Modeling and Finite Analysis of Overall Structure Mechanical Behavior of Steel Frame—Cold-formed Thin-walled Steel Composite Wall

Huqing Liang²,⁴, Mengxiong Tang¹,⁴, Ruicong Huang³,*, Zhengrong Jiang³, Junming Qiu³ and Jian Cai³

¹Guangzhou Research Institute of Construction Industry Co., Ltd., Guangzhou, China
²Guangzhou Construction Engineering Co., Ltd., Guangzhou, China
³School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, China
⁴Guangzhou Municipal Construction Group Co., Ltd., Guangzhou, China

*Corresponding author email: cthalmruicong@mail.scut.edu.cn

Abstract. Based on the finite element method, the typical layout and parameters were selected to establish the overall structure model of steel frame—cold-formed thin-walled steel composite wall and their influence on the mechanical properties and the economic steel amount was analyzed. The results show that the screw spacing, purlin section and purlin spacing have little effect on the lateral stiffness and the amount of steel used in the overall structure, while the width of wall opening has obvious effect. It is suggested that the screw spacing should be consistent with the relevant provisions in the cold-formed thin-walled steel structure specification, the purlin section should be selected relatively small according to the wall thickness and the purlin spacing should be properly amplified. The applicable height of this structure system is higher than that of pure cold-formed thin-wall steel structure system in ordinary residential buildings. The amount of steel used in this structure system is obviously less than that of pure steel frame structure system.

1. Introduction

Cold-formed thin-walled steel structure housing system has the advantage of light deadweight, short construction period, simple manufacture, etc. Different from the beam-column system of ordinary steel frame structure, the force transmission system of this structure consists of composite floors and walls composed of cold-formed thin-walled steel rods and clad plates. Therefore, the structure is neat both inside and outside, and there is no beams and columns protruding from the interior which means a larger available space. However, due to the characteristics of elongated and small cross sections of cold-formed thin-walled steel bars, the bearing capacity and resistive overturning ability of this structure system are limited and it is mainly used for construction of low-rise residential and office. And the domestic technical specification [1] and standard [2] only stipulate the design and fabrication of cold-formed thin-walled steel structure within six floors and 20m high. There are some methods abroad to improve the cold-formed thin-walled steel structure system so as to increase its applicable height, such as replacing local load-bearing members with hot-rolled steel, or replacing the lower story of the structure with reinforced concrete frames [3]. Based on this strengthening concept, domestic research on the combination of steel frame and cold-formed thin-walled steel has begun. However, the
existing tests and numerical simulations [4-8] mostly focus on the wall, and there are few analyses on
the overall performance of steel frame—cold-formed thin-walled steel structure [9-10].
In this paper, the general finite element program SAP2000 is used to study the influence of different
parameters of vertical structure system of steel frame—cold-formed thin-walled steel composite wall
on the overall structure level and get the recommended parameters and applicable height of it.

2. Analytical Model

2.1. Modeling Method
The vertical lateral force members of this structure system are composed of steel frame and cold-
formed thin-walled steel composite wall embedded in the steel frame. The general finite element
program SAP2000 is used to model the overall structure. Frame beams and columns and cold-formed
thin-walled steel purlins of the walls are simulated by beam elements, and wall panels are simulated
by layered-shell elements. The two ends of the cold-formed thin-walled steel purlins in the wall are
hinged to the frame beam, and the coupling between shell element and beam element at the screw joint
is realized through the automatic division of finite element, without considering the slip between beam
element and shell element [11]. The vertical displacement of upper purlin is released and the vertical
in-plane axial stiffness of layered-shell element is set as inactive state, so that the embedded cold-
formed thin-walled steel composite wall does not directly bear the vertical load but provides lateral
stiffness. In addition, floor openings are not considered in all the models in this paper, and the
command of partition constraint is used to realize the rigid floor assumption. As vertical structural
system is mainly studied in this paper, the modelling of floors is not considered but taken as uniform-
distributed plane load transmitted to frame beams.

2.2. Model Overview
The structure system studied is mainly applied to residential and office buildings, so the story height \( H \)
is set as 3m and the column distance \( A \) is set as 4.5m or 6m. The openings of doors and windows are
considered as the complete openings from the top of the lower beams to the bottom of the upper beams,
and the opening width \( K \) is set as 1.5~2.7m (values are determined according to different analyses).
The plane layout of the model is selected as horizontal and longitudinal three spans. The plane layout
and the serial number of beams and columns are shown in figure 1. \( Z_1\sim3 \) represent the serial number
of frame column, \( L_1 \) and \( L_2 \) represent the serial number of frame beam, \( \Xi \) represents the composite
wall composed of purlin and wall panel. DK represents the openings in the walls (the default opening
position is located in the middle of the span). One Y-oriented secondary beam is arranged at the
middle span of each X-oriented main beam and numbered as \( L^* \)(omitted in figure 1).

In practical engineering of cold-formed thin-walled steel structure system, the wall thickness is usually
less than 150 mm and the beam and column sections made of cold-formed thin-walled steel sections
do not protrude the wall. While improving the structural stiffness by adding steel frame, the advantages of original cold-formed thin-walled steel structure with neat interior and large usable space should be retained. Therefore, the section width of all frame beams and columns does not exceed the maximum wall thickness of 150mm in the models. Among them, the beam section is narrow flange H-beam or welded I-steel, and the column section is square steel pipe. Figure 2 is the schematic diagram of the model with 6 stories \( N=6 \).

2.3. Materials and Loads

The beam element material of all models is Q355B and the layered-shell element material of all models is Oriented-strand board (OSB) and gypsum board. Among them, the external wall panel material is OSB with 9mm thickness on one side and gypsum board with 12mm thickness on the other side. The interior wall panel is gypsum board with 12mm thickness on both sides. Material parameters are shown in table 1.

### Table 1. Material parameters.

| Material       | Elastic modulus (MPa) | Poisson ratio | Mass density (kg/m³) |
|----------------|-----------------------|---------------|----------------------|
| Steel          | 2.06×10⁹              | 0.30          | 7850                 |
| OSB            | 3500                  | 0.30          | 600                  |
| Gypsum board   | 1125                  | 0.23          | 900                  |

The dead load of wall beam of all models in this paper is uniformly set as 3kN/m. The dead and live load of floor of all models in this paper are uniformly set as 2.0kN/m². The dead and live load of roof are set as 3.5kN/m² and 0.5kN/m² respectively. The basic wind pressure of all models in this paper is 0.5kN/m² and the surface roughness is B. Consider frequent horizontal earthquakes and the seismic fortification intensity is 7 degrees (0.10g) and the maximum horizontal earthquake influence coefficient is \( \alpha_{max} = 0.08 \). The design earthquake groups are all group 1 class II, corresponding characteristic period is \( T_s = 0.35s \). The damping ratio is 0.04. The default load combination is generated according to the load code.

3. Parameter Analysis

In this paper, the vertical structure system of steel frame—cold-formed thin-walled composite steel wall is studied on the overall structure level to analyze the influence of different parameters on the mechanical performance and economic steel amount. The parameters include: spacing of self-tapping screw on composite wall, section and spacing of cold-formed thin-walled steel purlin, width of wall opening. In this section, column spacing of all models is \( A=4.5m \), story height is \( H=3m \), number of floors is \( N=6 \). In the process of analysis and design, the strength, deformation and stability of all frame members are checked and optimized in accordance with the 《Standard for design of steel structures》 [12]. The limit of cross-section stress ratio is set at 0.9, and the design indexes such as structural period ratio and displacement ratio are ensured to meet the requirements of the code.

Three steel frame—cold-formed thin-walled steel overall structure models with screw spacing of 100mm, 150mm and 300mm are respectively named as Model 1, Model 2 and Model 3. The width of wall opening is 2.1m, the section of wall purlin is C109×50×15×2.0 and the spacing of purlin is 600mm. On the basis of model 3, the cross-sections of wall purlin are adjusted to C109×50×20×2.5 and C109×60×20×3.0, and the adjusted models are named as model 4 and model 5 respectively. On the basis of model 3, move the openings of all external walls to the right end of the wall and move those of all internal walls to the near external wall, and the width of opening \( K \) is still 2.1m. The purlin spacing is adjusted to 400mm, 600mm and 800mm, and name the adjusted models as Model 6 to 8 respectively. According to the result of design checking and optimization adjustment, the inter-story displacement angles of Model 1 to 8 are basically the same which are far less than the limit of the specification, and the stress ratio of beam-column member is also similar. The steel amount of Model 1 to 3 is all the same, and those of Model 4 and 5 increase with the increase of purlin section, and those of Model 6 to 8 decrease with the increase of purlin spacing. It can be seen that the screw spacing has almost no effect on the design section of the beam and column but plays a role in fixing
the wall panel to make it deform in coordination with the purlin and frame. Therefore, it is suggested that the screw spacing in practical engineering should keep the requirements of "the ones at the edge of the panel should be within 150mm and that of in the middle of the panel should be within 300mm" in the code of cold-formed thin-walled steel structure [2]. Since the frame beams and columns in the model bear the main vertical load, the stress of the purlin section itself is very small, and it only acts to fix the wall panels and make them deform in coordination with the frame. To avoid waste, the wall purlin only needs to choose a relatively small section which meet the requirements of the wall thickness and the purlin spacing is recommended to be properly amplified to 600~800mm.

On the basis of Model 7, the width of the wall opening is adjusted to \( K = 2.7 \)m and \( K = 1.5 \)m and the adjusted models are named Model 9 and Model 10 respectively. Other parameters are the same as Model 7. After design checking and optimization adjustment, the beam and column sections of three models are all the same. The steel amount used increase from Model 9, 7 and 10, while the stress ratio of beam and column members decrease from Model 9, 10 and 7. Figure 3 shows the statistics of inter-story displacement angles of them. It can be seen that reducing the opening width of the wall will significantly improve the lateral stiffness of the structure, but too small opening width will lead to the increase of internal forces of the frame and the waste of steel used in the composite wall.

4. Applicable Height

Based on the above analysis, a series of models are established according to Figure 1. The spacing of wall purlin of all models is 600mm, and the spacing of screws is 300mm. The section of the purlin is adjusted according to the width of the frame beam and column. When beam and column width is 130mm, 140mm and 150mm, the purlin section is C109 50 15 2.0, C119 50 20 2.0 and C129 50 20 2.5 respectively. The two column distances are \( A = 4.5 \)m and \( A = 6 \)m, and the corresponding opening width is \( K = 2.1 \)m and \( K = 2.4 \)m respectively, which are located in the middle of the wall. The story height is \( H = 3.0 \)m. The seismic fortification intensity is 7 degrees (0.10g), and the wind load is 0.5kN/m². After design checking and optimization adjustment, table 2 and table 3 are the beam and column sections of models with two column distances and different stories.

![Figure 3. Inter-story displacement angle of Model 7, 9, 10.](image)

| stories | 6  | 7  | 8  | 9  | 10 |
|---------|----|----|----|----|----|
| Z1(n=1~3) | 130×130×6 | 130×130×6 | 130×130×8 | 140×140×8 | 150×150×8 |
| Z2(n=1~3) | 130×130×6 | 130×130×6 | 130×130×8 | 140×140×8 | 150×150×10 |
| Z3(n=1~3) | 130×130×10 | 130×130×10 | 130×130×12 | 140×140×12 | 150×150×12 |
| Z1(n=4~6) | 130×130×6 | 130×130×6 | 130×130×8 | 140×140×8 | 150×150×6 |
| Z2(n=4~6) | 130×130×6 | 130×130×6 | 130×130×8 | 140×140×8 | 150×150×6 |
| Z3(n=4~6) | 130×130×6 | 130×130×6 | 130×130×8 | 140×140×8 | 150×150×8 |
| Z1=3(n=7~10) | 130×130×6 | 130×130×6 | 130×130×6 | 140×140×6 | 150×150×6 |
| L1, L2 | HN250×125×5×8 | HN250×125×5×8 | HN250×125×5×8 | H250×140×5×8 | H250×140×5×8 |
| L* | HN250×125×5×8 | HN250×125×5×8 | HN250×125×5×8 | HN250×125×5×8 | HN250×125×5×8 |

Note: When \( N = 6 \), the column width is 130mm= the minimum width of beam is 125mm.

When \( N < 6 \), the column width should be kept equal to the beam width, resulting in steel waste.
When \( N > 10 \), the column width will exceed 150mm, which does not meet the section width limit.

| Stories | 4 | 5 | 6 |
|---------|---|---|---|
| Z1(n=1~3) | 150×150×6 | 150×150×6 | 150×150×8 |
| Z2(n=1~3) | 150×150×6 | 150×150×6 | 150×150×10 |
| Z3(n=1~3) | 150×150×8 | 150×150×12 | 150×150×12 |
| Z1~3(n=4~6) | 150×150×6 | 150×150×6 | 150×150×6 |
| L1, L2 | HN360×150×7×11 | HN360×150×7×11 | HN360×150×7×11 |
| L* | HN350×175×6×9 | HN350×175×6×9 | HN350×175×6×9 |

Note: When \( N = 4 \), the column width is 150mm= the beam width is 150mm= the section width limit.

When \( N < 4 \), the column width should be kept equal to the beam width, resulting in steel waste.

When \( N > 6 \), the column width will exceed 150mm, which does not meet the section width limit.

When the seismic fortification intensity is adjusted from 7 degrees (0.1g) to 8 degrees (0.2g), the design section of the beam and column is basically unchanged. According to the query, due to the light deadweight of structure and small load, the wind load is relatively large. The seismic action does not play a major control role, and the load combination corresponding to the design internal force of the beam and column section is mostly related to the wind load. At the same time, due to the large redundancy of the lateral stiffness of the structure, the increased inter-story displacement angles caused by the increase of seismic fortification intensity will not lead to the increase of the design section. With the further increase of seismic action and the adjustment of wind load, this characteristic may not be applicable. Therefore, when the wind load is 0.5kN/m², the seismic fortification intensity is less than 8 degrees, and the limit width of the section of beam and column is 150mm, the maximum applicable height of the steel frame—cold-formed thin-walled steel composite wall structure system with column spacing of 4.5m and 6.0m is about 30m and 18m respectively.

5. Contrast of Steel Amount

Figure 4 and figure 5 show the steel amount statistics for the models with column distance of 4.5m and 6.0m and the corresponding pure frame model. As can be seen from the figures, the steel amount of steel frame—cold-formed thin-walled steel structure system is about 30~40kg/m² when it is applied to residential and office buildings with column distance of 4.5m or 6m, which can significantly reduce the steel amount compared with pure steel frame structure. Among them, when the column distance is 4.5m, the steel amount is about 10-20% less than that of pure steel frame structure, and when the column distance is 6.0m, the reduction is about 10%.

Figure 4. The steel amount statistics of models with column distance \( A=4.5m \).

Figure 5. The steel amount statistics of models with column distance \( A=6.0m \).

6. Conclusions

Based on the above test results, the following conclusions can be drawn: the screw spacing, purlin section and purlin spacing in the composite wall of the system have little effect on the elastic stage of
the structure. It is suggested that the screw spacing in practical engineering should keep the requirements of "the ones at the edge of the panel should be within 150mm and that of in the middle of the panel should be within 300mm" in the code of cold-formed thin-walled steel structure, purlin section should be relatively small according to wall thickness, and purlin spacing should be 600–800mm. The opening width of the composite wall has a significant effect on the lateral stiffness and the steel amount of the structure. Reducing the opening width will significantly improve the lateral stiffness of the structure, but too small opening width will lead to the increase of the internal force of beam and column and the waste of steel. When the wind load is 0.5kN/m², the seismic fortification intensity is less than 8 degrees, and the limit width of the section of beam and column is 150mm, the maximum applicable height of the steel frame—cold-formed thin-walled steel composite wall structure system with column spacing of 4.5m and 6.0m is about 30m and 18m respectively. The steel amount of steel frame—cold-formed thin-walled steel structure system is about 30~40kg/m² when it is applied to residential and office buildings with column distance of 4.5m or 6m. When the column distance is 4.5m, the steel amount is about 10-20% less than that of pure steel frame structure, and when the column distance is 6.0m, the reduction is about 10%.

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