STUDY ON THE INTERACTION BETWEEN FORMWORK SHORING SYSTEMS AND RC STRUCTURES IN A HIGH-RISE BUILDING DURING CONSTRUCTION 2

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ABSTRACT

In the construction process of high-rise building structure, the formwork temporary supports and the concrete structure are considered as a whole. Quantifying the load under the template supports can provide a better reference for the design of the template supports. In order to study the load transfer law between formwork support scaffolds and multi-storey structure, through the installation of sensors at the bottom of formwork supports and the floor slab, the load transfer law of the 3 adjacent formwork supports were monitored for a long time during the construction of high-rise buildings via the high-frequency wireless transmission systems. The main conclusions are as follows: (1) The monitoring data shows that the most unfavourable load occurs when concrete is poured into the upper story, about 1.9 times the axial force generated when concrete is poured into the test floor. (2) The monitoring data has a similar shape which is summed up as an ideal curve of change, 3 times of peak value, 3 times of decline and 1 time of sudden drop. (3)The transfer ratio of load accounts for about 57% ~ 69% of a total load of fresh concrete. (4) Considering the fluid-plastic state of concrete, a correction factor of 1.22 for vertical pole axial force is proposed, and the deviation between the modified simulated value and the measured value is less than 3%.

KEYWORDS

Formwork; Multistory; Shore; Load transfer law

INTRODUCTION

In recent years, the collapse of the formwork temporary supports has been frequent, which has brought serious economic property losses and casualties and caused a bad social impact. Multistory formwork shoring systems are a complex and huge issue, its arrangement method and form changes with the structural loads and its stability capacity and other factors. As a temporary support structure, it has a complex composition of components, various connection joints and many uncertainties.

So study on the template supports are from different angles. Chan et al. [1], Peng et al. [2–6], Yu [7], and Weesner [8] produced many studies on the stability capacity and design method of door-type scaffolds experimentally and theoretically. Reynolds et al [9-12] studied the influence of various components of the formwork scaffolding system. Timothy P Ambrose et al [13-17] monitor the load of shoring systems and propose a monitoring method. Manuel et al [18] propose a calculation method that allows the loads on individual shores to be calculated for each construction phase without having to resort to the use of advanced software. Mosallam, K et al [19] propose a three-dimensional computer model capable of simulating the concrete construction process is developed. The model accounts for the interaction of gravity and lateral loads and can include temporary lateral bracing elements in the supporting assembly. Qing Rong Tang [20] research for mechanism of concrete structure interacting with formwork support by manufacturing 2 test models

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of two-layer and single-span reinforced concrete frame at laboratory, and analysis interaction performance between concrete structure and formwork support and the influence of construction period, curing time of concrete and load on mechanical performance of the formwork support system during the construction period.

We think that formwork temporary supports interact with the building structure to form a time-varying system. The design of multilayer formwork support system is not considered single layer load. There is, therefore, a clear need to carry out more thorough studies on the interaction between formwork shoring systems and RC structures in a high-rise building during construction. It would reveal the load change of the multilayer formwork support system and provide a guarantee for construction safety that carrying out the long-term measurement work of formwork support system.

Engineering Situation

Test high-rise building is located in Qingdao, China. There are 4 floors underground, 25 floors above ground and 2 podium floors. The main building is 96.4m high, which is the frame-core wall system.

The actual measurement of this project involves 11th floor to the 16th floor. The strength of concrete in this interval is: column fc'39.5Mpa, wall and connecting beam fc'31.6Mpa, beam board fc'23.7Mpa, the story height of the test area is 3800mm and the floor thickness is 120mm. It is measured from April 19, 2016, until May 24, 2016, ended in the summer during the test average temperature of 16.5 degrees Celsius. The construction speed of the main structure of the project is 6 or 7 days per floor.
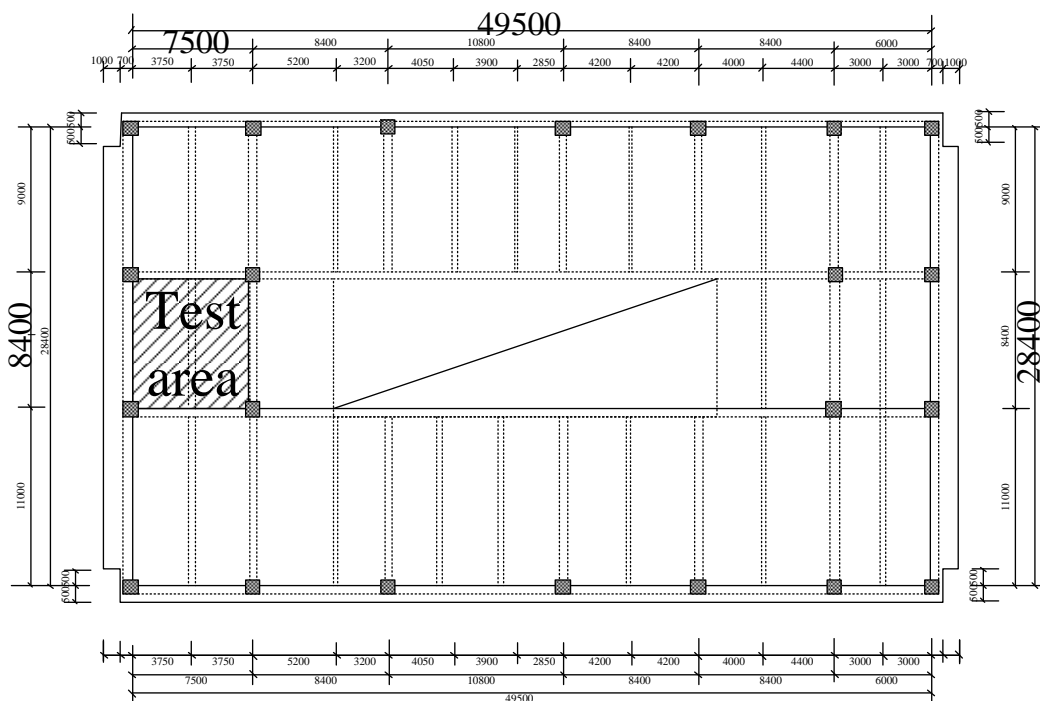

Fig.1 – Plane layout of structure

Measurement Scheme

The Measurement Content

(1)   Monitoring formwork support system pole axial force changes: select the representative site and layout pressure sensor, continuously monitor pole axial force during the construction cycle includes erecting scaffold - setting template - lashing steel - pouring concrete - conservation concrete from 11 to 13 layers;

(2)   Monitoring changes in floor slab stress: select the cross or support at the reinforced part of the larger force to install steel bar sensor, continuously monitor the steel floor tensile force changes during the construction cycle includes erecting scaffold - setting template - lashing steel - pouring concrete - conservation concrete from 11 to 13 layers;

(3)   Monitoring the concrete strength changes in the corresponding floor: Making a multi-group of same condition test blocks (100 × 100 × 100 mm)and pressing a group of test blocks two or three days interval.

Testing point instructions

In this testing, 10 axial force sensors are arranged at corresponding positions of 11th, 12th, and 13th floors respectively, for a total of 30 pieces;2 steel bar sensors are arranged at the 11th,12th floors along the short side of the floors, the measuring point layout plan shown in Figure 2.
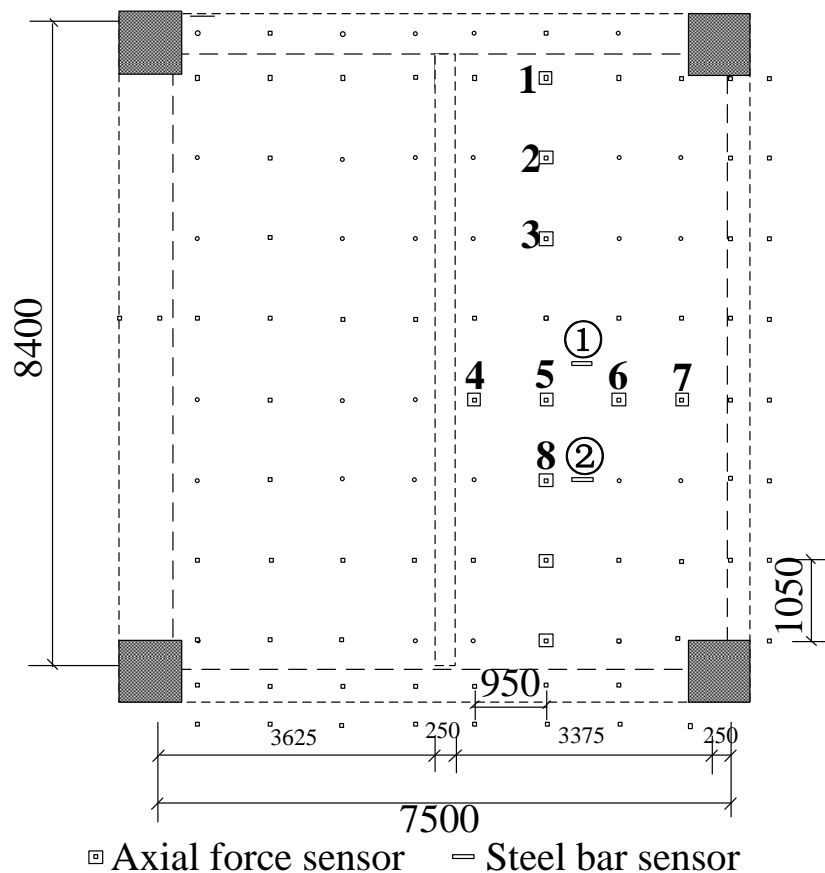

Fig.2 – Arrangement of testing points

Key construction node

The project uses a tubular scaffold with couplers as the template support frame. Tubular scaffold spacing is 950 × 1050mm. In Table 1, the erection scaffold on the 11th floor is regarded as the first day to record the construction of the key construction node.

Tab. 1 - Key construction node

Time（day）	Key events
1	erection scaffold on the 11th floor
2～4	setting template - lashing steel on the 11th floor
5	pouring concrete on the 11th floor
6～10	erection scaffold-setting template - lashing steel on the 12th floor
11	pouring concrete on the 12th floor
12～17	erection scaffold-setting template - lashing steel on the 13th floor
18	pouring concrete on the 13th floor
19	disassembling scaffold and template on the 11th floor
20～24	erection scaffold-setting template - lashing steel on the 14th floor
25	pouring concrete on the 14th floor
26	disassembling scaffold and template on the 12th floor
27～31	erection scaffold-setting template - lashing steel on the 15th floor
32	pouring concrete on the 15th floor
33	disassembling scaffold and template on the 12th floor

Monitoring equipment and installation

The main monitoring equipment and performance are showed in Table 2.

Tab. 2 - Monitoring equipment

name	Introduction
axial force sensors	Vibrating wire axial force sensor, precision is 0.1KN, the range is 20KN
steel bar sensors	Vibrating wire steel bar sensors, precision is 0.1KN, range is 10KN
acquisition system	40 channels, can simultaneously capture 40 sensor data

The installation method:
(1)   Steel bar sensors installation: In order to ensure the test precision, the steel bars to be tested in the slab are cut off, and then both ends of the steel bar are welded and connected to the steel bar, such as Figure 3a. The ends of steel bar sensors should be wrapped with a wet towel before welding to avoid burning the steel bar sensors out due to the over-temperature of welding.
(2)   Axial force sensors installation: The steel plate is placed between axial force sensors and scaffold pole to ensure the centre line of the pole and axial force sensors are in a same vertical line, such as Figure 3b.
(3)   The connection of sensor and acquisition system: After the sensors are installed, the wire of sensors are connected to the collection device, and after the power is turned on, the wireless transmitter inside the collection device can send the received data back to the terminal to complete a collection process, such as Figure 3c.

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a. steel bar sensors installation

b. axial force sensors installation

c. acquisition system

Fig.3 – Installation of sensors and acquisition equipment

The data transmission

The wireless transmission system, which achieves high-frequency non-stop data, is used to collect on-site sensors data in this measure. Acquisition system consists of sensors, acquisition equipment, and a wireless transmitter, remote end (computer) and analysis software, the consists of data transmission system is shown in Figure 4.The acquisition frequency is set to 20 minutes interval in the actual measurement.
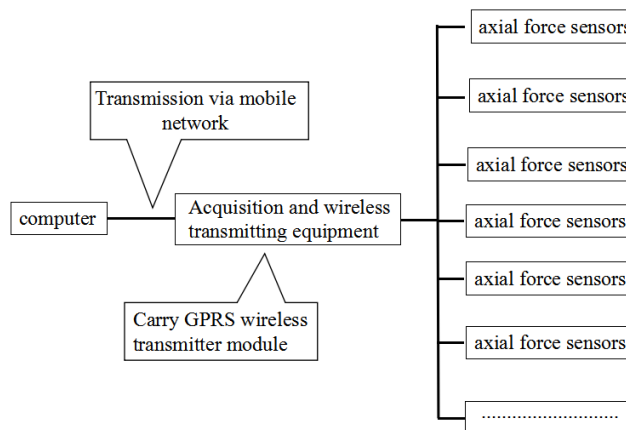

Fig.4 – Sketch map of data transmission

Concrete compressive strength monitoring

The strength and stiffness of concrete is an important variable in the process of load transfer in multilayer formwork support system. In order to monitor the concrete strength in the slab with the growth of age, 40 sets of the same test blocks were placed in the first concrete pouring, and a set of the same conditions test block is pressured every 2 to 3 days to find the average as the representative of the age, the press machine in Figure 5, the representative values are shown in Table 3. Draw the concrete strength growth curve, shown in Figure 6.

Fig.5 – Press machine

Tab. 3 - Strength of same condition test block（MPa）

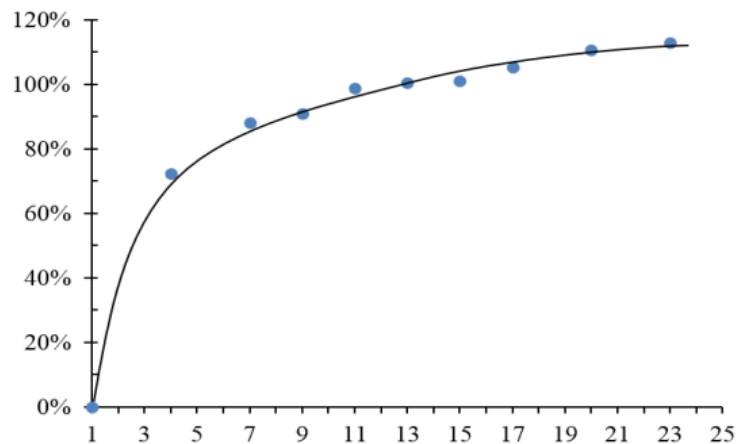| age	3	6	8	10	12	14	16	19	22
$F_{cu,k}$	21.7	26.4	27.3	29.6	30.1	30.4	31.6	33.2	33.9
percentage	72%	88%	91%	99%	100%	101%	105%	111%	113%

Fig.6 – Concrete strength change curve

Results and analysis of the field test

All data, from the axial force sensors, is analysed after the end of the survey to draw a line chart. The axial force changes in the vertical pole are clearly displayed in these line charts. Figure 7 to 9 are summary of all floors of axial force sensors change line chart, Figures 10 to 19 are the change line chart in the axial force sensors of the representative positions for each layer, of which the axial force sensors 1101, 1201, and 1301 are beam-side poles and the others are the under-floor poles.

The uneven force in the vertical pole

As can be seen from the line chart, the arrangement of the spacing of the vertical pole under the floor is the same, but it appeared obvious as an uneven force. The main reasons for this situation are the characteristics of the tubular scaffold with couplers, the specific reasons are as follows:

(1)　The location is different. The axial force of the vertical pole has nothing to do with the position before the concrete has been poured without strength. But structures began to bear the load autonomously as the strength of concrete, then the deflection in the middle of the structure is the largest which causes a greater force of vertical pole near the midspan. For example, the order of the thirteen-layer pole axial force from small to high order is axial force sensors 1304, axial force sensors 1305, axial force sensors 1306, an axial force sensors 1307;

(2)　The tightness of the U-shaped support at the top of the vertical pole is the main reason of the uneven force of vertical pole. If one U-shaped support at the top of the vertical pole is in a state of relaxation, it will cause the adjacent poles to endure larger load. In fact, even if there is only a slight difference between the heights of the adjacent poles and the top of the U-shaped supports, the force exerted on the pole will be greatly affected;

(3)　The degree of tightness of nodes is different, resulting in differences in the lateral transmission of the axis force, so that the force of the pole is uneven.
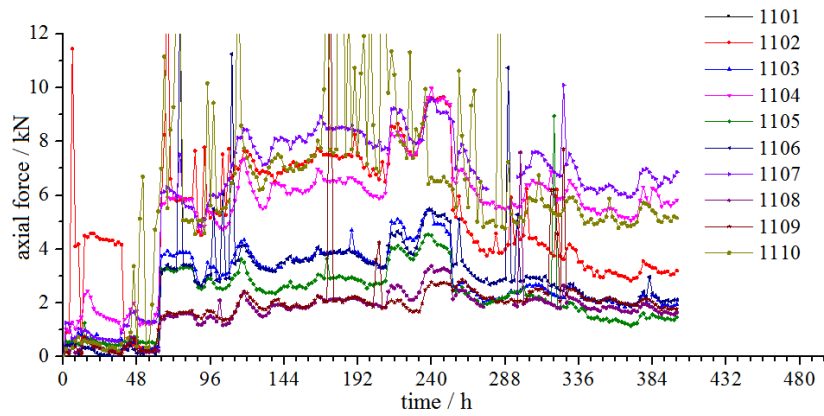
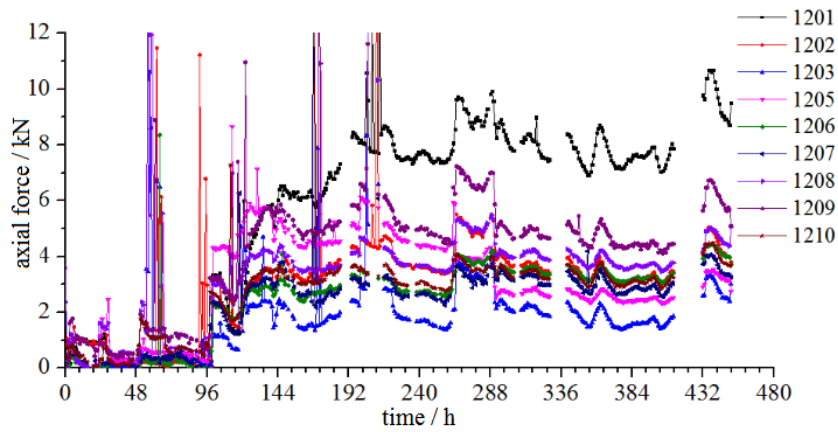*Fig.7 – 11 floor axial force variation of vertical pole*

Fig.8 – 12 floor axial force variation of vertical pole
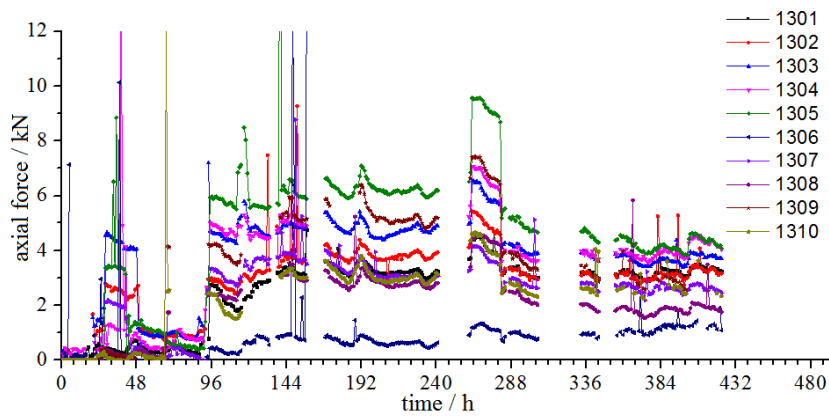

Fig.9 – 13 floor axial force variation of vertical pole
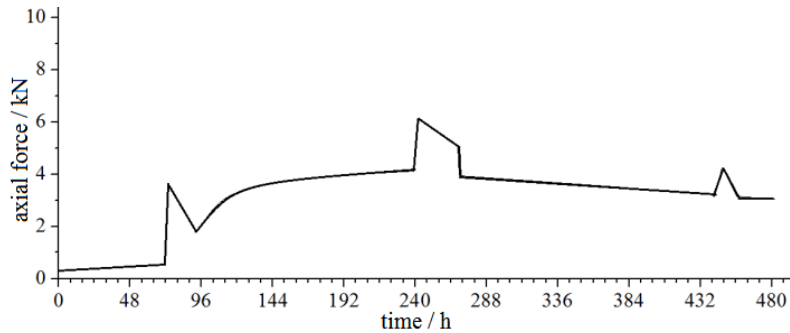
Fig.10 – The axial force of vertical pole ideal simulation figure
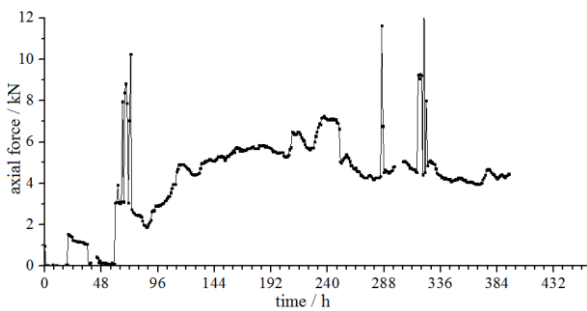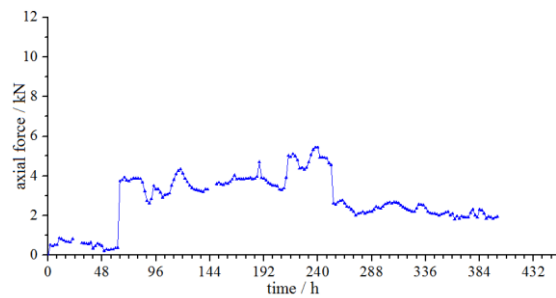

Fig.11 – 1101 axis force variation

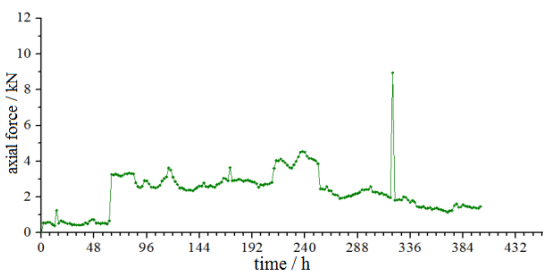*Fig.12 – 1103 axis force variation*

Fig.13 – 1105 axis force variation

Fig.14 – 1201 axis force variation

Fig.15 – 1202 axis force variation

Fig.16 – 1208 axis force variation

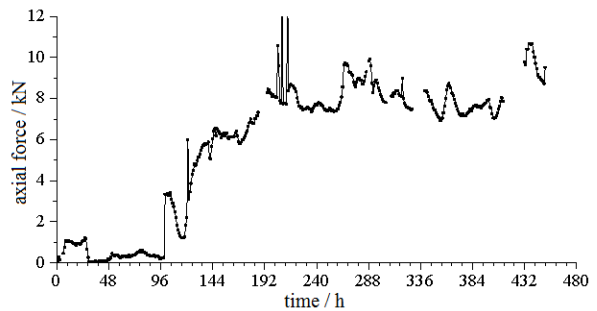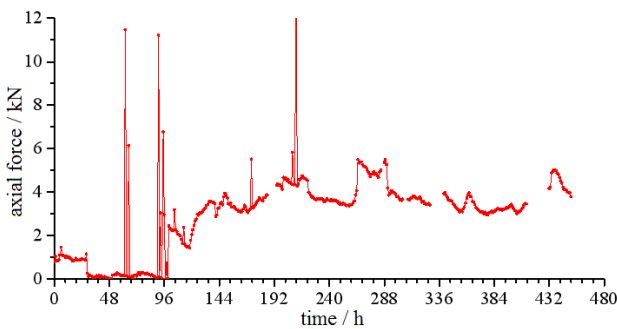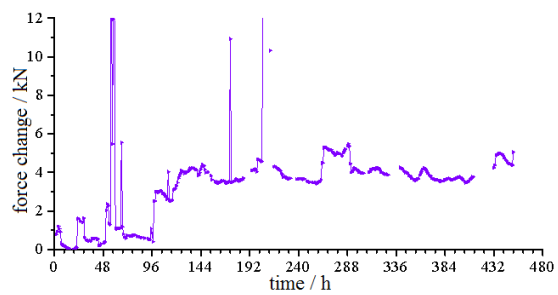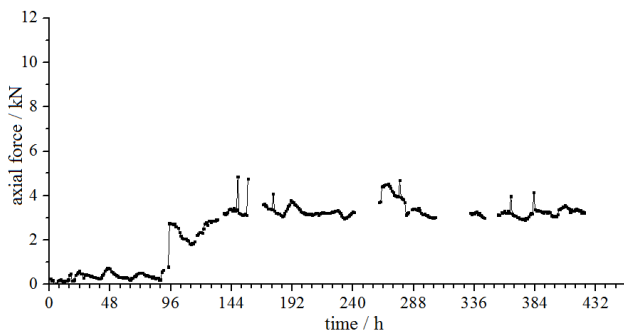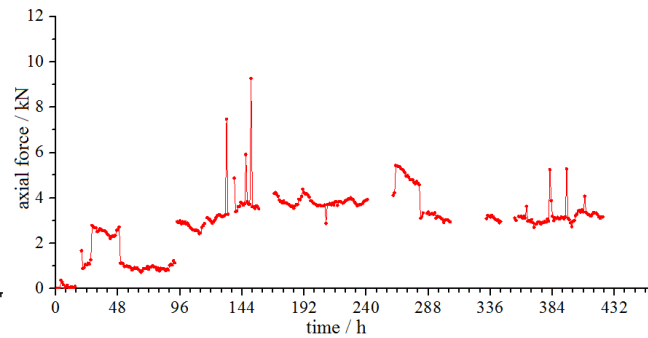

Fig.17 – 1301 axis force variation
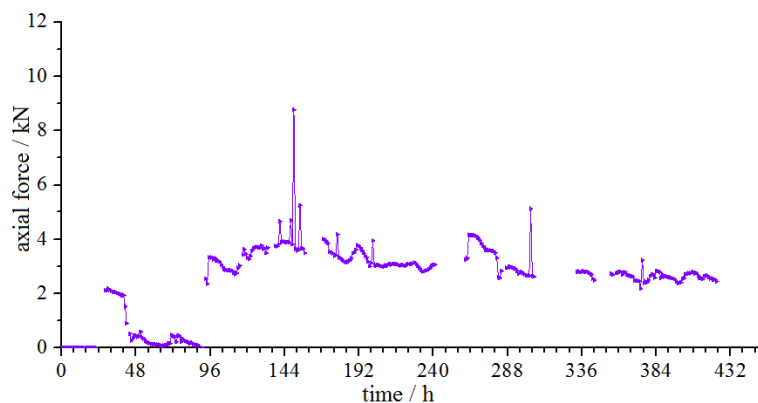

Fig.18 – 1302 axis force variation

Fig.19 – 1307 axis force variation

Analysis of pole axial force change process

From Figures 7-19, it can be seen that the axial force of each pole varies greatly due to the influence of live load, and the influence of live load should be eliminated as much as possible during the analysis. The vertical pole force is not uniform but has a uniform law of variation (Figure 10), the process of change and the reasons are summarized as follows:

Before the first pouring of concrete, the axial force increases slowly and slightly. As the support systems of the formwork are set up gradually, the self-weight of the support systems is increasing. In the non-ideal model, it can be seen that there is a large load fluctuation at this stage, which is caused by the live load.

After the first pouring of concrete, the axial force suddenly increased to about 3kN to appear the first peak, which is caused by the weight of concrete. Horizontal structural members deflect when concrete is poured. With the hardening of concrete, horizontal concrete structural members shrink. The vertical resultant force produced by shrinkage of concrete members is the resultant force of the decrease of formwork supports. The axial force of the pole decreases uniformly at a faster rate. After about 8 hours, the axial force of the pole starts to rise slowly again, because, at this time, the upper formwork support systems began to be set up.

After second pouring of concrete, the axial force of the pole appeared the second peak and then decreased again at a faster rate due to the hardening of the concrete, which is similar to the changing law of the first pouring concrete, however, the change is small. In particular, it should be noted that after a certain period of time, the axial force of the pole has dropped greatly, which is mainly caused by the removal of the formwork support systems under the floor where the axial force sensor is located.

Before the third pouring of the concrete, the axial force of the pole in the process of setting up the formwork support systems did not show the phenomenon of "slow increase",which is similar to the previous two times, mainly because the strength of the upper two floors continued to

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increase and the pole was continuously unloaded, offsetting the increased constant load. After the third pouring of the concrete, there is still a small peak, and then gradually disappear.

(5)   As shown in Figure 11 and Figure 12, comparing the difference of the axial force between the beam-side pole and middle span pole, it is found that the axial force increase between the first and the second pouring concrete is obviously greater than that of the upper formwork support dead weight. This is because as the strength of concrete increases, the stiffness of the slab gradually increases, the force transmission path changes, the beam takes more load, resulting in an increase of the axial force of the beam-side pole.

In summary, the load is shared by all floors, beams and support frame in multi-layer formwork supports system. The axial force has several changes and with the increase of the concrete strength and the process of the construction, the share of the load on the beam and slab and the support frame is also constantly changing. Therefore, the multi-layer formwork supports system is a dynamic integration, the law of force is influenced by a variety of factors. However, the current main calculation method ignores the internal rules of the multi-layer formwork system. It is not advisable to consider only the single-layer formwork in the design and calculation. Through the measurement, we can find that the force transmission of the multi-layer formwork supports system has a regular pattern, which makes it possible to find a more accurate design calculation method.

Quantitative analysis of axial force of support
After statistics and calculation, the axial force of the main pole is shown in Tables 4 ~ 7. Due to the supported layout under the beam is different from the one under the floor, so the data of the pole under the beam is not included.

Load of fresh concrete
The increment of axial force during the first pouring of concrete refers to the difference of axial force before and after pouring concrete, which does not include the self-weight of the formwork support frame and the slab reinforcement, mainly the self-weight of the newly poured concrete. The measured first averaged an increase of the axial force of pouring concrete is 2.80kN, theoretically, the axial force should be 24kN/m3 × 1.05m × 0.95m × 0.12m = 2.87kN, they are very close.

Load transfer
When the upper test floor is poured into the concrete, the concrete of the test floor already has a considerable strength (about 90%), so the load transferred from the fresh concrete is "resisted" by the upper floor and the other part is transferred to the test floor, the statistics passed down the load accounts for about 57% ~ 69% of a total load of fresh concrete.

The most unfavourable load
Statistics show that the maximum axial force of each test layer pole appears when the upper floor is poured into the concrete, and the maximum axial force is 1.9 times the axial force generated when the test floor is poured into concrete. Therefore, in the design of multi-layer formwork support systems, the load of single-layer concrete should not only be considered, but a load of concrete poured from the upper floor to the lower floor should be emphasized. If the design ignores the synergetic effect between the multi-layer formwork support system and the building structure, it will only reduce the safety and reliability of the formwork support system if it is considered as a single-layer formwork support.

Unloading speed
After the first and second pouring of concrete, the unloading speed of the pole is also very fast due to the rapid increase of the strength of the concrete in the initial stage of hardening. According to the statistics, the average unloading speed is about 0.10kN / h. However, considering the continuity of construction, the change of unloading speed in the late stage of concrete hardening and the final residual axial force after unloading cannot be continuously monitored.

Pole axial force residual before demolition

The pole still has an axial force of about 1.6-3.5kN before dismantling, indicating that the support frame still provides some protection to the concrete of the roof immediately before demolition. At the same time, the force support frame of a layer on the test layer is in the second peak descent phase, bearing about 4kN axial force. Therefore, before the support frame is dismantled, the upper floor is still subjected to a large load. At this moment, it is particularly important to ensure the strength of the floor concrete during form removal. If the form removal is too early it may cause concrete cracking, deformation, and other issues.

Analysis of the changes in steel bar tension

The measured results show that the tensile strength of steel bars is small, generally not more than 1.5kN, converted to a stress is 29.85N / mm2, far less than the yield strength of steel bars. In addition, due to the constraint of the formwork support below the test layer, the variation of the steel tension in the key construction nodes is not as sensitive as the axial force of the pole. Even when the lower formwork support was removed, there was no sudden increase in the tensile strength of the steel bar and the tensile force is remained about 1 kN. After the first pouring of concrete, steel bar has a compressive process, which is mainly caused by the pressure of the concrete shrinking during the initial hardening. In general, the variation of steel tension and pole axial force is consistent.
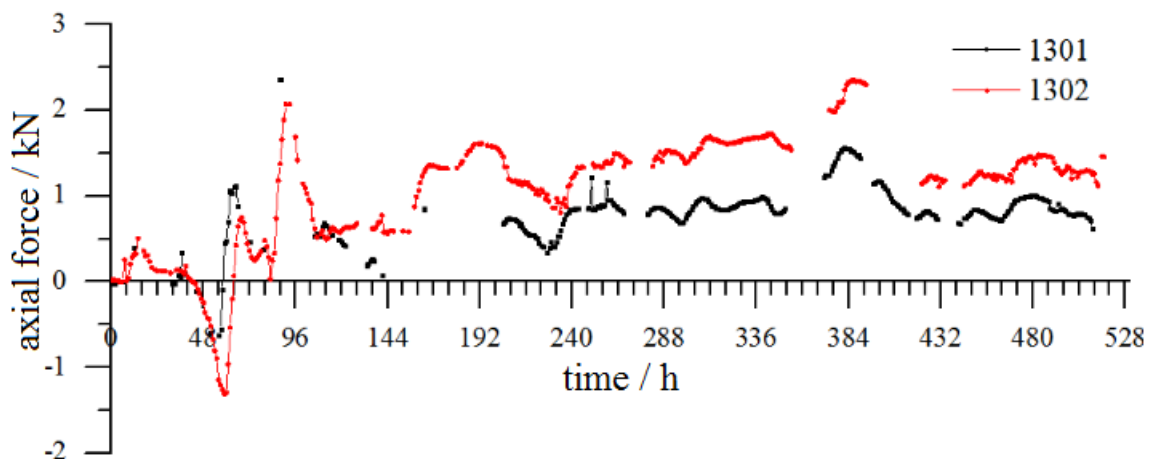
Fig.21 – Change of steel bar

Tab. 4 - Statistics of axial force change of vertical pole

The average value of each measuring point	The increase in axial force when the first pouring of concrete （kN）	Unloading speed （kN/h）	The increase in axial force when the second pouring of concrete （kN）	Unloading speed （kN/h）	The increase in axial force when the third pouring of concrete （kN）	Maximum axial force （kN）	Axial force before formwork removal （kN）
11th floor	2.96	0.16	1.38	0.12	0.55	6.05	1.66
12th floor	2.43	0.10	2.06	0.08	1.68	5.88	3.46
13th floor	3.08	0.06	2.06	0.07	0.53	5.89	2.38
The average	2.80	0.10	1.84	0.09	0.92	5.94	2.50

Tab. 5 - Changes of axial force of each floor after pouring concrete with 14F

	Pole axial force / kN	The increase of axial force / kN	Increase ratio	Age / d	Concrete strength
14th floor	/	3.00	100%	0	0
13th floor	5.89	2.06	69%	7	90%
12th floor	3.96	1.68	56%	14	101%
11th floor	Demolished			21	112%

Tab. 6 - Changes of axial force of each floor after pouring concrete with 13F

	Pole axial force / kN	The increase of axial force / kN	Increase ratio	Age / d	Concrete strength
13th floor	3.58	3.08	100%	0	0
12th floor	5.68	2.06	67%	7	90%
11th floor	3.00	0.55	18%	14	101%
10th floor	Demolished			21	112%

Tab. 7 - Changes of axial force of each floor after pouring concrete with 12F

	Pole axial force / kN	The increase of axial force / kN	Increase ratio	Age / d	Concrete strength
12th floor	2.93	2.43	100%	0	0
11th floor	5.85	1.38	57%	7	90%
10th floor	/	/	/	14	101%
9th floor	Demolished			21	112%

Numerical simulation and analysis

The calculation model is established according to the actual size of the test project. The elastic modulus of concrete for each floor needs to be determined in advance. The elastic modulus of each layer of concrete is closely related to the age. The elastic modulus of concrete can be deduced from the compressive strength of concrete cube according to the formula (1) given in the literature [22], as shown in the Table 8.

$$E_c = \frac{10^5}{2.2 + (33 / f_{cu})}$$

（1）

Tab. 8 - Estimated values of elastic modulus at different ages

Age/d	0	3	7	14	21
F_{cu}/MPa	0	21.7	27.0	30.4	33.9
E_C/10^4 MPa	0.00	2.68	2.92	3.04	3.14

The strength grade of beams and slabs concrete are C30, and that of column concrete is C50. The measured value is input according to the concrete age during modelling. The slabs thickness is 120mm, tubular scaffold spacing is 950 × 1050mm, the diameter of tubular scaffold is 48.3mm and the thickness is 3.6mm, the density of reinforced concrete is 25kN/m³, poisson's ratio is 0.2, and the elastic modulus is input according to Tab. 8. Live loads are not considered in

SAP2000 simulation. The self-weight load of the concrete is simplified to uniform load, which is directly added to the panel of the formwork support system.

Fig.22 – Sketch of the computational model

In the establishment of the finite element model (Figure22), the connection between the vertical poles and the slabs are considered as hinge. The connection between the vertical poles and the horizontal poles are set as semi-rigid node, and the rotational stiffness is 5.5rad/(kN•m).

Figure 23a is a three-dimensional model of SAP2000. The age of newly poured concrete on the top slab is 0 days, the age of the next slab is 7 days, the age of concrete on the penultimate slab is 14 days, and the age of concrete on the bottom slab is 21 days. Relevant parameters are set according to the age of each slab. Figure 23b is the simulation value of the vertical force of each floor. The average value of the vertical force of each floor is compared with the measured value as shown in Table 9.

a. A three-dimensional model   b. Axial forces of vertical poles

Fig.23 – Sketch of the computational model

Tab. 9 - Comparison of measured and simulated values

Items	Pole on the top floor	Pole on the middle floor	Pole on the bottom floor
Simulated Axis Force Mean/ kN	3.41	4.82	2.38
Measured Axis Force Mean/ kN	3.30	5.94	3.50
Deviation range	+3.3%	-19.1%	-32.0%
Simulated Axis Force Mean Considering Stress Redistribution Coefficient of Concrete/ kN	3.41	5.88 （4.82×1.22）	3.54 （2.38×1.22×1.22）
Corrected simulation deviation	+3.3%	-1.0%	+1.14%

It can be found from Table 9 that the accuracy of finite element simulation of newly poured concrete vertical pole on top floor is very high, and the deviation range is only 3.3% compared with the measured data. Similarly, it can be found that after newly poured concrete in the upper layer, part of the load is transferred to the lower layer, and the axial force of the lower column reaches the maximum value of 4.82 kN at this time, which is in accordance with the law obtained from the experimental results.

However, the axial forces of the penultimate and bottom vertical poles of the numerical simulation are quite different from the measured data, with deviations of 19.1% and 32%, respectively. The main reasons for the deviation are that the concrete is still in a fluid-plastic state and there is a redistribution of stress between the support system and the structure. However, when calculating, the vertical and horizontal components are loaded with rigid bodies, and the concrete Flow-Plastic state is not taken into account, resulting in more loads still being borne by the support system. According to the simulation data, it can be seen that the stress redistribution should be taken into account in the shorter age, the stress reduction of concrete members and the increase of the vertical bar axial force. When the axial force of vertical pole increases by about 22%, the deviations between measured and simulated values can be better controlled within 3%.

CONCLUSION

In the multi-layer formwork support system, the support frame and the building structure is an integration. However, construction design for scaffold neglects the interaction between the multi-layer formwork support frame and the main structure. There are obvious deficiencies that make the design for multi-layer formwork support system have a security risk.

The main conclusions are summarized as follows:
(1)   In the multi-layer formwork support system, the load is shared by floor, beams, and support. With the increase of concrete strength and the progress of construction, the proportion of beams and support frame to loads is also constantly changing. Multi-layer formwork support system is a dynamic integration; the law of force is influenced by a variety of factors.
(2)   The stress of the multi-layer formwork support can be simplified as 3 times of peak value, 3 times of decline and 1 time of sudden drop. It is caused by 3 times of concrete pouring, early rapid hardening of concrete and removes the formwork of the lower floor.
(3)   The maximum axial force of each test floor pole appears when the upper floor is poured into the concrete, and the maximum axial force is 1.9 times the axial force generated when the test floor is poured into concrete. Therefore, in the design of multi-layer formwork support systems, the

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load of single-layer concrete should not only be considered, but a load of concrete poured from the upper floor to the lower floor should be emphasized.

(4)   When the upper test floor is poured into the concrete, the concrete of the test floor already has a considerable strength (about 90%), so the load transferred from the fresh concrete is "resisted" by the upper floor and the other part is transferred to the test floor, the statistics passed down the load accounts for about 57% ~ 69% of a total load of fresh concrete.

(5)   After the first and second pouring of concrete, the unloading speed of the pole is also very fast due to the rapid increase in the strength of the concrete in the initial stage of hardening. According to the statistics, the average unloading speed is about 0.10kN/h.

(6)   Considering the fluid-plastic state of concrete, a correction factor of 1.22 for vertical pole axial force is proposed, and the deviation between the modified simulated value and the measured value is less than 3%.

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