17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

RESEARCH ON SIMPLIFIED METHOD OF BOTTOM LATERAL STIFFNESS OF THE STEP-TERRACE FRAME-SHEARWALL STRUCTURES

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Abstract

The step-terrace structure refers to a structural system supported by foundation with different elevations to adapt the different elevations of the terrain, and it has been widely constructed in hillside buildings. The concept of lateral story stiffness based on traditional structure is not clear because of multiple embedding ends. The shear distribution characteristic of the upper and lower embedding components depends on the lateral stiffness of the bottom of step-terrace structure. To study on the method to calculate the lateral stiffness of the bottom of step-terrace structure is of great significance.

In this paper, the step-terrace frame-shearwall structures are taken as the research object.

Firstly, by studying on the different arrangement of shear wall of the single-story single-span step-terrace frame-shearwall structures, three simplified calculation models are proposed: i) the left single hinged model in which the shearwall is mainly arranged on the lower embedding end; ii) the right single hinge model in which the shearwall is mainly arranged on the upper embedding end; iii) the rigid connection model in which the shearwall is arranged on the upper and lower embedding end. The calculation methods of the lateral stiffness for the three models are derived respectively. In order to achieve the reasonable arrangement of the structure, the structural arrangement principles of the three models are proposed by comparing the differences in the lateral stiffness of the upper and lower embedding components.

Next, the lateral stiffness of the multi-span step-terrace frame-shearwall structure is studied. The structure is separated by the characteristic of the foundations with different elevations, and it can be regarded as separated substructures which are connected by beams. The simplified method of the lateral stiffness of the substructures is proposed, and the analysis process of the multi-span step-terrace frame-shearwall structure is put forward. Taking the single-layer multi-span step-terrace frame-shearwall structures which shear walls are arranged on the upper and lower embedding ends as an example, the calculation process of shear force and lateral stiffness of the components is deduced in detail.

Finally, taking the left single hinge model as an example, the maximum error of the lateral stiffness and the shear calculating by the simplified method and the SAP2000 software is less than 5%. And based on the single-layer multi-span step-terrace frame-shearwall structures which shear walls example, the results calculating by the simplified method and the SAP2000 software show that the results of most components are in good agreement except for the under embedding column. The proposed method can provide a good reference for the reasonable arrangement of the structure.

Keywords: frame-shearwall structure, step-terrace structure, simplified model, lateral stiffness

1. Introduction

Due to the different elevation of the foundation embedding ends, the step-terrace structure has serious vertical irregularity, and its performance indexes are significantly different from the traditional structure[1]. Compared with traditional frame-shearwall structures which have relatively continuous vertical stiffness, the foundations with different elevations at the upper and lower embedding ends of the step-terrace frame-shearwall structure will cause a significant change in lateral stiffness, which will causes a large shear difference between the upper embedding end and lower embedding end of the structure under horizontal earthquake. Adopted the assumptions for simplification of the traditional frame-shearwall structure: the structural stiffness parameters of the frame and the shearwall are constant along the height of the structure[2], which is not applicable to the step-terrace frame-shearwall structure. Therefore, study on the method to calculate the lateral stiffness of the bottom of the step-terrace structure is of great significance to grasp the seismic performance of such structures.

In this paper, the frame in the step-terrace frame-shearwall structure works in conjunction with the shearwall is analyzed based on two assumptions:

i) All slabs are considered infinitely rigid in their own plane, that is, rigid slab assumptions;

ii) The combined force of the lateral forces passes through the center of the structure, and the overall stiffness center of the structure coincides with the center of mass, that is, there is no overall torsion of the structural plane.

The bottom lateral stiffness of the step-terrace frame-shearwall structure is selected as the research object. The step-terrace frame-shearwall structure is simplified to a plane model[3], and the simplified calculation method is derived. The purpose is to make the system can reasonably arrange in the upper and lower embedding ends and the stiffness distribution is reasonable when the structure is initially layout.

The specific contents are as follows:

Firstly, the single-layer single-span step-terrace structure is studied to form different stiffness arrangements. The calculation models of the structure and the lateral stiffness calculation method of different models are studied.

Then, the multi-span step-terrace structure is studied, the multi-span model is simplified and calculated by the single-span model of lateral stiffness calculation method.

Finally, the bottom lateral stiffness are calculated for different model design examples, and compared with the bottom lateral stiffness calculated by finite element software, the validity and applicability of the lateral stiffness calculation formula are verified.

2. Definition of stiffness

Commonly used stiffness calculation methods are: calculation method of inter-layer displacement angle ratio; calculation method of equivalent shear stiffness ratio; calculation method of floor shear force and inter-layer displacement ratio. The research in this article is to evaluate the structural performance and find a reasonable structure layout. Therefore, it is decided to adopt the definition of stiffness in the Chinese Code[4,5]: the calculation method of floor shear force and inter-layer displacement ratio. This method is consistent with the actual engineering when controlling the lateral stiffness of the floor, and it is also consistent with the mechanical definition of stiffness.

2.1 Definition of layer stiffness

According to the rigid slab assumption, the layer stiffness is equal to the ratio of floor shear to floor inter-layer displacement.

$$K_i = \frac{F_i}{\Delta_i} \tag{1}$$

2.2 Definition of member stiffness

2.2.1 Shearwall lateral stiffness correction

Due to the large height of the section of the shearwall, the influence of the section shear deformation must be considered in the calculation[6~7]. Therefore, according to the stiffness definition, the stiffness of the shearwall can be expressed as:

$$D = \frac{F}{\Delta} = \frac{3EI_w}{\alpha H^3} = \frac{3i^e}{H^2} \tag{2}$$

Where $\alpha = \frac{1}{1+\frac{3\mu EI_w}{GA_w H^2}}$ is shearwall lateral stiffness correction factor, $i^e = \frac{EI_w}{\alpha H}$ is shearwall correction linear stiffness, μ is the section coefficient, E is the elastic modulus of concrete, G is the shear modulus of concrete, I_w is the moment of inertia of the shearwall, A_w is the cross-sectional area of the shearwall, H is the height of the shearwall.

2.2.2 Definition of frame column lateral stiffness

The D-value method is used to define the lateral stiffness of the column:

$$D = \alpha \frac{12 i_c}{h^2} \tag{3}$$

Where i_c is the linear stiffness of the column, h is the height of the column.

3. Study on stiffness characteristics of the single-layer single-span step-terrace frame-shearwall structure

Firstly, the single-layer step-terrace frame-shearwall structure is studied. According to the different structural arrangement forms, the influence of different stiffness characteristics of the upper embedding ends and the lower embedding ends[8] on the mechanical performance of the structure is analyzed, and simplified analysis models are obtained.

3.1 Basic assumptions and simplified analysis models

Using the frame model, the structure is simplified according to the following assumptions:

i) The material obeys Hooke's law, that is, the linear-elastic assumption of the material;

ii) The deformation of the member under load is small compared to the size of the member, that is, small deformation assumption;

iii) The frame column and the frame beam are mainly bent deformation, the shearwall correction stiffness is determined according to the aspect ratio, and only consider the in-plane stiffness;

iv) Each member is an equal-section straight rod, and its section stiffness does not change in the length direction of the member.

The structural simplification model is shown in Fig.1. The single-layer single-span step-terrace structure has three independent degrees of freedom when subjected to horizontal loads:

Where Z_1 is the end angle of the AC column or end angle of the AC wall, Z_2 is the end angle of BD column or end angle of BD wall, Z_3 is the lateral displacement of the structure.

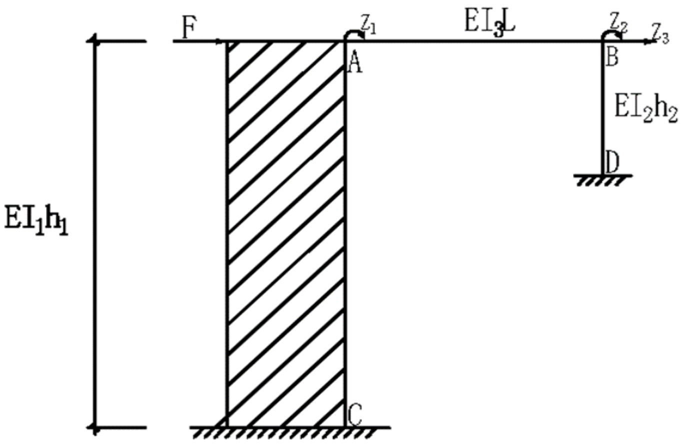


Fig. 1– Simplified mechanical model

Where A, B, C, D are node numbers; EI_i is the lateral stiffness of the beam and column or the equivalent lateral stiffness of the shearwall; h_i、 L is the calculated length of the component; I_i is the equivalent linear stiffness of the wall or the linear stiffness of the column and the beam; Z_i is a node independent angular displacement or line displacement; F is the horizontal loads.

Using the displacement method, equations for three degrees of freedom Z_1, Z_2, Z_3 are established:

$$\begin{cases} k_{11}Z_1 + k_{12}Z_2 + k_{13}Z_3 = 0 \\ k_{21}Z_1 + k_{22}Z_2 + k_{23}Z_3 = 0 \\ k_{31}Z_1 + k_{32}Z_2 + k_3Z_3 = F \end{cases} \tag{4}$$

Where:

$$\begin{cases} k_{11} = 4(i_{AC} + 4i_{AB}) \\ k_{12} = 2i_{AB} \\ k_{13} = -\dfrac{6i_{AC}}{h_{AC}} \end{cases} \qquad \begin{cases} k_{22} = 4(i_{BD} + 4i_{AB}) \\ k_{23} = -\dfrac{6i_{BD}}{h_{BD}} \\ k_{33} = 12(\dfrac{i_{AC}}{h_{AC}} + \dfrac{i_{BD}}{h_{BD}}) \end{cases} \tag{5}$$

The displacement of the structure can be expressed as:

$$\Delta = \frac{F}{(1+3\bullet\dfrac{1+\dfrac{i_{AB}}{i_{BD}}-\dfrac{1}{2}\bullet\dfrac{i_{AB}}{i_{AC}}\bullet\dfrac{h_{AC}}{h_{BD}}}{4+4\bullet\dfrac{i_{AB}}{i_{AC}}+4\bullet\dfrac{i_{AB}}{i_{BD}}+3\bullet\dfrac{i_{AB}}{i_{AC}}\bullet\dfrac{i_{AB}}{i_{BD}}})\bullet\dfrac{12i_{AC}}{h_{AC}^2}+(1+3\bullet\dfrac{1+\dfrac{i_{AB}}{i_{AC}}-\dfrac{1}{2}\bullet\dfrac{i_{AB}}{i_{BD}}\bullet\dfrac{h_{BD}}{h_{AC}}}{4+4\bullet\dfrac{i_{AB}}{i_{AC}}+4\bullet\dfrac{i_{AB}}{i_{BD}}+3\bullet\dfrac{i_{AB}}{i_{AC}}\bullet\dfrac{i_{AB}}{i_{BD}}})\bullet\dfrac{12i_{BD}}{h_{BD}^2}} \tag{6}$$

Taking the following coefficients:

$$\begin{cases} \alpha_1 = 1 + \frac{i_{AB}}{i_{BD}} - \frac{1}{2} \bullet \frac{i_{AB}}{i_{AC}} \bullet \frac{h_{AC}}{h_{BD}} \\ \alpha_2 = 1 + \frac{i_{AB}}{i_{AC}} - \frac{1}{2} \bullet \frac{i_{AB}}{i_{BD}} \bullet \frac{h_{BD}}{h_{AC}} \\ \beta = 4 + 4 \bullet \frac{i_{AB}}{i_{AC}} + 4 \bullet \frac{i_{AB}}{i_{BD}} + 3 \bullet \frac{i_{AB}}{i_{AC}} \bullet \frac{i_{AB}}{i_{BD}} \end{cases} \tag{7}$$

And $\mu_1 = \frac{i_{AC}}{i_{AB}}$、$\mu_2 = \frac{i_{BD}}{i_{AB}}$、$\eta = \frac{h_{AC}}{h_{BD}}$.

Therefore, Eq. (6) can be written as:

$$\Delta = \frac{F}{(1+\alpha_1\beta)\frac{12i_{AC}}{h_{AC}^2} + (1+\alpha_2\beta)\frac{12i_{BD}}{h_{BD}^2}} \tag{8}$$

Where, $D_{AC}^{`} = (1+\alpha_1\beta)\frac{12i_{AC}}{h_{AC}^2}$ is the lateral stiffness of the lower embedding ends, and $D_{BD}^{`} = (1+\alpha_2\beta)\frac{12i_{BD}}{h_{BD}^2}$ is the lateral stiffness of the upper embedding ends. The influence of the lateral stiffness about different simplified models of the mechanical behavior is analyzed below.

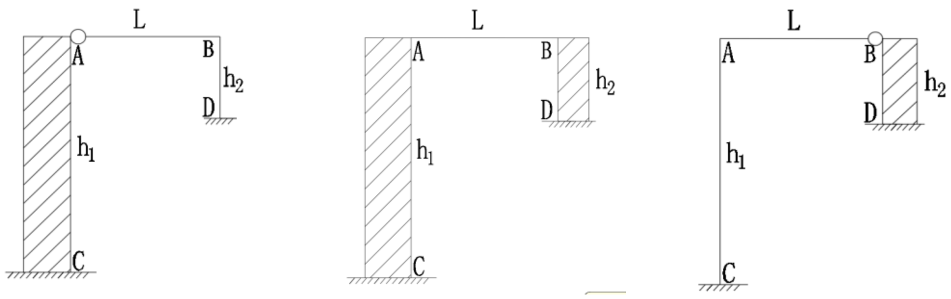
3.2 Single-layer single-span simplified model analysis

The single-layer single-span step-terrace frame-shearwall structure is classified according to the stiffness distribution of the upper and lower embedding ends, and the following three models can be obtained (Fig. 2):

i) The left single hinge model (Fig.2(a)): The stiffness of the lower embedding ends is much greater than that of the upper embedding ends, that is, the lower embedding component is shearwall and the upper embedding component is frame column;

ii) The rigid connection model (Fig.2(b)): The stiffness of the lower embedding ends is not significantly different from the stiffness of the upper embedding ends, that is, the upper and lower embedding components are shearwall;

iii) The right single hinge model (Fig.2(c)): The stiffness of the lower embedding ends is much smaller than the stiffness of the upper embedding ends, that is, the lower embedding component is frame column and the upper embedding component is shearwall.



(a) The left single hinge model (b) The rigid connection model (c)The right single hinge model

Fig. 2 – Simplified hinge model

The stiffness calculation methods are derived for the simplified models of the three stiffness cases.

3.2.1 The left single hinge model

When the lower lateral force-resisting component is shearwall and the upper lateral force-resisting component is column, μ_2 is very small compared to μ_1, so μ_2 is considered constant, and $\mu_1 = \infty$. Thus, the lateral stiffness can be simplified as follow:

$$\begin{cases} D^{`}_{AC} = \dfrac{3i_{AC}}{h^2_{AC}} \\ D^{`}_{BD} = (1 - \dfrac{3}{4} \bullet \dfrac{2\eta\mu_2 - 1}{2\eta(\mu_2 + 1)}) \bullet \dfrac{12i_{BD}}{h^2_{BD}} \end{cases} \quad (9)$$

In the left single hinge model, the impact of the beam on the upper embedding column is much greater than the impact of the lower embedding shearwall. Therefore, the influence of the beam on the shearwall is ignored. The stiffness of the lower embedding shearwall is the modified stiffness of the equivalent cantilever wall, and the stiffness of the upper embedding column is weakened.

3.2.2 The rigid connection model

When the lateral force-resisting component at the upper and lower embedding ends are shearwall, the lateral stiffness is greater than that of the beam. At this time, μ_1 and μ_2 are very close, so both μ_1 and μ_2 are considered constant. Thus, the lateral stiffness can be simplified as follow:

$$\begin{cases} D^{`}_{AC} = (1 - \dfrac{3}{4} \bullet \dfrac{2\mu_1 - \eta}{2\mu_1 + 2}) \bullet \dfrac{12i_{AC}}{h^2_{AC}} \\ D^{`}_{BD} = (1 - \dfrac{3}{4} \bullet \dfrac{2\eta\mu_2 - 1}{2\eta(\mu_2 + 1)}) \bullet \dfrac{12i_{BD}}{h^2_{BD}} \end{cases} \quad (10)$$

In rigid connection model, the cross beam will have a close effect on the upper and the lower embedding shearwall, and the stiffness of the upper and the lower embedding shearwall will be weakened.

3.2.3 The right single hinge model

When the upper lateral force-resisting component is shearwall and the lower lateral force-resisting component is column, μ_1 is very small compared to μ_2, so μ_1 is considered constant, and $\mu_2 = \infty$. Thus, the lateral stiffness can be simplified as follow:

$$\begin{cases} D^{`}_{AC} = (1 - \dfrac{3}{4} \bullet \dfrac{2\mu_1 - \eta}{2\mu_1 + 2}) \bullet \dfrac{12i_{AC}}{h^2_{AC}} \\ D^{`}_{BD} = \dfrac{3i_{BD}}{h^2_{BD}} \end{cases} \quad (11)$$

In the right single hinge model, the impact of the beam on the lower embedding column is much greater than the impact on the upper embedding shearwall. Therefore, the influence of the beam on the shearwall is ignored. The stiffness of the upper embedding shearwall is the modified stiffness of the equivalent cantilever wall, and the stiffness of the lower embedding column is weakened.

3.3 Comparison of stiffness of upper and lower grounded members

Considering the different structural layouts of the upper and lower embedding ends, a left single hinge model, a rigid connection model and a right single hinge model are obtained. Simplified calculation formulas for the lateral stiffness of the single-layer single-span step-terrace frame-shearwall structure are derived.

Compare the lateral stiffness of the lower embedding ends and the upper embedding ends:

i) The left single hinge model:

$$\frac{D`_{AC}}{D`_{BD}} = \frac{i_{AC}}{i_{BD}} / [(4-3 \bullet \frac{2\eta\mu_2 - 1}{2\eta(\mu_2+1)}) \bullet \eta^3] \quad (12)$$

ii) The rigid connection model:

$$\frac{D`_{AC}}{D`_{BD}} = \frac{i_{AC}}{i_{BD}} \times (1 - \frac{3}{4} \bullet \frac{2\mu_1 - \eta}{2\mu_1 + 2}) / [(1 - \frac{3}{4} \bullet \frac{2\eta\mu_2 - 1}{2\eta(\mu_2+1)}) \bullet \eta^3] \quad (13)$$

iii) The right single hinge model:

$$\frac{D`_{AC}}{D`_{BD}} = \frac{i_{AC}}{i_{BD}} \times (4 - 3 \bullet \frac{2\mu_1 - \eta}{2\mu_1 + 2}) / \eta^3 \quad (14)$$

Due to the existence of the height ratio coefficient η^3, the proportion of the lateral stiffness of the upper embedding ends increases. Because of $F_i = K_i\Delta$, the shear force on the upper embedding ends increases. Therefore, in order to avoid excessive shear force on the upper embedding ends, the height ratio of the upper and lower embedding ends should be strictly controlled.

3.4 The verification of simplified calculation method

In order to verify the effectiveness of the above simplified model stiffness calculation method, taking the left single hinge model as an example (Figure.2(a)), the finite element analysis software SAP2000 and the simplified formula in this paper are used for comparative analysis.

The horizontal force of the model is 500kN, the beam size is $0.25m \times 0.6m$, the parameter of the column and shearwall are shown in Table 1. The results of shear force and lateral stiffness are shown in Table 2.

Table 1 – Parameter of the Model

Model number	Elastic modulus (kN/m²)	Shear modulus (kN/m²)	Size of the wall (m²)	Size of the column (m²)	Size of the beam (m²)	h_1 (m)	h_2 (m)	L (m)
1	3×10^7	1.25×10^7	0.25×3	0.5×0.5	0.25×0.6	9	3	6
2	3×10^7	1.25×10^7	0.25×3	0.5×0.5	0.25×0.6	12	3	6
3	3×10^7	1.25×10^7	0.25×3	0.6×0.6	0.25×0.6	12	3	6
4	3×10^7	1.25×10^7	0.25×4	0.5×0.5	0.25×0.6	9	3	6
5	3×10^7	1.25×10^7	0.25×4	0.5×0.5	0.25×0.6	12	3	6
6	3×10^7	1.25×10^7	0.25×4	0.6×0.6	0.25×0.6	12	3	6

Comparing the results of shear force and lateral stiffness, the following conclusion can be drawn:

The lateral stiffness and shear results of the shearwall calculated by the simplified formula are smaller than those calculated by SAP2000, while the lateral stiffness and shear results of the column calculated by the simplified formula are larger than those calculated by SAP2000.

The reason of the above result is that the stiffness ratio of the upper and lower embedding ends is not infinite, and the effect of column stiffness is ignored. However, the formula calculation and SAP2000 calculated correction stiffness and component shear error are less than 5%, which meets the engineering design accuracy requirements, that is, the formula has practicality.

Table 2 – The Result of Shear force and Lateral stiffness

Number and item		Lateral stiffness (kN/mm)				Shear force (kN)			
		K_{AC}	Error	K_{BD}	Error	V_{AC}	Error	V_{BD}	Error
1	Calculation results of SAP	70.59	-	34.45	-	336.04	-	163.96	-
	Calculation result of formula	69.44	-1.6%	35.66	3.5%	330.35	-1.6%	169.65	3.5%
2	Calculation results of SAP	31.67	-	33.6	-	242.63	-	257.37	-
	Calculation result of formula	31.26	-1.3%	34.99	4%	235.92	-2.7%	264.08	2.6%
3	Calculation results of SAP	32.07	-	54.89	-	184.38	-	315.62	-
	Calculation result of formula	31.66	-1.3%	56.85	3.6%	178.85	-3%	321.15	1.75%
4	Calculation results of SAP	153.63	-	36.12	-	404.82	-	95.18	-
	Calculation result of formula	149.05	-3%	35.69	-1.2%	403.4	-0.35%	96.6	1.5%
5	Calculation results of SAP	69.63	-	34.43	-	334.58	-	165.42	-
	Calculation result of formula	67.52	-3%	35.02	1.7%	329.24	-1.6%	170.76	3.8%
6	Calculation results of SAP	70.15	-	55.91	-	278.24	-	221.76	-
	Calculation result of formula	67.53	-3.7%	56.91	1.8%	271.34	-2.5%	228.66	3.1%

4. Study on the stiffness characteristics of the bottom of a multi-span step-terrace frame-shearwall structure

Most of the step-terrace structures are multi-layer multi-span structures. Therefore, it is more valuable to analyze the bottom stiffness of the multi-span step-terrace frame-shearwall structure. Through trial calculations, it is found that the stiffness and shear characteristic of the multi-span step-terrace structure above the upper embedding ends are not significantly different from the traditional frame-shearwall structures[9]. Therefore, the analysis of this article focus on the embedding ends, and the internal force and deformation characteristics are analyzed through a single-layer multi-span structure calculation model.

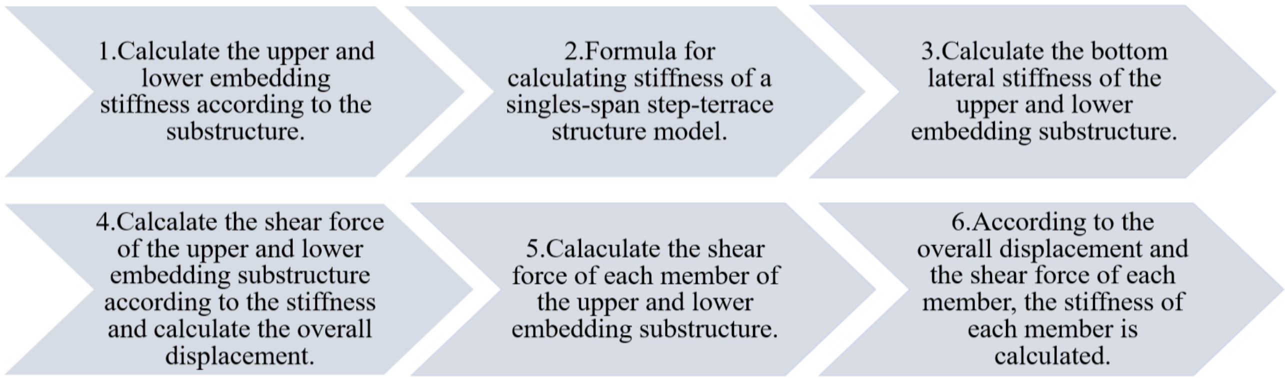


Fig. 3 – Multi-span step-terrace structure shear force and stiffness analysis process

Due to the different elevation of the foundation embedding ends, the layer concept of the ordinary frame shearwall structure is not clear at the bottom. the possible structural layout are analyzed, the overall structure is considered a combination of upper embedding substructure and lower embedding substructure, and the structure of the upper and lower embedding ends are considered as independent lateral force-resisting systems. A feasible research idea is adopted to reflect the connection between the upper and lower embedding ends by considering the difference in the arrangement position of the shearwall.

This section analyzes the calculation process of shear force and stiffness of the multi-span step-terrace structure as shown in Fig.3.

4.1 Calculation of shear force and stiffness at the bottom of single-layer multi-span step-terrace frame-shearwall structure

The only difference between a multi-layer multi-span and single-layer multi-span structure is the difference between the lateral stiffness of the shearwall and the anti-pushing stiffness of the frame column in the comprehensive stiffness calculation. The single-layer multi-span step-terrace frame-shearwall structure which has shearwalls in upper and lower embedding ends is taken as an example to calculate and derive the bottom stiffness of the substructure:

i) Calculate the anti-pushing stiffness C_f of the frame column:

For frame columns, the D-value method is used to calculate the anti-pushing stiffness C_f of the comprehensive frame, where α is calculated according to the D-value method:

$$C_f = \sum Dh = \sum \alpha \frac{12i}{h} \tag{15}$$

ii) Calculate the equivalent shear stiffness EI_e of the shearwall:

For the shearwall, the influence of section shear deformation[6~7] must be considered in the calculation, and the equivalent lateral stiffness of the shearwall can be obtained:

$$EI_e = EI_w \frac{1}{1+\dfrac{3\mu EL_w}{GA_w H^2}} \tag{16}$$

iii) Calculate the comprehensive stiffness of frame-shearwall substructure under horizontal force:

$$K = \frac{EI_e}{H^3} / \left[\frac{sh\lambda}{\lambda^3 ch\lambda}(ch\lambda - 1) - \frac{1}{\lambda^3} sh\lambda + \frac{1}{\lambda^2} \right] \tag{17}$$

Where $\lambda = H\sqrt{\dfrac{C_f}{EI_e}}$ is the stiffness characteristic value of the substructure.

iv) Calculate the lateral stiffness of the upper and lower embedding substructure:

The comprehensive stiffness of the upper embedding substructure and the lower embedding substructure is calculated by Eq.17. Since the upper and lower embedding substructure has shearwalls, the rigid connection model is adopted and brought into Eq.7 to obtain:

$$\begin{cases} \alpha_L = 1 + \dfrac{i_L}{i_R} - \dfrac{1}{2} \bullet \dfrac{i_L}{i_{AC}} \bullet \dfrac{h_L}{h_R} \\ \alpha_R = 1 + \dfrac{i_L}{i_{AC}} - \dfrac{1}{2} \bullet \dfrac{i_L}{i_R} \bullet \dfrac{h_R}{h_L} \\ \beta = -\dfrac{3}{4 + 4 \bullet \dfrac{i_L}{i_{AC}} + 4 \bullet \dfrac{i_L}{i_R} + 3 \bullet \dfrac{i_L}{i_{AC}} \bullet \dfrac{i_L}{i_R}} \end{cases} \tag{18}$$

As shown in Fig.4, $i_L = \frac{K_L \times h_L^2}{3}$ is the linear stiffness of the lower embedding substructure, and $i_R = \frac{K_R \times h_R^2}{3}$ is the linear stiffness of the upper embedding substructure, i_{AC} is the linear stiffness of the connecting beam, h_L is the height of the lower embedding substructure, and h_R is the height of the upper embedding substructure.

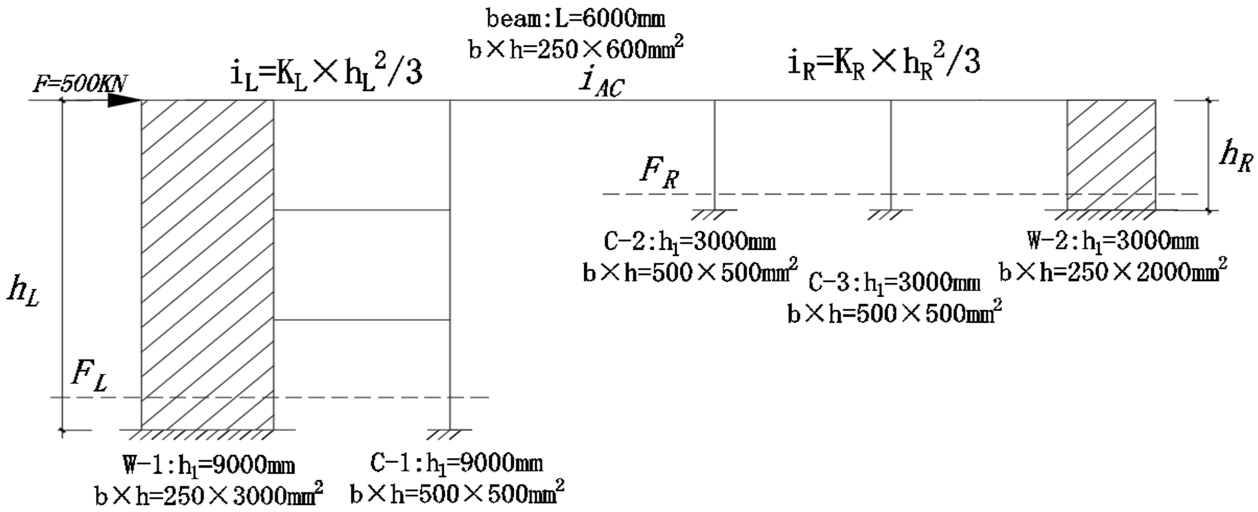


Fig. 4 – Parameters of multi-span simplified model

The lateral stiffness of the upper and lower embedding substructure can be obtained by Eq.10:

$$\begin{cases} D_L^` = (1+\alpha_L \beta) \bullet \frac{12 i_L}{h_L} \\ D_R^` = (1+\alpha_R \beta) \bullet \frac{12 i_R}{h_R} \end{cases} \tag{19}$$

v) Calculate the overall displacement of the structure:

$$\Delta = \frac{F}{D^`} = \frac{F}{D_L^` + D_R^`} \tag{20}$$

vi) Distribution of forces between upper and lower substructures:

$$\begin{cases} F_L = F \bullet \frac{D_L^`}{D_L^` + D_R^`} \\ F_R = F \bullet \frac{D_R^`}{D_L^` + D_R^`} \end{cases} \tag{21}$$

vii) Calculate the shear force of the anti-lateral force member of the upper and lower substructures:

According to the shear force calculation method of traditional frame-shearwall structure, the shear forces of the upper and lower substructures shearwalls are calculated:

$$\begin{cases} V_{LW} = F_L (ch\lambda_L - \frac{sh\lambda_L}{ch\lambda_L} sh\lambda_L) \\ V_{RW} = F_R (ch\lambda_R - \frac{sh\lambda_R}{ch\lambda_R} sh\lambda_R) \end{cases} \tag{22}$$

The distribution of the shear force between the shearwalls is distributed according to the equivalent lateral stiffness EI_e; and the distribution of the shear force between the frame columns is distributed according to the D-value of the frame. The lower substructure is taken as an example:

$$\begin{cases} V_{LWi} = V_{LW} \dfrac{EI_{ei}}{\sum EI_{ei}} \\ V_{LCi} = (F_L - V_{LW}) \dfrac{D_i}{\sum D_i} \end{cases} \tag{23}$$

Where V_{LW} is the shear force of the lower substructure shearwall, V_{LWi} is the shear force of a shearwall of the lower substructure, EI_{ei} is the lateral stiffness of a shearwall of the lower substructure, V_{LCi} is the shear force of a column of the lower substructure, D_i is the D-value of a column of the lower substructure.

viii) Calculate the lateral stiffness of each member:

$$\begin{cases} D_{LWi} = \dfrac{V_{LWi}}{\Delta} \\ D_{LCi} = \dfrac{V_{LCi}}{\Delta} \end{cases} \tag{24}$$

Where D_{LWi} is the lateral stiffness of a shearwall of the lower substructure, D_{LCi} is the lateral stiffness of a column of the lower substructure.

4.2 The verification of simplified calculation method

The results calculated by SAP2000 are compared with the proposed method above. The calculation parameters are shown in Fig.4. The shear force results are shown in Table 3, and stiffness results are shown in Table 4.

Table 3 – Comparison of SAP2000 shear results with formula calculation shear force results

Contrasting project	V_{W-1}	V_{C-1}	V_{C-2}	V_{C-3}	V_{W-2}	F_L	F_R	**Δ (mm)**
Calculation results of SAP (kN)	54.16	11	34.63	40.21	360	65.16	434.84	0.79
Calculation result of formula (kN)	57	8	35.33	43.17	356.5	65	435	0.82
Calculation error (%)	5.2%	-27%	2%	7%	-1%	-0.25%	0.036%	3.7%

Table 4 – Comparison of SAP2000 stiffness results with formula calculation stiffness results

Contrasting project	D_{W-1}	D_{C-1}	D_{C-2}	D_{C-3}	D_{W-2}	$D_L^`$	$D_R^`$
Calculation results of SAP kN/mm)	68.57	13.9	43.83	50.9	455.7	82.48	550.4
Calculation result of formula (kN/mm)	69.51	9.8	43.84	52.65	434.8	79.3	530.5
Calculation error (%)	1.4%	-29%	0.02%	3.4%	-4.5%	-3.9%	-3.6%

The calculation results show that, except for the lower embedding column (C-1), the errors of other results are small, indicating that the calculation formula is accurate. The calculation method can meet the engineering requirements when it is used for the initial layout of the structure.

The reasons for the large errors in the calculation results of the lower embedding column are: i) The calculation model is used. ii) The calculation is simplified. iii) There is an error in the actual structure. The result itself is small, and the small difference in results will cause a large error.

5. Conclusions

In this paper, through the study of the simplified calculation method of the bottom stiffness of the step-terrace frame-shearwall structure, the main work and conclusions are as follows:

1) Through theoretical derivation, three simplified models of single-span step-terrace structures and the stiffness calculation methods corresponding to different simplified models are obtained.

2) On the basis of the single-span step-terrace structure, the multi-span step-terrace structure is simplified, and the analysis ideas for the multi-span step-terrace structure are given, and the calculation methods of component shear force and lateral stiffness are derived by taking a single-layer multi-span step-terrace frame-shearwall structure as an example.

3) By comparing the stiffness of the upper and lower embedding ends, it is concluded that the height ratio of the upper and lower embedding ends has a significant effect on the stiffness and the shear force on the upper embedding ends, so it is recommended to control the height ratio of the upper and lower embedding ends.

4) Using finite element software, taking the left single hinge model and the single-layer multi-span step-terrace model as examples, the accuracy of the formula proposed in this paper is verified, which shows that the calculation formula proposed in this paper can meet the engineering requirements when it is used for the initial layout of the structure.

6. Acknowledgements

The authors acknowledge the National Natural Science Foundation of China (51478067) and the Fundamental Research Funds for the Central Universities (No. CDJZR10200004).

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