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Optimal Design of Tall Residential Building with RC Shear Wall and with Rectangular Layout

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Abstract

The objective of optimization is to present a design process that minimizes the total material consumption while satisfying current codes and specifications. In the research an optimization formulation for RC shear wall structures is proposed. And based on conceptual design methodology, an optimization process is investigated. Then optimal design techniques and specific explanations are introduced for residential buildings with shear wall structure, especially for that with a rectangular layout. An example of 30-story building is presented to illustrate the effectiveness of the proposed optimal design process. Furthermore, the influence of aspect ratio on the concrete consumption and the steel consumption of the superstructure are analyzed for this typical RC shear wall structure; and their relations are obtained by regressive analysis. Finally, the optimal material consumption is suggested for the residential building with RC shear wall structure and with rectangular layout. The relation and the data suggested can be used for guiding the design of similar RC shear wall structures.

Keywords: Optimization, Structural design, Shear wall structures, Optimal techniques, Tall residential buildings, Aspect ratio, Material consumptions

1. Introduction

Reinforced concrete (RC) shear wall structures are widely used in tall residential buildings for its excellent seismic behavior. However, in most architectural design institutes, RC structures are usually designed mainly according to experience in previous work. This often leads to suboptimal use of building materials. It is known that a well designed structure can decrease the project cost by 5~10%, even 10~30%. Fortunately, in recent years, more and more scholars and designers realized this problem and many optimal design theories and methods were put forward. In fact, many mathematical programming methods have been developed during the last four decades. However, most mathematical optimization applications are only suited for continuous design variables. In discrete optimization problems, searching for the optimal solution becomes a difficult task. Genetic algorithm (GA) approaches are proved to be an efficient design tool for discrete optimization and have been used in structural optimization by researchers (Goldberg and Samtani, 1986; Rajeev and Krishnamoorthy, 1992). However, for its complicated iterative process and tremendous calculation workload, most GA approaches are suited for 2D structure (Rajeev and Krishnamoorthy, 1992) or structures consisting of homogenous material, such as steel frame structure (Kargahiand *et al*., 2006). By far, no single method has been found to be entirely efficient and robust for the optimization problem for RC shear wall structures.

Recently, researchers have investigated computer-based optimization processes or techniques (Baker *et al*., 2000; Gu *et al*., 2012). The structural optimization approach proposed by Kargahiand et al. (2006) is suited for structures consisting of homogenous material. For structures consisting of inhomogeneous material, such as RC shear wall structures, it seems to be inefficient. Today, computer soft wares, including structural design soft wares have developed quickly and almost spread every corner in our lives. And almost there is no unresolvable technical problem for performing the optimal design of the structure. Hence, one of the most important things for the optimization is the conceptual design and optimal design techniques. Some basic principles have been emphasized by Park et al. (2007) for the moment-resisting frames to limit the extent of structural damage. Oh and Jeon (2014) proposed an optimum formula to calculate the story shear force distributions by comparing numerical analysis results of most seismic design codes. However, much specific work for the optimal design of RC shear wall structure still needs to be clarified.

This paper develops an optimization process for tall residential buildings with RC shear wall structure and with rectangular layout. Some optimization techniques for conceptual seismic design are presented. Though an example

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of a tall residential building, structural analysis and design are performed repetitively by use of computer soft wares to reach an optimal design. By mainly controlling the material consumption to a minimum magnitude, optimal design process is demonstrated and optimal design schemes are given. In addition, optimal material consumption is suggested for this kind of residential building.

It is well known that the ratio of height H to width B of the building, has much influence on the overall behavior of tall buildings. A large aspect ratio may decrease capacity of the structure; sometimes even cause overturning of the building. In China a tall residential building with a rectangular layout usually means its aspect ratio is very large. Sometimes, according to the demand of real estate developers, it is even larger than the limited value suggested by the Technical Specification for Concrete Structure of Tall Building (CSTB) specification (MOHURD, 2011). Hence, in the research the influence of aspect ratio on the material consumption of the structure is also investigated.

2. Optimization Process

2.1. Optimization formulation

Theoretically, the best structural design is the one that satisfies the stress and displacement constraints and results in the lowest cost of construction. It should be noted that, particularly in seismic regions, a delicate balance exists between the initial cost of construction and the future maintenance cost due to seismic risk. Although there are many factors that may affect the initial construction cost, the first and most obvious one is the amount of material used to build the structure. The subject of this study is minimization of the structural consumption or weight, which is directly related to the initial cost of the structure. Subsequently the terms material consumption and material weight used for RC shear wall have the similar meaning.

The general weight-based structural optimization problem for structures with "n" members and "m" total degrees of freedom can be stated as

$$\text{Minimize} \quad Z=\Sigma A_i L_i \quad i=1,2,\ldots,n$$

$$\text{Subject to} \quad D_j \le D_{jmax} \quad j=1,2,\ldots,m$$

$$-S_{imin} \le S_i \le S_{imax}$$

where A_i = cross-sectional areas of the members (design variables); L_i = lengths of the members; D_j = nodal displacements; and S_i = stresses in the members. Unlike the conventional way of stating a mathematical programming problem, the constraints in the preceding problem are not expressed explicitly in terms of the discrete design variables.

It can be seen that the objective function Z is a linear function of the design variables (A_i). However the constraints are nonlinear functions of the design variables. This makes the displacements and forces nonlinear functions of the cross-sectional properties of the members (Kargahiand et al., 2006).

As the problem indicates, the constraints consist of restrictions on the stresses and displacements. Because the subject of the study is the optimization of RC shear wall structure, the CSTB specification is chosen for the purpose of determining the constraints on the stresses and displacements. If so, when satisfying CSTB specifications, the objective function can be simplified as

Minimize:

$$F=\{f_1,f_2\}=\Sigma(f_{1\text{wi}}+f_{1\text{fi}}+f_{1\text{bi}})+\Sigma(f_{2\text{wi}}+f_{2\text{fi}}+f_{2\text{bi}}) \quad (1)$$

where f_1 and f_2 = total material consumption of concrete and steel reinforcement; $f_{1\text{wi}}$ and $f_{1\text{fi}}$ = concrete consumption of ith shear wall and floor; and $f_{2\text{wi}}$ and $f_{2\text{fi}}$ = steel reinforcement consumption of ith shear wall and floor; and $f_{1\text{bi}}$ and $f_{2\text{bi}}$ = concrete and steel reinforcement consumption of ith strip beams of foundation, respectively. It's important to note that $f_{1\text{wi}}$, $f_{1\text{fi}}$, $f_{2\text{wi}}$, and $f_{2\text{fi}}$ are concerned with material consumption of the superstructure and basement structure, while $f_{1\text{bi}}$ and $f_{2\text{bi}}$ are only concerned with material consumption of the basement structure.

Some main limitations prescribed by the CSTB specification for service level are introduced as follows:

(1) Ratio of inter-story drift. It defines the ratio of a story drift to its upper story. It is used to assure that the structure would be in fully operational performance level when subjected to frequent earthquake action. The limited value of the ratio for RC shear wall structure is 1/1000.

(2) Torsional period ratio. It defines the ratio of the first torsional period to the first translation period. It is usually adopted to control the structural torsional effect when subjected to horizontal earthquake action or wind load. The limited value of the ratio is 0.9 for "A" level tall building and 0.85 for "B" level tall building.

(3) Shear-weight ratio. It defines the ratio of seismic shear force of a story and the total weight above the story. It is used to avoid underestimating the seismic response force of the story. For structures in the seismic zone of 8 degrees, the limited value of shear-weight ratio is 3.20%.

Besides the objective function, for an optimal design, not only the main limitations should satisfy the requirement of CSTB specification, but also they should be close to the relevant limited values. Furthermore some of them, such as the maximum ratio of inter-story drift, should be close to each other in the two principal axes and the range of variation is considered to be no larger than 5%.

2.2. Optimization process

The optimization process is based on the following steps:

(1) Initial structural layout scheme is arranged mainly based on the architectural requirements.

(2) Structural design and analysis are performed by using finite element software (SATWE).The constraints, including story lateral stiffness, ratio of inter-story drift, torsional period ratio etc. are analyzed to determine whether it satisfies the requirement described by the specification. If so, the material consumption of the concrete and steel will be calculated.

(3) Otherwise form a new structural layout scheme based on the design techniques described in the following section, and go to step (2).

(4) Sometimes, a same design technique can lead to more than one scheme. If they all satisfy the constraint well, select the more economical one as the optimal design.

3. Conceptual Seismic Design and Optimal Design Techniques

The experiences from the past strong earthquakes prove that conceptual design of a building is extremely important for the behavior of the building during an earthquake. Design codes, such as ATC-3-06, Eurocode 8, IBC 2006 and MOHURD (2011) also prescribe regulations for conceptual seismic design. However most of the regulations are conceptual or the formulae with parameters could not be obtained only by simply meeting the regulations. In the practice of structural design, much more explanation should be clarified. Based on the conceptual design methodology, four basic optimal design techniques are clarified here for the design of residential building with shear wall structure, especially for that with a rectangular layout or approximately rectangular layout.

Make the lateral stiffness in a reasonable level. Earthquake damage investigation has indicated that most shear wall structures with a larger lateral stiffness behave well when subjected to seismic action. Structures with too large stiffness, however, will experience much higher internal forces which may cause more serious damage. In addition, too much wall members will cost much on the building material. Reasonable lateral stiffness is determined by two factors. One is the horizontal displacement of the structure, which is recommended by CSTB (2010). The other one is the seismic respond forces, like seismic shear force. The displacement, usually defined by maximum inter-story drift or ratio of inter-story drift can impose restrictions on the lower limited value of lateral stiffness and the seismic respond force can impose restrictions on the upper limited value.

Make shear walls with regular width and avoid using short-leg shear wall. Each wall has contribution to the lateral stiffness of the whole structure. And generally, long walls behave more efficiently than short walls. Hence, in order to make full use of each wall, the width of the wall should be in a reasonable level. It is concluded that the regular shear wall, defined as a wall with a width-to-thickness ratio larger than 8, can play the most effective role when resisting the seismic action or the other lateral load. While the short-leg shear wall, defined as a wall with a width-to-thickness ratio from 5 to 8, should be avoid using in shear wall structure. It is not only because that the former behaves more effectively than the latter, but also because the regular shear wall contains fewer embedded column. Embedded columns require more longitudinal and stirrup reinforcing bars to meet seismic design requirements. That is to say, the regular shear wall need less steel reinforcement and can save much more money in the same condition.

In addition, width diversity of the wall should be adjusted to a minimum level, for it is available to make each wall bearing the same magnitude of earthquake action. And this is helpful for decreasing the torsional effect of the whole structure and can make full use of the reinforcement in the wall.

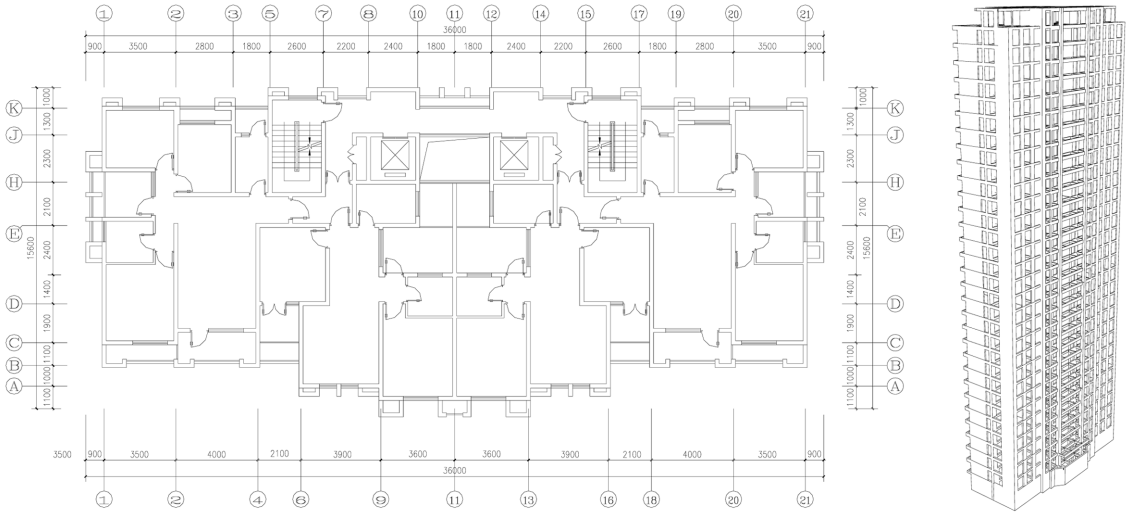
Combine the stirrup and horizontal distribution steel bar of short-leg shear wall. In order to satisfy the architectural requirement, sometimes, it is inevitable to use short-leg shear wall. However, as mentioned above, the width of short-leg shear wall is relatively small, and a large numbers of stirrup reinforcement are required to be set in the confined boundary elements of the wall. As a result, the stirrup reinforcement in the confined boundary element, such as embedded column, makes up a high proportion of the cross section. Moreover it is overlapped with the horizontal distribution steel bar of the wall body. In this situation, it is suggested to combine the stirrup and horizontal distribution steel bar in the overlapped part. This is also helpful for cutting down the cost of the building material.

Design structural openings more reasonably. In residential buildings, window and door openings are often set up in the wall for architectural requirement. Besides, structural openings are also required in some shear walls to form coupled walls. And this is helpful to make better use of the shear wall for resisting the horizontal load in some conditions, especially when the width of the wall is larger than 8 meters. However the width of the wall shouldn't be too short, as mentioned before. In the research, it is suggested that structural openings shouldn't be adopted unless internal force of one of the walls is much larger than the others or the width of the wall is larger than 8 meters.

4. Optimal Design Example

4.1. Project introduction

The example is from a community located in the city of Xi'an. The total floor area is 13940 m^2, and the number of stories above the ground is 30, with part of 31 and 2 stories underground. The height of each story is 2.9 m.



(a) Layout of typical floor (b) 3-D view of the building

Figure 1. Architecture layout and 3-D view of the building.

The design return period is 50 years, the seismic precautionary intensity (seismic zone) is 8, the seismic catalogue is the first catalogue, the design basic earthquake acceleration of ground motion is 0.20 g and the site classification is group two. It is concluded that the aspect ratio of the building is 6.1, which is larger than the limited value 5.0, suggested by CSTB specification. The architecture layout of typical floor and the 3-D view of the building are shown in Fig. 1. This is a typical residential building in China.

On the whole, the layout of each floor is regular and it is the same from the first story to the thirtieth story except the roof floor with a bulge part. To keep the lateral stiffness varying smoothly in the height, the cross sectional thickness and the concrete strength of the shear wall are designed to decrease interlacedly from the bottom to the top. The thickness of shear wall is 300 mm, 250 mm and 200 mm for story one to five, six to thirteen and fourteen to thirty one, respectively. The concrete strength is defined as C35, for beams and slabs, from the first floor to the fourteenth and C30 from the fifteenth to the roof; for shear walls, C40 from story one to seven, C35 from story eight to nineteen and C30 from story twenty to the top, respectively. The wall thickness, concrete strength and the strip beams of the basement structure is as the same as the first story. In this paper, the optimal progress is introduced by two parts: the superstructure and the basement structure.

4.2. Designing schemes of the superstructure

Based on steps (1)~(4) of the optimal process, totally more than ten structural schemes of the superstructure are obtained, among of them only six schemes are introduced here.

Scheme A. The shear wall is arranged mainly based on the architectural requirements, as shown in Fig. 2(a).

Scheme B. Based on the arrangement of Scheme A, to balance the lateral stiffness of the whole structure in X and Y directions, structural openings are set up in some shear wall members to adjust the lateral stiffness in both X and Y directions, such as the wall with the length of 8 meters or more. In order to make the best use of cross walls, some shear wall members with “one” shape cross section are adjusted to “T” shape or “L”shape. For example, openings are set up in the cross walls of 5, 6, 9, 11, 13, 16 and 17 axes, and cross walls of 11 axes are divided into two limbs with “T” shape, as shown in Fig. 2(b).

Scheme C. To obtain the influence of concrete strength on lateral stiffness based on Scheme B, the concrete strength grade of shear walls above story eight are increased from C35 to C40. And the layout is the same as Scheme B as shown in Fig. 2(b).

Scheme D. On the basis of Scheme B, in order to obtain influence of the wall thickness on lateral stiffness, the thickness of shear wall above story fourteen are increased from 200 mm to 250 mm. And the layout is the same as Scheme B as shown in Fig. 2(b).

Scheme E. In this scheme, the shear wall is arranged based on the preliminary design drawings. It is concluded from the preliminary calculation result that the maximum ratio of inter-story drift in Y direction is 1/809, which is far larger than the limited value. Therefore, some shear walls in Y direction are strengthened to satisfy the requirement. And the layout is shown in Fig. 2(c).

Scheme F. On the basis of Scheme E, the arrangement of shear wall is further adjusted to make the lateral stiffness of the whole structure in X and Y directions into a same magnitude. For example, the length of wall limb of

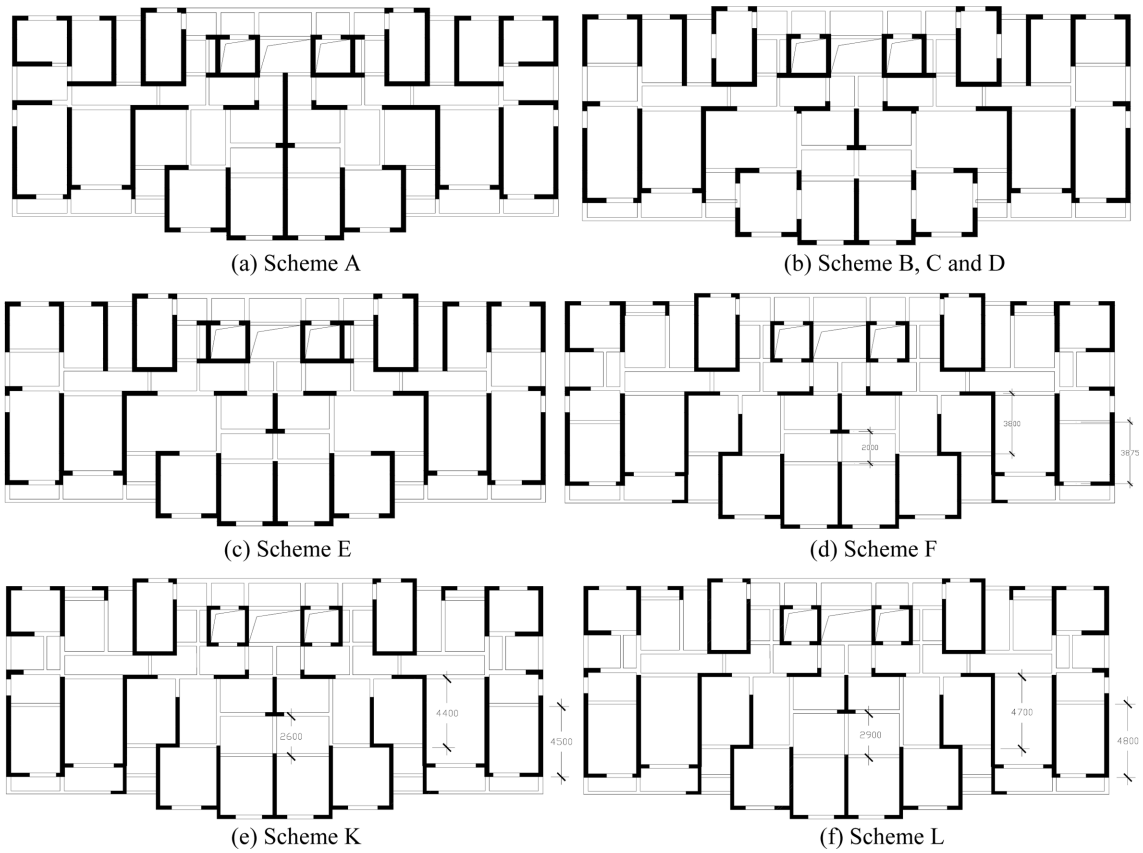


Figure 2. Structural layouts.

3 and 19 axes are adjusted to shorter; the cross section of 7 and DE, 15 and DE are turned to "T" shape. And the thickness of shear wall of story one to three is adjusted from 300 mm to 250 mm (that of 1 and 2 axes still remain 300 mm). And the layout is shown in Fig. 2(d).

4.3. Optimal design result and analysis

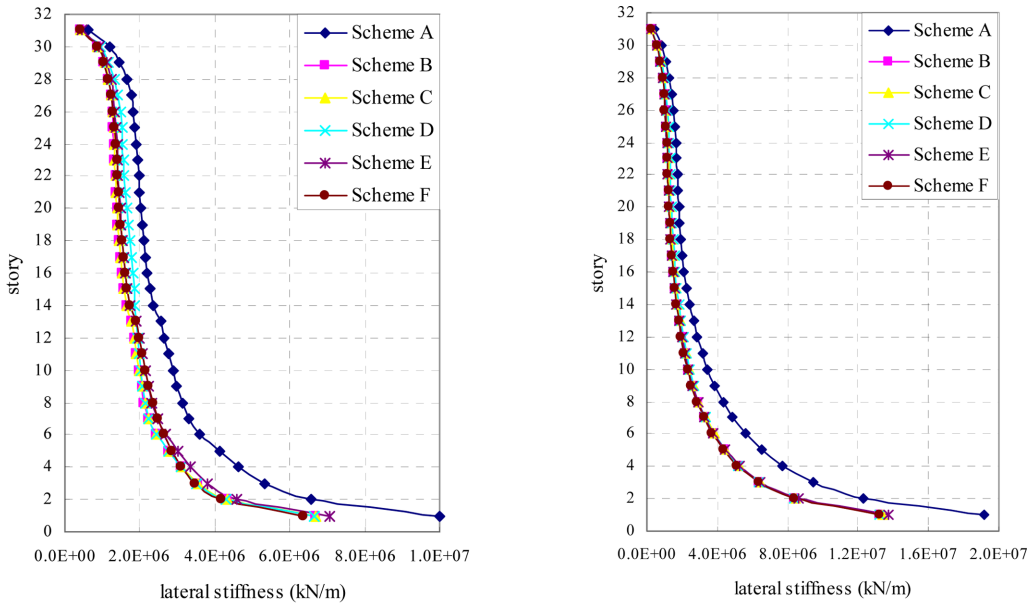
Models of this six structure schemes are set up and calculated by using SATWE module of PKPM software. Story lateral stiffness, ratio of inter-story drift, ratio of story shear to weight of the total upper story, story seismic response force, ratio of torsional period to translation period and axial compression ratio of the schemes are obtained. Part of them is introduced in this paper, and the others are referred in the literature by Shi and Men et al. (2011).

Story lateral stiffness. The lateral stiffness distribution curves of the six structural schemes in the X and Y directions are illustrated in Fig. 3.

It is shown that the stiffness of Scheme A is the largest, for much more shear walls are arranged than the others, according to the architectural requirements. The stiffness of Scheme B is smaller than Scheme A, because of more structural openings set up in wall limbs. In Scheme C and Scheme D, the stiffness distribution doesn't t have much difference with Scheme B, except the stiffness of the upper story of Scheme D in X direction is larger than Scheme B. It is just because the wall width above story fourteen of Scheme D is 250 mm, which is larger than that of Scheme B. So it is concluded that it is not an effective way for adjusting the lateral stiffness, only by changing the concrete strength grade or the width of shear wall. The stiffness of Scheme E and Scheme F is a little larger and smaller than that of Scheme B, respectively. Hence, if all the other indexes meet the standard requirements, Scheme B or Scheme F can be selected as the optimal scheme.

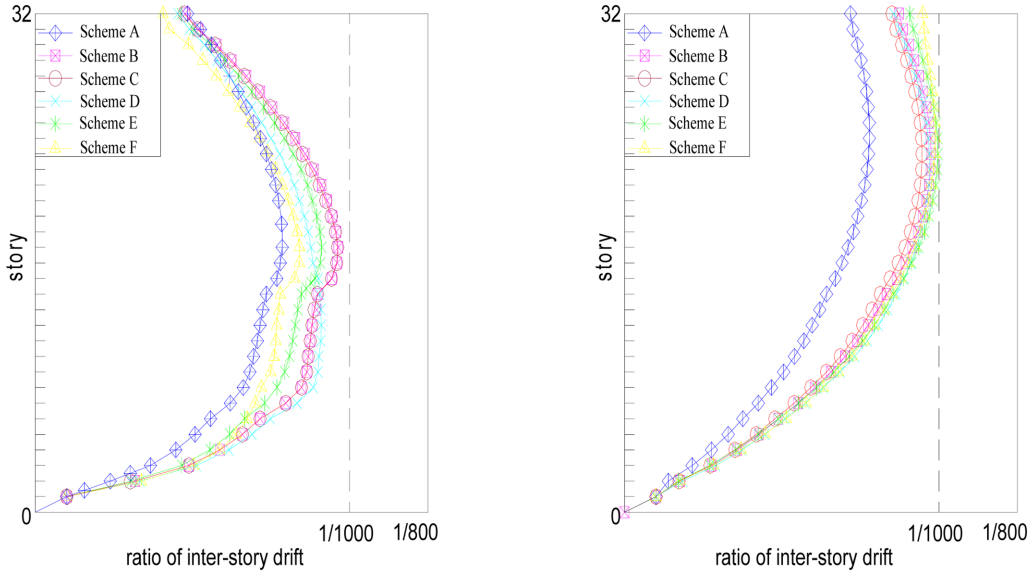
Ratio of inter-story drift. Ratio of inter-story drift curves of these six schemes in the X and Y directions are illustrated in Fig. 4.

It can be seen that ratio of the six schemes are all smaller than 1/1000, which is the limited value prescribed by the CSTB specification. In Scheme A, ratios of inter-story drift both in X- and Y- direction, with the maximum value is 1/1272 and 1/1283, are smaller than the others, for its lateral stiffness is the largest, incidental with the most amount of shear walls. In Scheme B the maximum values are 1/1037 and 1/1025, respectively, which nicely satisfy the requirements of CSTB specification, and are similar in X- and Y- direction. Ratios of inter-story drift of Scheme C and Scheme D are both a little smaller than Scheme B. However, considering the amount of shear walls Scheme B is a more economical one. In Scheme E, the ratios



(a) X direction (b) Y direction

Figure 3. Story lateral stiffness curves.

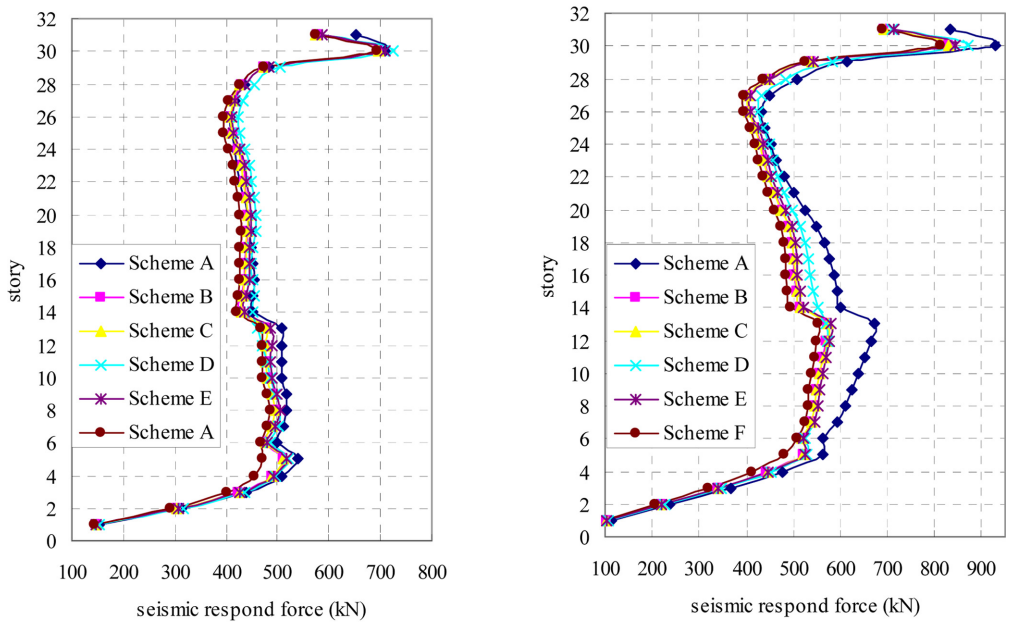


(a) X direction (b) Y direction

Figure 4. Ratio of inter-story drift curves.

in X- and Y- direction are different a lot. This is not beneficial for resisting earthquake. While in Scheme F, the maximum ratios in X- and Y- direction are 1/1073 and 1/1007, respectively, which not only exactly satisfy requirements of CSTB specification, but also are almost the same in the two directions. It is very beneficial for resisting earthquake, especially for reducing the torsional effect when subjected to earthquake action from random direction. In addition, it is more economical for part shear wall of story one to three is thinner than the others.

Seismic response force and shear-weigh ratio. The seismic response force of the six schemes in X and Y directions are illustrated in Fig. 5. It is shown that the order from big to small of the seismic response force is of Scheme A and D, Scheme C and E, Scheme B and F. This order is dependent to a great extent on their lateral stiffness or amount of shear walls. In the same condition



(a) X direction (b) Y direction

Figure 5. Distribution of seismic respond force.

a smaller seismic response force is beneficial to reducing earthquake damage. It should be noticed that the seismic response force are abruptly changed between 29- and 30-story in Fig. 5. It is because that the weight of 30-story is much larger than that of 29-story, which is mainly contributed by the slab. Thickness of the most slab in 30-story is 120 mm, while that in and beneath 29-story is 100 mm.

Shear-weight ratio, which defines the ratio of seismic shear of a story and the total weight above the story, is used to avoid underestimating the seismic response force of the story. It is noted that the shear-weight ratio increase from the bottom to the top for these six schemes. And they are all greater than 3.20%, which is the limited value prescribed by the CSTB specification.

Torsional period ratio. The torsional period ratios of the six schemes are all less than 0.9. Among of them, the ratio of Scheme F is the least, which means that the lowest probability for producing torsional effect might occur in Scheme F.

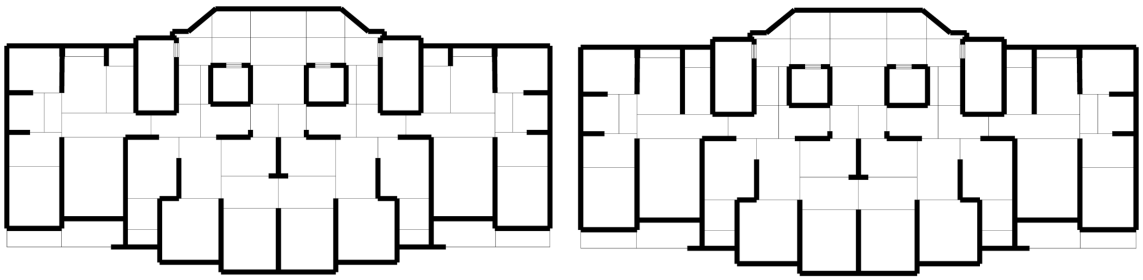
As has been described above, Scheme F not only satisfies all the constraints but also conform to the optimal design techniques for shear wall structures. In addition, it was proved to be more economic for its least material consumption introduced in the later section. Hence Scheme F is advised as the optimal design scheme and Scheme B as the second one.

4.4. Designing schemes of the basement structure

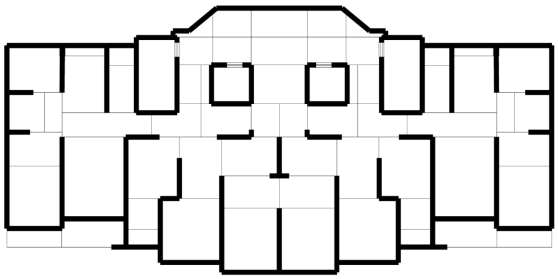
Pile foundation is design to be used in this building. And strip beam is set up to connect the wall of basement and the pile foundation. The detail about the design of pile foundation is not discussed in this paper. The key problem in the optimal progress of the basement structure is to confirm two important parameters: the height of the basement and the height of the strip beam. To some extent, they determine the depth of foundation and the lateral stiffness ratio of the first story of the basement and the first story of the upper structure. The sum of the height of basement and the strip beam is equal to the embedded depth of foundation, which is limited to be not smaller than 1/18~1/20 of the total height of the building prescribed by the CSTB specification. So a larger height of the basement is beneficial for this purpose. However, in the other hand, the lateral stiffness ratio of the first story of the basement K_0, and that of the upper structure K_1, is limited to be not smaller than 2. From this point a smaller height of the basement is prefer to be chosen.

Based on Scheme F of the superstructure, six schemes of the basement structure illustrated in Fig. 6 are designed mainly by changing the height of the basement H_0, and the height of the strip beam h, also accompany with the arrangement of the wall. Details of the basement structure are shown in Table 1. Number of the scheme is express by the height of basement, for example, 42a means that the height of basement is 4.2m. And the latter “a”, “b”, “c”, is used to distinguish the arrangement of walls when the height is the same. It should be noted that only the lateral stiffness ratio in Y direction is presented here, for that in X direction varies about from 4 to 5, which has few space for changing and optimization.

It can be seen from Table 1 that the lateral stiffness ratio of Scheme 42*a*, 40*a*, 42*b*, 42*c* are all far less than 2,



(a) Scheme 38*a*, 40*a*, 42*a* (b) Scheme 42b



(c) Scheme 40b, 42c

Figure 6. Layout of basement structural members.

Table 1. Details of the basement structure

Scheme Number	H_0 (m)	h (m)	K_0/K_1	Arrangement of Shear Walls
42*a*	4.2	0.8	1.74	The same as the first story and filling all the structural openings
40*a*	4.0	1.0	1.84	The same as Scheme 42*a*
38*a*	3.8	1.2	2.01	The same as Scheme 42*a*
42*b*	4.2	0.8	1.80	The same as Scheme 42*a* and adding walls of 3 axis and 19 axis
42*c*	4.2	0.8	1.84	The same as Scheme 42*b* and adding walls of 9 axis and 13 axis
40*b*	4.0	1.0	2.01	The same as Scheme 42*c*

which is not satisfy the requirement. And the ratio of Scheme 38*a* and 40*b* is about 2.01, which nicely meets the requirement. Hence Scheme 38*a* or Scheme 40*b* is advised as the optimal design scheme of the basement structure. It is also concluded that the height of basement, the height of strip beams, and the arrangement of shear walls all have distinctly effect on the structural scheme. For Scheme 38*a* and Scheme 40*b*, besides the lateral stiffness ratio, the better one should be decided by their material consumptions.

4.5. Material consumptions

Material consumption of the superstructure. The concrete consumption and steel reinforcement consumption of each member are calculated one by one, through multiplying the length, area, unit weight of material and the total number of members and summarizing them. As described in Eq. (1), the material consumption consist of shear wall and floor of the superstructure, and shear wall, floor and strip beams of the basement structure. It should be noted that the reinforcement of members for each scheme are extracted and calculated based on the result of SAT WE, which are displayed by the software only if the full design are finished. And that the material consumptions are calculated theoretically and without consideration of constructional requirements.

The concrete consumption and the steel consumption of the six schemes are shown in Table 2. Obviously, the concrete consumption of Scheme F is the lowest, which is about 0.4025 m^3/m^2, the second lowest one is Scheme B and Scheme C, and the largest one is Scheme A. Moreover, the steel consumption of Scheme F is the lowest, which is about 44.3069 kg/m^2. All these indicate that Scheme F can be selected as the optimal one. It should be noted that the reason why the material consumption of Scheme F, even of Scheme B is in a lower magnitude is to a great extent decided by the reasonable arrangement of shear walls.

Material consumption of the basement structure. The concrete consumption of these six schemes of the basement structure is shown in Table 3. And the sum of shear

Table 2. Concrete and steel consumption of the superstructure

Items	Scheme A	Scheme B	Scheme C	Scheme D	Scheme E	Scheme F
Concrete in Shear Walls (m^3)	4007.5	3485.9	3485.9	3885.5	3578.6	3438.2
Concrete in Floors (m^3)	1960.9	1988.6	1988.6	1988.6	1990.4	1993.5
Total (m^3)	5968.4	5474.5	5474.5	5874.1	5569.0	5431.7
Unit Area Concrete Consumptions (m^3/m^2)	0.4423	0.4057	0.4057	0.4354	0.4127	0.4025
Steel in Shear Walls (kg)	371435.9	365977.3	365977.3	390782.5	361942.1	350132.1
Steel in Floors (kg)	247806.2	247806.2	247806.2	247806.2	247806.2	247806.2
Total (kg)	619242.1	613783.5	613783.5	638588.7	609748.3	597938.3
Unit Area Steel Consumption (kg/m^2)	45.8855	45.4810	45.4810	47.3191	45.1820	44.3069

Note: the total floor area above ±0.000 is 13495.37m^2; and ±0.000 represents the relative building elevation of the first floor.

Table 3. Concrete and steel consumption of the basement structure

Scheme Number	Concrete Items				
	Shear Walls (m^3)	Floors (m^3)	Sub-total (m^3)	Strip Beams(m^3)	Total (m^3)
42a	285.9	93.6	379.5	223.1	602.6
40a	272.3	93.6	365.9	272.7	638.6
38a	258.9	93.6	352.5	322.3	674.8
42b	293.6	93.6	387.2	227.9	615.1
42c	296.7	93.6	390.3	232.4	622.7
40b	282.5	93.6	376.1	284.1	660.2
Scheme Number	Steel Items				
	Shear Walls (kg)	Floors (kg)	Strip Beams(kg)	Total (kg)	Unit Area Cons. (kg/m^2)
38a	38676.58	13261.56	40459.12	92397.26	207.75
40b	40946.58	13261.56	37218.41	91426.55	205.57

Note: the total floor area beneath ±0.000 is 444.75 m^2.

wall and floor is shown in line 4 of Table 3. It can be seen that the concrete consumption of Scheme 38*a* and 40*b*, which are 352.5 m^3 and 376.1 m^3, respectively, are both in a lower magnitude. However, when taking the strip beam concrete consumption into account, Scheme 40*b* should be the best one. The steel consumption of the Scheme 38*a* and 40*b* are also calculated, as shown in Table 3. It is clear that the strip beam steel of Scheme 40*b* is much less than Scheme 38*a*. And this result in the total steel consumption is smaller too. Hence Scheme 40*b* is advised as the optimal design scheme for the basement structure.

5. Influence of Aspect Ratio on the Material Consumption

An optimal process for structural scheme has been recommended in the previous section. Now influence of aspect ratio on the material consumption is presented based on two ways: by changing the height of building H and by changing the width of building B to achieve different aspect ratios of the building.

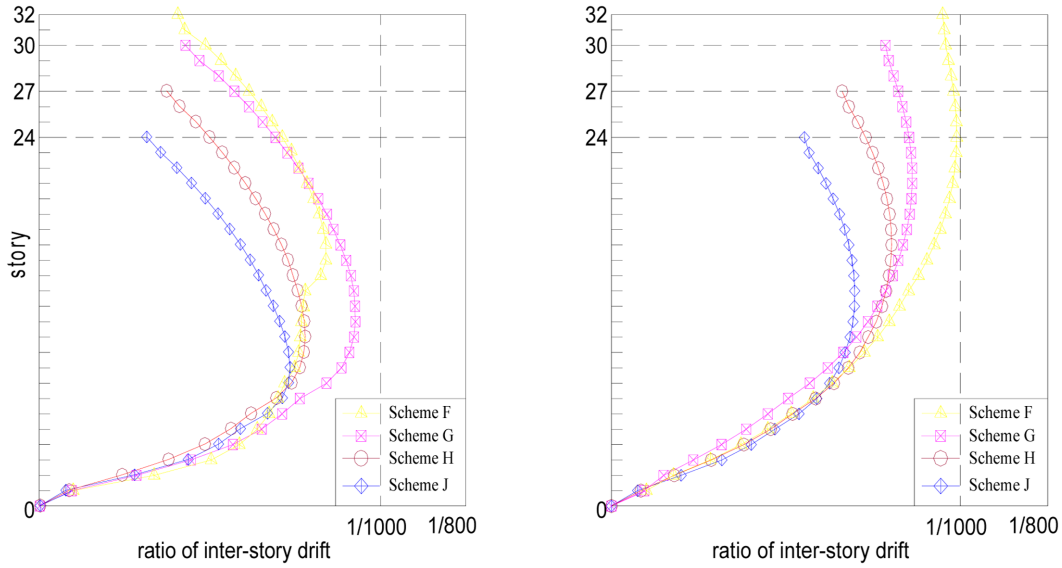
By changing the height of the building. As mentioned in section 4, the aspect ratio of the building is 6.1. It exceeds the limited value 5.0, advised by the CSTB specification. Therefore, based on Scheme F, by changing numbers of the building story to 28, 25 and 22, another three structural schemes with the aspect ratios of 5.7, 5.1 and 4.5, named Scheme G, Scheme H, Scheme J are provided, respectively. In order to maintain the lateral stiffness varying smoothly along the height, the concrete strength and the width of shear walls are changed interactively. Along with Scheme F, the ratios of inter-story drift of the four schemes are illustrated in Fig. 7 and the concrete, the steel reinforcement consumption are shown in Table 4. Furthermore, relations between aspect ratio and the concrete consumption, the steel consumption are obtained by regressive analysis and can be expressed by Eqs. (2) and (3), respectively.

$$F_1 = 0.048\alpha + 0.109 \tag{2}$$

$$F_2 = -2.249\alpha^2 + 26.96\alpha - 36.584 \tag{3}$$

where F_1, F_2 = concrete, steel reinforcements consumption; $\alpha = H/B$, aspect ratio of the building.

By changing the width of the building. Based on Scheme F, the depth of part rooms increases by 600 mm and 900 mm, that is the width of building B increases by the same value. Then another two new structural schemes with the aspect ratios of 5.8 and 5.7, named Scheme K, and Scheme L are provided, respectively, which are illustrated in Fig. 2(e) and (f). Along with Scheme F, the ra-



(a) X direction (b) Y direction

Figure 7. Ratio of inter-story drift curves (by changing the height of building).

Table 4. Concrete consumption and steel consumption (by changing the height and width of building)

Items	Scheme F	Scheme G	Scheme H	Scheme J	Scheme K	Scheme L
Aspct Ratio	6.1	5.7	5.1	4.5	5.8	5.7
Total Concrete Consumption (m^3)	5431.7	4797.8	3933.2	3264.6	5614.9	5705.3
Unit Area Concrete Consumption (m^3/m^2)	0.4025	0.3820	0.3490	0.3270	0.3979	0.3957
Total Steel Consumption (kg)	597938.7	549068.8	476135.5	381989.5	604070.7	607136.7
Unit Area Steel Consumption (kg/m^2)	44.31	43.70	42.65	39.11	42.8086	42.1074

tios of inter-story drift of the three schemes are displayed in Fig. 8 and the concrete, the steel reinforcement consumption are shown in Table 4. Relations between aspect ratio and the concrete and the steel consumption can be expressed by Eqs. (4) and (5), respectively.

$$F_1 = 0.020\alpha + 0.281 \tag{4}$$

$$F_2 = 6.476\alpha + 4.994 \tag{5}$$

It is shown from Eqs. (2)~(5) that the relation between the concrete consumption and aspect ratio is linear and the rate of increase may be about of 4.8% or 2.0%. The relation between the steel consumption and aspect ratio may be linear or nonlinear and the rate of increase may be about of 5.9% or 6.5%. It seems that the increase rates are not so large, however, when taking the base value of the material cost (usually tens of millions, even hundreds of millions dollars) into account, the increase is absolutely non-neglectable.

The different type of expression of the steel consumption and aspect ratio maybe mainly result from the reinforcement in the end-zones of the shear wall. When the height of the building changes during a certain range, the stirrup and longitudinal reinforcement in the end-zones, also with the distributing bars in the wall body, change a little in different stories, which have not much influence on the unit area steel consumption. However when the width of the building increases, the length of some shear wall limbs along the corresponding direction will increases too. And this will largely cause the increases of the stirrup and longitudinal reinforcement in the end-zones. Hence, increase the height versus decrease the width of the building, the former is a relatively more effective way to make the steel consumption increase not so notable for the tall building with a large aspect ratio.

6. Suggested Value of Material Consumptions

Besides the concrete and the steel consumption presented above, material consumptions resulted from the constructional requirement were provided by a professional calculation institute. They were calculated based on the structural construction drawing designed by the authors according to Scheme F and Scheme 40b. Hence, a more accurate material consumption for the concrete and the steel are obtained, listed in Table 5.

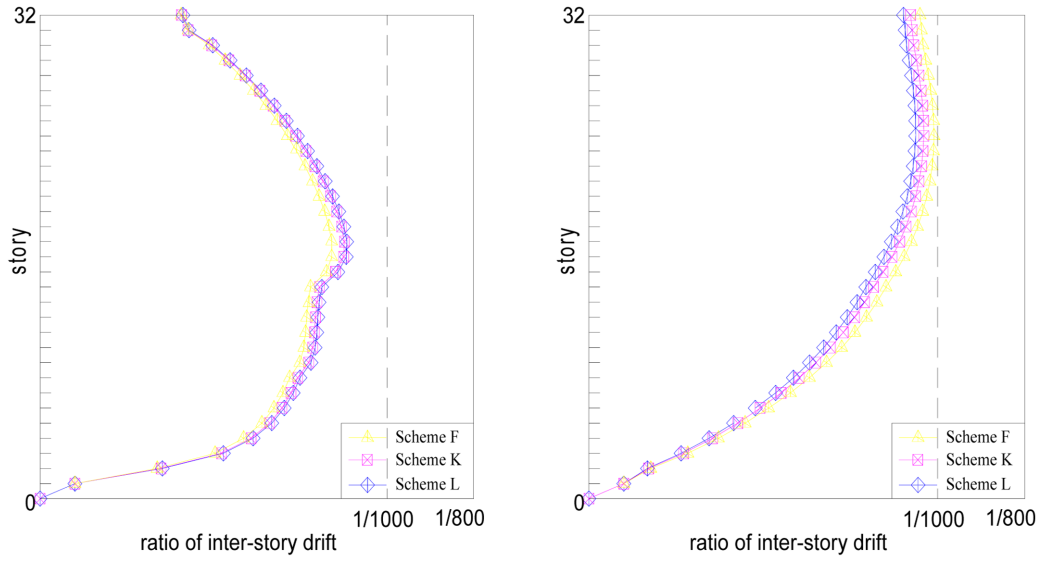


Figure 8. Ratio of inter-story drift curves (by changing the width of building).

Table 5. Suggested material consumptions

Part of Structure	Items	Unit Area Concrete Consumption (m^3/m^2)		Unit Area Steel Consumption (kg/m^2)	
		Calculated	Suggested	Calculated	Suggested
above ±0.000	Shear Walls	0.2465	0.220~0.250	25.1169	24~29
	Floors	0.1429	0.130~0.160	17.7765	16~23
beneath ±0.000	Shear Walls	0.0203	0.017~0.020	2.7745	2.8~4.0
	Floors	0.0067	0.006~0.007	0.9513	0.75~0.98
	Strip Beams	0.0285	0.029~0.040	3.5787	3.5~4.5
Sum		0.4449	0.410~0.450	50.1979	54~60

In addition, the data of four similar tall residential buildings were collected. And the concrete and steel consumptions were calculated in the same way. Then the optimal material consumptions are suggested in this research, as shown in Table 5. The suggested values are suitable to tall residential buildings with shear wall structure, especially with rectangle layout.

7. Summary and Conclusions

Reinforced concrete shear wall structure is very common in tall residential buildings in China. Aiming at minimizing the total structural material consumption, the authors have presented an optimization process and four optimization techniques for RC shear wall structure. By use of computer software, the optimization process is adopted to determine the structural scheme. And it is very convenient for the structural engineer or designer to operate. Certainly much attention should be paid on the optimization techniques for RC shear wall during the designing procedure.

As a typical example, a tall residential building with RC shear wall and with rectangle layout is presented. According to the proposed optimization process and techniques, six shear wall structural schemes of the superstructure are investigated. The parameter of constraints, including story lateral stiffness, ratio of inter-story drift, seismic response force, and ratio of torsional period to translation period are calculated and analyzed in detail. Based on the structural scheme of the superstructure, optimization process are also carried on the basement structure. Then the optimal design scheme of the superstructure and the basement structure are both suggested. Moreover, the concrete consumption (by weight) and steel reinforcement consumption (by weight) of each member are calculated. It is concluded by comparing with the concrete strength and the width of shear walls that the arrangement of shear walls have obvious influence on the material consumptions. In addition, the concrete consumption and steel consumption all increase largely with the increase of the aspect ratio of the building. In the end, the optimal material consumptions are suggested. The suggested value can be used as reference for the design of tall residential buildings with shear wall structure, especially

with rectangular layout.

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