Research Article

An Experimental Study on the Lateral Stress of Composite Steel Wall Structure by Using Self-Compacting Concrete

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Composite steel wall structures with concrete have been broadly applied in engineering, and self-compacting concrete with high fluidity is usually employed for the concrete placement of complex structures. Testing mock-up was established to monitor strain and displacement changes of the external steel plate while pouring concrete. The survey data show that the lateral stress was first shifted from rapid growth to slow decay and then get stabilized, which can be referenced to the design and construction of the composite structure module.

1. Introduction

Large steel plate concrete wall composite structure has been increasingly used on-site, and it is now used in a large number of fields, for example, power facilities, mines, fuel storage, urban roads, and bridges [1–4]. The steel plate concrete composite structure is filled with concrete between two steel plates. Steel plate and concrete are linked by shear studs [5–8]. Concrete can effectively restrain the buckling of the steel plate, and steel plates on both sides can effectively control the growth of concrete cracks, thereby improving the anti-deformation ability and ductility of the combination. Because of the complexity of steel concrete, it is hard to manual vibrate, and conventional concrete cannot meet the requirement of its internal self-flow filling. Thus, self-compacting concrete (SCC) has taken its place in engineering practice [9–12].

SCC, as concrete with high fluidity, does not require manual vibration. It can freely flow and fill the wall space under the action of gravity, and it can be fully compacted, and high fluidity also makes the lateral stress generated by SCC different from conventional concrete [12–15]. Over-estimation of lateral stress will lead to an increase in the construction cost, while less frequent estimation may lead to component deformation or structural collapse [16–19]. Many factors affect the result of lateral stress, for example, consistency, consolidation method, concrete temperature, maximum aggregate size, casting height, pouring rate, size and shape of the structure [20–24]. Many scholars work on the mechanism of lateral stress from the theoretical perspective or based on a small-scale experiment [25–28] considering the arrangement rate, slump, structural height, concrete temperature, minimum shape size, and section size. Based on this model, the lateral stress is always lower than the hydrostatic pressure distribution [29–33]. Through tons of experiments, Omran et al. [34] consider that the major reason why the lateral stress of SCC is significantly smaller than the hydrostatic pressure generated by fluids with the same density of concrete. Based on numerous experimental data obtained by different researchers, Teixeira et al. [35] concluded that the prediction model of the maximum lateral stress applied to the vertical form work of the self-compacting concrete. They believe that the maximum lateral stress can be different according to different pouring speeds by different theoretical models. McCarthy et al. [36] studied the effects of self-compacting concrete on the lateral stress of
2 Advances in Civil Engineering

conditions, taking the case of three-story casting as an example, the following lateral stress distribution diagram is illustrated in Figure 1.

2.2. Numerical Analysis Results. The strain and deformation characteristics of the steel plate wall of the structural module during concrete pouring were calculated using the software. Under the assumption of lateral stress distribution as shown in Figure 2, the wall deformation of solid layered pouring was calculated. In this study, the cases of one, two, and three layers of typical pouring were calculated as examples. The change of horizontal strain in the middle of 1-, 2-, and 3-layer continuous casting calculation model is shown in Figure 3:

As shown in Figure 3, under the above lateral stress distribution, the maximum strain calculated is 200 με, and the absolute value of negative strain in ribs is larger than that of positive strain in intercostals. The variation of node displacement with height in the range of 5 m height calculated at different heights is as follows:

It is suggested that under the above lateral stress distribution in Figure 2, the maximum displacement is about 0.85 mm near the height of 1 m during the first 1.8 m layer pouring process and about 1.7 mm close to the height of 1 m during the second 1.8 m layer pouring process. Subsequently, with the pouring of the third 1.8 m layer, the first two layers of self-compacting concrete were successively poured. During gradual solidification and shrinkage, the displacement started to decrease, and the displacements at 2.5 m and 3.5 m heights successively reached the stage peak values of 1.4 mm and 1.6 mm. With the shrinkage of concrete, the displacement of each point decreased gradually. During the continuous pouring of self-compacting concrete, the peak value distribution was slightly different, yet the displacement increased gradually to decrease gradually. It is therefore verified that the whole structure was in a state of elastic deformation.

2.3. Summary of Numerical Analysis. In the case of continuous pouring of 5.4 m (at pouring speed less than 1.8 m/h), the bearing capacity of the modular wall was analyzed numerically. Therefore, the results are as follows:

(1) In this numerical analysis of pouring, the structural model was generally in the state of elastic deformation.

(2) In general, the lateral stress experienced a process of “rapid growth slow attenuation stability” over time. The peak value was affected by pouring height and pouring rate. The attenuation degree was not only affected by the height and rate of pouring but also closely associated with material characteristics. The lateral stress remained stable in the later period.

(3) The variation of the horizontal strain of steel plate over time was similar to the lateral stress in the pouring stage and later period, and the overall change range was within the controllable range.
The variation of displacement was similar to that of lateral stress, yet the change range was small and stable in the later period.

In general, the stress-strain characteristics of steel sheet wall calculated using a numerical method to a certain extent reflect the stress-strain characteristics of steel sheet wall under self-compacting concrete placement, and it is reasonable to some extent. At the same time, however, it is noteworthy that the simplification of some conditions in numerical calculation will bring some errors, which still need improvement in line with the actual situation. Appropriate amendments should be made, and further analysis should be conducted by physical pouring inspection.

3. Concrete Pouring Test and Data Monitoring

Based on the numerical model analysis, the concrete pouring test was performed, and the lateral stress, strain, and displacement were monitored in the pouring process. In the initial stage, real-time monitoring was performed according to the single casting height of 5 m. To find the maximum possible pouring height for safety, the single layer was poured to 5 m and then poured upward with 50 cm layer until reaching the top elevation of 10.5 m. For safety, in the initial stage, real-time monitoring was performed according to a single pouring height of 5 m. After pouring in a single layer of 5 m, it is continuously poured upwards in a single 50 cm layer until the pouring height is 10.5 m. The strain gauges and displacement gauges placed outside the wall were employed to monitor the strain and displacement changes of the steel wall in the pouring process.

16 pressure cells were vertically distributed within a height of 8 meters inside the middle position of the steel plate wall model, and the gap between them is about 500 mm. Three rows of strain gauges were attached on the surface of the model wall (1 column in the ribs and 2 columns located intercostal); 1 strain gauge was arranged on the side; the bottom measuring points were appropriately encrypted.

4. Test Results and Analysis

4.1. Lateral Stress. The variations of lateral stress between the start of pouring and after the end of pouring for another 24 h are shown in Figure 4.

As shown in Figure 4, the shape of lateral stress and time curves can roughly fall into two types: one type exhibits obvious "peak", for example, statistics below 2 m and above 6 m. Its pressure change process roughly shifted from "rapidly increasing to slow end with stable", the peak appeared at about 1 to 2 h after the start of the test, and the lateral stress at the end of the test takes up 70% to 80% of the peak. The other type of curve does not exhibit an obvious "peak", primarily occurring between 2 m and 6 m. Besides, they are relatively stable along with the test to a certain value, and the range of variation is small.

4.2. Horizontal Strain. Figure 5 shows the horizontal strain of steel plate at different heights at typical parts over time during the whole test (Figure 5(b) is the enlargement of the first part of Figure 5(a)).

Figure 5 suggests that in the pouring stage and its following period, the horizontal strain changed very similarly
4.3. Lateral Displacement. The relationship between the displacements of different heights from various parts and the pouring stage over time is shown in Figure 6.

It is suggested that the displacement values of most measuring points were relatively stable. In general, the lateral displacement of 1.3 m height was greater than the displacement value of 0.3 m height. At the same height, the displacement of cell 1 was slightly larger than the displacement of cell 5 and much larger than the broadside cell 10 because of the structure, the form of the constraint, and the rigidity. In addition, similar to the change of the lateral stress and strain, the displacement of cell 1 and cell 5 reached a peak around 1 to 2 h after the start of the pouring. Next, it slightly decreased and then remained stable. However, the displacement of cell 10 still slowly increased at a later stage.

From the test results, the increase in displacement was significantly smaller than the lateral stress and horizontal strain. The pouring rate was regulated as the process begins, and the deformation of the steel sheet can be controlled in a relatively stable interval.

4.4. Analysis of Factors Affecting Lateral Stress Distribution. Figure 7 shows the lateral stress of steel plate when the concrete was poured to different elevations; Figure 8 shows the distribution of steel plate’s lateral stress within 24 h after pouring.

According to the above figures, in the initial stage of pouring, the lateral stress increased linearly. As the concrete continued to be poured, the lateral stress in a certain range of the lower layer no longer increased significantly, and it is no longer affected by the upper layer pouring. In the meantime, the bottom lateral stress started to decay. At the end of the pouring process, the pressure on the upper side increased and had certain effects on the lateral stress in the lower finite depth. After the pouring, the pressure on the other side was basically stabilized except that the pressure on the upper side continued to attenuate.

To further explain the lateral stress distribution in the pouring process, Figure 9 shows several relationships between the lateral stress and the theoretical hydraulic distribution at different elevations.

According to the above Figure 9, the lateral stress loaded on the steel plate was substantially equal to the hydraulic pressure before being concrete poured to five meters height. When pouring concrete up to five meters height (about 1.5 h later), the bottom growth rate was reduced and became less than hydraulic value. At the same time, the upper part is still linear as hydraulic pressure. Subsequently, it was poured upwards with a layer of 0.5 m concrete, and it was found that the shape of the curve changed significantly.

To understand the above, the different sections of the pressure curve are named "hydraulic zone", "transition zone", and "constant zone" from high to low in height. The sum of the ranges of the hydraulic zone and the transition zone is called the "influence depth". The closed pattern and area of the curves from the "hydraulic zone" and "transition zone" reflect the distribution of pressure at different heights between the layers.

For instance, in 6 m diagram, the section height of the hydraulic zone and the transition zone is 2 m, namely, the influence depth is 3.5 m. In the 7.5 m diagram, the hydraulic zone is about 0.75 m, and the depth of influence is about 2.75 m due to the increase in the pouring rate of the layer. In fact, it was not stopped when it was poured to 8 m but was directly poured to the 8.5 m position, so the layer was poured about 1 m of concrete at a time. It is suggested that the hydraulic zone range is increased to approximately 1.5 m, the transition zone is approximately 3.5 m, and the total depth of influence is approximately 5 m. From the above 7.5 m map and 8.5 m map, it can be found that at the same pouring rate, the boundary points between the hydraulic zone and the transition zone are basically the same, namely the hydraulic zone only adds the newly poured part, while the latter transition zone. The range was not only expanded by nearly 1.5 m but also the pressure value of the measuring point in the transition zone increased significantly compared with the former. This reveals that at the same casting rate, the thickness of the single-layer casting will have greater effects on the depth of influence and the pressure value of the lower layer. Due to the limitation of the buried height of the Earth.
pressure box, the distribution of the lateral stress cannot be completely recorded after 9 m.

For instance, in 6 m diagram, the hydraulic zone is from 4.5 m to 6 m, and the transition zone is from 2.5 m to 4.5 m, so the influence depth is 3.5 m. In 7.5 m diagram, the hydraulic zone is from 6.75 m to 7.5 m, and the transition zone is from 4.75 m to 6.75 m, so the influence depth is 2.75 m. In 8.5 m diagram, the hydraulic zone is from 6.75 m to 8.5 m, and the transition zone is from 3.25 m to 6.75 m, so the influence depth is about 5.25 m. Due to the limitation of the buried height of the pressure cell, the distribution of the lateral stress cannot be recorded after 9 m. In fact, the pouring process did not stop when it gets to eight meters height, and it keeps pouring until it gets to 8.5 meters height. From diagram 7.5 m and diagram 8.5 m, we can see that with the same pouring rate, the hydraulic zone only increases with the newly poured concrete, and in this case, it is from 7.5 to 8.5 meters; on the other hand, the transition zone has increased approximately 1.5 m, and also the lateral stress is significantly increased. Therefore, with the same pouring rate, the thickness of one single layer will be a great factor affecting the influence depth and the pressure value of the lower layer.
Figure 7: Curves of lateral stress-concrete heights.

Figure 8: Distribution of lateral stress along with the height at different times.

Figure 9: Continued.
In general, when pouring 0.5 meters each time, the hydraulic zone is basically between 1 meter to 2 meters, mostly about 1.5 meters (the pouring time is about 1.5 h); the transition zone is largely 1.5 meters to 2.5 meters, and the influence depth is basically 3 meters to 4 meters (the pouring time used is mostly 2.5 to 3 h). If the thickness of each casting increases, the influence depth will also increase significantly.

5. Conclusion

When the pouring height and speed were regulated, the combined structure was in an elastic deformed state. However, in the pouring process, the variation of the lateral stress from different elevations was primarily associated with the layer thickness of the newly poured concrete and the average pouring rate (or time interval). In general, the lateral stress experienced a “rapid growth to slow decay and then turned stable” over time. Through this process, some useful conclusions can be drawn for the actual project: first, if the thickness and interval of each pouring are reasonably regulated, continuous concrete pouring can be done on-site as combining structural module; second, the lateral stress of newly poured concrete within 1.5 h is hydraulically distributed, and afterward, the lateral stress of the newly poured concrete is substantially lower than the hydraulic pressure; third, the sum of the range of the “hydraulic zone” and the “transition zone” can be referred to as the “influence depth”, and for structural yielding, the structure will be in a safe state if the “hydraulic zone” is always lower than four meters during the pouring process, and the “influence depth” can be regulated within five meters. To minimize the structural deformation, the initial pouring height and the lateral stress distribution of the later structure should be regulated. The conclusions above can be referenced for the design and construction organization of the steel plate concrete composite wall structure on-site.

Data Availability

There are no available data for this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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