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Finite element analysis of double-layer box type modular building

Jianfei Zhang\(^1\), Lin Peng\(^2\)*, Yijian Shi\(^2\), Baoguang Chen\(^1\), Xidong Sun\(^1\) and Chuang Liu\(^1\)

\(^1\)China State Construction Development Co., Ltd. Beijing 100037, China
\(^2\)China State Construction Engineering Corporation Limited Technical Center, Beijing 101300, China
*Corresponding author’s e-mail: peng.l@cscec.com

Abstract. Box-type modular building with advantages of quick installation, good comfort, beautiful appearance and convenient turnover, is widely used in construction of temporary construction, business services, holiday villas and other projects. In this paper, a single span double-layer box-type modular building in Shenzhen was taken as an example, using modular building system with a special-shaped corner column and cold-formed thin-walled beam. The finite element software ANSYS was used to calculate the overall structural strength and stiffness, and the stress and displacement calculation results under the control of vertical load and horizontal wind load were respectively given. The results show that under the snow load, the maximum stress of the whole structure is 163.14MPa, which appears in the middle of the second layer top frame purlin. Under the horizontal wind load, the maximum stress of the whole structure appears at the beam-to-column connection panel, and the stress of the first story is more unfavourable than that of the second one. The maximum displacement in the horizontal direction is 10.37mm. The maximum displacement angle between layers is 1/278. The above calculation results all meet the requirements of "Standard for design of steel structures" (GB50017-2017), which can ensure the safety and reliability during normal use. Furthermore, it can provide reference for the design and optimization of multi-storey box buildings.

1. Introduction
With the continuous deepening of the supply-side reform of construction industry and the continuous expansion of construction scale, industrialization and assembly of buildings have become an important direction for the development of construction industry\(^{[1,2]}\). Steel structure modular box building is single or multi-layer light-weight modular with assembly function construction composed of modular units such as bottom frame, top frame, column and wall panel which can be prefabricated and assembled on site\(^{[3]}\). Modular buildings are in line with the development of industrial buildings in China, with the advantages of industrial construction, excellent quality control, short construction period, low investment cost, construction savings in manpower and environmentally friendly.

However, the design of box-type modular buildings still has many problems, such as the overall anti-side shift does not meet the requirements of the specification; the rigidity of the beam is insufficient; the square steel tube column is not conducive to the connection between the modular box columns, which thus affects the overall carrying capacity of the building\(^{[2]}\). The connection between box-type modular buildings is relatively complicated and cannot be simplified directly into steel joints.
between ordinary frames. Therefore, it is necessary to simulate with appropriate connection methods to provide reference for finite element analysis of multi-storey box-type modular buildings.

In this paper, a single span double-layer box-type modular building in Shenzhen is taken as an example, using modular building system with a special-shaped corner column and cold-formed thin-walled beam. The finite element software ANSYS is used to calculate the overall structural strength and stiffness, and the stress and displacement calculation results under the control of vertical load and horizontal wind load were respectively given. Furthermore, it can provide reference for the design and optimization of multi-storey box buildings.

2. Model and calculation method

2.1. Model size parameter

The steel material of the modular building is made of Q235 steel. The material type is the same, the elastic modulus is $E=2.06 \times 10^5$ MPa, the poisson's ratio is $\nu=0.3$, the density is 7850 kg/m$^3$, and the yield strength is 215 MPa. Mechanical properties of cement particle board: elastic modulus $E = 2.28 \times 10^3$ MPa, poisson's ratio $\nu=0.125$, density of 1000 kg/m$^3$. Single box outer contour size: length × width × height is 6055mm × 2990mm × 2896 mm, regardless of the contribution of the maintenance structure to the overall stiffness. The cross-section design dimensions of the main components are as follows (Table. 1): the bottom beam is 140 mm high and 110 mm wide; the top beam is 185 mm high and 105 mm wide, and the column is 150 mm × 210 mm (Fig. 1).

| Component                | Sectional form | Sectional dimension (mm×mm×mm) |
|--------------------------|----------------|---------------------------------|
| Bottom frame beam        | irregular section | 110×140×3.0                   |
| Top frame beam           | irregular section | 105×185×3.0                   |
| Column                   | irregular section | 150×210×3.0                   |
| Bottom frame purlins     | irregular section | 98×50×3.0                      |
| Top frame purlins        | rectangle        | 40×40×2.5                      |

Figure 1. Bottom beam section.  
Figure 2. Top beam section.  
Figure 3. Column section.

2.2. Load analysis

The main loads of box buildings are dead load, live load, wind load and snow load. According to the requirements of "Load code for the design of building structures" (GB50009-2012)[4], the load values are as follows: floor constant load is 0.25kN/m$^2$, floor living load is 2.0kN/m$^2$, roof constant load is 0.25kN/m$^2$, roof live load is 0.5kN/m$^2$; the standard value of snow load is 0.4kN/m$^2$, and the combined value coefficient is 0.7; according to the 20-year return period of wind in Shenzhen, the basic wind
pressure is 0.53 kN/m². The wind-body and leeward wind loads are 0.8 and -0.5 respectively, the wind pressure height is 1.0, and the wind-induced vibration coefficient is 1.0, the combined value coefficient is 0.6.

According to the load that may occur at the same time in the structure during use, the load effect combination is carried out according to the bearing capacity limit state and the normal use limit state. The design should be based on the combination of the most adverse effects. Only the case where the permanent load is unfavourable to the structure is considered here.

A. Carrying capacity limit state
(1) Permanent load control combination:
\[ S = \gamma_0 \times (1.35 \times S_{Gk} + 1.4 \times \gamma_L \times 0.7 \times S_{Qk}) \] (1)

(2) Snow load control combination:
\[ S = \gamma_0 \times (1.2 \times S_{Gk} + 1.4 \times \gamma_L \times S_k) \] (2)

(3) Wind load control combination:
\[ S = \gamma_0 \times (1.0 \times S_{Gk} + 1.4 \times \gamma_L \times 0.7 \times S_{Qk} + 1.4 \times S_{Qw}) \] (3)

B. Normal use limit state
(4) Standard combination of snow load control:
\[ S = S_{Gk} + S_{Qk} \] (4)

(5) Standard combination of wind load control:
\[ S = S_{Gk} + 0.7 \times S_{Qk} + S_{Qw} \] (5)

In the above formulas, \( \gamma_0 \) is the structural importance coefficient, taken as 0.9; \( S_{Gk} \) is load effect value calculated by permanent load standard value \( G_k \); \( S_{Qk} \) is load effect value calculated from variable load standard value \( Q_k \); \( S_k \) is load effect value calculated according to the standard value of snow load; \( S_{Qw} \) is load effect value calculated according to the standard value of wind load. \( \gamma_L \) is the adjustment factor of variable load considering the design life. According to the "Code for Loads of Building Structures" (GB50009-2012) [4]: for structural members with the second safety level or a design life of 50 years, it should not be less than 1.0; the third safety level or the design life is 1-5 years of structural components, should not be less than 0.9. The value of the age between them is determined by linear interpolation. As can be seen from the above, this box type design has a service life of 20 years, then
\[ \gamma_L = 0.9 + \frac{1.0-0.9}{50-5} \times (20-5) = 0.933 \] (6)

2.3. Finite element modeling
In the calculation model, the beam, column and rafter are simulated by Beam188 unit, and the beam unit is given as a custom section. The cement particle board and the top iron sheet are simulated by Shell181 unit, and the calculation model is shown in Fig.4. The vertical displacement in the middle of the bottom long beam is constrained, that is, \( U_z = 0 \). The cement particleboard and the bottom frame are connected by coupling, and the three translational degrees of freedom of the corresponding nodes are coupled. The top iron sheet and the top frame are also coupled by coupling, and the three translational degrees of freedom of the corresponding nodes are coupled, and the corresponding nodes of the column constrain the z-direction rotational degrees of freedom of the column. The column, the upper and lower corner pieces are connected by a rigid panel. The connection between the first-layer box and the second-layer box considers four-node articulation, that is, three translational degrees of freedom coupling the top of first-layer node and the bottom of the second-layer node. Considering the common force, the method of coupling the vertical degrees of freedom at the finite point is used in the middle of the beam. The top frame of the first-layer does not bear the load.
Considering the working condition (1) is more unfavourable than the working condition (2), calculation is performed according to the condition (2). Finally, the stress of the box is calculated under working condition (2) and (3), the vertical deformation of the box is calculated under the working condition (4), and the horizontal deformation of the building is calculated under condition (5). The calculation model and boundary conditions are shown in the figures below. (Fig.4-Fig.5)

2.4. Analysis of calculation results
In order to analyse the effect of vertical load on the double-layer box-type modular building, figure 6 to figure 8 show the mises stress nephogram of the whole frame, the column and the bottom frame under the working condition (2) of the snow load control. It can be seen that under the action of snow load control, the maximum stress of the whole structure is 163.14MPa, which occurs in the middle position of the secondary beam of the second floor. Since the snow load acts on the top layer and the relative stiffness of the beam is small in the overall structure, the deformation of the middle part of the stringer causes a large stress. The maximum stress of the column is 81.72MPa, which occurs at the column connection between the first and second layer. It can be seen that the position of the column between the layers is relatively unfavourable. The maximum stress value of the sill frame is 107.39MPa, which occurs at the end of the second beam. The above stress results are all less than 215MPa. It can be known from the "standard for design of steel structures' that the structure satisfies the strength calculation requirements under the snow load.

In order to analyse the normal use limit state, the change of the displacement of the building, figure 9 to figure 11 show the vertical displacement nephogram of the overall structure, the top frame beam and the bottom frame beam under the standard load combination condition (4). It can be seen that under the standard combination of vertical load loads, the maximum vertical displacement of the overall structure is 22.16 mm, which occurs in the top frame of the beam. Due to the relatively small stiffness of the beam in the overall structure, the displacement is larger. The maximum vertical displacement of the top frame beam is 6.76 mm, which occurs in the middle of the first layer of longer beams. The maximum vertical displacement of the bottom frame beam is 6.85 mm, which occurs in the middle of the longer beam of the second layer. According to the requirements of steel structure displacement in "standard for design of steel structures" [5], the deflection limit of the flexural member is L/200, where L is the length of the flexural member, and the above calculation results all meet the deflection limit requirement.
In order to analyse the effect of wind load on the two-storey box-type building, figure 12 to figure 14 show the mises stress nephogram of the overall structure, the columns and the bottom frame of each layer under the working condition (3) of the wind load control. It can be seen that under the combined action of wind load control, the maximum structural stress is 99.83MPa, which occurs at the beam-to-column connection panel between the first and the second story of the leeward plane. The
maximum stress of the column is 78.96 MPa, which occurs at the top of a column of leeward direction. It can be seen from the above that, unlike the load on the column under the snow load, the first layer of the column is more disadvantageous under the wind load. The maximum stress of the bottom frame beam is 69.58 MPa, which occurs at the end of a long beam at the windward direction. So the leeward side structure is more unfavorable than the windward side, and the beam-to-column connection panel between the two layers are unfavorable, especially the long beam position. Components of the first-story are more stressed than the second layer.

In order to further analyse the deformation of the building under the standard combined working condition (5) of the normal use limit state in which the wind load controls the action. Figure 15 shows the horizontal deformation of the two-story box module. It can be seen that the maximum displacement in x-direction of the overall structure is 10.37 mm, which appears in the top frame of the second layer. The interlayer displacement angle of the single layer is less than the allowable value h/250, and the top displacement of the column is less than H/500, which satisfies the allowable value of the interlayer displacement angle under the wind load.

3. Conclusion
(1) The double-layer box type modular building is easy to assemble and disassemble, and the modulus is fixed, which meets the industrialization and standardization requirements of the building.

(2) Under the combined conditions of snow load control, due to the relatively small stiffness of the beam in the overall structure, the maximum stress and displacement appear in the middle of the second
layer of the top frame. Between the different layers, beam-to-column connection panel plays an important role in structural stress.

3. Under the combined working conditions of horizontal wind load control, the maximum stress of the whole structure, the columns and the bottom frame all appear at beam-to-column connection panel of the leeward side. The first layer of the column and the bottom frame beam are more stressed than the second layer, and the connection of the long beam is more disadvantageous than the direction of the short beam. The maximum horizontal displacement appears in the top frame of the second layer, and the displacement angle between layers is 1/278.

4. The overall structure meets the strength and stiffness requirements of the “standard for design of steel structures”, so this double-layer modular building can be safe and reliable during normal use.

5. In order to further optimize the structure of such box-type buildings, different beam and column sections can be used for different layers. For example, columns of second-story can be used with a smaller cross section than the first-story. And the beam-to-column connection panel of different layers should be appropriately strengthened.

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