APPROXIMATE ANALYTICAL METHOD OF MULTI-STOREY OR HIGH-RISE STEEL THREE-DIMENSIONAL PARKING STRUCTURES

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ABSTRACT: The configuration of a kind of multi-storey or high-rise steel three-dimensional parking structure is introduced in this paper. The approximate analytical method is studied in detail. The whole structure is regarded as a vertical cantilever. The equivalent bending stiffness and shear stiffness of the structure, including the shear stiffness of the lateral bracing system and that of the beam-column system, are derived. The lateral displacement formula of the structure under horizontal load is subsequently developed. Then the calculation formulae of internal forces of various structural components are derived. Numerical example shows that the error of the results by the presented formulas does not exceed 7.2% in comparison with those by finite element method. Therefore, the method and its related formulae are feasible for preliminary design of this kind of steel three-dimensional parking structure since it is accurate and brief.

Keywords: Steel three-dimensional parking structure, Configuration, Approximate analytical method, Equivalent stiffness, Calculation formulas

1. INTRODUCTION

With the development of urban economy and automobile industry, the amount of private cars is rapidly increasing. However, the parking lots cannot keep pace with the growing number of the private cars; the difficulty of parking and the caused transportation congestion are obviously not in harmony with the development of modern society, it has become a major restraining factor in urban development (Chen et al. [1] and Mei et al. [2]). The development of the mechanical three-dimensional (3D) garages is undoubtedly the effective way to solve this problem. The 3D parking structures has been studied and applied in practice earlier in some developed countries (JRA [3], Kim [4], Kwar and Song [5-6]).

The structural configuration of a kind of multi-storey or high-rise steel 3D parking structure is introduced in this paper. And it is regarded as a cantilever fixed to the ground to simplify the calculation; the equivalent shear stiffness and bending stiffness of the structure are derived based on continuum analogy method (Zhou and Dong [7]), including the shear stiffness of the lateral bracing system and that of the frame. The lateral displacement formula of the structure under horizontal load is subsequently developed. Then the calculation formulae of internal forces of the structural components are derived. A numerical example is given for illustration, and the results by the presented formulae are compared with those by finite element method.

2. THE CONFIGURATION OF THE 3D PARKING STRUCTURE

As we all know, the internal space and structural layout of various high-rise buildings vary with their functions. As to the 3D parking structures, a hoisting shaft in it is needed to ensure that car can be lifted to the level of a parking space. And the car needs to be horizontally shifted to the corresponding parking space within the 3D garage in the process of parking, so the separating walls can not be set between the parking space and the hoisting shaft. The planar layout of garage needs not only to meet the technical requirements of parking, but also to consider the rationality of the structure. Whether the layout of steel 3D parking structure is reasonable or not may greatly affect the economic performance and the convenience of use. The system displayed in Figure 1 is a typical parking structure with high efficiency (He et al. [8-9]). There are two parking spaces on the two sides of the hoisting shaft, as shown in Figure 1(a). In the parking process, the car is lifted to the height of a parking space by the vertical elevator through the hoisting shaft, and then transferred to the parking board in the parking space by the horizontal transition device. The planar dimensions depend on the sizes of cars. When a car is put on the parking board, the safety distance between car and parking board should also be considered. Synthesizing architectural modulus, the length and width of a parking space can be taken as 6m and 2.4m, respectively. And the width of hoisting shaft can generally be taken as 3.0m to guarantee that the cars can be carried up and down. The multi-storey or high-rise steel 3D parking structure generally consists of the ground, typical, and top stories. The ground storey with height of h_1 is the place for entering and leaving of the vehicles. The typical stories with height h_2 of each storey are used for parking. And according to the actually required capacity of parking, the number of typical stories can be increased or reduced. The top storey with height of h_3 is for installing of equipment. Obviously, when the required number of the parking spaces is $2N$, the corresponding number of typical stories must be no less than N . Therefore the minimum total number of stories is $N+2$, and the corresponding total height is $h_1 + h_2 \times N + h_3$. There are four lifting chains attached to the columns of the hoisting shaft to lift cars. To improve the lateral stiffness, bracings should be set in the transverse and longitudinal side frames as shown in Figures 1(b) and (d). However, to ensure the horizontal shift of the car between the parking spaces and hoisting shaft, bracing can not be set in the middle transverse frames as shown in Figure 1(c). The simplified analytical method of this kind of structure is studied in this paper.

3. INTERNAL FORCE AND DISPLACEMENT ANALYSES

To confine our research, some basic assumptions are made as follows.

- (1) The contraflexure points of the frame beams are located on their mid-spans. (Generally, the inflection point of a beam in a frame with lateral displacement is close to its mid-span point (Shen [10]).)
- (2) The braces are connected with the frame by pin connection and the bracing system mainly bears horizontal shear force in the structure (Zheng and Zhao [11]).
- (3) The bending and shearing actions of the two orthogonal frames are independent.
- (4) The beams are rigidly connected with the columns; and the shearing resistance effect of the beam-column system is taken into account.
- (5) The steel is considered as homogeneous linearly elastic material.
- (6) The lateral displacements of all the nodes at the same level are identical.

- 1: Column of hoisting shaft;
 2: Lateral diagonal brace of the typical storey;
 3: Lateral beam of the structure;
 4: Side column;
 5: The diagonal brace in the front and back facades;
 6: Lateral diagonal brace of the ground storey;
 7: Front/rear beam of the typical stories;
 W: The direction of exit and entrance of the parking structure for cars

Figure 1. Schematic of the Multi-storey or High-rise Steel 3D Parking Structure:
 (a) Planar layout; (b) Frame in axis I or IV; (c) Frame in axes II or III; (d) Frame in axes A or B

3.1 The Equivalent Shear Stiffness

Obviously, the shear stiffness of the braced frame structure is provided by both the frame and the bracing system. And according to the basic assumptions (2) and (4), the inter-storey shear deformation of the i -th storey of the structure is shown in Figure 2.

Figure 2. Schematic of Inter-storey Shear Deformation of the Structure

Figure 3. Free-body Diagram of a Node of K-shaped Brace

3.1.1 The equivalent shear stiffness of the bracing system

According to basic assumption (2), free-body diagram of a node of K-shaped brace under horizontal unit force can be shown as Figure 3. Then the equilibrium equation due to unit horizontal force in X-direction can be obtained as

$$T_1 \cos \alpha + T_2 \cos \alpha = 1 \quad (1)$$

And that in Y-direction is

$$T_1 \sin \alpha = T_2 \sin \alpha \quad (2)$$

Based on the above equations, the internal force of the brace can be obtained as $T_1 = T_2 = T = 1/(2 \cos \alpha)$. Thus, the horizontal displacement of the brace node under the unit force can be calculated as

$$\Delta = 2T^2 L_C / (EA_1) \quad (3)$$

where, $L_C = h / \sin \alpha$ is the length of the diagonal brace. Since the shear angle is $\gamma = \Delta / h$, the shear stiffness C_d of a K-shaped brace can then be obtained as follows,

$$C_d = 1 / \gamma = 2EA_1 \cos^2 \alpha \sin \alpha \quad (4)$$

in which, A_1 is the cross-sectional area of a member of the K-shaped brace, and E is the elastic modulus of steel.

The total shear stiffness of the bracing system equals to the sum of those of all K-shaped braces in the same direction of a storey, namely $C_b = \sum C_{di}$. Generally, two single-diagonal bracing members can be considered as a K-shaped brace.

3.1.2 The equivalent shear stiffness of the beam-column system

In calculation of the i^{th} storey shear stiffness of the beam-column system, it is assumed that the beams connected with the far ends of the columns in the $i-1^{th}$ and $i+1^{th}$ stories of the frame is infinitely rigid. Based on this and assumption (1), the lateral deformation of the column ab of the frame can be shown as Figure 4(b). In the figure, points 1, 2, 3, and 4 stand for the inflection points of beams am , af , bk , and bg , respectively, which also are the midpoints of the beams. The relationship of the column ab with other components is displayed in Figure 4(c) when the end rotation restraint of the column is freed and replaced by the end bending moments. The M_{ab} and M_{ba} indicate the end bending moments of the column at ends a and b , respectively. Thus, the angular rotation of both ends can be calculated as follows (Schafer and Bajpai [12], Vasilopoulos and Beskos [13]).

$$\theta_{ab} = \Delta / h - \alpha_{ab} M_{ab} + \beta M_{ba} \quad (5)$$

$$\theta_{ba} = \Delta / h + \beta M_{ab} - \alpha_{ba} M_{ba} \quad (6)$$

Figure 4. Lateral Deformation of Column of the Beam-column System

Figure 5. Calculation Models of Components

in which, Δ/h is the shear angle due to the storey drift Δ ; α_{ab} is the angular rotation of end a when the column is subjected to unit bending moment at end a ; α_{ba} is that of end b when it is subjected to a unit bending moment at end b ; while β is the angular rotation of end b when the column is subjected to a unit bending moment at end a or that of end a when it is subjected to unit bending moment at end b ; for the steel components with uniform section (Bao [14]),

$$\alpha_{ab} = \alpha_{ba} = 1/(3K_{ab}), \quad \beta = 1/(6K_{ab}) \quad (7)$$

where $K_{ab} = EI_{ab}/h_{ab}$, I_{ab} and h_{ab} are the cross sectional moment of inertia and the length of column ab , respectively.

As shown in Figure 4(c), there must appear an angular rotation $\Phi_a = M_{ab}/\sum S_{ai}$ on node a for the action of end bending moment M_{ab} . Here $\sum S_{ai} = S_{a1} + S_{a2} + S_{ad}$ is the sum of bending stiffness of all the components connected to node a . The models to calculate the bending stiffness of various components connected to node a are displayed in Figure 5. For the column ad as shown in Figure 5(a),

$$\theta_a = \int_0^h M_{ad}/(EI_{ad})dx = M_{ad} \times h/(EI_{ad}) \quad (8)$$

And M_{ad} represents the bending stiffness of column ad when $\theta_a = 1$. Thus

$$S_{ad} = K_{ad} = EI_{ad}/h_{ad} \quad (9)$$

where I_{ad} and h_{ad} are the cross sectional moment of inertia and the length of component ad , respectively.

For a beam as shown in Figure 5(b),

$$M_{a1} = 4EI_{am}/(L_{am}/2) \times \theta_a + 2EI_{am}/(L_{am}/2) \times (-\theta_a/2) \quad (10)$$

Obviously, M_{a1} represents the bending stiffness of beam am when $\theta_a = 1$. Thus

$$S_{a1} = 6K_{am} = 6EI_{am}/L_{am} \quad (11)$$

where I_{am} and L_{am} are the cross sectional moment of inertia and the length of beam am , respectively. Analogously,

$$S_{a2} = 6K_{af} = 6EI_{af}/L_{af} \quad (12)$$

in which, I_{af} and L_{af} are the cross sectional moment of inertia and the length of beam af , respectively.

Similarly, the angular rotation of node b under the action of M_{ba} can be derived as

$\Phi_b = M_{ba} / \sum S_{bi}$, where $\sum S_{bi} = S_{b4} + S_{b3} + S_{bc}$, $S_{bc} = K_{bc} = EI_{bc} / h$, $S_{b3} = 6K_{bk} = 6EI_{bk} / L_{bk}$, and $S_{b4} = 6K_{bg} = 6EI_{bg} / L_{bg}$. (The meanings of various parameters are the same as those stated above.) Considering $\theta_{ab} = \Phi_a$, $\theta_{ba} = \Phi_b$, and substituting α_{ab} , α_{ba} , and β into Eqs. 5 and 6, the following equations can then be obtained.

$$M_{ab} / \sum S_{ai} = \Delta / h - M_{ab} / (3K_{ab}) + M_{ba} / (6K_{ab}) \quad (13)$$

$$M_{ba} / \sum S_{bi} = \Delta / h + M_{ab} / (6K_{ab}) - M_{ba} / (3K_{ab}) \quad (14)$$

Let $f_a = 2 + 6K_{ab} / \sum S_{ai}$, $f_b = 2 + 6K_{ab} / \sum S_{bi}$, and solve Eqs. 13 as well as 14, M_{ab} and M_{ba} can be obtained as follows,

$$M_{ab} = ((\Delta / h) \times 6K_{ab} \times (f_a + 1)) / (f_a \times f_b - 1) \quad (15)$$

$$M_{ba} = ((\Delta / h) \times 6K_{ab} \times (f_b + 1)) / (f_a \times f_b - 1) \quad (16)$$

Suppose that the distances between the contraflexure point of the column and ends a as well as b are $i_0 h$ and $(1 - i_0)h$, respectively. Then

$$M_{ab} = H_{ab} \times i_0 \times h \quad (17)$$

$$M_{ba} = H_{ab} \times (1 - i_0) \times h \quad (18)$$

where H_{ab} is the horizontal load applied to the end of column as shown in Figure 4(c). Substituting them into Eqs. 15 and 16, coefficient i_0 can be obtained as

$$i_0 = (f_a + 1) / (f_a + f_b + 2) \quad (19)$$

Thus,

$$H_{ab} = \frac{M_{ab}}{i_0 h} = \frac{f_a + 1}{i_0 (f_a f_b - 1)} \times \frac{6K_{ab} \Delta}{h^2} \quad (20)$$

Based on the definition of shear stiffness, H_{ab} equals to the shear stiffness of the column C_{ab} when $\Delta / h = 1$. Then

$$C_{ab} = 6K_{ab} (f_a + 1) / (i_0 (f_a f_b - 1) h) \quad (21)$$

Analogously, other columns have the similar expression. The inter-storey shear stiffness of the beam-column system equals to the sum of those of all the columns in a same storey, namely $C_f = \sum C_i$. Considering the shear stiffness of the bracing system, the total shear stiffness of the k -th storey of the structure can be obtained as

$$C_k = C_b + C_f \quad (22)$$

For simplicity, the shear stiffness of the equivalent cantilever mast is calculated by weighted average along the height of the structure. Namely,

$$\text{X direction:} \quad C_x = \sum_{i=1}^N C_{xi} \times h_i / H \quad (23)$$

$$\text{Y direction:} \quad C_y = \sum_{i=1}^N C_{yi} \times h_i / H \quad (24)$$

in which, C_{xi} , C_{yi} are the equivalent shear stiffness of the i -th storey of the structure along the X and Y directions, respectively; H is the total height of the structure, and h_i is the storey height of the i -th storey.

3.2 Lateral Displacement Analysis of the Parking Structure

The high-rise parking structure described may be simplified as a vertical cantilever. Regarding it as a cantilever to simplify the calculation, the equivalent bending stiffness of the structure can be derived as follows based on continuum analogy method.

$$\text{X-axis:} \quad EI_x = E(4A_2[(\frac{L_1}{2})^2 + (\frac{L_2}{2})^2] + 4I_{xs} + 4I_{xc}) \quad (25)$$

$$\text{Y-axis:} \quad EI_y = E(8A_2a^2 + 8I_{yc}) \quad (26)$$

where, E is the elastic modulus of the steel, A_2 is the cross-sectional area of the column; L_1 , L_2 are the spans of the mid-span and side-span along the Y-direction of the parking structure (see Figure 1), respectively; I_{xs} and I_{xc} are the cross sectional moment of inertia of the side column and mid column to the centroidal axis which is parallel to X-axis, respectively; $2a$ is the span along X-direction, I_{yc} is the cross-sectional moment of inertia of the column to the centroidal axis which is parallel to Y-axis.

The second-order effect of the structure must be taken into consideration due to the large height-to-width ratio of the structure. For convenience in calculation and consistence with the linear elastic method in the specifications (GB50017-2003 [15]), the $P-\Delta$ effect of gravity is estimated by using the linear elastic stiffness of the structure. Namely, the lateral displacement of the structure can be calculated by adding an assumed horizontal force H_{mi} as follows to the top of each storey (GB50017-2003 [15]).

$$H_{mi} = \frac{\alpha Q_i}{250} \sqrt{0.2 + 1/n} \quad (27)$$

where, Q_i is the total design gravity load on the i -th storey; n is the total number of stories; and α is the influence coefficient of strength of the steel, for Q235, Q345, Q390 and Q420, α equals to 1.0, 1.1, 1.2, and 1.25, respectively; additionally, $\sqrt{0.2 + 1/n} \leq 1$, namely, it is taken as 1.0 when $\sqrt{0.2 + 1/n} > 1$.

The lateral displacement calculation model of the parking structure is shown in Figure 6. The equivalent concentrated force H_i of each storey is the sum of the assumed horizontal force H_{mi} and all the actually applied horizontal loads. After the equivalent parameters are obtained, the storey drift of the i -th storey can be derived as follows based on the method of structural mechanics.

Figure 6. Lateral Displacement Calculation Model of the Parking Structure

$$\Delta_i = \Delta_{vi} + \Delta_{Mi} = h_i \sum_{j=i}^n H_j / C_x + h_i^2 (M_i + \frac{2}{3} \sum_{j=i}^n H_j) / (2EI_y) \quad (28)$$

where, $\Delta_{vi} = h_i \sum_{j=i}^n H_j / C_x$ and $\Delta_{Mi} = h_i^2 (M_i + \frac{2}{3} \sum_{j=i}^n H_j) / (2EI_y)$ are the shear and bending relative displacements of the i -th storey, respectively; h_i is the storey height; and M_i is the total moment of various concentrated horizontal forces H_j acting at the i -th storey and those above it relative to the top of the i -th storey.

3.3 Internal Forces of Various Structural Components under Horizontal Loads

While the storey drift Δ_i is obtained by Eq. 28, the axial deformation of the diagonal brace can be calculated as $\Delta_c = \Delta_i \cos \alpha$ according to Figure 2. Then the axial force of a lateral brace of the i -th storey can be gotten as

$$T = \Delta_c EA_1 / L_c = \Delta_i \sin \alpha \cos \alpha EA_1 / h \quad (29)$$

Substituting Δ_i into Eqs. 15 and 16, the bending moments of the upper and lower ends of the column of the i -th storey can be obtained as follows,

$$M_{iup} = (\Delta_i / h) \times 6K_{ab} \times (f_a + 1) / (f_a + f_b + 1) \quad (30)$$

$$M_{ilow} = (\Delta_i / h) \times 6K_{ab} \times (f_b + 1) / (f_a + f_b + 1) \quad (31)$$

Substitute Δ_i into the shear stiffness of the column as shown in Eq. 21, the shear of the column of the i -th storey can be obtained as,

$$V_i = 6K_{ab}\Delta_i(f_a + 1)/(i_0(f_a f_b - 1)h^2) \quad (32)$$

After the bending moments of various columns are obtained, the moments at the ends of various beams can be calculated based on the moment equilibrium condition of nodes.

For the beam connected with side column as shown in Figure 7(a), one has

$$M_{ibm} = M_{iup} + M_{i+1low} \quad (33)$$

And for the beam connected with mid column as shown in Figure 7(b),

$$M_{ibml} = (M_{i+1up} + M_{ilow}) \frac{S_{il}}{S_{il} + S_{ir}} \quad (34)$$

$$M_{ibmr} = (M_{i+1up} + M_{ilow}) \frac{S_{ir}}{S_{il} + S_{ir}} \quad (35)$$

Figure 7. Bending Moment Diagram of Nodes

where, S_{il} and S_{ir} are the bending stiffness of the left and right beams, respectively.

After the bending moments of the beams are obtained, the shears of the beams can be obtained according to the equilibrium condition of individual beam as shown in Figure 8. Namely,

$$V_{il} = V_{ir} = (M_{il} + M_{ir}) / L \quad (36)$$

where, V_{il} and V_{ir} are the shear forces on the left and right ends of the beam i , respectively; while M_{il} and M_{ir} are the corresponding end moments of the beam.

Figure 8. Free-body Diagram of Individual Beam

Figure 9. Free-body Diagram of Nodes

The axial forces of the beam and column under horizontal loads can be calculated based on the equilibrium condition of nodes. From Figure 9(a), one has

$$N_{tpbm} = F_{tp} - V_{tpcn}, \quad N_{tpcn} = V_{tpbm} \quad (37)$$

and from Figure 9(b),

$$N_{ibm} = V_{i+1cn} - V_{icn} + N_{ibrh} + F_i, \quad N_{icn} = N_{i+1cn} + N_{ibm} + N_{ibrv} \quad (38)$$

in which, N_{tpbm} and V_{tpbm} are the axial and shear forces in the beam of the top storey, respectively; N_{tpcn} and V_{tpcn} are those of the column of the top storey; and N_{ibrh} as well as N_{ibrv} are the horizontal and vertical components of the axial internal force of the brace, respectively.

3.4 Internal Forces Analyses of Parking Structures under the Vertical Loads

When a vehicle is parked in the parking structure, it is generally put on the parking board. The parking board is connected with the structure only by the four adjacent columns, through which the vehicle load is transferred to the parking structure. Therefore, in analyses, the vertical load transferred by the parking board can be regarded as four equal concentrated forces applied at the tops of the adjacent columns of the parking space. The numerical analysis by finite element method shows that, the columns are the dominating load-carrying components under the vertical load, whereas, the internal forces of the other components are very small, which can be basically ignored. Therefore, in this case, the axial forces of various columns of the i -th storey of the parking structure can be calculated as

$$N_{ic} = \sum_{j=i+1}^n G_j / m_i \quad (39)$$

where, $\sum_{j=i+1}^n G_j$ is the total vertical load acting at various stories above the i -th one; m_i is the number of columns of the i -th storey.

Additionally, the internal forces of the other components are assumed to be zero under the vertical loads.

4. NUMERICAL EXAMPLES

To confirm the validity of the derived formula, a numerical example is given in this section, compared with the results by ANSYS finite element analysis. The schematic diagram of the structure in the example is shown in Figure 1. The span along X direction of the structure is 6.0m and those of various bays along Y direction are all 3.0m. The storey heights of the bottom, standard, and the top stories are 2.7m, 2.5m, and 1.5m, respectively. The components are assumed to be made of Q235 steel (Yield Strength 235 MPa). The beams and columns are made of H-shaped sections H-250×150×6×8 (in which, 250, 150, 6, and 8 are the height of the cross section, width of the flange, thickness of the web, and the thickness of the flange, respectively.) and H-300×200×8×10, respectively. And the braces are circular steel tube $\Phi 80 \times 10$. The total number of stories is six. Two 1.5-ton cars are parked on each standard storey, and the horizontal load of 10kN/m is applied to the structure along X direction. The results are displayed in Tables 1 and 2.

Table 1. Result Comparison of Axial Internal Forces of the Columns of the Structure under the Vertical load

Storey number	By ANSYS software N /kN	By the derived formula N_1 /kN	$\left \frac{N_1 - N}{N} \right \times 100\%$
No.4	3.394	3.615	6.51%
No.3	6.954	7.350	5.69%
No.2	10.906	11.025	1.09%
No.1	15.258	14.70	3.66%

Table 2. Result Comparison of Internal Forces of Various Components of the Structure under the Horizontal Load

Floor number	Axial forces of components /kN			Shears of components /kN		Moments of components /kNm		
	Beam	Column	Brace	Beam	Column	Beam	Upper end of column	Lower end of column
No.6	7.05(6.65)	0.14(0.13)	5.62(5.39)	0.14(0.13)	0.44(0.42)	0.41(0.39)	0.41(0.39)	0.25(0.24)
	5.67%	7.14%	4.09%	7.14%	4.54%	4.88%	4.88%	4.00%
No.5	30.08(29.52)	3.0(2.91)	13.8(12.95)	0.35(0.33)	0.68(0.64)	1.05(1.01)	0.80(0.78)	0.91(0.89)
	1.86%	3.00%	6.16%	5.71%	5.88%	3.81%	2.50%	2.20%
No.4	43.03(42.6)	12.56(12.31)	20.7(19.56)	0.69(0.65)	0.93(0.87)	2.07(2.06)	1.16(1.08)	1.16(1.15)
	1.00%	1.99%	5.50%	5.80%	6.45%	0.48%	6.89%	0.86%
No.3	57.58(56.4)	26.75(26.23)	27.7(26.96)	0.90(0.86)	1.24(1.20)	2.7(2.68)	1.54(1.46)	1.54(1.47)
	2.05%	1.94%	2.67%	4.44%	3.23%	0.74%	5.19%	4.55%
No.2	76.80(74.8)	45.62(44.41)	34.6(32.34)	1.15(1.12)	1.53(1.42)	3.44(3.25)	1.89(1.85)	1.93(1.91)
	2.60%	2.65%	6.53%	2.61%	7.19%	5.52%	2.12%	1.04%
No.1	99.6(94.9)	70.32(68.8)	41.9(39.57)	2.55(2.51)	3.22(3.10)	7.64(7.41)	5.72(5.66)	3.00(2.95)
	4.72%	2.16%	5.56%	1.57%	3.72%	3.01%	1.05%	1.67%

Note: data in brackets refer to the results based on the derived formula, the others are the results by ANSYS software, and the percentages are the errors of the derived formula.

From the results in the tables it can be seen that, in comparison with the results by ANSYS software, the maximum error of the internal forces of various components of the structure under the vertical and horizontal loads are 6.51% and 7.19%, respectively. This indicates that the formulae are highly accurate. Therefore, the method and its related formulas derived in this paper are feasible for preliminary design of this kind of steel 3D parking structure. And it is also convenient to be used.

5. CONCLUSIONS

The multi-storey or high-rise steel 3D parking structures are introduced in this paper and its approximate analytical method is studied. It is regarded as a vertical cantilever fixed on the ground level. The equivalent bending and shear stiffness of the structure is derived, including the shear stiffness of the lateral bracing system and that of the beam-column system. The lateral displacement formula of the structure under the horizontal load is subsequently developed. Then the calculation formulae of internal forces of the structural components are derived. A numerical example is given for illustration, and it is indicated that the error of the results by the presented formulae do not exceed 7.2% in comparison with those by computer analysis. Therefore, the method and its related formulae are feasible for preliminary design of the steel parking structures due to its accuracy and briefness.

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