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Application of laminated vierendeel truss in high-position transfer story structure

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Abstract: To meet the demands for large space and flexible compartmentation of buildings, laminated vierendeel trusses are adopted in high-position transfer story structures. First the bearing characteristics are analyzed, in which reasonable stiffness ratio of the upper chord, middle chord, and lower chord is derived. Then combined with an actual engineering model (1 : 8 similar ratio), the static loading and pseudo-dynamic tests of two models for laminated vierendeel truss used in transfer story structures are conducted, in which one model adopts reinforced concrete, and the other adopts prestressed concrete and shape steel concrete. Seismic behaviors are analyzed, including inter-story displacement, base shear-displacement skeleton curves, and equivalent viscosity-damping curves. A program is programmed to carry out the elasto-plastic dynamic analysis, and displacement time-history curves of the two models are derived. The test and analysis results show that the laminated vierendeel truss with prestressed concrete and shape steel concrete has excellent seismic behaviors. It can solve the disadvantages of laminated vierendeel trusses used in transfer story structures. Finally, some design suggestions are put forward, which can be referenced by similar engineering.

Key words: laminated vierendeel truss; steel concrete; transfer story structure; prestressed concrete; elastoplasticity analysis

To date, the major transfer story structure forms applied in projects are beam, truss, slab, and box. Among these transfer story forms, the truss transfer story is one of the unique features[1,2]. It transfers the vertical and the horizontal loads by the interaction of web members of upper chords and lower chords. But the project examples for laminated vierendeel truss used as transfer story are very few, especially in high positions of buildings. This paper will introduce the applications of laminated vierendeel truss transfer structures[3-6].

1 Bearing Characteristics of Laminated Vierendeel Truss Transfer Story Structures

By internal force analysis of two-story vierendeel trusses subjected to distributed loads and point loads (see Fig. 1), the following can be concluded[3].

1) The axial forces are maximal in the middle of the upper, middle and lower chords and gradually decrease to the supporting seat. At the same time the shear force exists in all chords since there are no diagonal web members undertaking the shear force in laminated vierendeel trusses. The shear force and moment are minimal in the middle of the span, and they gradually increase to the supporting seat. Thus it can be seen that the upper chords are eccentric compression members and the lower ones are eccentric tension members. The moments of upper chords and lower chords are distributed in a sawtooth shape. Prestressing force on the lower chord members can improve their crack resistance capability. At the same time, the shear forces of lower chords in the end span can be undertaken by arranging some shape steel bars.

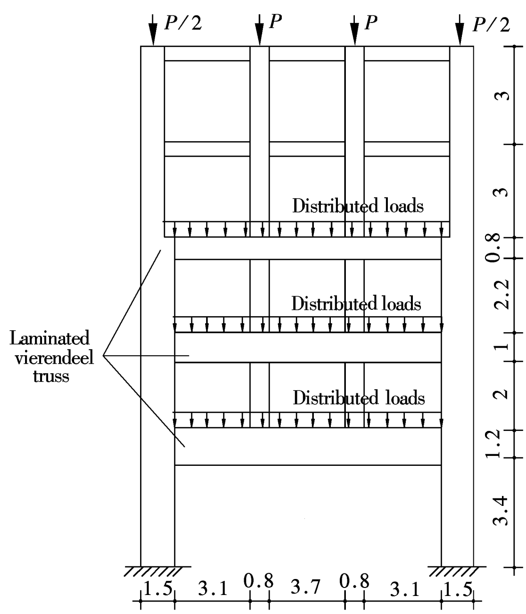

Fig. 1 Laminated vierendeel model (unit: m)

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2) The shear forces in the vertical web members in the laminated vierendeel truss transfer story structure are distributed similarly to the chords', that is, the shear forces are minimal in the middle and gradually increase to the supporting seat. Thus, the web member sections in the end span are larger than the sections in the middle. The shape steel can be applied to undertake the shear force in the end web members.

3) Increasing the sectional height of upper chords and middle chords and appropriately reducing the section height of lower chords can regulate the vertical force which the upper structure passes to the other straight web members to a large extent and transfer much more upper vertical force to frame columns, and can reduce the moments and shear forces in lower chords, but with a precondition that the section areas of lower chords are still a bit bigger than those of upper and middle chords. At the same time, the ratio of the maximum positive moment to the maximum negative moment decreases. It makes the truss undertake loads much more reasonably and reduce the vertical displacement of lower chords, which shows that the combined effect of the whole structure is strengthened with the stiffness increase of upper chords and middle chords.

4) Comparing trusses where the web members are compactly arranged in the neighborhood of the supporting seat with trusses where the web members are uniformly arranged, the former is more reasonable than the latter, which can reduce the moments and axial forces of upper chords and lower chords.

2 Project Example

The second phase of the Shandong World Trade Center[3] project is an integrated office building, entertainment center and large scale exhibition center, which is designed by the America Caokang Structure Design Office. The 6th floor is designed as a large exhibition center, which covers 31. 0 m × 27. 3 m. The 7th and 8th floors are common office, and the roof is an open-air tennis court. It adopts a frame structure and sets the 7th floor as a transfer structure in conventional thought. With such a large span, it is unaccepted in architecture to adopt a transfer beam with the beam section nearly 3 m deep. Designers regard the 7th floor, the 8th floor and the roof as a whole laminated vierendeel truss to meet the transformation of the upper structure, and impose prestressing force in the transfer beam (i. e. the corresponding lower chords in whole laminated vierendeel truss) to meet the need of serviceability limits of the transfer structure. In order to improve the ability to undertake the shear forces and moments, the end supporting seats, i. e. the joints that connect the lower chord and the first vertical web member adopt shape steel concrete. These joints can undertake much more shear force. In the end, the design of the whole transfer structure system is successfully carried out, i. e. the larger space under the transfer structure is met. The transfer story also has a large space, which can ensure architecture headroom and make the compartmentation flexible.

3 Test Study

3. 1 Model design

With the bearing characteristics of laminated vierendeel truss and the engineering background of Shandong World Trade Center, pseudo-dynamic tests of two models of laminated vierendeel truss used in transfer story structure are conducted. Limited by the loading condition of the test, the number of the middle vertical members of the transfer story is reduced from seven in actual structure to three in the model, which leads to little effect on the overall behaviors of a large span transfer structure. In order to simulate the effect of an outboard-continuous-span structure in an actual large space transfer structure, it is designed such that the stiffness of the side-columns in the model is equal to that of the columns in outboard-continuous-span structure, and the model is made to a 1∶8 scale of an actual structure. Two models of laminated vierendeel truss used in transfer story structures are conducted, in which one adopts reinforced concrete (PC model for short), and the other adopts prestressed concrete and shape steel (PSRC model for short). Model design principles follow so that the two models have equal sectional size; the bearing forces of every controlled section of the two models are equal; the concrete strength grades of the two models are C60. Prestressing wires of lower chords of the PSRC model is $7\phi^{j}5$ (f_{ptk} = 1 860 MPa) and the control stress $\sigma_{con} = 0.6 f_{ptk}$, of which the total tensile force N_p = 156 kN. In order to make sure the model bottom columns are fixed, the ground beam is designed with relative larger stiffness to prevent the glide of the model bottom columns. Fig. 2 shows the sectional size and the bar distribution. To ensure the steel concrete and reinforced concrete can work together, the PSRC model is designed according to Ref. [7]. Tab. 1 shows the performance of the model materials.

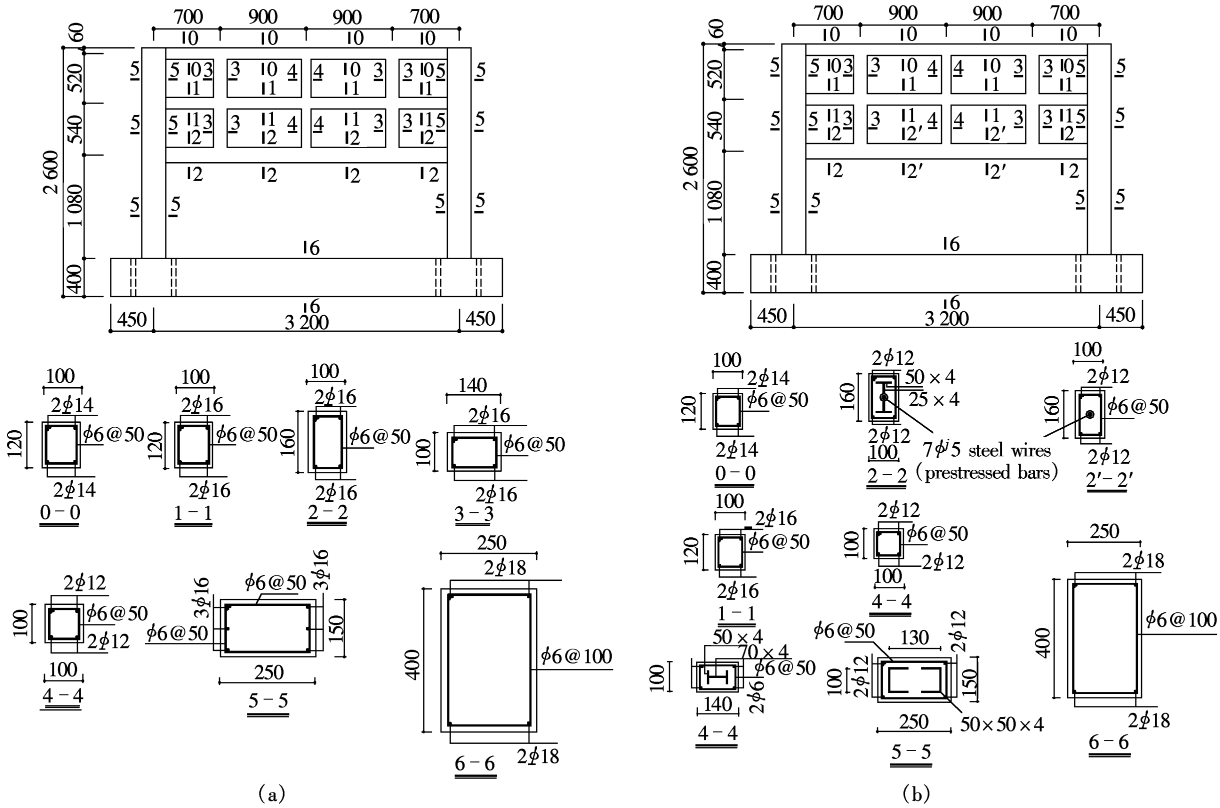

Fig. 2 Model size and bar distribution. (a) RC model; (b) PSRC model

Tab. 1 Performance of model materials

Model	Concrete	Steel			
	f_{cu}/MPa	Diameter/mm	f_y/MPa	f_u/MPa	E_s/GPa
RC	56.64	ϕ8	370	461.55	178
		ϕ12	322.73	449.47	197
PSRC	62.36	ϕ12	394.94	552.62	191
		ϕ14	389.76	559.75	192
		ϕ16	379.65	592.69	195
		7ϕ^j5 prestressing wires	1 000	1 860	185
		4 mm steel plate	328.88	435.40	190

3.2 General description of tests

First the vertical loading test is carried out, and then the pseudo-dynamic test is conducted in the condition of keeping the same vertical loads. In order to ascertain the variation status of strain in the longitudinal bars in the area of the plastic hinges during the load tests, some strain gauges are arranged in the longitudinal bars in these positions, and this is also done for the shape steels in corresponding positions of bars in the PSRC model. The displacement transducers in the center axis lines of the upper chords and lower chords are used to measure the horizontal displacement of the model. The displacement transducers in lower chords are input to an *X-Y* function recorder to draw the hysteresis curve. Fig. 3 is the sketch of the loading system. In the tests, the seismic wave adopts El-Centro record (1 940 s), of which the time interval is 0.02 s and the lasting time is 8 s. According to the similar ratio of the model to the actual structure, the model testing time interval of the wave is 7 ms and the lasting time is 2.8 s.

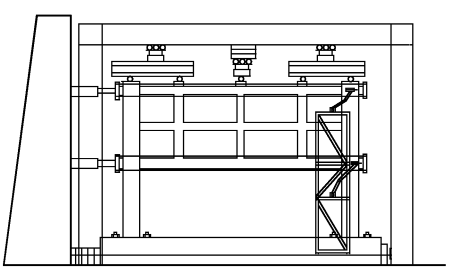

Fig. 3 Sketch of loading system

3.3 Main results and analysis

3.3.1 Under vertical loads

Comparing the cracking distribution of the RC model under vertical load with the PSRC model's, the PSRC model's ability to resist cracking has an advantage over the RC model. The application of prestressing force and steel concrete increases the stiffness of the lower chord. As a result, the stiffness ratios among each member of the transfer structure is changed, and the bearing capacity of the lower chord increases. Correspondingly the forces undertaken by the upper and middle members reduce, which leads to postponement of cracking.

Comparing the displacement in the middle span of the lower chord in the PC model under the vertical load with that of the PSRC model's, the stiffness of the PSRC model is superior to the RC model's. When the vertical load on the top of each column in the model is 10 kN, the displacement in the middle of the span in the PSRC model is 0. 545 mm while the PC model's is 0. 637 mm. Otherwise, the actual vertical displacement of the PSRC model would be less than the test results since there is reverse arch action in the lower chord including the whole transfer structure during the procedure of applying prestressing force. As a result, the laminated vierendeel truss used in transfer story structures in the PSRC form easily controls vertical displacement.

Comparing the strain of the PC model under vertical load with the PSRC model's, it can be seen that the PC model cracks much earlier and its ability to resist cracking is obviously less than the PSRC model's. The lower chord of the PRSC model undertakes prestressed compressive stress before loading. Under the vertical load, the tension force and moment are increased in the lower chord. When the vertical load on the top of each column in the model is 10 kN, there is still axial compressive stress in the lower chord of the PRSC model. On the other hand, the tension increases much more in the lower chord of the PC model under vertical load.

3.3.2 Pseudo-dynamic tests

Keeping vertical load constant (10 kN on the top of each column), the pseudo-dynamic tests are carried out. The peak value of the seismic wave takes 0. 35g, 0. 7g, 1. 4g and 2. 1g in turn.

Figs. 4(a) and (b) respectively show the distribution of the maximum inter-story displacement of two models under seismic wave where the vertical axis indicates the story and the horizontal axis indicates the ratio of the displacement of each story to the roof's. From Fig. 4, it is seen that the horizontal deformation is concentrated increasingly in the first floor of each model with the increase of seismic wave peak value. The deformation concentration degree of the PSRC model is apparently less than the RC model's. It can easily be seen that the seismic performance of the PSRC model is better than the RC model's.

Fig. 5 shows the base shear-displacement skeleton curves of two models. It can be seen that bearing capacity and deformation capacity of the PSRC model is increased to a large extent. After entering the descent segment of the curves, the bearing capacity of the RC

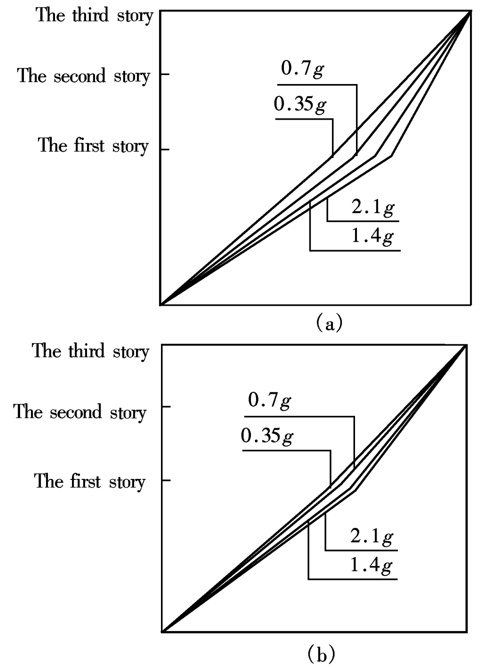

Fig. 4 Distributions of inter-story displacement. (a) RC model; (b) PSRC model

model rapidly decreases; in contrast, the PSRC model's descends slowly, which indicates its good ductility. It indicates that the application of shape steel takes good effect and obviously improves the seismic capability.

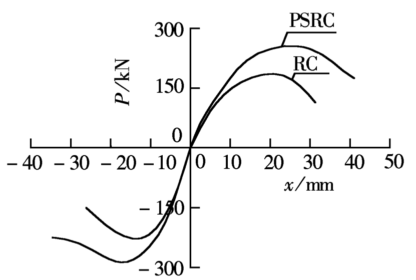

Fig. 5 Base shear-displacement skeleton curves

Fig. 6 shows the equivalent viscosity-damping curves of RC mode and PSRC model[4]. The PSRC model's equivalent viscosity-damping coefficient increases more slowly. But, with the increase of peak value acceleration of the seismic function, due to the rapid spread of the tilted cracks, the displacement and the equivalent viscosity-damping coefficient of PSRC model are gradually increased, which are obviously

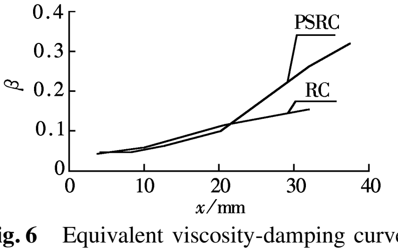

Fig. 6 Equivalent viscosity-damping curves

larger than the PC model's. It indicates that the application of shape steel and the prestressing force can improve the energy dissipation capacity of the whole structure to a large extent.

3.4 Elasto-plastic dynamic analysis

A program is programmed to carry out the elasto-plastic dynamic analysis of the laminated vierendeel truss transfer story structure, which adopts different reinforced models for common concrete elements and prestressed concrete elements[8-10]. The differential equations are solved with the Newmark-β method. Adopting the El-Centro record used in the pseudo-dynamic tests, the elasto-plastic dynamic analyses of the two models are carried out in this program. Fig. 7 shows the computing and testing time-history curve of the two models under the seismic wave with the peak value of 1.4g. It can be seen that the two curves spread much more similarly, the indication tendency is the same, and the response periods and the maximum amplitude are similar. But there are still some differences, especially at the major peak value stage of the seismic wave and the end part of the curves. The main reasons are the error caused by the restore force model used in the computing, the error caused by the solution method, the error caused by the vibrators not working at the same pace, and the error caused by the whole online measurement system. At the same time, it can be seen that the displacement of the RC model is larger than the PSRC model's at the same seismic function.

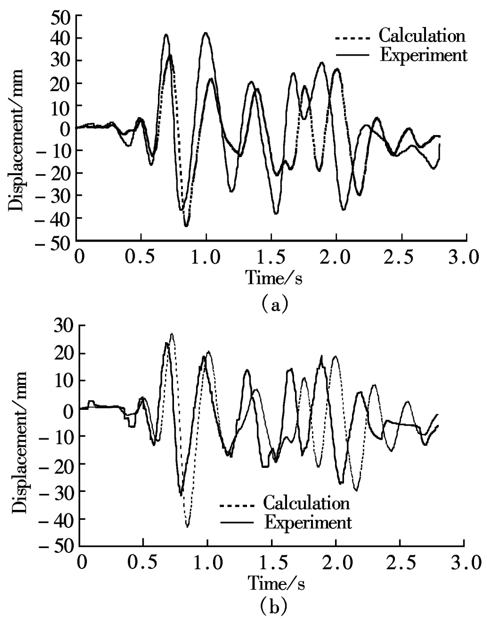

Fig. 7 Contrast of calculation and experiment time-history curves under seismic function with peak value of 1.4g. (a) RC model; (b) PSRC model

4 Discussion

In view of seismic characteristics, the large span laminated vierendeel truss transfer story structure is the vulnerable part. This paper proposes that the transfer structure cannot be destroyed firstly by earthquake[11]. In a laminated vierendeel truss transfer story structure, the seismic ductibility design should be overemphasized. First, stronger shear and weaker bend must be met in the section design of the laminated vierendeel truss transfer story structure members. Secondly, the design of joints should be underlined. The steel-concrete joints can be firstly adopted in view of the test results. Thirdly, the multi-defense principle should also be considered in design. In order to avoid the vertical collapse of the transfer structure, the bottommost member itself should not form a destroyed structure. The ends of other transfer structure members may firstly form to plastic hinges in turns so as to subject the seismic function and energy dissipation of the whole structure. It can be deduced from the former test results that the bottom horizontal transfer members will not form a destroyed system by itself under an unusual earthquake wave owing to the prestressing force and steel concrete, and to the precondition of adopting efficient measures to make sure that the steel concrete will work together with the reinforced concrete. The manual plastic hinge technology can be adopted in the yielding order design of transfer members. Otherwise, the ductility design can be especially emphased in the member-end section design.

It is concluded that the seismic design principles of laminated vierendeel truss transfer story structures are as follows: ① Under the precondition of meeting the need of the inter-story stiffness ratio, the seismic design of the whole structure should follow the principle of "strong transfer story"; ② Under the precondition of meeting the suitable stiffness ratio among members, the design of the transfer structure itself should follow the principle of "strong lower chord, strong joints"; ③ The design of the transfer structure members should follow the principle of "stronger shear and weaker bend".

5 Conclusions

1) The adoption of laminated vierendeel truss in high-position transfer story structures and the application of prestressing force and shape steel are in favor of improving the architecture imagery, which increases the serviceability. The materials would be economized

to some extent and the self-weight of the structure would be reduced. What's more, it will improve the seismic performance of the whole structure. At the same time, laminated vierendeel truss used as transfer story structure will have greater stiffness, which would reduce the vertical displacement of the transfer story structure and reduce the sectional moment. It is equivalent to a horizontal reinforced story set in a frame, which can reduce the vertical displacement at the top point in the structure.

2) The major internal forces of the vertical members in the laminated vierendeel truss transfer story structure are moment and shear force, so they can be considered as a member in bending, while considering the advantageous or disadvantageous effects properly in the case of relative large axial force. The lower chords undertake some tension and the top ones undertake some compression. However, the major internal forces are still moment and shear forces, of which the peak values occur at the supporting seat sections of the transfer structure, since the axial forces in the middle section of the transfer structure span are larger than the ones of supporting seat section. The major forces in the supporting seat section of lower chords are moment. In contrast, the forces in the middle section of the span present apparently eccentric tension properties.

3) The large span laminated vierendeel truss transfer story structure is in the main protected part in the whole seismic structure. It cannot be destroyed firstly in an earthquake. Its seismic ductility design should be overemphasized. The multi-defense principle should also be considered in the whole laminated vierendeel truss transfer story structure design. In order to avoid the vertical collapse of the transfer structure, the lower chords should not form destroyed structures. Considering all of these factors, this paper puts forward the principles of "stronger transfer structure", "stronger lower chord", "stronger joints", and "stronger shear and weaker bend".

The laminated vierendeel truss related in this paper was designed in the second phase of the Shandong World Trade Center project, which belongs to a high position transfer structure. As to the application of the laminated vierendeel truss on a low position transfer structure, another paper could be written to expatiate.

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迭层空腹桁架在高位转换层结构中的应用

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摘要: 为满足建筑物大空间和灵活隔断要求, 在高位转换层结构中采用迭层空腹桁架结构. 首先分析了其受力性能, 得出了空腹桁架各构件合理的截面刚度以及布局形式. 然后结合一实际工程, 进行了两榀迭层空腹桁架转换结构模型(1∶8相似比)的竖向荷载下静力试验以及拟动力试验. 其中一榀为普通混凝土迭层空腹桁架, 另一榀配置了预应力和钢骨混凝土, 对比分析了两模型的层间位移比、骨架曲线以及等效粘质阻力系数等抗震性能的比较, 并进行了弹塑性动力分析. 试验和分析结果表明, 配置预应力和型钢混凝土的迭层空腹桁架转换结构具有良好的抗震性能, 可以成功地解决迭层空腹桁架作为转换层结构所产生的弊端问题, 最后对这类转换层结构提出了相应的设计建议.

关键词: 迭层空腹桁架; 钢骨混凝土; 转换层结构; 预应力; 弹塑性分析

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