Numerical Analysis of Seismic Performance and Structural System of High Rise Steel Structures

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***Abstract* — This paper investigates the numerical analysis of seismic performance and structural systems of high rise steel structures. Steel-concrete composite structures in high-rise and super high-rise buildings in China have been increasingly widely used, but the corresponding design specifications are still not perfect and theoretical research is also lagging behind practice. Here modal analysis and time history analysis were performed on experimental frames. Using Sap2000, the analytical models were verified. Computed results were obtained and analyzed for: i) the dynamic responses of displacement, ii) acceleration and iii) base shear forces under: a) different earthquake waves with the same maximum acceleration, and b) the same earthquake wave with different maximum accelerations. Referring to the current codes, five performance levels were put forward for SRC frame with special-shaped columns under: i) full operation, ii) temporary operation, iii) reparable operation, iv) life safety and v) collapse prevention.**

Keywords - numerical analysis; seismic performance; structural system; high rise steel structure

I. INTRODUCTION

With the development of city construction, more and more beautiful high-rise buildings with diversification of structural style emerge. To the modern city, add a beautiful landscape on the basis of satisfaction for people's demand of use, and also bring some problems when doing structural design especially doing the analysis of seismic performance. Because of the characteristic and innovation of these structural style, and unsuitability of traditional structural analysis method, it's a challenge for structural engineer; hence it's necessary for specialized research and exploration. With the rapid development of computer analysis technology and FEA program, the anti-seismic analysis of complicated project is possible, and this can greatly facilitate the structural design of complex high-rise building.

In Yan's [1] paper, a complicated steel structure - Hangzhou international conference center is considered. Execute modal analysis of the structure to research its dynamic characteristics and analysis the vibration form, then find out the week position through partial modal. In addition, the effect of braces in different position and with different function to structural vibration form is studied. Execute spectrum analysis to study the dynamic response of this structure under moderate earthquake. make sure the modal steps for analysis, consider X direction and Y direction respectively, obtain the deformation style, maximum displacement, maximum relative displacement of the adjacent floors and stress distributing, compare the anti-seismic capabilities of two different directions. Also, do elastic time-history analysis of the structure to compare with spectrum analysis, and get some results for project design.

In order to get the elastic-plastic responses of the structure under heavy earthquake, elastic-plastic time-history analysis is performed in Zhou's [2] paper. Restoring force model and yield criterion is discussed. Get the displacement-time curve and the stress condition of the whole structure and the distributing of plastic point under different ground motion and under uni- and bi-directional input ground motion. Analysis of the stress condition is performed to the converted truss specially. Zhao [3] explains some questions that must be paid attention to when we use ANSYS to perform elastic-plastic time-history analysis, including establishing model, controlling analytic process, handling of results and so on, and the currently existing problems are also presented.

According to the experimental study on 3 models of two-bay and three-story frame composed of reinforced concrete beams and SRC special-shaped columns under low cyclic reversed loading, the failure process and pattern were observed in Guo's paper [4]. The strain distribution of shaped steel, load-displacement hysteretic loops and skeleton curves were obtained.

The mechanical behaviors such as load bearing capacity, inter-story drift ratio, ductile, energy dissipation and stiffness degradation were analyzed in Shi's paper [5]. The results show that the SRC frame with special-shaped columns is a typical strong column and weak beam structure, and can form the beam-hinged failure mechanism. The hysteretic loops are symmetric and plump. Compared with the reinforced concrete frame with special-shaped columns, the ductile and energy dissipation are better. Based on the experimental results, the restoring force model of SRC frame with special-shaped columns is presented in Cui's [6] paper. The static elastic-plastic analysis on SRC frame with special-shaped columns under monotonic loading was carried out by using Abacus. The calculated results agree well with experimental results. According to the calculated results, the mechanical mechanisms of SRC frame with special-shaped columns are analyzed, obtaining the law of stress distribution and development of section and failure modes. Furthermore, parametric analysis of mechanical behavior of SRC frames with special-shaped columns was performed in Lai's paper [7]. The concrete strength, steel strength, axial compression ratio, ratio of special-shaped column limb height to thickness, stiffness ratio of beam to column and yield bending moment of beam to column were all considered as analysis parameters. The hysteretic performance analysis and dynamic analysis on SRC frame with special-shaped columns were carried out by using Openness. The finite element calculation of experimental specimens under cyclic loading is finished, of which the results agree well with experimental results. According to the calculated results, the moment-curvature hysteretic loops of beam ends and column ends are given, and the influences of P-Δ effect and axial compression ratio are analyzed in his paper.

II. The Framework and Basic Model

Steel structure house, which have perfect earthquake-resistant capacity, good material strength and ductility, convenient construction and recovery, high space utilization ratio, efficient in saving land and energy, reducing consumption, will be a very good choice in housing industrialization development. Now, China has the most steel production, and maturity technology in steel structure production, designing and installation. So, steel house industrialization development will be an important aspect of housing industrialization development.

It also introduces architecture supporting system and structure system in earthquake-resistant suitable for steel structure house. Here the researchers focus on the earthquake-resistant designing method for steel structure house. In Wang's paper [8] he choose 2 typical building 6 floors and 11 floors and establish three models, which are frame structure, frame brace structure and frame wall structure, on them. The 6 floors building has been searched by using response spectrum analysis of frequently occurred earthquake and pushover analysis of seldom are occurred earthquake in 9 degree intensity. The 11 floors building has been searched by using response spectrum analysis of frequently occurred earthquake and pushover analysis of seldom are occurred earthquake in 8 degree intensity. Compared with the model analysis, column shear, floor Centroid displacement, story drift and angles of drift in frequently occurred earthquake, hinge property in PUSHOVER analysis and capacity point in seldom occurred earthquake, we have briefly known the structure property, force information, sideway, energy dissipation, the begin and development of hinge in each structure.

Residential structure is directly related to the living needs of human being and the development of national economy. Adoption of steel structure is great signification to accelerate residential structure, meet the house quantity and quality needs of people which are increasing improved day by day, decrease the consume of soil resources, regeneration utilize of building material and sustainable development of construction industry. Social reform open and economic development ,especially large increase of steel production, improvement and application of new style building material and building technology、the engineering practice empirical accumulated recent years, all above established foundation for the application of the steel structure systems and created a favorable environment for developing the industry.

The steel frame structural system supplies a larger interior space and all parts stiffness of the structure are more uniform. Although steel frame structure has bigger ductility and long natural vibration period, the non-structural element is easy to destroy because of the smaller lateral stiffness and the larger lateral displacement, so the steel frame structural system is built too high inadvisable. The disposal principle and the column grid size of the frame in the steel braced frame structural system are the same as that of the steel frame structural system basically. The steel braced frame structural system adopts that vertical support formed by axial-direction strength staff instead of frame structure formed by bending resistance staff. Therefore, it can obtain much larger resistance lateral force stiffness and much more small interlamination lateral displacement of the structure. The figure 1 shows the fabricated steel structure.

Figure 1.. The fabricated steel structure

The steel frame-concrete shear wall (kernel canister) structural system usually uses stair well (elevator space) or toilet to set up reinforced concrete shear wall, which forms the main resist-side force structure. The periphery frame adopts steel frame or steel tube concrete frame, which possesses bigger resist-side stiffness and level shear resistant bearing capacity, can advance structural earthquake resistance and satisfy structural distortion require. Due to the mismatching of stiffness and the ductility of the periphery steel frame and the kernel canister, the steel frame-concrete kernel canister structure will lose the aseismic ability basically when suffering the large earthquake, the steel frame does not react as the secondary defense once the kernel canister meets with destroy. In order to avoid above phenomena, this thesis advises that the simplex steel frame-kernel canister structure is not to be used and the steel frame-kernel canister-shear wall structure should be adopted to

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resist earthquake. The figure 2 shows the common usage structure for the rise steel structure.

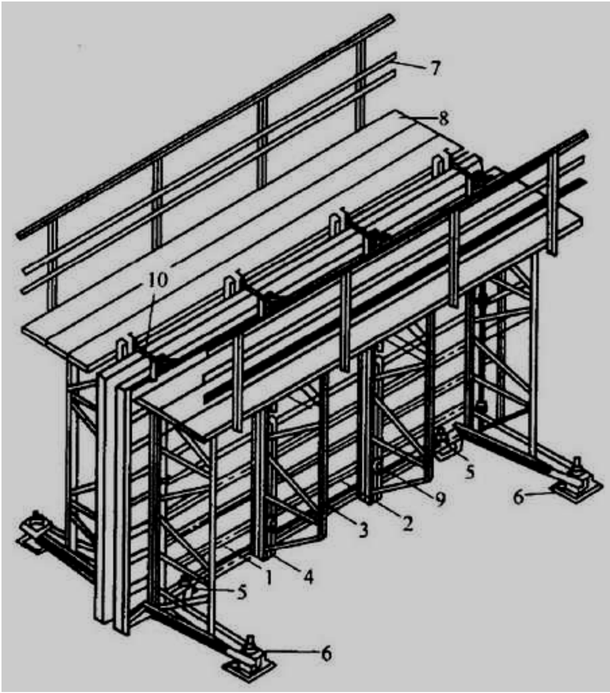

Figure 2. The common usage structure for the rise steel structure

III. THE HIGH RISE STEEL STRUCTURES MODEL AND STRUCTURAL ANALYSIS

Since the 1980s, as the result of rapid economic growth and urbanization, many tall buildings have been constructed in Mainland China. The development of tall building structural systems has been accelerated in recent 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, 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. The steel-concrete hybrid structure, with its unique advantages due to the combination of the advantages of individual material, steel and concrete, has been widely used around the world. In Mainland China considerable structures of super tall buildings are hybrid although the seismic performance of hybrid structure is lack of verification by real earthquakes. There have been many types of steel-concrete hybrid structures developed in the world. The seismic performance of steel-concrete hybrid structure has not been acknowledged as well as RC structures or steel structures. To ensure the seismic safety of hybrid structures, model tests or computation simulations are indispensable to acquire the knowledge and predict the behavior under earthquakes. Nonlinear time history analysis has been well recognized as an efficient tool to evaluate the seismic performance of a complete big structure that cannot be modeled for laboratory study. In this study, the seismic performance of a code-exceeding tall building with the hybrid frame-tube structure to be constructed in Beijing is evaluated by nonlinear time history analysis with the aid of PERFORM-3D program.

The 61-story office building with the total structural height of 263.65 m is located in Beijing with the seismic intensity of eight. The perspective view is shown in Fig. 3. The hybrid superstructure consists of an outer steel reinforced concrete (SRC) frame and a steel reinforced concrete core tube. There are not any big openings set in the floors, forming rigid diaphragms to link the core tube and the outer frame. Four steel outrigger trusses are installed at the 28th and 44th floors respectively in the east-west direction (X direction as indicated in Fig. 4) to increase the lateral stiffness of this direction with much shorter dimension. Moreover, two U-shaped steel belt trusses are installed in the same floors. Therefore, the 28th and 44th floors act as strengthened floors to reduce the lateral displacement under winds and earthquakes. The structural plan layout of the typical floor and the strengthened floor is shown in Fig. 4.

Figure 3. The overlook of the aimed high building

In the core tube, steel plates and steel braces are embedded below the 20th floor, and reinforced concrete trusses are arranged above the 20th floor. Steel beams and columns are embedded at the edges of steel plates to effectively restrain the plates, which make the bearing capacity of steel plates fully developed. The embedded edge steel columns increase the flexural carrying capacity of the shear wall significantly as well. The peripheral frame consists of concrete filled circular steel tubular (circular CFST) columns and steel beams. The total structural height of the building exceeds the allowable maximum limit of 150

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m. The structure is also classified as vertical irregular due to the existence of strengthened floors.

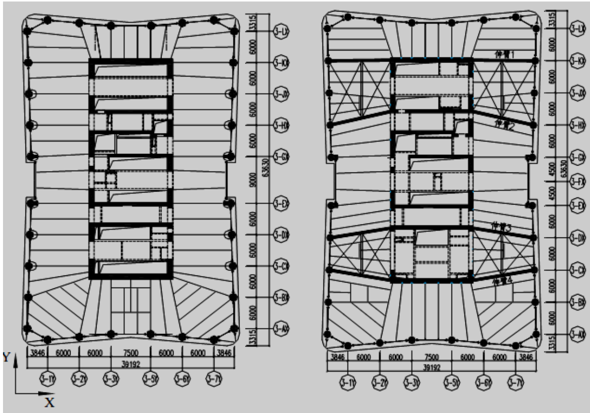


Figure 4. The structure layout

IV. RESULTS AND DISCUSSION

Bilinear constitutive relationship is adopted for the steel and reinforcement rebar. The post-yielding stiffness ratio is taken as 0.01. The bilinear kinematic model is used to simulate the hysteretic behavior, which is the default setting in PERFORM-3D.

The constitutive relationship is applied here for shear walls and RC beams. For the core concrete surrounded by stirrups, the confined concrete constitutive model is applied. It is widely acknowledged that the confining effect on the compressive behavior of core concrete in circular CFST columns is very significant. The constitutive model developed by fitting the experimental data is adopted. The constitutive relationship curves with different confining factors are shown in Fig. 5. As the limit of PERFORM-3D program itself, the constitutive relationship curves should be firstly converted into piecewise linear line (as shown in Fig. 6) on the basis of the principle of equal energy, so as to obtain the parameters of corresponding key points required in the program.

The rigid floor assumption is adopted. Beams and columns are simulated by plastic hinge models. The assumption that plastic hinges occur only at the two ends of members is adopted. The length of plastic hinge is taken as one half of the cross-section height. There are two methods to define the parameters of plastic hinges. In the first method, the cross-section is simulated by the fiber model, and the force-deformation relationship at the cross-section level is derived automatically by the program according to the constitutive law for the constituent material. P-M-M interaction can be considered for columns. In the second method, the force-deformation skeleton curve of the member is derived with the aid of section designer program called X tract and then transformed into bilinear form, as shown in Fig. 7. The characteristic parameters of the skeleton curve are recommended by FEMA356. The first method spends more time than the second method. In this study the first method is applied for circular CFST columns and the second method is for beams. The meshing of the cross-section of CFST column is shown in Fig. 8 For the coupling beams with the span-to-depth ratio less than 2.5, shear hinges are added to simulate the behavior after shear yielding.

The core walls are modeled by shear wall element specified in PERFORM-3D. The shear wall element consists of vertical fibers and concrete shear layer. The fiber layers are used to model the bending and axial loading behavior, and the concrete shear layer takes the contribution of concrete to the shear strength into account.

Clough model is adopted for flexural hinges and shear hinges. The reduction factor of unloading stiffness is taken as 0.4. The modified Takeda model, accurately reflecting the main characteristics of shear behavior, is used for shear material. The hysteretic model in PERFORM-3D is obtained by adjusting the energy degradation factor and unloading stiffness coefficient. The energy degradation factor of every critical point is calculated by the definition specified in PERFORM-3D. The shape of the hysteretic curve is obtained by modifying the unloading stiffness coefficient. The comparison of original hysteretic model with the modified one used in PERFORM-3D is shown in Fig. 9 although the modified hysteretic curve cannot agree exactly with the original one; they are equal in energy dissipation.

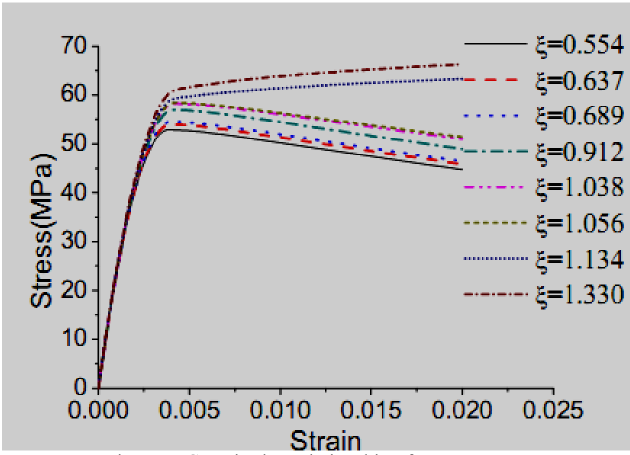


Figure 5. Constitutive relationship of core concrete

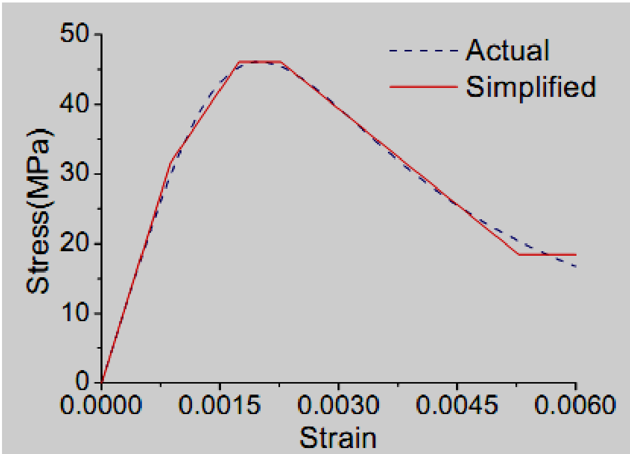


Figure 6. The simplified constitutive model of concrete

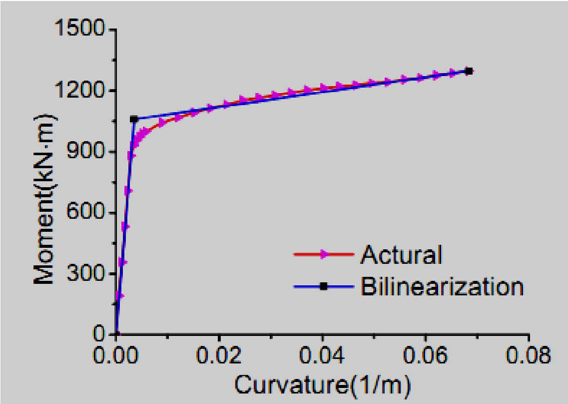


Figure 7. Simplified moment-curvature relationship

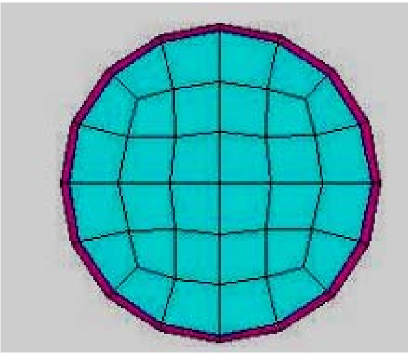
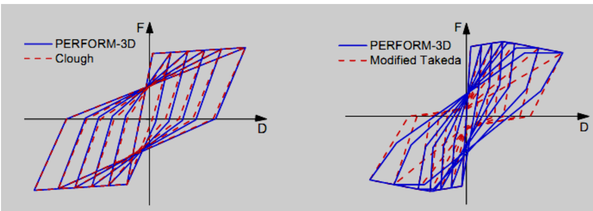


Figure 8. The resulting mesh.



(a) Clough model (b) Modified Takeda model

Figure 9. The experiment result.

V. CONCLUSIONS

In this paper, the author researches about the numerical analysis of seismic performance and structural system of high rise steel structures. Steel-concrete composite structure in high-rise and super high-rise buildings in China has been increasingly widely used, but the corresponding design specifications are still not perfect and theoretical research is also lagging behind in the practice. In addition, the effect of braces in different position and with different function to structural vibration form is studied. Execute spectrum analysis to study the dynamic response of this structure under moderate earthquake. make sure the modal steps for analysis, consider X direction and Y direction respectively, obtain the deformation style, maximum displacement, maximum relative displacement of the adjacent floors and stress distributing, compare the anti-seismic capabilities of two different directions.

In this paper, the modal analysis and time history analysis were performed on the experimental frames. The results show that the SRC frame with special-shaped columns is a typical strong column and weak beam structure, and can form the beam-hinged failure mechanism. The hysteretic loops are symmetric and plump. Compared with the reinforced concrete frame with special-shaped columns, the ductile and energy dissipation are better.

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