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Application Research on Large Profiled Statues of Steel-Concrete Composite Shear Wall

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Abstract**—**Twin steel plates-concrete composite shear walls are composed of a pair of steel plate layers and a concrete layer sandwiched between them, which have the characteristics of both reinforced concrete shear walls and steel plate shear walls. Twin steel plates-composite shear walls contain very high ultimsate bearing capacity and ductility, which have great potential to be applied in the super high-rise buildings and special structures. In this paper, we analyzed the basic characteristics and stress mechanism of the twin steel plates-composite shear walls. Specifically, we analyzed the effects of the steel plate thickness, wall thickness and concrete strength on the bearing capacity of the twin steel plates-composite shear walls. The analysis results indicate that: (1) the initial shear stiffness and ultimate shear-carrying capacity is not significantly affected by the thickness of concrete wall but by the class of concrete, (2) both factors significantly impact the shear distribution of the shear walls in ultimate shear-carrying capacity. The technique of twin steel plates-composite shear walls has been successfully applied in the construction of an 88-meter Huge Statue of Buddha located in Hunan Province, China. The analysis results and engineering experiences showed that the twin steel plates-composite shear walls have great potential for future research and applications.

Keywords—Twin steel plates-concrete composite shear wall, huge statue of Buddha, shear capacity, initial lateral stiffness, overturning moment bearing.

I. INTRODUCTION

THE twin steel plates-concrete composite shear walls, presented in the paper, are composed of a pair of steel plate layers and a concrete layer sandwiched between them. The steel plates are connected with neighboring steel frame beams and columns, as well as to the inner concrete, using joiners such as goggle pins. The distribution of the goggle pins is determined by both the distortion of the outside steel plates and the restraining stiffness of the inner concrete Because of the out plane restraining action of the concrete, local and the entire distortion outside the plane is commonly observed. The goggle pins are distributed in order to reduce the distortion to lowest level. The twin steel plates-concrete composite shear walls have the advantages of reinforced concrete shear walls. Meanwhile, they are able to avoid the disadvantages of steel plate shear walls. Therefore, the twin steel plates-composite shear walls contain more advanced characteristics [1], [7]. Studies have shown that the twin steel plates-concrete composite shear walls have higher bearing capacity and better ductility due to their properties of being able to prevent the local distortion of the steel plate as well as the constrain of the concrete from the surrounding steel plate [2]-[8].

Based on the project of constructing the statue of Thousand Hands Buddhist (built in Ningxiang, Hunan Province, China), the paper analyzed the basic characteristics and the stress mechanism of the twin steel plates-concrete composite shear walls. Specifically, this paper analyzed the effect of the steel plate thickness, wall thickness and concrete strength on the bearing capacity of the twin steel plates-concrete composite shear walls. The technique of the twin steel plates-concrete composite shear walls has been successfully applied in construction of the huge statue, which shows great potential in future research and applications.

II. EFFECTS OF PARAMETERS ON TWIN STEEL PLATES-CONCRETE COMPOSITE SHEAR WALLS

The software ANSYS was used to analyze the effects of the following parameters on the shear-carrying performance of the twin steel plates-concrete composite shear walls: 1) span-depth ratio (α) of the wall, 2) height-thickness ratio (β) of the steel plate, 3) thickness of the filled-in concrete (W), and 4) class of the concrete.

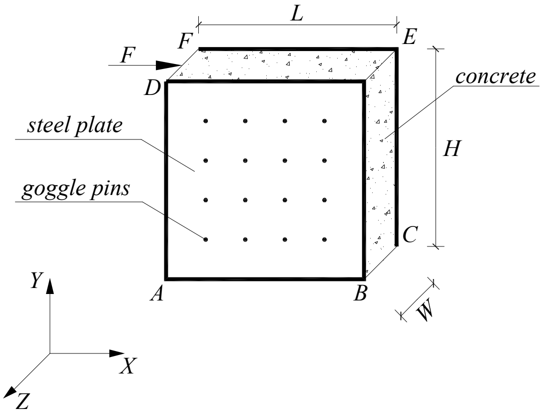

Fig. 1 Application of load and correlative parameters of twin steel plates-concrete composite shear wall

As shown in Fig. 1, let parameters H, L and t be the height, length and thickness of the wall, respectively. The parameter span-depth ratio of the wall is defined to be $\alpha = L/H$, and the parameter height-thickness ratio of the steel plate is defined to be $\beta = H/t$. In this model, the steel plate is represented by SHELL181 element (4-node shell element, representing

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plastic, stress intensification, large distortion, and large strain), and the concrete is represented by SOLID65 3-D element. In the analysis of elastoplastic, MISO, Mises yield criteria and relevant fluidity principles were used. The finite element model is shown in Fig. 2.

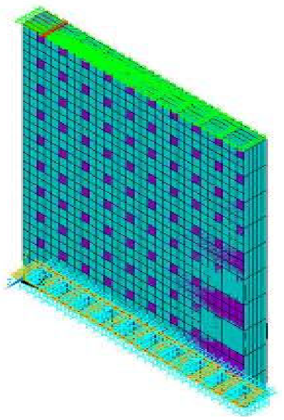


Fig. 2 FEM model of twin steel plates-concrete composite shear walls

A. Effect of Span-Depth Ratio on Twin Steel Plates-Concrete Composite Shear Walls

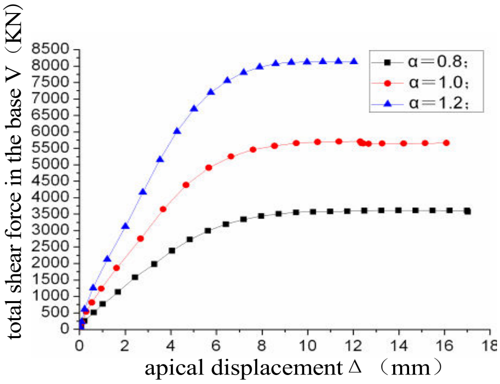


Fig. 3 The α influences to load-displacement curve

As shown in Fig. 3, as the span-depth ratio increases, both the ultimate shear-carrying capacity of the composite shear wall and the initial stiffness increase significantly. This indicates that the higher span-depth ratio is advantageous to the integral shear-carrying capacity of the composite shear wall.

As shown in Fig. 4, when the displacement △ at the top of the wall is close to 0, the steel plates bear a small proportion of the total shear force. However, as the displacement △ increases, the proportion climbs. As the displacement increases from 0 to 2mm, the portion of total shear force increases to 50%. Obviously, during this phase, the structure still works in elastic condition. With the apical displacement continues to increase, the structure steps into the plastic condition. After that, the proportion of shear force bore by the steel plate fluctuates, yet the general trend is rising. In general, as span-depth ratio increases, the changes in the proportion of shear force bore by the steel plate is insignificant. Thus, span-depth ratio α has slight effect on shear distribution form of the composite shear wall.

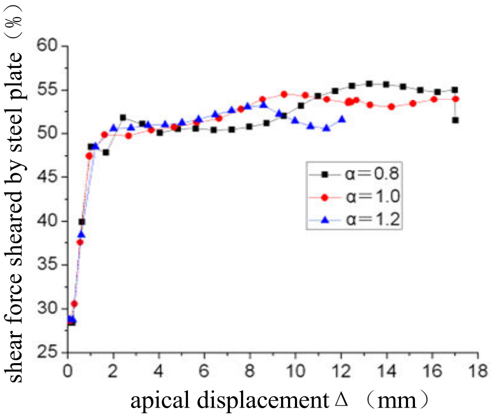


Fig. 4 The α influences to distribution of shear in Steel-concrete Composite Shear Wall

B. Effect of Height-thickness Ratio β on Shear-Carrying Performance on Composite Shear Wall

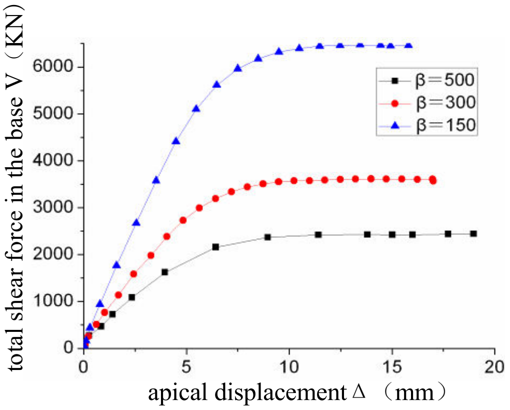


Fig. 5 The β influences to load-displacement curve

As shown in Fig. 5, as the height-thickness ratio β decreases, the shear-carrying capacity of the composite shear wall enhances, and the initial stiffness also increases significantly. The studies show that the decrease of height-thickness ratio β is beneficial to integral shearing resistance of the composite shear wall.

As shown in Fig. 6, as the displacement △ at the top of the wall increases, the steel plates share more shear force, and the displacement rises straightly upwards between 0～2mm. Yet, as the height-thickness ratio β varies, the rate of rise in the curve varies, as well as the value of the displacement △ at the top of the wall where the displacement reaches maximum. The slope of curves of medium gauge steel plate is larger than that of the sheet steel, and the proportion of shear force the steel plate bear reaches more than 65%. When the thickness of steel plate increases to a certain level, it plays a dominant role in later bearing phase of the structure. As the apical displacement continues to increase, the structure steps into the plastic condition, after that, the proportion of shear force bore by the steel plate fluctuates, yet the general trend is rising. Thus, the height-thickness ratio has a great effect on shear distribution between concrete and steel plate.

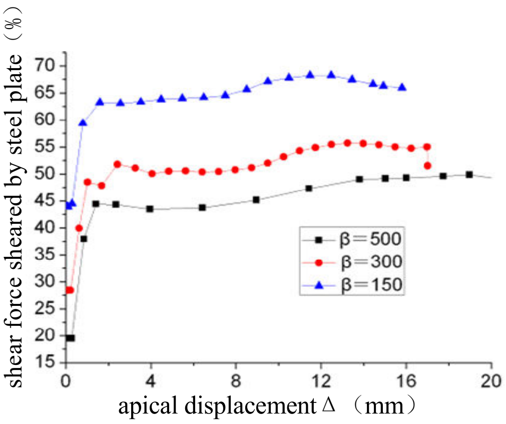


Fig. 6 The β influences to distribution of shear in Steel-concrete Composite Shear Wall

C. Effect of Thickness of Concrete on Shear-Carrying Performance of Composite Shear Wall

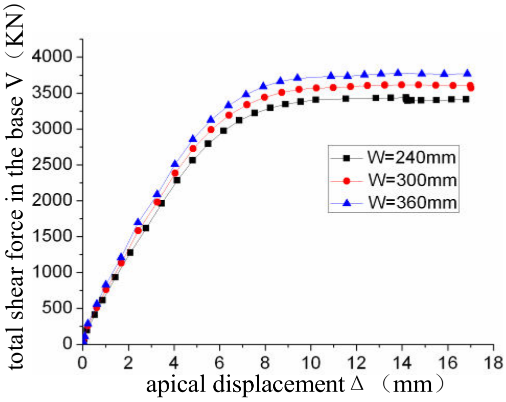


Fig. 7 The W influences to load-displacement curve

As shown in Fig. 7, as the thickness of wall increases, the initial stiffness and shear-carrying capacity of the composite shear wall improve insignificantly. Thus, the thickness of concrete has slight effect on integral shearing resistance of the composite shear wall.

As shown in Fig. 8, the proportion of shear force bore by steel plate increases in accordance with the increase of apical displacement. After the structure becomes plastic condition, the proportion fluctuates with a general trend of increase. When the apical displacement is small, with the wall thickness increasing, the slope of the ascending branch of the curve decreases slightly. Thus, the wall thickness has slight effect on the shear distribution of composite shear wall at the elastic phase. However, at the elastoplastic phase, the curve decreases obviously with wall thickness increases. Thus, the wall thickness has significant effect on the shear distribution of composite shear wall during the elastoplastic phase.

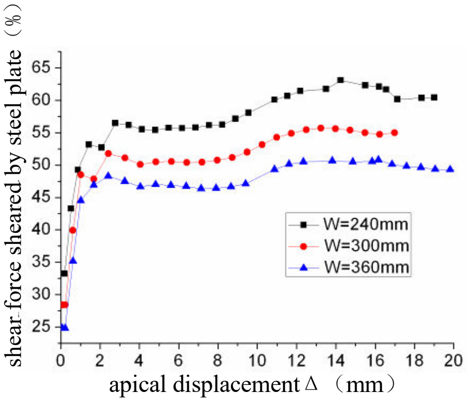


Fig. 8 The W influences to distribution of shear in Steel-concrete Composite Shear Wall

D. Effect of Grade of Concrete on Shear-Carrying Performance of Composite Shear Wall

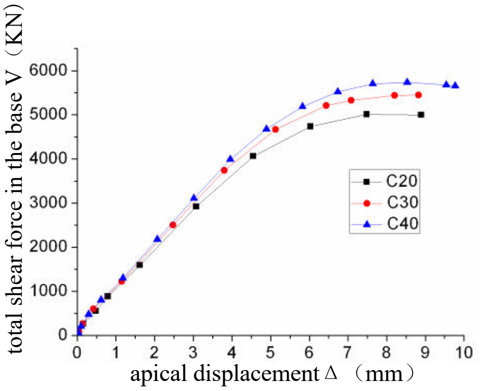


Fig. 9 The influences of strength grade of the concrete to load-displacement curve

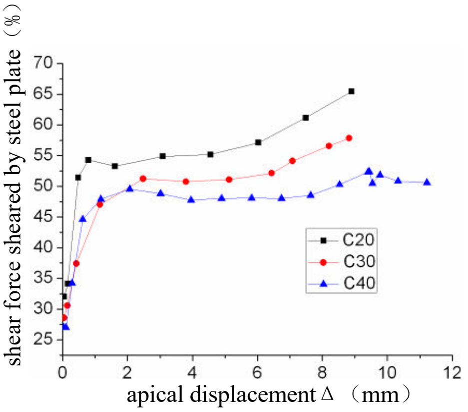


Fig. 10 The influences of strength grade of the concrete to shear distribution of Steel-concrete Composite Shear Wall

As shown in Fig. 9, as the concrete strength increases, the initial stiffness and shear-carrying capacity of the wall enhance, which shows the effect of class of concrete on the shear-carrying capacity of the structure.

As shown in Fig. 10, at the elastic phase, when the apical displacement is small, class of concrete has slight effect on the shear distribution between the steel plate and concrete. However, at the elastoplastic phase, as the concrete strength increases, the curve decreases significantly. This indicates that the class of concrete has great effect on the shear distribution of the composite shear wall.

III. ENGINEERING APPLICATIONS

The technique of twin steel plates-concrete composite shear walls was applied in a large statues – "Avalokitesvara statue" as shown in Fig. 11 (built in Hunan Province, China). The statue was built on top of a 600m high mountain. The height of the whole construction is 88 m. This project started in 2007 and finished in 2009.

(a) Front View (b) Side View

(c) Inner steel structures

Fig. 11 Construction process of Avalokitesvara statue

The major challenge of the project was the unbalanced-force exerted upon the statue due to the following several reasons: (1) the statue is located on top of a mountain with uneven ground; (2) the body of the statue is so irregular that forces of gravity differ significantly on different parts of the structure; (3) the statue has 36 "unfolded arms" with about 10-meter length, which generated unbalanced force on the upper part of the statue when blew by wind and (4) the statue leans forward, which makes it even more difficult to keep balanced. Another challenge of the project is that the support of the statue is limited. The area of the statue base is only 4 meters by 6 meters as shown in Fig. 13 (structural floor plan of landings of the statue, the dotted lines are outer contour lines of the statue's two feet). The whole statue is tall and narrow, with the narrowest cross section of 2.8 meters and height-width ratio of 20, which is much higher than that of normal buildings. With these challenges ahead of us, it is very challenging to use regular reinforced concrete shear wall or steel frame structural system in this project, which will lead to overlarge horizontal displacement on top of the statue and cracking in bottom concrete of the foundation. In other words, they cannot meet the requirement of the structural stiffness. After careful comparisons, we decided to use the twin steel plates-concrete composite shear walls, which have been implemented successfully in this project. Since wind load in the Y axis direction is the controlling load, we have applied three twin steel plates-concrete composite shear walls along the Y axis, and two along the X axis.

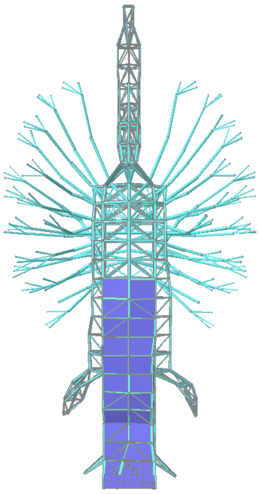


Fig. 12 FEM model of inner primary structure

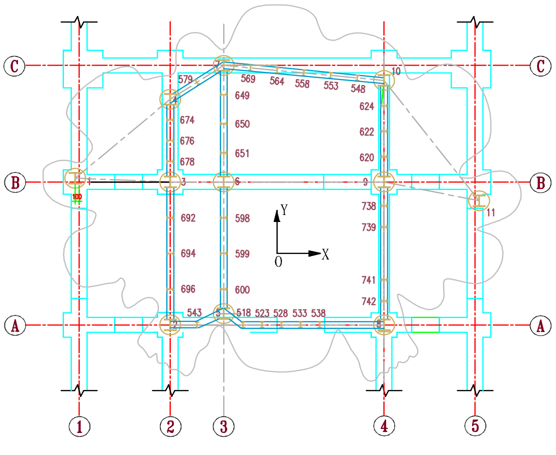


Fig. 13 Plane arrangement chart of steel-concrete (SC) composite shear wall

A. Structure Analysis

The finite element analysis model is shown in Fig. 12. The pole structure such as steel frame and arming steel pipe were applied with 3-D beam element. The steel plate-concrete composite shear wall was applied with shell element which was established by the simplified method called "using elastic modulus as parameters, converting concrete to steel plate with equivalent stiffness" [9]. The load cases are described as following:

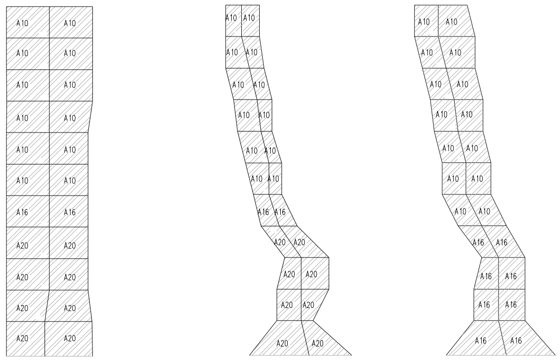
1. Dead load: copper plate deadweight of the statue's outer contour (not including the deadweight of the steel structure) is about 800KN, single arm's weight is 12KN.
2. Wind load: the value "shape factor of wind load" is taken from the report of wind tunnel testing about the statue model in Nanjing University of Aeronautics and Astronautics.
3. Earthquake action: seismic fortification intensity 7, basic seismic acceleration 0.1g, class II field.

The thickness of the steel plate of the composite shear wall is adopted in accordance with the force action: 10mm, 16mm and 20mm (corresponding to A10, A16 and A20 as shown in Fig. 14).

We have considered the wind load coming from four different direction +X, -X, +Y, -Y, and the seismic action coming from two horizontal direction X, Y.

The following four cases of load combinations during stiffness calculation were considered: Load case 1: 1.0D+1.0W+X; load case 2: 1.0D+1.0W-X; load case 3: 1.0D+1.0W+Y; load case 4: 1.0D+1.0W-Y.

In the formula, parameter D represents dead load, and parameter W represents wind load.

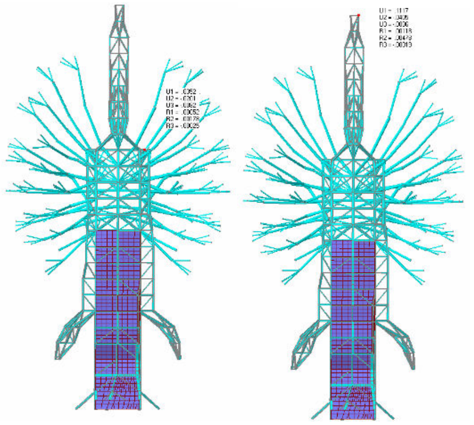


(a) Front wall of ○,A axis (b) Side wall of ④axis (c) Side wall of ③axis

Fig. 14 The cross-section distribution of Steel-concrete Composite Shear Wall

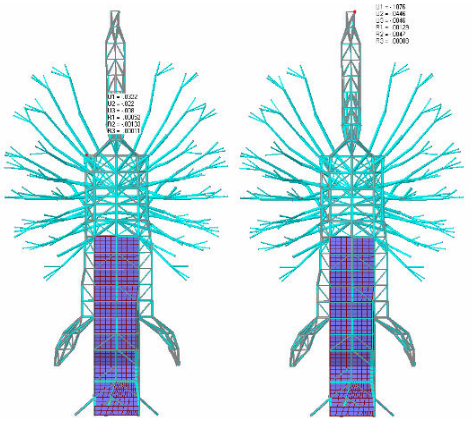
1. Stiffness Analysis

As shown in Figs. 15-18, the statue has thin and long arms with the body leaning forward, which is very different from the normal buildings. Therefore, the worst case occurs when wind force is applied along the Y-axis, during which the load reaches the maximum and the structure has maximum shift. We have confirmed that the statue can stand even in such a worst condition [10].



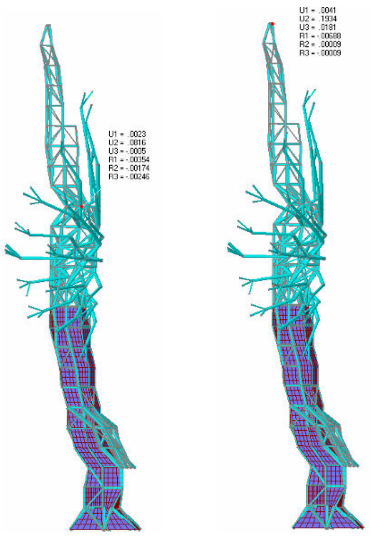
(a) Shoulder (25mm）　　(b Top (81mm)

Fig. 15 The max displacement in load cases 1



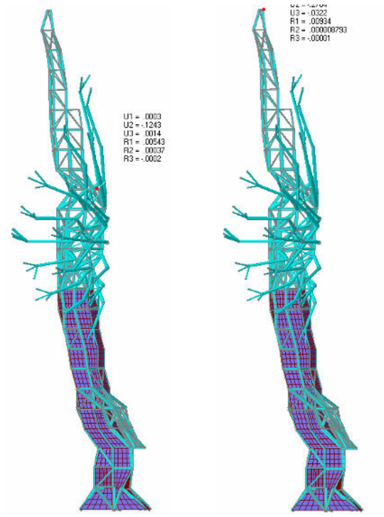
(a) Shoulder（23mm）　(b) Top (72mm)

Fig. 16 The max displacement in load cases 2



(a) Shoulder（38mm）　(b) Top (120mm)

Fig. 17 The max displacement in load cases 3



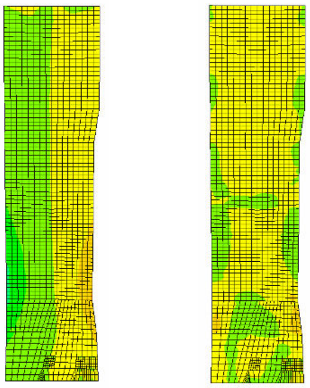
(a) Shoulder（42mm） (b) Top (135mm)

Fig. 18 The max displacement in load cases 4

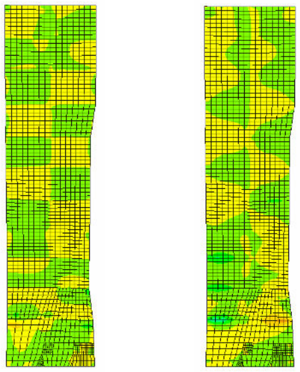
2. Intensity Analysis

Fig. 19 shows the internal force diagram of ○,A axis wall under +X direction wind load. Fig. 19 (a) shows that the boundary between tension and compression is obvious, and therefore the wall is in the status of total cross section working. Fig. 19 (b) shows that the horizontal shear force is large, and in some local bending area the force is negative. Figs. 19 (c) and (d) show that the lateral shear force and lateral moment appear in local area of the composite shear wall, yet both are small.

Fig. 20 shows the internal force diagram of ○,2axis wall under +X direction wind load. Fig. 20 (a) shows that the tensile region covers the whole wall and the tensile force is comparatively high. Fig. 20 (b) shows that there is a significant amount of horizontal shear force in the wall, which is considered to be caused by the distortion in the structure. Figs. 20 (c) and (d) show that both the lateral shear force and the lateral moment appear in the local area of the composite shear wall.



(a) Vertical axial force (b) Level shear force



(c) Lateral shear force (d) Lateral bending moment

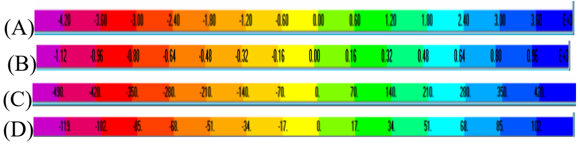
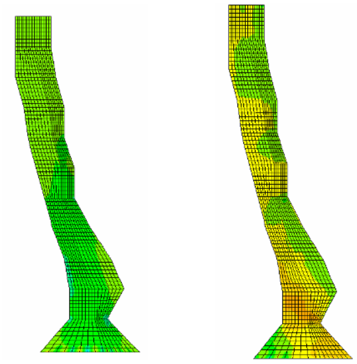
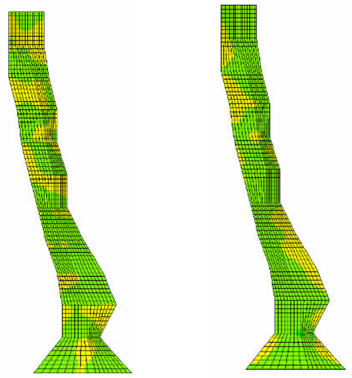


Fig. 19 Internal force diagram of ○,A axis wall in +X direction wind load case



(a) Vertical axial force (b) Level’s shear force



(c) Lateral shear force (d) Lateral bending moment

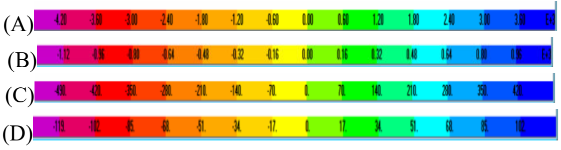
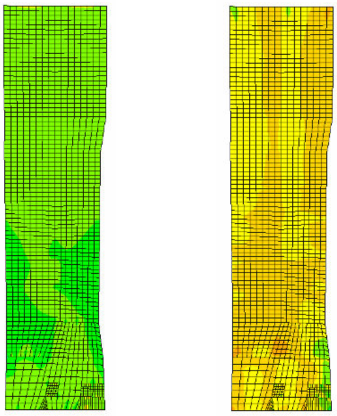
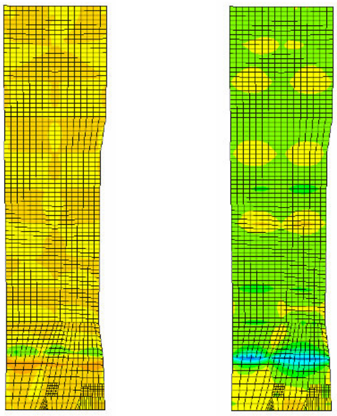


Fig. 20 Internal force diagram of ○,2axis wall in +X direction wind load case

Fig. 21 shows the internal force diagram of ○,Aaxis wall under +Y direction wind load. From Fig. 21 (a), the tensile region covers the whole wall and tensile force is strong. From Fig. 21 (b), there is a horizontal shear in the wall, and the force is not weak. Also, the structure has been twisted. From Fig. 21 (c), the horizontal shear is comparatively strong, and the wall plates also bear shear force in the vertical direction.



(a) Vertical axial force (b) Level's shear force



(c) Lateral shear force (d) Lateral bending moment

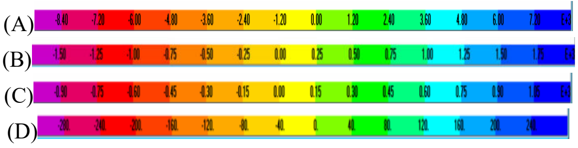
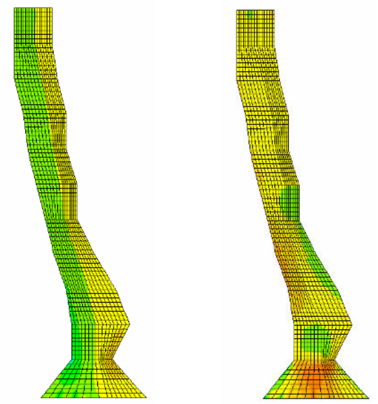
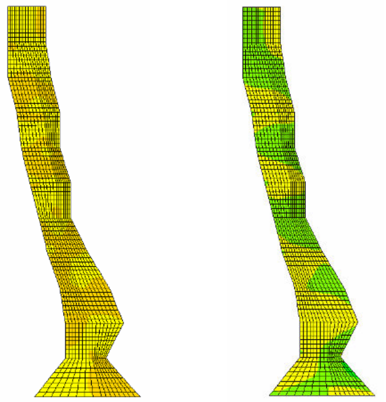


Fig. 21 Internal force diagram of ○,Aaxis wall in +Y direction wind load case

Fig. 22 shows the internal force diagram of ○,2axis wall under +Y direction wind load. Fig. 22 (a) shows that the left wall is under tensile strain and the right wall is under compressive strain. And the boundary between the tensile strain and the compressive strain is clear. Fig. 22 (b) shows that the horizontal shear force is large in upper part of the wall, which is primarily due to a part of the shear force counteracted by the shear force caused by torsion. Fig. 22 (c) shows that there is horizontal shear in the wall plates, and the structure has been twisted. Fig. 22 (d) shows that the horizontal moment is comparatively small in the composite shear wall.



(a) Vertical axial force (b) Level's shear force



(c) Lateral shear force (d) Lateral bending moment

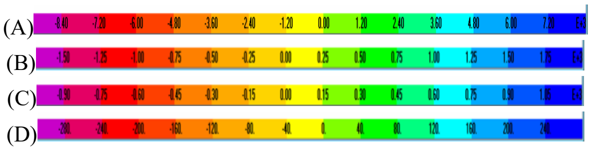


Fig. 22 Internal force diagram of ○,2axis wall in +Y direction wind load case

The above analysis shows the twin steel plates-concrete composite shear walls can bear not only the shear force but also the relevant upsetting moment as a main lateral force resistant component. The shear walls in the middle bear larger shear force in the parallel direction than the walls aside. Due to tension in one wall and compression in the other, two shear walls, which are perpendicular to shearing direction, bear tremendous upsetting moment coming from the perpendicular direction of the face of the wall.

IV. CONCLUSION

The paper presented the challenges in the construction of a 60-meter high statue in Hunan, China. The construction was built on a small base, with both high height-to-width ratio and height overturning moment caused by wind force. The steel-concrete composite shear walls were successfully applied in this project. We analyzed the effects of the main parameters such as height-thickness ratio, span-depth ratio, the thickness of the wall and the grade of concrete on the shear walls by using finite element analysis. The major conclusions are listed as follows:

1. With the increase of span-hight ratio α, the ultimate shear-carrying capacity of composite shear wall and initial stiffness increases, while no significant changes in the distribution of shear force is observed.
2. With the decrease of the thickness steel wall β, the ultimate shear-carrying capacity and initial stiffness of composite shear wall increases with significant changes in the distribution of shear force.
3. With the increase of concrete strength grade and the thickness concrete wall, the initial stiffness and the ultimate shear-carrying capacity increase slightly. The thickness of the concrete wall has little affect on the distribution of composite shear force during elastic deformation, while has significant affect during elastic-plastic deformation.
4. As compared to the other lateral force resisting members such as shear walls composed of simply steel or concrete, steel-concrete composite shear walls are able to stand higher forces caused by overturning moment.
5. The results of the project indicate that steel-concrete composite shear walls are an effective structure to build high constructions with small basis and large overturning moment.

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