectra. The dimensions and reinforcement of structural members are derived by using the current strength-based design code. Elastic time history analysis is carried out as the supplementary calculation to provide additional information. The inter-story drift ratios are checked against the limit. The design is modified until the performance objective under the frequent earthquake is satisfied.

The seismic strengths of structural components are checked against the demands under the basic earthquake. The seismic effects are determined by the modal response spectrum analysis using elastic design spectra based on the fact that the structure keeps rough elastic. The design is modified until the performance objective under the basic earthquake is satisfied. To check the requirement of keeping elastic for the structural component, the following equation is applied:

$$1.2S_{GE} + 1.3\beta_{E1}S_{Ek} < R/\gamma_{RE} \tag{1}$$

where S_{GE} is the effect of the representative value of gravity load; S_{EK} is the effect of the standard value of frequent earthquake; $\beta_{E1}$is the ratio of the PGA of the considered earthquake level to that of the frequent earthquake; R is the design value of the load-carrying capacity; and γ_{RE} is the seismic modification coefficient of load-carrying capacity. The following equation is applied to check the requirement of unyielding:

$$S_{GE} + \beta_{E1}S_{Ek} < R_k \tag{2}$$

where R_k is the standard value of the load-carrying capacity.

Nonlinear time history analysis is carried out under the rare earthquake by inputting the selected earthquake ground motions. The average demands are applied for evaluation. It is required to be analyzed by using two different computer programs executed by two different research groups to validate the results. Nonlinear analysis should be properly substantiated with respect to the seismic input, the constitutive model used, the method of interpreting the results of the analysis and the requirements to be met. The earthquake responses, plastic mechanism, distribution of damages, etc., are predicted. The design is modified until the performance objective under the rare earthquake is satisfied. The weak positions (components or stories) should be strengthened if found by numerical analysis.

Structural model testing is often used to help structural engineers directly acquire the knowledge about the prototype, especially in the case of complex tall buildings for which the numerical simulations are considered unreliable. Shaking table tests on a 1/50-scaled full structural model, and static tests on two types of 1/8-scaled joint, the joint connecting the mega-column, belt truss, and outrigger truss and the joint connecting the outrigger truss and core wall, are conducted to evaluate the seismic performance under three levels of design earthquake. By shaking table tests, the earthquake responses and dynamic characteristics are derived, the global failure process and mechanism, and structural weak positions are discovered, and then the overall seismic performance of the prototype structure can be evaluated accordingly. By the static tests, the local failure process and mechanism, the load-carrying capacity, deformation capacity, and hysteretic characteristics are obtained. The structural design is improved from the test results.

7. Conclusions

In mainland China in recent years, a large number of code-exceeding tall buildings, whether their heights exceed the limit for the respective structure type or the extent of irregularity is violated, have been constructed. PBSD approach has been highly recommended and become necessary to demonstrate the performance of code-exceeding tall buildings at least equivalent to code intent of safety. The general methodologies of performance-based seismic analysis and design of code-exceeding tall buildings in Mainland China are introduced in this study, which is the conventional strength-based design with upgrades by selection of performance objectives, establishment of design criteria, and comprehensive performance evaluation and validation. Accordingly, PBSD principles and objectives of Shanghai Tower which is a typical code-exceeding tall building are introduced in detail. The enhanced seismic performance objectives are adopted for this building. To realize the predefined performance objectives, different performance requirements are proposed for different type of structural components.

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