

Integrated Optimal Life Cycle Design of Super Tall Buildings with Viscous Dampers

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1. Abstract

The life cycle of a super tall building has many stages such as design, construction, operation, maintenance and so on. The life cycle cost of the structure is mainly composed of the construction, maintenance and disaster lost costs. Viscous dampers can effectively improve the energy dissipation capacity of super tall building structures under earthquakes. The life cycle cost could be reduced by the introduction of viscous dampers due to two facts. One is that the structural members can be further optimized for considering the reduction of earthquake actions due to additional damping, and the other is that the structural damage could be alleviated with the viscous dampers to reduce the maintenance and disaster lost. The integrated optimal design of the life cycle cost about the main structural members using viscous dampers was addressed in this paper. Integrated optimal design was then applied to minimize the sizes of structural members. A life cycle cost assessment method was proposed to evaluate the whole life cycle cost of buildings which include construction, maintenance and disaster lost costs. A super tall building located in high seismicity area was applied in the final part of this paper to illustrate the effectiveness of the proposed optimal life cycle design method.

2. Keywords: super tall building; viscous dampers; life cycle cost; integrated optimal design.

3. Introduction

The past decade has witnessed the great development of super tall buildings in China. Especially for those buildings in seismic prone area, special measures are needed for improving the seismic performance of the super tall buildings. Energy dissipation system is widely applied in the design of high-rise buildings. Viscous dampers can effectively improve the energy dissipation capacity of super tall building structures under earthquakes. Viscous dampers can generate damping forces by velocity-dependent viscosity effects of the viscous liquid under different earthquake levels, and thus have been widely applied in engineering practices^[1].

According to previous study^[2,3], the damped outriggers are installed between service core and column and it will not occupy space. The structure will be safer with the reduction of response and internal forces due to increase of damping, furthermore the structural damage could be alleviated with the viscous dampers.

The optimal design of super tall building is usually equal to the optimization of construction cost. But the life cycle of a super tall building has many stages such as design, construction, operation, maintenance and etc. When engineers optimize the structure, they always neglect the damage cost under different levels of earthquake.

This paper developed an integrated optimal life cycle design method which can further optimize the additional redundancies introduced by the installation of viscous dampers in the outrigger trusses in super tall buildings. An optimal design process was applied to further optimize the structural members with high redundancies in iterative nature. A life cycle cost assessment method was proposed to evaluate the whole life cycle cost of buildings. A 250 meter high super high-rise building is adopted in the last part to show the effectiveness of the proposed method. The performance and cost of the optimized structure and primitive structure were compared at the end.

4. Optimal Design Process

Viscous dampers offer additional damping to the structure and dissipate the energy during different earthquake intensity. The seismic performance of structure can be improved with the energy dissipation capacity of the viscous dampers. The structural members can be further optimized for considering the reduction of earthquake actions. On the other hand, the damage lost could be much less than the original structure. To reduce the redundancies introduced by the viscous dampers, the following integrated optimal design process can be employed:

- (1) Assess the contribution of different outrigger trusses on the structural lateral stiffness;
- (2) Remove those outriggers which have small contribution on the lateral stiffness;
- (3) Install damped outriggers with viscous dampers, and calculate the addition damping ratios;
- (4) Determine the design constraints of components, such as story drift, period and stress ratio;
- (5) Conduct sensitivity analysis and indicate those members which need to be optimized;
- (6) Optimize those components of high redundancies, and check the design constraints to make sure they are

- below specified limits;
- (7) After the optimization of structural components, sensitivity analysis will be conducted using updated sizes of structural components. Those components of high redundancies will be optimized again like in step (6) until the margins of design constraints are as small as specified;
 - (8) Step (1) to (7) will be conducted for different structural schemes with different number of damped outrigger and stiff outrigger combinations;
 - (9) The overall life cycle costs of different structural schemes will be compared and the scheme with least cost will be the final scheme to be employed.

It is worth pointing out that in step (6), structural member sizes are commonly determined by multiple constraints. The multiple constraints are related with numerous design requirements, say global design criteria (such as period, story drift, shear weight ratio and etc.) and component design criteria (such as stability, bending strength, shearing strength, stress ratio, axial compression ratio and etc.).

The sensitivity analysis and optimization design of structure used in this paper is based on the virtual work principle. The virtual work principle indicates that when the system is given any geometric possible displacement and deformation, the sum of all the virtual work produced by external forces in the system is equal to the sum of all the virtual work produced by internal forces with micro deformation of each section in the system^[4].

Assuming d_i is the virtual work on real displacement about this component. The sensitivity index is shown in Eq.1:

$$\alpha_i = \frac{d_i}{\beta_i} \quad (1)$$

where d_i is the virtual work of component's displacement, β_i is generally chosen the component's weight or cost, etc.

According to the sensitivity indices, we can easily obtain one component's contribution to the monitoring parameter, and it is convenient to obtain the effectiveness of the structural system, the rationality of layout and the sensitivity of the components for several criteria.

5. Life Cycle Cost Assessment

With the rapid development of construction industry, engineers need comprehensive assessment method to evaluate the different schemes in preliminary design. Life cycle cost assessment, which is an effective assessment method, is being used more and more widely in the study of structural life cycle design. Life cycle cost assessment method is used to evaluate the cost in whole life cycle, and to guide engineers how to select a safer and more economical scheme.

The previous study has already put forward that the optimization objective is to minimize the life cycle cost^[5].

The scholars in China and other countries had a deep study on the theory and analysis model^[6]. The expression of analysis model is shown in Eq.2:

$$C_{tot} = C_b + C_m + C_f \quad (2)$$

where C_b is construction cost; C_m is maintenance cost; C_f is loss cost.

The significance of performance based design is to make a balance of economic and safety, and to minimize the life cycle cost. The life cycle cost refers to the construction cost, maintenance cost and lost cost. The lost cost may be caused by external force (such as wind load, earthquake, fire, explosion and etc.) or internal function (such as corrosion, aging and etc.). To super tall buildings, the main cause that we should consider in design is external force.

Different earthquake intensity has different probability of occurrence. The earthquake intensity and loss have a corresponding relation to the same structure. The expression of loss cost under the earthquake is shown in Eq.3:

$$C_f = \int_0^1 c_i dp_i \quad (3)$$

where p_i is the probability of earthquake of intensity i , c_i is the loss cost under earthquake of intensity i .

According to Eq.3, the loss cost can be expressed in Eq.4:

$$c_i = \sum_{j=1}^N \beta(B_j) \cdot n \cdot c_j \quad (4)$$

Where j is the component category, $\beta(B_j)$ is the loss coefficient of component, n is the number of damaged component, c_j is the lost cost of component.

The relation between peak acceleration of earthquake, earthquake intensity and probability of earthquake is given as Eq.5 and Eq.6^[7]:

$$A = 10^{(I \lg 2 - 2.11)} \quad (\text{m/s}^2) \quad (5)$$

$$p_i = 1 - F_{III}(x) = 1 - \exp\left(-\left(\frac{w-x}{w-\varepsilon}\right)^k\right) \quad (6)$$

where A is peak acceleration of earthquake; I is earthquake intensity; w is upper limit of earthquake intensity; k is shape function.

With Eq.6, we can easily get the relationship between the probability of earthquake and the peak acceleration. For example, when the peak acceleration is 0.15g, earthquake intensity I is 7.56, w is 6.14, and shape function K is 8.110, Eq.6 can be expressed in Eq.7.

$$p_i = 1 - F_{III}(x) = 1 - \exp\left[-\left(\frac{12 \lg 2 - 2.11 - \lg A}{5.86 \lg 2}\right)^{8.11}\right] \quad (7)$$

The lost coefficient can be gained from classification of earthquake damage to buildings and special structures. The damage state can be divided into 5 states, and every state has its own corresponding lost coefficient. As it is shown in Table.1, $\beta(B_i) = 0$ indicates that the component is undamaged, and $\beta(B_i) = 1$ indicates that the component cannot be repaired.

Fig.1 shows that most finite element analysis software judge the damage levels of components with performance level in FEMA 356. In FEMA 356, ‘IO’ is operational performance, ‘LS’ is life safety, and ‘CP’ is collapse prevention. Fig.2 is the relationship between the damage levels and performance levels. So we can easily obtain the performance level with finite element analysis software, then we can gain the lost coefficient.

To assess the life cycle cost, the following Life cycle cost assessment process can be employed:

- (1) To simplify the calculation, select several typical peak acceleration, such as the peak accelerations of frequent earthquake, moderate earthquake, and rare earthquake in *Code for Seismic Design of Buildings*.
- (2) Calculate the probability of different earthquake intensity (p_i).
- (3) Analyze the structure with different earthquake intensity.
- (4) Calculate every component's loss coefficient $\beta(B_i)$.
- (5) Obtain the lost cost with Eq.4.

Table.1 Definition of damage coefficient on different level for the reinforced concrete elements

| Damage level | Description of classification | $\beta(B_i)$ |
|----------------------|---|--------------|
| Undamaged (B1) | No crack and no need to repair. (<0.5IO) | 0.00 |
| Slight damage (B2) | A little crack, and just need simple repair. (0.5IO) | 0.05 |
| Moderate damage (B3) | Concrete occur obvious crack, but the steel bars do not yield. (IO) | 0.15 |
| Severe damage (B4) | The concrete spalls severely, and the steel bars yield. The component should be repaired and reinforced. (LS) | 0.90 |
| Collapse (B5) | The component is absolutely damaged, and cannot be repaired. (CP) | 1.00 |

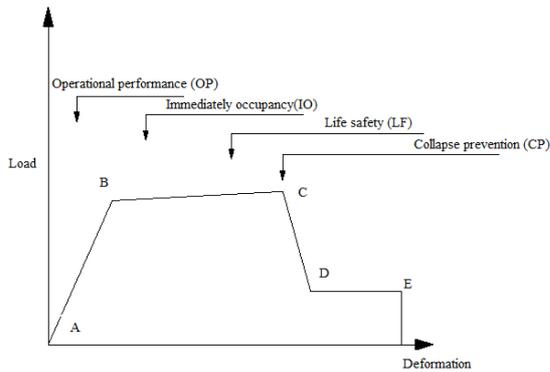


Fig.1 Performance levels of elements from FEMA



Fig.2 Damage levels and performance levels

6. Case Study

A 250-meter-high super high-rise building with 63 floors and 3 mechanical floors is adopted in this study. The structural system is frame-core wall structure. The plane of tower is 57.02m×35.62m, and the spacing of frame column is 10.2 meters along the long side and 5.6 meters along the short side. The core tube is in the middle with the size of 32.2m×13.7m. There are three belt trusses (16th floor、32th floor、48th floor) and two outriggers (32th floor、48th floor). Fig.3 and Fig.4 show the structural system of tower. The outriggers are only installed in the X direction. Five ground motion records were used for nonlinear time history analysis. The acceleration amplitude is set to 35 gal and the duration is set to 40s. The damping ratio is 4% in frequent earthquake.



Fig.3. 250 meters high model

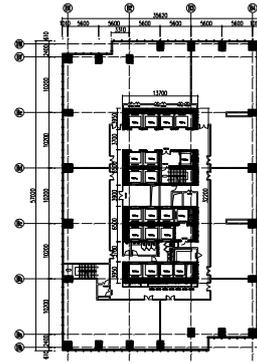


Fig. 4 Typical layout plan of tower

6.1 Remove Outriggers

As is shown in Table.2, the story drift about one outrigger in zone 3 is 1/545, and it is better to remove the outrigger in zone 2 because of the less stiffness loss. When two outriggers are removed, the story drift will be amplified too much, and the structural stiffness and stability are difficult to meet the requirements. So the damped outriggers should be installed on the outrigger in zone 3.

Table.2 Optimal position of outriggers

| Number of outriggers | 2 | 1 | 1 | 0 |
|--------------------------------|----------|--------|--------|-------|
| Location | Zone 2,3 | Zone 2 | Zone 3 | -- |
| Story drift in the X direction | 1/674 | 1/571 | 1/545 | 1/496 |

6.2 Install Viscous Dampers

The structure will be safer with the reduction of response and internal forces due to increase of damping. Fig.5 shows that the dampers can be put in 8 grids, Fig.7 and 8 show the layout of damped outriggers. The parameters of dampers are as follows: the maximum damping force is 2000kN, the damping coefficient is $C=400 \text{ kN}/(\text{m/s})^{0.3}$, the damping exponent is $\alpha=0.3$ and the stiffness is $K=4.0 \times 10^5 \text{ kN/m}$. Fig.6 and Table.3 show that the story drift decreased, and the additional damping ratio increased with the increase of dampers. The calculation results about four various quantities of dampers are shown in following Table.3.

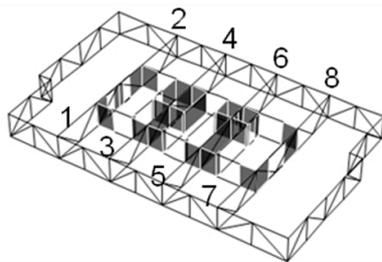


Fig.5 8 grids that can be installed viscous dampers

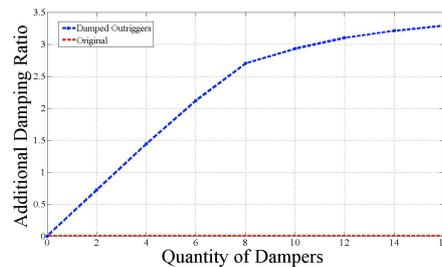


Fig.6 Additional damping ratio with different quantity of VDs

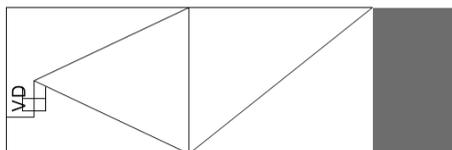


Fig.7 Damped outrigger with 1 VD

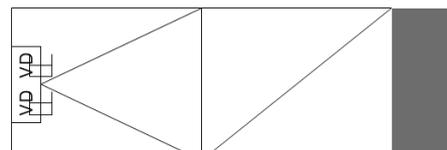


Figure.8 Damped outrigger with 2 VDs

Table.3 Calculation result of four schemes

| Scheme | Location | Story Drift | Additional Damping Ratio |
|-------------|--|-------------|--------------------------|
| with 4 VDs | Grid 3,4,5,6 (one VD in one grid) | 1/666 | 1.44% |
| with 8 VDs | Grid 3,4,5,6 (2VDs in every two grids) | 1/706 | 2.70% |
| with 12 VDs | Grid 3,2,7,8 (one VD in one grid) | 1/744 | 3.10% |
| with 16VDs | Grid1,2,3,4,5,6,7,8 (2VDs in every two grids) | 1/769 | 3.29% |

6.3 Sensitivity Analysis

Virtual couple and actual seismic force are put on the structure to conduct the sensitivity analysis for determining the optimization strategy. The virtual force is acted on the 49th floor where is the maximum story drift. Sensitivity index $\alpha_i = d_i / \beta_i$ of component is shown in following Table.4.

Table.4 shows that the diagonal members of belt trusses in Zone 3 and Zone 4 have the most contribution to maximum story drift and the second is chord members in Zone 3. To save the cost, the size of components that have small contribution to the story drift should be reduced, such as the belt trusses in Zone 1 and Zone 2.

Table.4 Sensitivity index of belt truss

| | Zone1 (16F) | Zone2 (32F) | Zone 3 (48F) | Zone 4 (63F) |
|-----------------|-------------|-------------|--------------|--------------|
| Chord Member | <5 | <5 | 10-30 | <5 |
| Diagonal Member | <5 | <5 | 50-80 | 50-100 |

6.4 Component Redundancy Analysis

This study chose belt trusses optimization as an example for the limits of paper. The design of outriggers usually needs to consider global design criteria and component design criteria. As is shown in Table.5, the stress ratio is about 0.6 to 0.9 which is under 0.9 that the Chinese code limits.

Table.5 Stress ratio of belt trusses (unit: mm)

| Story | Member | Section Size | Stress Ratio |
|-------|-----------------|---------------|--------------|
| 16F | Diagonal Member | 500x500x50x50 | 0.760 |
| | Chord Member | 700x500x50x50 | 0.729 |
| 32F | Diagonal Member | 500x500x50x50 | 0.850 |
| | Chord Member | 700x500x50x50 | 0.736 |
| 48F | Diagonal Member | 500x500x50x50 | 0.666 |
| | Chord Member | 700x500x50x50 | 0.687 |
| 63F | Diagonal Member | 500x500x50x50 | 0.732 |
| | Chord Member | 700x500x50x50 | 0.784 |

6.5 Member Optimization

The members of belt trusses whose sensitivity index to story drift is low will be the first to be optimized, when the seismic performance criteria is met. With the integrated optimal design method, the materials are distributed reasonably, and the economy of the structure is improved. Table.6 shows the section size of belt trusses which are optimized with the guidance of sensitivity analysis after several iterations.

Table.6 Optimization scheme comparison (unit: mm)

| | Component | Original Structure | Scheme with 4VDs | Scheme with 8 VDs |
|-------|-----------------|--------------------|------------------|-------------------|
| Zone1 | Diagonal Member | 500x500x50x50 | 500x450x45x45 | 500x450x45x45 |
| | Chord Member | 700x500x50x50 | 600x500x40x40 | 600x450x40x40 |
| Zone2 | Diagonal Member | 500x500x50x50 | 500x500x45x45 | 500x450x45x40 |
| | Chord Member | 700x500x50x50 | 600x500x40x40 | 550x450x40x40 |
| Zone3 | Diagonal Member | 500x500x50x50 | 500x500x50x50 | 500x500x50x50 |
| | Chord Member | 700x500x50x50 | 700x500x45x45 | 700x450x45x45 |
| Zone4 | Diagonal Member | 500x500x50x50 | 500x500x50x50 | 500x500x50x50 |
| | Chord Member | 700x500x50x50 | 700x500x45x45 | 700x450x45x45 |

| | | Scheme with 12VDs | Scheme with 16 VDs |
|-------|-----------------|-------------------|--------------------|
| Zone1 | Diagonal Member | 500x450x45x40 | 500x450x45x35 |
| | Chord Member | 600x400x40x40 | 600x400x40x40 |
| Zone2 | Diagonal Member | 500x450x45x35 | 500x450x45x30 |
| | Chord Member | 550x450x40x35 | 550x450x40x30 |
| Zone3 | Diagonal Member | 500x500x50x50 | 500x500x50x50 |
| | Chord Member | 700x450x45x45 | 700x450x45x45 |
| Zone4 | Diagonal Member | 500x500x50x50 | 500x500x50x50 |
| | Chord Member | 700x450x45x45 | 700x450x45x45 |

6.6 Life Cycle Cost Assessment

The ground motion record will be used for nonlinear time history analysis. The acceleration amplitude is respectively set to 35 gal, 100gal and 220gal. And the duration is set to 30s. The frame beams and coupling beams are simulated with FEMA plastic twisted beam. The frame columns and shear walls are simulated with fiber units. Different components are assessed by failure condition with the plastic hinge rotation or strain.

This paper chose the steel bars in the shear walls as an example for the limits of paper. Fig.9 shows the failure condition under rare earthquake whose acceleration amplitude is 220 gal. The deeper color represents the greater damage. The steel bar about original scheme with no viscous damper damaged at the bottom and middle of structure. And the damage of integrated optimal structure is less with the additional damping ratio of the viscous dampers. The largest strain of reinforcement in the shear walls are under the condition of 'LS' which is Chinese code limits.

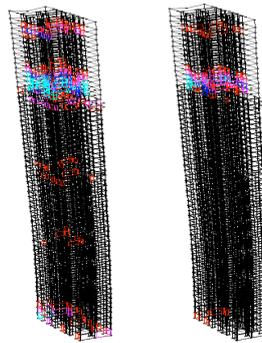


Fig.9 Damage condition of steel bars in shear walls

The lost cost of components under different earthquake intensity is shown in Table.7. The Lost cost of integrated optimal structure is much smaller than the cost of uncontrolled structure with the energy dissipation of viscous dampers. And the lost cost is smaller with the increase of viscous dampers. Every scheme is undamaged under the frequent earthquake.

Table.7 Lost Cost under different earthquake intensity (unit: RMB)

| | Original Structure | Scheme with 4VDs | Scheme with 8VDs | Scheme with 12VDs | Scheme with 16 VDs |
|-------------|--------------------|------------------|------------------|-------------------|--------------------|
| 35gal (63%) | 0 | 0 | 0 | 0 | 0 |
| 100ga (10%) | 3,770,000 | 3,010,000 | 2,430,000 | 2,210,000 | 1,910,000 |
| 220gal (2%) | 4,900,000 | 4,120,000 | 3,300,000 | 3,050,000 | 2,800,000 |
| Sum | 135,700 | 112,500 | 90,300 | 83,100 | 75,100 |

6.7 Optimization Result

Table.8 is the optimization comparison with different number of viscous dampers, in which it can be clearly observed that the damped outriggers can be removed the inner outriggers that cost 365 ton steels. The outer outriggers of the scheme with 12 and 16 VDs cost more steels than other schemes. The lost cost is smaller with the increase of viscous dampers. The optimal lost cost scheme with is the scheme with 16VDs. The price of every viscous damper is about 10,000 RMB. The price of steel is about 10,000RMB per ton. In Table 8, the economy of scheme with 8VDs is the best.

Table.9 shows the period and story drift about original structure and scheme with 8VDs. Period is a little larger than the previous scheme, and the story drift is reduced with the installation of viscous dampers.

Table.8 Optimization scheme comparison

| | Original Structure | Scheme with 4VDs | Scheme with 8 VDs | Scheme with 12VDs | Scheme with 16 VDs |
|-----------------|--------------------|------------------|-------------------|-------------------|--------------------|
| Outer Outrigger | 149t | 115t | 115t | 230t | 230t |
| Inner Outrigger | 365t | 0 | 0 | 0 | 0 |
| Belt Truss | 1181t | 1026t | 976t | 948t | 934t |
| Viscous Damper | 0 | 40,000RMB | 80,000RMB | 120,000RMB | 160,000RMB |
| Lost Cost | 135700 RMB | 112500 RMB | 90300 RMB | 83100 RMB | 75100 RMB |
| Total | 17.0 million RMB | 11.6 million RMB | 11.0 million RMB | 12.0 million RMB | 11.9million RMB |

Table.9 Optimization scheme comparison of global design criteria

| | Original Structure | Scheme with 8 VDs |
|---------------|--------------------|-------------------|
| First period | 5.83s | 6.06s |
| Second Period | 4.96s | 5.00s |
| Third Period | 3.96s | 3.96s |
| Story Drift | 1/674 | 1/692 |

7. Conclusion

This article discusses the optimization design method of viscous dampers for super high-rise building. This method is made use of sensitivity analysis, which is based on principle of virtual work. And the components can be optimized for the redundancies introduced by the viscous dampers. A 250-meter-high super high-rise building is addressed in this study, without reducing the safety of structure, the additional damping ratio is increased and the economy of the structure is improved.

We can draw the following conclusions:

1. The installation of the damped outriggers can increase additional damping ratio of structure, consume earthquake energy and reduce response under the earthquake. Meanwhile, there are some redundancies for component optimization.
2. In the process of integrated optimal design, sensitivity analysis, which is based on principle of virtual work, is used to judge the component's contribution to some criteria so that the optimal strategy can be obtained.
3. Life cycle cost assessment method is used to evaluate the cost in whole life cycle, and to guide engineers how to select a safer and more economical scheme.
4. Optimization calculation results show that the integrated optimal design of viscous dampers is reasonable and can be guidance to other designs of super tall buildings.

8. Acknowledgement

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