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Determination and comparison of the reasonable height of different flat vierendeel structures*

Wei Cuixia[2], Gao Lingling[2], Yu Haifeng[2], Yan Lijuan[2]

Abstract. The flat vierendeel structure is the main structure type of the long-span floor and roof, so its stiffness and thermal insulation property are very important. 396 finite element models were established to analyze the reasonable height of the three flat vierendeel structures: considering upper and lower rib plates, only considering upper rib plates, and irrespective of the rib plates. The results show that when the high-span ratio is 1/17.5 for the considering upper and lower rib plates, and only considering upper rib plates structures or 1/13 for the irrespective of the rib plates structure, the structure stiffness is the best. With regard to the flat vierendeel structure which considers upper and lower rib plates, when the structure height is 700mm, the thermal insulation property is the best. With regard to the flat vierendeel structure which only considers upper rib plates or is irrespective of the rib plates, the change of structure height has little effect on its thermal insulation property. Furthermore, the stiffness and thermal insulation property of the flat vierendeel structure which considers upper and lower rib plates are significantly better than other two structures. In sum, the flat vierendeel structure which considers upper and lower rib plates should be adopted in priority and the structure height should be the smaller one between high-span ratio - 1/17.5 and 700mm, when the flat vierendeel structure is only considering upper rib plates or irrespective of the rib plates structure, the height should choose 1/17.5 and 1/13 of the span respectively. The conclusions could provide a reference for the design of relevant projects to increase the stiffness and the thermal insulation property.

Key words. Flat vierendeel structure, stiffness, thermal insulation property, reasonable height.

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[2]Workshop 1 - School of Civil Engineering of Hebei University of Science and Technology, Shijiazhuang, 050018, China

1. Introduction

Generally speaking, the flat vierendeel structure is reinforced concrete structure, which boasts many advantages, such as high stiffness, good thermal insulation property, etc, and is widely used in concrete floor and roof with long span and large column network. According to the stress, the flat vierendeel structure can be divided into three types: vierendeel truss structure, vierendeel grid structure, and vierendeel sandwich plate structure, according to whether the effect of concrete plates is considered, the flat vierendeel structure can be divided into considering upper and lower rib plates, only considering upper rib plates, andrrespective of the rib plates. In terms of the first case, it refers to the II type of the vierendeel sandwich plate structure where there are concrete rib plates in both surfaces and the effect of the concrete rib plates is taken into account when conducting the deformation control, in terms of the second case, it refers to the I type of the vierendeel sandwich plate structure where only the upper surface has the concrete rib plates and the effect of the concrete rib plates is taken into account when conducting the deformation control, in terms of the third case, it not only refers to the II type of the vierendeel sandwich plate structure where there is no laminated layer on the upper rib plates, but also refers to the vierendeel grid structure.

The flat vierendeel structure is the main structure type of the long-span floor and roof, so, its stiffness and thermal insulation property are the main considerations. However, current research results are mainly related with mechanical property[1], calculation methods[2-3], and dynamic characteristics[4]. The researches focusing on stiffness and thermal insulation property are few. The references [5] only analyzed the stiffness of the vierendeel truss structure and vierendeel grid structure under the condition of the same vertical load, and determined the reasonable structure height from the stiffness perspective. They didn't take the influence of the structure's self-weight into account and didn't pay attention to the full realization of the structure's thermal insulation property.

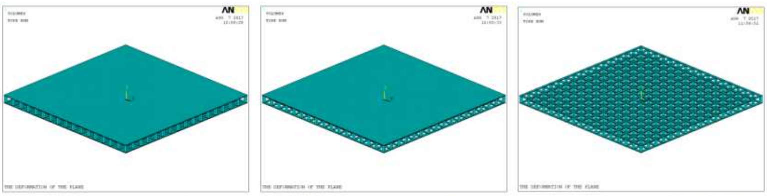
Taking the stiffness and the thermal insulation property into account, this paper analyzed the three vierendeel structures: considering upper and lower rib plates, only considering upper rib plates, andrrespective of the rib plates, and offers some suggestions on the design of the reasonable height, so as to provide some useful references for similar practical projects.

2. Analysis of stiffness characteristic

2.1. Numerical model

Based on the finite element software - ANSYS, the writer establishes simply-supported and orthotropic quadrangle numerical models with regard to the three flat vierendeel structures, as shown in Figure1. The plane size of the model is 21m , 21m, the grid size is 1.5m, and the number of grids is 14 14, the concrete strength garde is C30. It is assumed that materials are homogeneous elastic materials, and the effect of rebar is neglected. All units is SOLID45 unit.

To observe the influence of structure height and other related major geometric parameters on the stiffness of the three flat vierendeel structures, the structure height is taken as 0.3m, 0.4m, 0.5m and other 15 values, and the plate thickness, the section size of the upper and lower chord members, and the section size of the vertical web members are shown in Table 1. The number of the working condition of the three flat vierendeel structures is 342. When the calculation model is the flat vierendeel structure which considers upper and lower rib plates, the plate thickness shown in Table 1 is the thickness of the upper and lower rib plates of the model, that is, the thickness of the upper and lower rib plates is same, when the calculation model is the flat vierendeel structure which only considers upper rib plates, the plate thickness shown in Table 1 is the thickness of the upper rib plates of the model, and the thickness of the lower rib plates is 0mm, and when the calculation model is the flat vierendeel structure which is irrespective of the rib plates, the thickness of the upper and lower rib plates is 0mm.



(a) Consider upper and lower rib plates (b) Only consider upper rib plates (c) Irrespective of the rib plates

Fig. 1. Finite Element Model of Flat Vierendeel Structure

Table 1. Description on the Model's Working Conditions

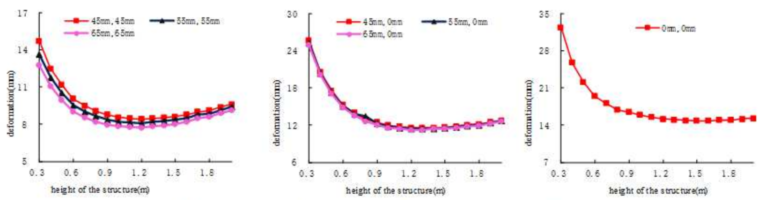
Plate thickness mm	Section size of the upper and lower chord members mm^2	Section size of the vertical web members mm^2	Structure height m
45	**400×75**	**300×300**	**[0.3,0.1,2.0]**
55	400×95	280×280	
65	400×115	250×250	

Note: the plate thickness, the section size of the upper and lower chord members and the section size of the vertical web members are changed based on the bold data which is basic data in the table. For example: when the plate thickness is changed, the section size of the upper and lower chord members of all the calculation models is 400mm, 75mm, and the section size of the vertical web members is 300mm , 300mm.

A vertical distributed load will be applied to every numerical model, and the design load is the bigger one between 1.2 × constant load + 1.4 × variable load and 1.35 × constant load + 1.4 × 0.7 × variable load, wherein the constant load is the structure's self-weight, and the variable load is $3kN/m^2$. For the (c) model of Figure 1, the vertical distributed load is equivalently applied to the upper surface of the rib beam, and the calculation results are shown in Figure 2, Figure 3 and Figure 4.

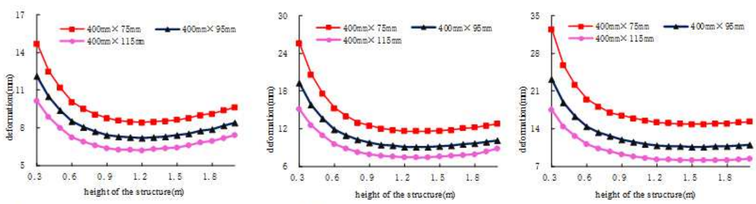
2.2. Calculation results and analysis.

2.2.1. The determination of the most reasonable structure height From Figure 2, Figure 3 and Figure 4, we can know that: when the structure height is relatively small, the deformation of the three flat vierendeel structures under the function of vertical load decreases sharply as the structure height increases. When the structure height exceeds a certain value, the deformation increases slightly as the structure height increases. Obviously, there is a certain structure height for the three flat vierendeel structures: considering upper and lower rib plates, only considering upper rib plates, and irrespective of the rib plates. Under this height, the structure stiffness reaches the maximum, while the deformation reaches the minimum. This specific height is the most reasonable structure height. With regard to the flat vierendeel structure which considers upper and lower rib plates or only considers upper rib plates, when geometric parameters, such as plate thickness, section size of upper and lower chord members and section size of vertical web members, are changed, the most reasonable structure height only slightly changes, and the value is basically kept around the 1/17.5 high-span ratio, that is, the plate thickness, the section size of upper and lower chord members, the section size of vertical web members, and the existence of lower rib plates have little influence on the most reasonable structure height of these two flat vierendeel structures. With regard to the flat vierendeel structure which isrrespective of the rib plates, because there is no concrete rib plate, so the most reasonable structure height is basically kept around the 1/13 high-span ratio. Similarly, when geometrical parameters, such as plate thickness, are changed, the most reasonable structure height also only slightly changes.



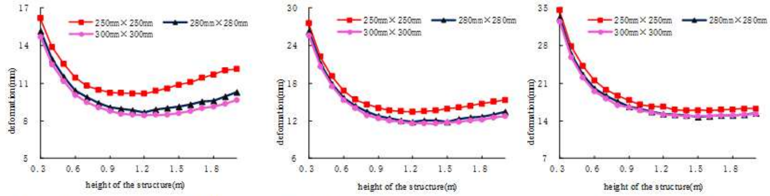
(a) Consider upper and lower rib plates (b) Only consider upper rib plates (c) Irrespective of the rib plates

Fig. 2. The Flat Vierendeel Structure's Deformation and Height Curve Under Different Plate Thickness



(a) Consider upper and lower rib plates (b) Only consider upper rib plates (c) Irrespective of the rib plates

Fig. 3. The Flat Vierendeel Structure's Deformation and Height Curve Under Different Sizes of Upper and Lower Chord Members



(a) Consider upper and lower rib plates (b) Only consider upper rib plates (c) Irrespective of the rib plates

Fig. 4. The Flat Vierendeel Structure's Deformation and Height Curve Under Different Sizes of Vertical Web Members

2.2.2. Comparison of the three structures From Figure 2, Figure 3 and Figure 4, we can know that when plate thickness, section size of vertical web members, and other parameters are changed, the change of the deformation of the three flat vierendeel structures is not significant. However, when the size of the upper and lower chord members is increased, the deformation of the three flat vierendeel structures is significantly declined.

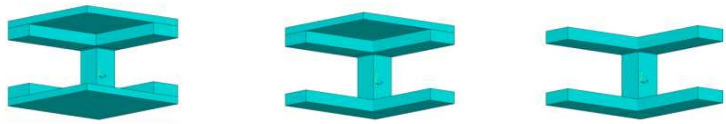
Furthermore, after comparing the deformation data of the three flat vierendeel structures shown in Figure 2, Figure 3 and Figure 4, we can find that when the components have the same size, the deformation of the flat vierendeel structure which considers upper and lower rib plates is about 30% lower than that of the flat vierendeel structure which only considers upper rib plates, and is about 50% lower than that of the flat vierendeel structure which is irrespective of the rib plates. That is, among the three structures, the flat vierendeel structure which considers upper and lower rib plates boats the highest stiffness, and its performance is obviously superior to the other two structures.

3. Thermal insulation property

3.1. Numerical model

The finite element software - FLUENT is used to analyze the thermal insulation property of the three flat vierendeel structures in Figure 1. Because the heat transferred by the three structures to the surroundings is little and wasn't taken into account, and only considers the vertical thermal insulation property. The amount of the structure's vertical heat transfer mainly depends on the thickness of the air space, the span, internode size, plate thickness, size of upper and lower chord members, and size of vertical web members only have little influence on it.

When establishing the numerical model, because the grid size of the three flat vierendeel structures shown in Figure 1 is same and the three structures are symmetric along the X and Y direction, so only simulate 1/4 typical internode was taken into account. The numerical models are shown in Figure 5. The geometric parameters are shown in Table 1. With regard to the flat vierendeel structure which isrrespective of the rib plates, because in practice, there are concrete sheets above it, so the thickness of the sheet is 40mm in the model. The upper surface of the model is in contact with outdoor air, and the temperature of the outdoor air is constant. The lower surface of the model is in contact with indoor air, and Shijiazhuang is taken as an example. Then, the writer calculates and analyzes a total of 54 finite element models with structure height ranging from 0.3m, 0.4m, 0.5m ... to 2.0m.



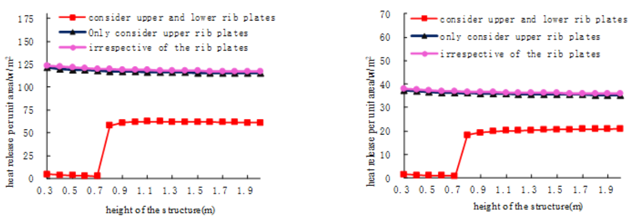
(a) Consider upper and lower rib plates (b) Only consider upper rib plates (c) Irrespective of the rib plates

Fig. 5. The Flat Vierendeel Structure's FLUENT Finite Element Model

3.2. *Calculation results and analysis.*

3.2.1. Determination of the most reasonable structure height The heat release per unit area of the three flat vierendeel structures and the indoor flat temperature in winter and summer are shown in Figure 6 and Figure 7.

From Figure 6 we can know that for flat vierendeel structure which considers upper and lower rib plates, when the structure height is less than 700mm, the structure's form of vertical heat transfer is mainly thermal conductivity. As the structure height, the thickness of the air space, and the thermal resistance of the structure increase, the heat release per unit area slowly decreases regardless of winter or summer, when the structure height is over 700mm, the structure's form of vertical heat transfer becomes heat convection. The heat release per unit area in winter and summer increases by 19 times and 16 times, respectively. The thermal insulation property sharply decreases, and then it slightly increases as the structure height increases. That is, there is a most reasonable structure height and the value is 700mm. Under this height, the heat release per unit area in winter and summer is the smallest, and the thermal insulation property is the best. From Figure 7 we can know that when the structure height is 700mm and the temperature of the lower surface of the indoor concrete plate approaches 18 degrees Celsius in winter, the indoor comfort degree can be greatly improved. Similarly, when the temperature of the lower surface of the indoor concrete plate doesn't reach 27 degrees Celsius, both the energy used to run the air conditioner and the carbon emission will be greatly decreased.



(a) Winter (b)Summer

Fig. 6. The Heat Release Per Unit Area of the Flat Vierendeel Structure in Winter and Summer

For flat vierendeel structure which only considers upper rib plates or isrrespective of the rib plates, due to the lack of lower rib plates, when the heat transfers vertically, there is no air space, so, the structure's heat transfer form is mainly thermal conductivity. From Figure 6 we can know that as the structure height changes, the thermal resistance slightly changes. In winter and summer, as the structure height increases, the heat release per unit area of the two structures both gradually decreases, but the change is relatively small. From Figure 7 we can know that, in winter and summer, the indoor surface temperature doesn't change significantly, either. That is, the change of the structure height has little influence on the thermal insulation property of the two flat vierendeel structures: only considering upper rib plates andrrespective of the rib plates.

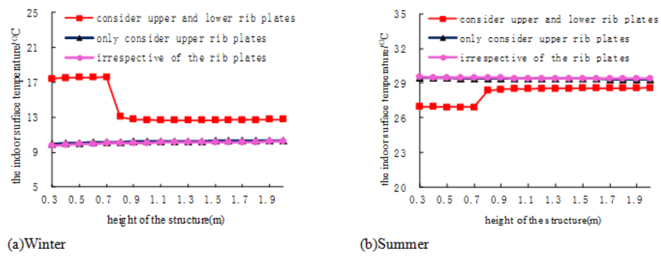


Fig. 7. The Indoor Surface Temperature of the Flat Vierendeel Structure in Winter and Summer

3.2.2. Comparison of the three structures The comparison of the thermal insulation property of the three flat vierendeel structures is listed in Table 2. It can be seen that when the structure height of the flat vierendeel structure which considers upper and lower rib plates is the most reasonable height - 700mm, the minimum heat release per unit area in winter and summer is about 98% lower than that of the other two structures, and the indoor surface temperature in winter is 7 degrees Celsius higher than that of the other two structures, and the indoor surface temperature in summer is 3 degrees Celsius lower than that of the other two structures. Therefore, the indoor comfort degree can be greatly improved, and it is also conducive to energy saving and emission reduction. That is, among the three structures, the thermal insulation property of the flat vierendeel structure which considers upper and lower rib plates is the best, which is obviously superior to the other two structures.

Table 2. Comparison of the Thermal Insulation Property of the Three Flat Vierendeel Structures

Structure types	Winter		Summer	
	Minimum heat release per unit area w/m^2	Highest indoor surface temperature	Minimum heat release per unit area w/m^2	Lowest indoor surface temperature
Consider upper and lower rib plates	2.713	17.62	0.844	26.92
Only consider upper rib plates	114.958	10.336	35.372	29.358
Irrespective of the rib plates	116.908	10.206	35.972	29.398

4. Conclusions

In this paper, through establishing 396 ANSYS and FLUENT finite element models, the writer analyzes the stiffness characteristic and the thermal insulation property of three flat vierendeel structures, and reaches the following conclusions:

(1) There is a certain structure height for all of the three flat vierendeel structures, which maximizes the structure stiffness, and its value is maintained around the high-span ratio - 1/17.5, 1/17.5 and 1/13, respectively,

(2) For the flat vierendeel structure which considers upper and lower rib plates, when the structure height is less than 700mm, the thermal insulation property is good, when the structure height is 700mm, the thermal insulation property is the best, and when the structure height is over 700mm, the thermal insulation property sharply reduces. However, for the flat vierendeel structure which only considers upper rib plates or isrrespective of the rib plates, the change of structure height has little influence on its thermal insulation property.

(3) The stiffness and thermal insulation property of the flat vierendeel structure which considers upper and lower rib plates are significantly better than those of the other two structures: only considering upper rib plates and irrespective of the rib plates.

In sum, the flat vierendeel structure which considers upper and lower rib plates should be adopted in priority and the structure height should be the smaller one between high-span ratio - 1/17.5 and 700mm to get better stiffness and thermal insulation property. When the flat vierendeel structure which only considers upper rib plates or irrespective of the rib plates is applied, the height should choose 1/17.5 and 1/13 of the span respectively to get the highest stiffness. This conclusion can provide some references for the practical engineering so as to reduce the deformation and to give full play to the thermal insulation property.

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