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SEISMIC PERFORMANCE AND VIBRATION REDUCTION DESIGN OF TOPOLOGICAL SUPER HIGH-RISE DIAGRID STRUCTURE

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Abstract

Diagrid systems have enormous potentials in construction of super high-rise buildings. Their excellent capacity resisting lateral loads (such as earthquake and wind load) not only ensure the security and comfortableness of individuals, but also enhance their applicability in complex-shaped structures. Topological optimization is one of the effective methods to amplify the lateral stiffness of buildings. When the majority of current studies concentrate on traditional diagrid system, seismic response and failure mode of topological diagrid structures are essential to explore farther. In this paper, shaking table test about a 1/35 scaled super high-rise building adopting topological diagrid tube and core tube system was conducted. The appropriately simplified three-dimensional numerical model is established. Elastoplastic time history analyses covering three types of earthquake waves and four earthquake intensity levels are utilized to acquire a great deal of analysis data about frequencies, vibration modes, acceleration and displacement time-history curves. As the earthquake intensity enlarges, the yielding order and failure characteristics of structural components are recorded. The results reveal the predominant lateral resisting property of topological diagrid tube but insufficient energy-dissipating capacity. It verifies that exterior topological diagrid system consisting of concrete filled steel tubular components sustains over half of overturning moment and base shear versus interior reinforced concrete core tube. Furthermore, to control the earthquake response of weak story and increase additional damping to building, viscous dampers are arranged in this numerical model. Parameter analyses focusing on setting positions, energy dissipation and reduction of story drifts are enforced. Work capabilities of damping scheme and original model under four intensity levels are compared and assessed, which contribute to a more efficient vibration reduction scheme for this building. The energy-dissipation design method and assessment procedure provide references for achieving sustainability and resiliency of diagrid structures.

Keywords: topological diagrid system; elastoplastic time history analyses; seismic response; vibration reduction design

1. Introduction

With the continuous development of social economy, the structural systems of urban buildings are gradually upgraded. Due to the great progress in construction technology, skyscrapers are being built around the world. And super high-rise buildings have become an important choice in urban construction. As the height of structure increases, its resistance capacity under lateral loads needs to be paid more attention. Structural systems with excellent lateral stiffness deserve to be deeply studied and developed [1].

Diagrid structure is a new structural system which differs from traditional structures [2]. Its beams and columns are not vertical intersecting. And inclined columns are applied to form tubular structural system. Inclined columns can give full play to the compressive performance of concrete, which is conducive to the lateral stiffness of diagrid structure. In the diagrid tube and reinforced concrete core tube structural system, the former can bear more than half of overturning moment and base shear under different-intensity earthquake. From the perspective of architecture, diagrid structure can satisfy designers for more fanciful and complex architectural design ideas. In recent years, a good deal of research has been done on the seismic performance of diagrid structure [3-5]. Inclination angle of inclined column and new type of connections also attract the attention of researchers [6-10]. From another point of view, using the method of optimization to adjust the position of diagrid connections and the size of structural components can further improve the lateral stiffness of diagrid structure [11-13]. Nevertheless, the performance of topological diagrid structure under complex earthquakes is not clear enough. Its defects and failure mechanism need further research and proofs.

In order to study the dynamic characteristics, failure mechanism and defects of topological diagrid structure under the action of earthquake, a numerical simulation analysis of diagrid structure utilizing topological optimization is carried out in this paper. Before numerical simulation, a shaking table test with a 1/35 scaled model structure was conducted, from which its dynamic characteristics were obtained. Based on the experimental data, an elastoplastic numerical model similar to the prototype structure is established. By utilizing seismic waves of different intensity levels, its failure mode, weak parts and energy distribution are studied. This study finds that the energy dissipation capacity of diagrid structural system is poor. Aiming at this point, design and analysis of vibration reduction schemes are conducted. Viscous dampers with different parameters are applied in numerical model to choose the optimal scheme. By comparing the structural damage and energy dissipation of numerical model with or without dampers, the effect of viscous dampers on diagrid structure is verified.

2. Background and preliminary works

2.1 Engineering background

The prototype tower has 65 floors above ground and 4 floors below ground, with a height of 311.4m. The bottom plane of this building is roughly square with a side length of about 52m. As the height increases, building plane gradually changes, and the top plane becomes circular with a diameter of about 40m. The rendering of this tower is shown in Fig.1. Visually, this tower is made up of inclined columns and horizontal beams to form diagrid tube.

The lateral force resistance system of this tower is composed of the external diagrid tube and the internal reinforced concrete core tube. The diagrid tube is enclosed by 4 pieces of approximately flat inclined column grid, and they are connected by horizontal ductile beams to form a spatial working system, as shown in Fig.2. These inclined columns adopt concrete-filled steel tube due to its compression behavior and these beams adopt steel beam [14]. As can be seen from Fig.2, the inclination angles of columns are not uniform. As the building's height rises, the spacing of columns gradually increases and the number of columns gradually decreases, which is the distinction between this tower and typical diagrid structure [15]. In other words, this tower has been optimized for its lateral stiffness through topological optimization. In the meanwhile, the appearance of tower meets the requirements of architects. Rigid connections of horizontal beams are adopted in top floors and floors located at inclined column connections. And hinge connections are adopted in other floors, as shown in Fig.2 (The dark area means rigidly connected horizontal beams). This approach enhances lateral stiffness and progressive collapse-resistant performance of this building.

Fig.1 – The rendering of prototype tower

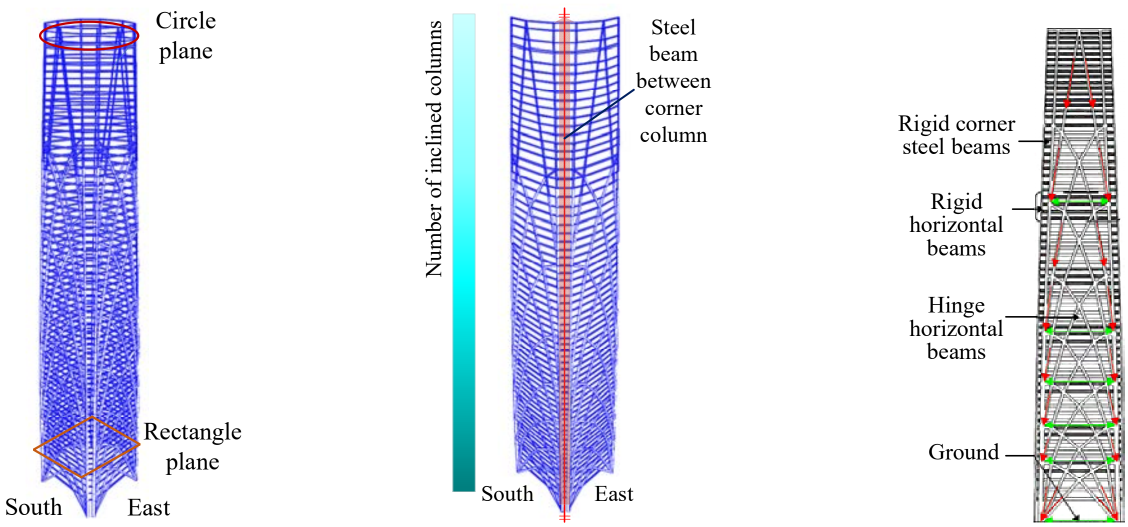

Fig.2 – Characteristics of diagrid tube and the distribution of rigidly connected steel beams

2.2 Shaking table test

2.2.1 Test model fabrication

In order to verify the seismic performance of prototype tower, especially its failure mode under high-intensity earthquakes, a 1/35 scaled shaking table test was conducted in State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China. The main research contents include: acceleration curves, displacement curves and strain response data of test model under different input earthquakes; failure mode and failure process of model; dynamic characteristics of model, etc. The test model is mainly composed of micro concrete, copper, iron wire and other materials. The main similarity ratio parameters of test model are shown in Table 1.

Table 1 – Similarity ratio parameters of test model

Physical property	Physical parameter	Similarity ratio	Value
Geometric property	Length	S_L	1/35
Material property	Elastic modulus	S_E	1/2
Loads property	Point force	S_F	4.08×10^{-4}
Dynamic property	Acceleration	S_a	4.4
	Gravity acceleration	S_g	1

According to the determined model similarity ratio parameters, final finished test model has a total height of 9.58m, of which the model base is 0.4m high and the model structure is 9.18m high. The total mass of this test model is 23.9 tons. The photos of model construction process and finished structure are shown in Fig.3.

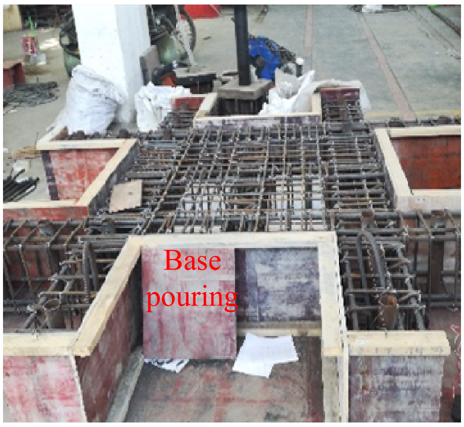

Fig.3 – The model construction process and finished structure

2.2.2 Test conditions

Three seismic waves are selected as the excitation of shaking table test, including El Centro wave, GM1 wave and GM2 wave (artificial wave). The test loading conditions are divided into three earthquake intensity levels: frequent earthquake of 7 degree (7FE), basic earthquake of 7 degree (7BE) and rare earthquake of 7 degree (7RE). In Chinese seismic code, the peak ground acceleration (PGA) corresponding to these three intensity levels of earthquake are 0.035g, 0.10g and 0.22g, respectively [16]. In each level of test, El Centro wave, GM1 wave and GM2 wave are input in sequence as seismic excitation. At the interval of each test level, white noise sweeping is performed on the model structure to obtain the changes of structure's fundamental frequency, mode shape and damping ratio.

2.2.3 Test phenomenon and conclusion

After 7FE stage, it is found that model structure's fundamental frequency doesn't change compared to value before test. This phenomenon indicates that structure model has not cracked yet, and it's still stay in elastic state. Then, after 7BE stage, there is also no obvious cracking and damage observed from the appearance of model structure. However, after 7RE stage, it is found according to white noise sweeping that the fundamental frequency of each order of model structure drops by more than 25%, and there are widespread cracks in the floor slabs. There are various signs that the model structure is obviously damaged. In general, it can be concluded that this model structure presents a sudden failure mode under high-intensity earthquake, and the ductility of this structure is poor.

3. Numerical simulation of topological diagrid structure

3.1 Establishment of elastoplastic model based on Perform 3D platform

Perform 3D is a structural analysis software which can do nonlinear analysis and performance assessment for 3D structure. It was originally developed by Prof. Granham H. Powell of the University of California, Berkeley, and is issued and maintained by the American structural software company CSI (Computers and Structures, Inc.) [17]. Perform 3D is a highly recognized structural nonlinear analysis and seismic performance evaluation software in the field of engineering structure research. It contains a wealth of linear and nonlinear elements: beam-column fiber element, beam-column plastic hinge element, shear wall fiber element, viscous damper element, buckling restrained brace element, and masonry infill wall element etc. In this paper, before establishing numerical model of this tower, some simplifications and assumptions are made to prototype structure. They mainly include that: (1) pay attention to main structural components, ignoring the contribution of secondary structural components; (2) merge the openings of shear wall; (3) simplify the cross section of irregular inclined columns. The principle of simplification is to ensure that the lateral stiffness and mass of numerical model are close to the prototype.

When establishing the elastoplastic model, the constrained concrete constitutive relationship is adopted for the concrete in the hidden column of shear wall and the concrete-filled steel tube column. These column and wall components adopt fiber element and beam components adopt plastic hinge element. In Perform 3D, you can quickly check whether the analysis results of structure exceed a certain limit level by setting a series of limit levels of element fibers or plastic hinges. The selection of limit levels can be determined with reference to standards (such as American standard ASCE41 [18]). Numerical model uses Rayleigh damping, and seismic waves adopt the same seismic excitation of shaking table test (El Centro wave, GM1 wave, GM2 wave). The seismic intensity levels newly include rare earthquake of 8 degree (8RE, PGA 0.4g) compared to the shaking table test. Finally, the simplified numerical model of this tower is completed in Perform 3D. The three-dimensional view of numerical model is shown in Fig.4. The entire nonlinear model contains a total of 3950 nodes, 5452 line elements and 1284 surface elements.

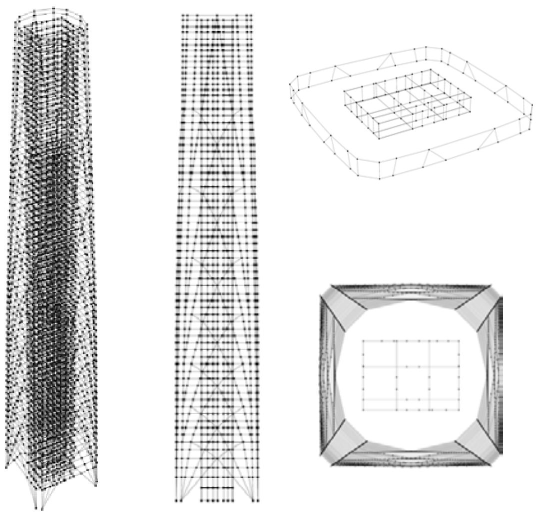

Fig.4 – Numerical model in Perform 3D

3.2 Periods analysis results

The mass source in Perform 3D is the representative value of gravity load, considering all dead loads and 0.5 times live loads. The periods comparison between numerical model and prototype obtained from experiment is shown in Table 2. The first two-order periods have a small difference from the experiment, but the later periods have a large difference. The mass of numerical model is basically same as prototype structure. Therefore, the numerical model can represent the dynamic characteristics of prototype to a certain extent.

Table 2 – Comparison of periods between numerical model and prototype

Vibration mode	Experiment		Perform 3D		Error
	Period/s	Direction	Period/s	Direction	
1	5.08	Y-direction	4.89	Y-direction	-3.7%
2	4.76	X-direction	4.69	X-direction	-1.5%
3	1.96	Torsion	2.38	Torsion	21.4%
4	1.64	Y-direction	2.01	Y-direction	22.6%
5	1.56	X-direction	1.83	X-direction	17.3%
Total mass/t	200732		206029		2.6%

3.3 Shear force results

The advantage of diagrid system is that it can provide structure with large lateral stiffness which reduces the shear force and overturning moment of internal reinforced concrete core tube under earthquake action. Furthermore, the mass of structure can be reduced and the economic efficiency can be improved. In this paper, considering the discreteness of structural response under seismic actions, the envelope values of base shear and overturning moment under three different seismic earthquakes are averaged. The distribution of base shear and overturning moment at the bottom of structure is shown in Fig.5. It can be seen from the figure that the base shear and overturning moment bore by core tube are much smaller than that of diagrid tube, and the gap is up to 3 times in some conditions. Therefore, between the lateral loads resistant systems, diagrid tube plays a major role.

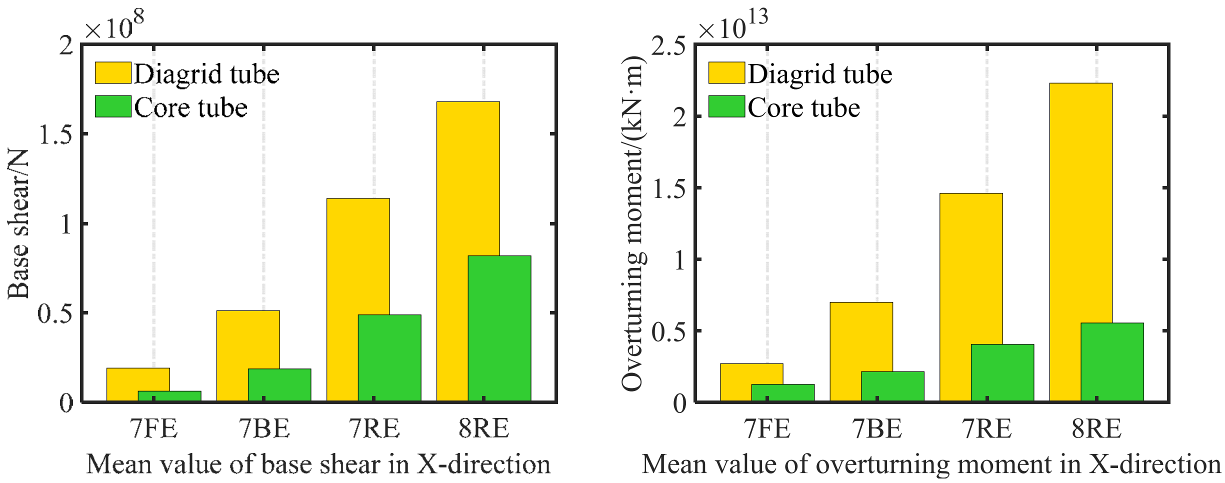

Fig.5 – Comparison of analysis results of diagrid tube and core tube

3.4 Structural damage

3.4.1 Coupling beam of shear wall

According to the research on diagrid tube and core tube structure, coupling beams of core tube will first enter yield state to dissipate energy during earthquake action. In this paper, numerical calculation and analysis of coupling beam damage under earthquakes of different intensity are conducted. Fig.6 shows the bending damage of coupling beams after 8RE stage. In this figure, the distribution of the coupling beams reaching the target level of bending performance is shown. Different colors indicate that these components have reached the corresponding multiples of target levels which include Immediate Occupancy, Life Safety and Collapse Prevention (IO, LS and CP).

Elastoplastic times-history analysis shows that core tube coupling beams have not yielded after 7FE stage (enter IO level), and some coupling beams have entered the plastic state after 7BE stage, and most of coupling beams have entered the plastic state to consume energy after 7RE stage. After 8RE stage, the overwhelming majority of coupling beams have yielded, but only a small part of them entered CP level. This phenomenon ensures the anti-collapse performance of this structure.

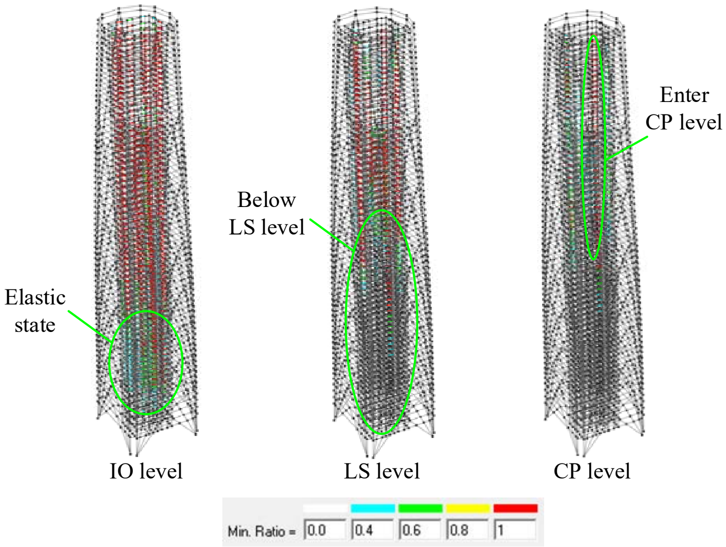

Fig.6 – Distribution of bending level of coupling beams after 8RE stage

3.4.2 Horizontal beams of diagrid tube

In this paper, the damage of rigidly connected horizontal beams between inclined columns are picked out for analysis. Fig.7 shows the distribution of the target levels of horizontal beams under 7RE and 8RE stage. In the whole structure, only horizontal beams of some floors and all corner columns adopt the form of rigid-connected beams (see Fig.2). These floors include 5-6F, 10-11F, 16-17F, 23-25F, 31-33F, 40-43F and 53F to roof. It can be seen from Fig.7 that the horizontal beams of corner columns enter plastic state earlier. The main reason is that they combine 4 pieces of approximately flat inclined column grid into a space diagrid tube, which transmit large internal force of tube structure. And the yield sequence of horizontal beams lags behind that of coupling beams. By comparing the distribution figure of target levels, it can be found that the stress state of horizontal beams on the top floors is higher than that of the lower floors. After entering the 8RE stage, most of them are on the edge of yielding, but none of them reach LS stage.

3.4.3 Inclined column and shear wall

It can be seen from analysis results that the steel fiber of concrete-filled steel tube column reaches the yield state earlier than its concrete fiber. Under rare earthquake state, the steel fiber strain of most component is maintained at a low state. The yield sequence of shear wall members is obviously lagging behind that of inclined columns. They are the final failure components of this diagrid tube and core tube structure.

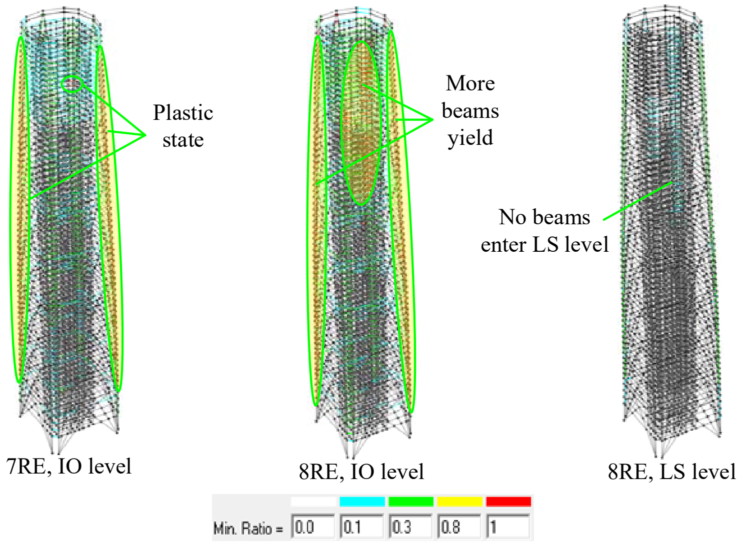

Fig.7 – The distribution of target levels of rigidly connected horizontal beams under earthquakes

3.5 Energy distribution of diagrid structure

The time-history diagrams of energy distribution ratio of structure in some analysis conditions are shown in Fig.8. It can be seen that structure hardly produces plastic energy dissipation (red part in figure) under 7FE and 7BE stage, and the main energy of structure is concentrated on elastic strain energy (light blue part in figure). As structural components gradually enter plasticity, plastic energy dissipation continue to accumulate and increase, and the energy distribution of structure gradually becomes uniform. At the end of 8RE stage, plastic energy dissipation, stiffness-related viscous energy, mass-related viscous energy, and elastic strain energy account for 24%, 15%, 41%, and 20%, respectively. The plastic energy dissipation suddenly increases in 8RE stage, which indicates that the damage of structure is brittle. In general, before 7RE stage, the energy dissipation capacity of structure is poor and there are less structural damages, which is consistent with experimental phenomenon.

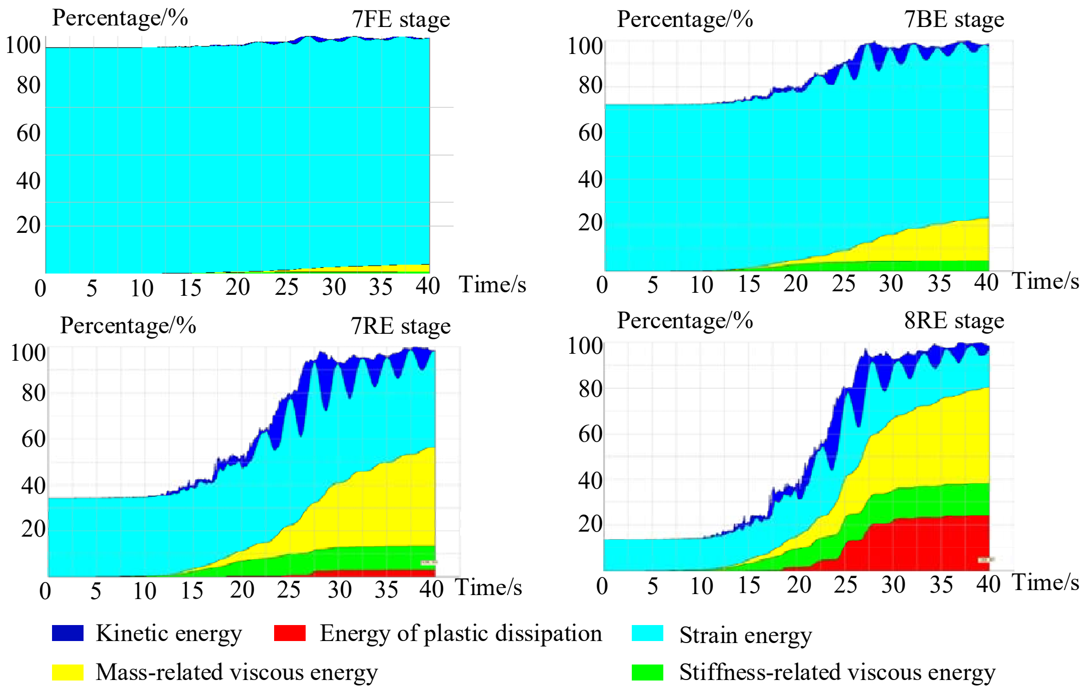

Fig.8 – Time-history diagrams of energy distribution ratio under different-intensity earthquakes

4. Vibration reduction scheme design of topological diagrid structure

Dampers are widely used in high-rise buildings and are also feasible in diagrid structure [19]. Viscous damper is a type of speed-dependent damper, which mainly relies on oily liquid to convert kinetic energy into heat energy during the reciprocating motion of piston. Its mechanics formula is shown in Eq. (1). This paper intends to design a more suitable energy dissipation scheme with viscous dampers to investigate the effect of viscous damper on structural damage control.

$$F = C \cdot v^{\alpha} \quad (1)$$

There are 6 refuge floors in prototype tower. It is proposed to arrange viscous dampers at the higher 4 floors to improve the utilization efficiency of dampers. At refuge floor, viscous dampers connect shear wall and inclined column in the form of diagonal braces. And the operation of damper is driven through the inter-story displacement. The number of dampers is set to 4 in each floor along X-direction and Y-direction, respectively. The working efficiency of viscous damper is greatly affected by the damping exponent α, and current common range of damping exponent is between 0.3 and 1. When α=1, damping force has a linear relationship with deformation rate (velocity). As α decreases, the relationship between damping force and deformation rate is close to rectangle. Generally speaking, the smaller damping exponent, the better energy dissipation effect of viscous damper. By reason of that the number of dampers is small, in order to ensure that more seismic energy can be consumed, the damping exponent is proposed to be selected as 0.3. The damping coefficient C also has a large impact on the energy dissipation of viscous damper. The larger damping coefficient, the more expensive viscous damper, which results in poor economic benefits. Through preliminary parameter analysis, dampers with different damping coefficients are compared. Finally, it is selected as 600 $kN{\cdot}(mm/s)^{-\alpha}$.

4.1 Control effect of structural damage

The main purpose of vibration reduction scheme is to reduce the damage of structure components under earthquake action, especially under high-intensity earthquake. The damage distribution diagram of coupling beams in viscous damper scheme is shown in Fig.9. It can be seen that during 7RE stage, the internal force of coupling beams in the range of 36th to 40th floors have been significantly decreased. Some coupling beams yield in original model still remain in elastic state in viscous damper scheme. The main reason is that structure has been equipped with viscous damper on the 49th and 53th floors. Under 8RE stage, the yield number of coupling beams in viscous damper scheme is almost the same as that of original model, which shows that the damage of structure under rare earthquake is much serious and the control effect of viscous dampers is limited. At the same time, the effect of viscous dampers on damage control of other structural components is basically similar.

4.2 Energy dissipation

Another purpose of arranging dampers in diagrid structure is to increase energy dissipation under earthquake action to reduce structural response. Calculating the energy dissipation of viscous dampers can reflect advantages of vibration reduction scheme from a macro perspective. Therefore, the energy distribution of structure under different-intensity earthquakes is calculated. The energy dissipation value of viscous dampers and plastic energy dissipation value of components are shown in Table 3. Then, a pie chart is drawn to compare the ratio of above two types of energy consumption, as shown in Fig.10. Where E_D represents the energy dissipation of viscous dampers, and E_I represents the plastic energy dissipation of structural components after yielding.

Viscous damper can start to work under 7FE stage, and its energy dissipation has been very considerable under 7BE stage, reaching 4000kJ. After 8RE stage, the plastic energy dissipation of components is between 40000kJ~64000kJ, and the energy dissipation of viscous dampers is between 23000kJ~36000kJ. The latter is more than half of the former, indicating that the setting of viscous dampers can indeed promote the energy dissipation of structure, especially under high-intensity earthquakes.

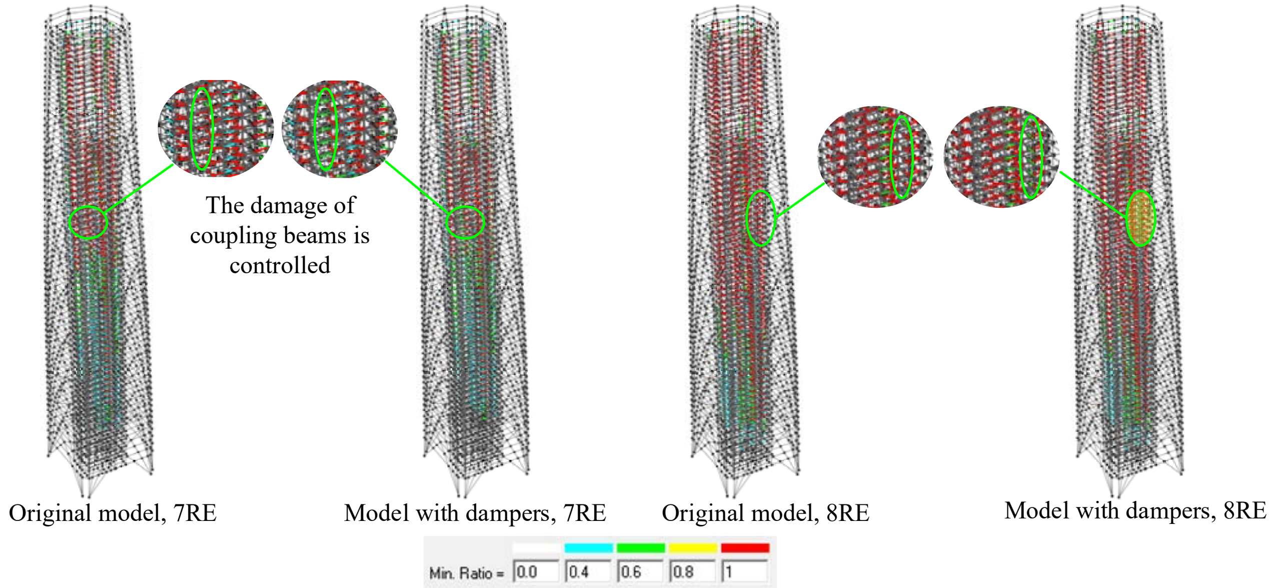

Fig.9 – Comparison of IO level of coupling beams under 7RE and 8RE stage

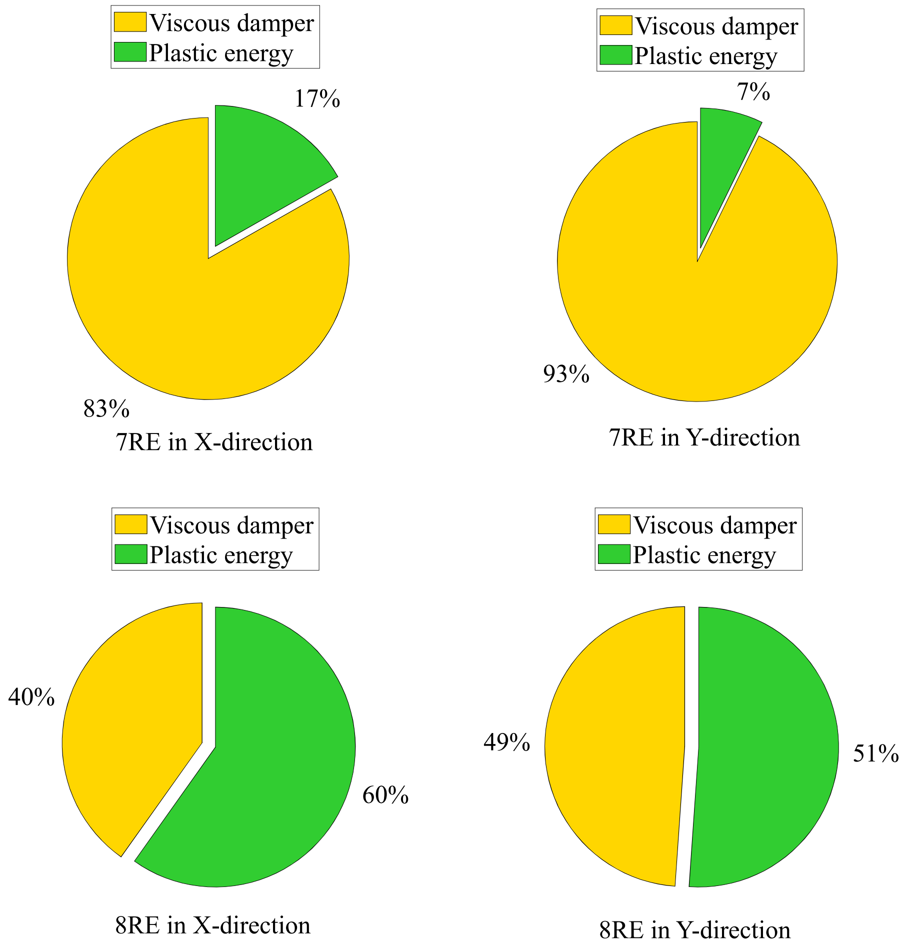

Fig.10 – Percentage comparison of energy dissipation of viscous dampers and components yielding about El Centro wave

Table 3 – Energy consumption value

Earthquake	X-direction of 7FE		X-direction of 7BE		X-direction of 7RE		X-direction of 8RE	
	E_D/kJ	E_I/kJ	E_D/kJ	E_I/kJ	E_D/kJ	E_I/kJ	E_D/kJ	E_I/kJ
El-Centro	667	/	4037	/	15932	3212	36658	54594
GM1	530	/	3166	/	10771	1728	24132	64371
GM2	525	/	3048	/	10540	1081	23829	39937

5. Conclusions

In this paper, the topological optimization diagrid structure is introduced firstly. On the basis of 1/35 scaled shaking table test, the elastoplastic model of prototype is established utilizing Perform 3D finite element software. This numerical model studies the dynamic characteristics, structural damage, and failure modes of structure under different intensity of earthquakes. At the same time, in the view of poor energy dissipation of diagrid structure, the vibration reduction scheme with viscous dampers is designed and analyzed. The following conclusions can be draw:

(1) The yield sequence of components in diagrid tube and core tube structural system is clear. Coupling beams of shear wall yield first in 7BE stage, dissipating seismic energy. Then, the internal force of diagrid tube increases, and the rigidly connected horizontal steel beams begin to enter plastic state. As the base shear and overturning moment of diagrid tube further increase, the bottom inclined columns begin to yield under tension and compression. The stress state of shear wall is always low. Even in 8RE stage, there is still almost no damage about shear wall.

(2) The energy dissipation of diagrid tube and core tube structure is relatively low. A large number of components will enter plastic state only when earthquake intensity is high. The main energy-dissipating components in this structure include coupling beams of shear wall and rigidly connected horizontal steel beams, and the plastic development of other structural members is limited. In 8RE stage, the plastic energy dissipation of structure suddenly reaches 24% of total energy, which shows that plenty of components are suddenly destroyed, and structure presents a certain degree of brittleness.

(3) The base shear and overturning moment bore by diagrid tube far exceed those of core tube. Diagrid tube has superior lateral stiffness, which can reduce the cross-sectional size of shear wall, reduce the weight of building, and achieve higher economic benefits in project.

(4) The energy dissipation effect of viscous dampers is obvious under the action of earthquakes. Viscous dampers can begin to dissipate seismic energy from 7FE stage. As seismic intensity increases, energy dissipation of dampers reaches 1/3~2/3 of plastic energy dissipation of components. And viscous dampers have a certain control effect on the damage of components.

6. Acknowledgements

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