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An improvement of a hydraulic self-climbing formwork

Nowadays, self-climbing formworks are commonly used in the construction of concrete buildings with a great height, such as high-rise buildings, silos, and bridge piers. A regular formwork can be improved to have more functions, e.g., the formwork itself can climb to the desired construction site. Climbing characteristics of the formwork as well as opening and closing characteristics of the formwork shell are essential criteria for evaluating the performance of a self-climbing formwork. The effective ones were mentioned in different studies, where most of them were published in patents of countries, e.g., the United States and China. Dissimilar from these studies, this paper presents several improvements for some certain groups to enhance the features of a hydraulic self-climbing formwork. Based on the analysis of the composition and the working principle of the actual climbing formwork types, a new opening and closing method of the formwork shells and a new rail clamping device are suggested. They are applied to design a self-climbing formwork with the shell's working size of 4 m × 3 m. Their load capacity, as well as the flatness of the concrete surface after casting, are assessed. The proposed solutions can result in various advantages, e.g., the shorter initial alignment time, the increase of the quality concrete surface, and the maximal automation for construction operations.

1. Introduction

The self-climbing formwork technology has been extensively used for constructing the cast-in-place reinforced concrete works which have great heights on the world. This advanced construction technology is particularly effective for the constructions whose walls and floors are independently constructed as silos, bridge

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piers, elevator pits, and walls of high buildings. A typical example of the effectiveness of applying climbing formwork on high-rise buildings is the use of the Doka's self-climbing formworks for building Burj Khalifa Tower, Dubai, United Arab Emirates [1]. In addition to pouring concrete to vertical structures, the formwork can be used to construct the structures with the normal maximum inclination of 25°. The difference from the conventional formwork is that the climbing formwork does not have to be erected many times. Additionally, it is not necessary to use a scaffolding system to support from the ground to the site being constructed. Therefore, it makes it possible to speed up the construction progress. Using the self-climbing formwork also increases safety and convenience for employees when working at high altitudes, reduces labor costs, and reduces the uptime of cranes which service during construction. After using the formwork, it can be even fully repossessed, refurbished, and reused for other projects, whose structure has identical or very similar sections [2].

Self-climbing formworks are provided by companies from Korea, China, and Germany, etc. In general, they consist of the following major components (see Fig. 1):

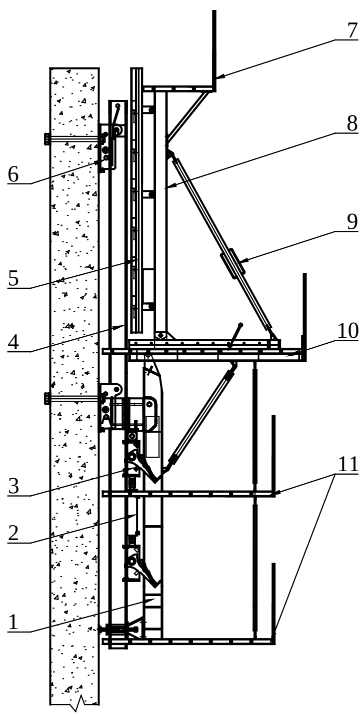


Fig. 1. Structure diagram of a self-climbing formwork. 1. lifting frame, 2. hydraulic system, 3. rail climbing device, 4. rail, 5. formwork shell, 6. climbing shoes, 7. concreting platform, 8. main frame, 9. cross brace, 10. main platform, 11. under platform

- A formwork system includes formwork shell 5 which is mounted on a fixed steel frame and linked to main frame 8 by bolts. The main frame is assembled on main platform 10 by articulated joints, sliding fits or trolleys. The stability of the frame is guaranteed by cross braces 9.
- A working platform system contains concreting platform 7, main platform 10 and the under platforms 11. In the process of working construction, workers stand on the platforms to control the moving operations, adjust the formwork system, pour concrete and finish the concrete surface after pouring.
- A climbing mechanism takes charge of lifting, lowering and hanging the formwork when moving and fixing with the concrete structure which was completed for pouring of the next concrete layer. It comprises lifting frame 1, rail climbing devices 3, rails 4, climbing shoes 6 and hydraulic system 2 which includes hydraulic cylinders, hydraulic valves, hydraulic power pack, etc.

There are various innovative researches which can be applied to general vertical formworks. It can be mentioned here such as the studies related to the calculation of fresh concrete pressure on the formwork shell surface [3, 4] and the influence of the shell surface materials on the lateral pressure [5]. To reduce self-weight while the rigidity and shell surface flatness are maintained, the anti and supporting structures of formwork systems can also be obtained by using the combination of steel staging formats or using aluminum alloy materials.

For self-climbing formworks, current studies focus on two directions. One is the exploitation research to increase efficiency, safety and suitability for specific projects, e.g. the assessment of the effectiveness of using them [6], the safety control during their operation [7], their structure optimization when they are used in the bridge tower with a slope of 30° [8], and the consideration of the formwork vibration reaction caused by wind when working at high altitudes [9]. The other is the studies to improve their features. In this second direction, the scientific works are primarily published by patent offices and focus on their two key activities. With the climbing operation, a wall climbing form hoist [10] was indicated as a device which is capable of climbing on the wall for lifting or lowering the formwork. For a simple climb from the lower stories of concrete structures, some climbing rail extension pieces were created [11]. For the operation of opening and closing the formwork shell, a rack-and-pinion gear could be used to move the shell as described in the patent No. US 2013/0020732 A1. In addition to opening and closing it, the formwork can also be adjusted to construct structures which have an overhanging [12]. This invention is one of the solutions that are commonly applied today.

Overall, climbing formwork system has gone through several generations with features increasingly more complete. A challenge always posed for them is the ability to automate the construction process. To maximize the work of formwork, in this article, the group proposed the other solutions for two regular operations based on the analysis and the evaluation of the structural principles of the kinds of current climbing formwork. These suggestions are applied to the calculation and design for one climbing formwork with the shell dimension of 4 m × 3 m. The application of the solution also helps to improve the quality of concrete surfaces, and the structure of the corresponding formwork ensures rigidity and compactness.

2. A proposed method to improve opening and closing the shell

Opening and closing the formwork shell in the kinds of current climbing formworks can be performed by two methods.

2.1. Method 1 – opening and closing with trolleys

The formwork shell is mounted on the frame and moved away from the surface of the concrete structure as it is sited on trolleys and controlled by rack-and-pinion gears or screw drives (see Fig. 2a). The trolley sometimes is simply a sliding fit. For pouring concrete, workers control the trolleys to move inward, adjust and fix its position. For lifting the formwork to the next concrete pouring location, the trolleys are controlled to move outward, thus the formwork shell is separated from the surface of the concrete structure.

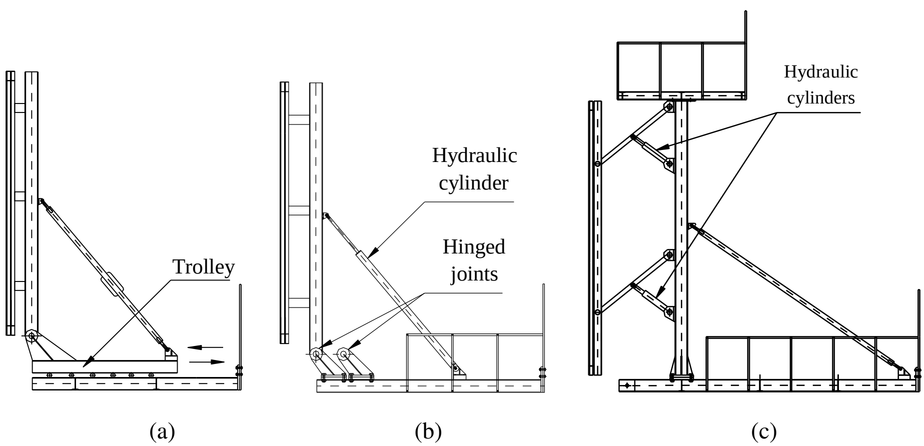


Fig. 2. Method for opening and closing the formwork shell by: a) trolleys, b) hydraulic cylinders and articulate joints, c) hydraulic cylinders and arms arranged parallelogram style

This method has advantages such as a simple operation, the adjustability of the thickness of the concrete, and a low manufacturing cost. On the contrary, its disadvantage is the susceptible stability as the shell and the main frame are placed on the trolleys. The manual adjustment may take a long time to ensure the correct placement of the shell and the uniformity among the shells.

2.2. Method 2 – opening and closing by hydraulic cylinders and articulated joints

The formwork shell is separated from the surface of concrete structure by the hydraulic cylinders. The bottom of the frame is fixed by articulated joints. Its upper part is linked with the hydraulic cylinder rods (see Fig. 2b). In case the size of casted concrete components is necessary to be changed, the frame should be moved to the other articulated joints.

The method's advantages are the high accuracy, the fine coplanarity among the shells, the easy calibration, the highly automated capacity, and the good stability. However, the high manufacturing cost due to the addition of the hydraulic cylinders and valves system is one of its disadvantages. Additionally, the opened extension of the shell at its bottom is narrow, and it is difficult to adjust the thickness of the concrete structure.

Based on the analysis of the above methods, the group proposed the 3rd method to open and close the shell with outstanding features. The method is able to be implemented in practice.

2.3. Proposed method – opening and closing the formwork shell by hydraulic cylinders and arms arranged in a parallelogram style

One formwork shell module is moved inwards or outwards by four parallel hydraulic cylinders and four parallel arms. The arms, the cylinders, the shell, and the frame are linked together by hinged joints. The main frame is fixed on the main platform by bolts and the cross braces. Thus, a completely rigid structure is established by the frame, the platform, and the braces. The arms, the shell, and the frame are arranged in parallelogram form. Hence, the shell will be always parallel to the plane containing the frame. The principle diagram of this method is shown in Fig. 2c.

This method is suggested because of the high accuracy, the fine coplanarity among the formwork shells, the easy calibration, the highly automated capacity, the good stability, and the easy adjustment of the thickness of the casted concrete components. However, the hydraulic cylinder and valve system must be added into the formwork, hence causing the increase of the fabrication cost.

By this method, the current climbing formworks can be improved with the reuse of their available hydraulic power, the frame structures, and the shells.

3. A new rail clamping device

Aiming at the climb on a vertical plane of formworks, the climbing method with rope hoists, cranes, and hydraulic cylinders system can be applied.

The climbing method with the hydraulic system has superior characteristics compared to other methods. By this method, a regular formwork has been developed to become a self-climbing formwork. The use of cranes for lifting the formwork is unnecessary. Therefore, the construction height may be unlimited. Nowadays this method is commonly applied to construct high rise constructions. It includes two types:

- The first type: hydraulic jacks are used for the climbing formwork. Here, odd and even hydraulic jacks designated by symbols 1 and 2 in Fig. 3, respectively, are attached to the concrete wall, which is poured in advance, by anchors. In the lifting process, the even hydraulic jacks lift and hold the formwork while the odd ones are released from the corresponding anchors. After the even jacks finish their upward stroke, the rods of the odd ones are pulled back maximally. The odd jacks are then fixed with the other anchors and the even ones are released from the corresponding anchors. Being performed repeatedly in this way, the formwork is lifted to the desired location.

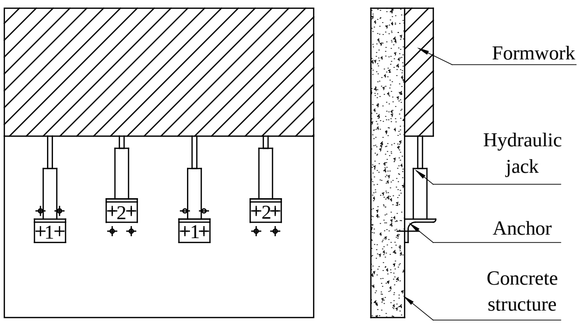


Fig. 3. Principle of the lifting process of formworks by hydraulic jacks with a parity type

- The second type: Hydraulic cylinders and rails are used to lift the formwork. By this method, a cylinder has the functions of both the even and odd jacks as described above. Dissimilar to the first type, the cylinder can work continuously and spend less time for mounting or removing. To achieve it, the links between the cylinder and the rail must be special clamping devices. They can be set up to the cylinder which has one one-directional action in formwork lifting process and one reversely directional action in rail lifting process, although the cylinder includes both forward and backward strokes. The method has a lot of advantages such as the decrease of the number of cylinders by 50%, a short climbing time, a compact formwork, and a simple attachment with the concrete construction. However, aforementioned, this formwork type has to use the special rail clamping device. Fig. 4 shows one frame lifting cycle of a self-climbing formwork which uses manual-operated rail clamping devices. To move the formwork to the next working location, the performance of several frame lifting cycles and rail lifting cycles is necessary.

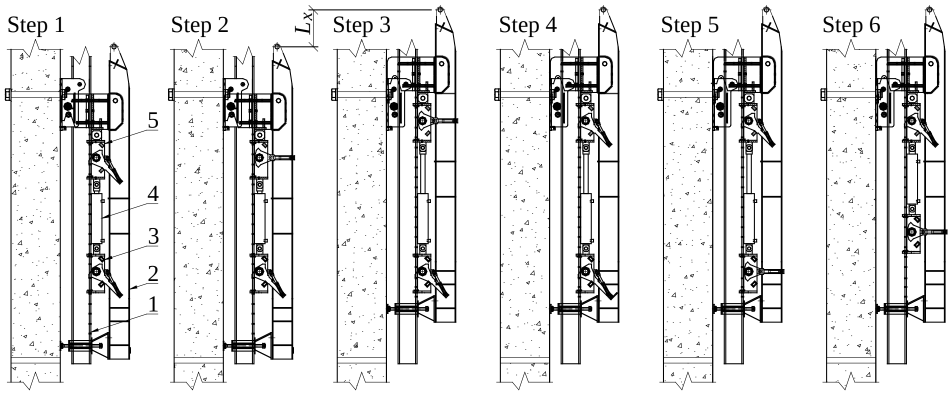


Fig. 4. A lifting cycle of the lifting frame. 1. rail, 2. lifting frame, 3. under rail clamping device, 4. hydraulic cylinder, 5. upper rail clamping device

(a) The frame lifting cycle consists of six steps. Step 1: All rail clamping devices are closed. The lifting frame is hanged on the rails by the clamping devices, i.e., the rails are fixed on the concrete structure by anchors. Step 2: Open the upper clamping devices. Step 3: The pistons of the cylinders are pushed up. The formwork is lifted with a journey of L_x while remaining on the rails. Step 4: Close the upper rail clamping devices. Step 5: Open the under ones. Step 6: The pistons are shrunk. Thus, after ending the cycle, the lifting frame is lifted by an elevated journey equal to the stroke of the pistons.

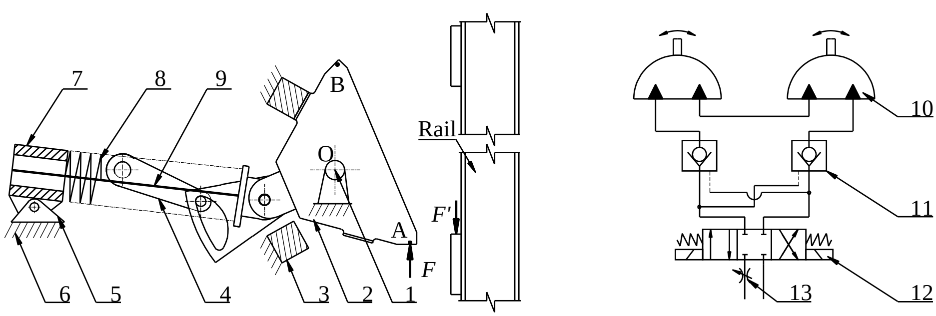
(b) The rail lifting cycle: After ending the frame lifting process, the lifting frame is fixed on the concrete structure by climbing shoes. The cycle includes six steps. Step 1: All rail clamping devices are closed. Step 2: Open the under clamping devices. Step 3: The pistons of the cylinders are pushed down. Step 4: Close the under clamping devices (in the opposite direction to their closing direction in Fig. 4). Step 5: Open the upper clamping devices. Step 6: Perform similarly to step 6 of the frame lifting cycle. Here, the rails are also pulled up by a journey equal to the stroke of the pistons.

For example: To achieve the formwork lifting height of 3 m in one concrete pouring turn, and use the cylinders which have piston strokes of 50 cm, it takes six lifting journeys of the lifting frame and six lifting journeys of the rails. The number of the opening and closing turns for each clamping device is 12.

Therefore, to reduce manual actions for opening and closing, the clamping devices are innovatively designed to each device as a one-way transmission. Then, operators will set up the working direction of each clamping device. Here, the directional setting times for each device in a formwork lifting process is two turns.

In another report [10], a hydraulic cylinder was used to change the direction of each clamping device and the formwork was simply and conveniently controlled during lifting. Based on our previous results, one self-climbing formwork with the shell size of 4 m × 3 m was suggested as the criteria indicated in [13] and [14]. Here, in this study, the group proposed a new clamping device which is more compact than the one in [10].

The structure diagram of the clamping device and its hydraulic control circuit are introduced in Fig. 5a and Fig. 5b, respectively. The device is simulated as shown in Fig. 6. Because clamp housing 6 of the device has a cleft, it can slide along the rail. In the working process, anchor 2 interlocks to the lug of the rail. To keep the rail or the lifting frame, the orientation of the anchor is set by the spring 8 which is always compressed. The working direction of the spring is determined by inclined shaft 9. The shaft can slide along the circular cleft of shaft button 7. Lid 5 fixed on clamp housing 6 is linked with button 7 by an articulated joint. According to the status of the device shown in Fig. 5a, the anchor can only support force F applied to its surface at point A. The direction of the supporting force of anchor 2 can be altered, i.e., the anchor can support the pressing force at point B which is inversely directional to force F. To achieve this purpose, shake bar 4 must be counterclockwise rotated with a certain rotation angle. Then the fixed lug on the bar impacts on anchor 2. Shaft 9 is shaken upward. The anchor is moved to the other position where anchor 2 presses down on bearer 3 because the spring is always compressed.



(a) (b)

Fig. 5. The new rail clamping device: a) the structure diagram of the clamping device; b) a hydraulic circuit for controlling rotary actuators. 1. horizontal shaft, 2. anchor, 3. bearer, 4. shake bar, 5. lid, 6. clamp housing, 7. shaft button, 8. spring, 9. inclined shaft, 10. hydraulic rotary actuator, 11. pilot-operated check valve, 12. directional valve, 13. variable throttle valve

The shake bar is turned by a certain angle by one of rotary actuators 10. Controlling and holding the shaft of the actuator at a certain position are performed by directional valve 12, variable throttle valve 13 and pilot-operated check valve 11.

The supporting force direction of the anchor can be also changed manually. It can also be performed by creating a torque at shaft button 7. Accordingly, it can be shaken around the articulated joint in the desired direction.

The clamping device and the hydraulic control system can have a small size. Additionally, the closing and opening performances can be automatically operated

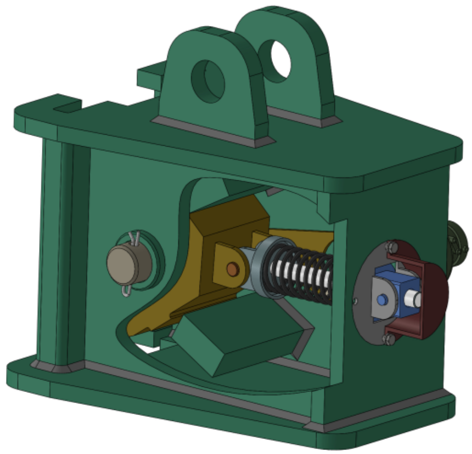


Fig. 6. 3D simulation of the rail clamping device

while the device moves across the fixed lugs of the rail. It results in the time saving for closing and opening the device. Moreover, the formwork on the concrete structure can remain safe for a long time without the impact of the pressure loss of the hydraulic system. For this reason, the adjustment of the mechanical system is unnecessary. Instead, the operational worker can control the hydraulic system without moving to the various positions of the devices.

4. Calculation result

The proposals in the article were applied to design a self-climbing formwork with the shell's working size of 4 m × 3 m. Its 3D view is shown in Fig. 7.

The tests of the stress and the displacement of the elements in the formwork structure were carried out. During the test process, the following load combinations were considered.

Combination 1: It does not work

$$1.1(G + G_h + 0.5q_f + q_w), \tag{1}$$

Combination 2: It works normally

$$1.1(G + G_h + q_f + q_w + q_v + q_b + q_c), \tag{2}$$

Combination 3: It works with the maximum wind load

$$1.1(G + G_h + q_f + 3q_w + q_v + q_b + q_c), \tag{3}$$

Combination 4: It does not work with the maximum wind load

$$1.1(G + G_h + 0.5q_f + 5q_w), \tag{4}$$

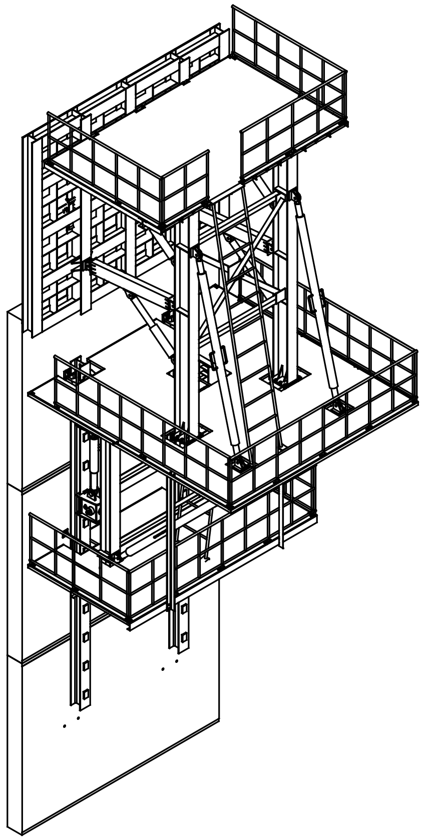


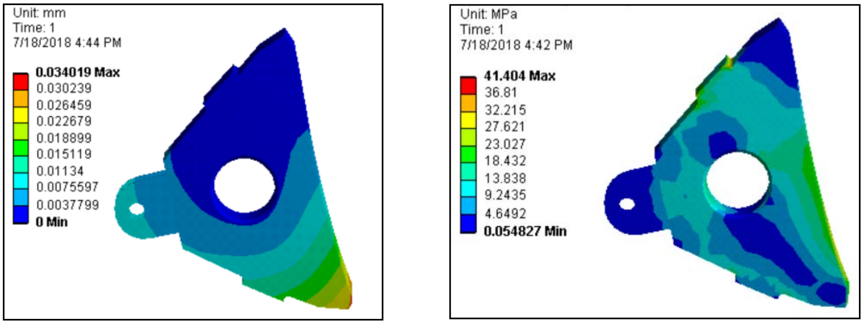
Fig. 7. The hydraulic self-climbing formwork with the shell's working size of 4 m × 3 m

where G is the gravity load of the structure, G_h is the gravity load of the hydraulic system, q_f is the load caused by equipment, materials and person on the working platform, q_w is the wind load, q_v is the load caused by the concrete vibrator, q_b is the load caused by the concrete pouring process, and q_c is the horizontal pressure of the cement concrete.

The results of the tests ensure the requirements according to the standard [13]. Two main elements of the rail clamping device have the values of the stress and the displacement when they support the maximum load as in Fig. 8 and Fig. 9.

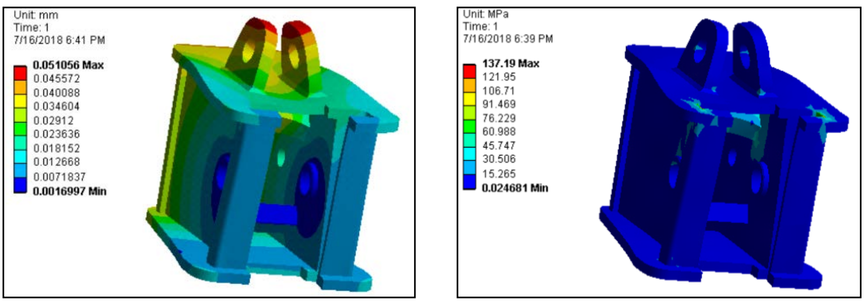
The maximum stress values that appear in these elements when working under the most severe conditions are less than the allowable stresses of structural steel used in formwork making. Similarly, their maximum displacement values are small. These parameters indicate their safe and secure working.

Considering the concrete pouring process with the most unfavorable loading conditions, the horizontal displacement perpendicular to the concrete surface of the shell is quite large. To overcome that disadvantage, in the first erection, the main



(a) (b)

Fig. 8. The values of stress and displacement of the anchor



(a) (b)

Fig. 9. The values of stress and displacement of the clamp housing

frame is adjusted forward (towards the concrete structure) of 0.2°. The displacement of the shell surface after the pouring concrete process is investigated through three vertical lines and three horizontal lines on it. Fig. 10 and Fig. 11 show the displacements of the points in the lines, respectively.

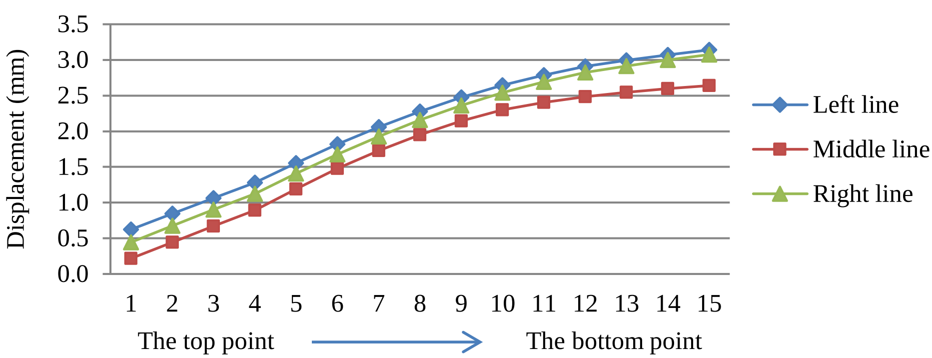


Fig. 10. Investigating the horizontal displacement of the shell by the height

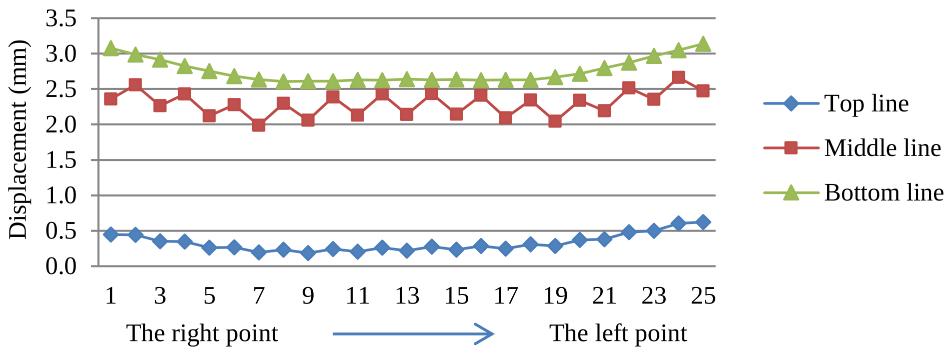


Fig. 11. Investigating the horizontal displacement of the shell by the length

According to Fig. 10 and Fig. 11, the shell is exposed at its bottom and its middle. This result is consistent with the deformation principle of the structure. The concrete surface shaped by the climbing formwork has concave and convex zones. That is an inevitably occurring phenomenon in the concrete pouring process that uses formworks to form the surface of the concrete structure. Compared to the standards [15] and [16], the above results meet the flatness deviation requirements.

5. Conclusions

A challenge always posed for self-climbing formworks is the ability to automate the construction process. To improve the automatic level of climbing formworks, the group suggested the solutions for two regular operations. They include the climbing operation and the operation of opening and closing the formwork shell.

The proposals showed outstanding advantages, such as reduced execution time, the increased quality of casted concrete surface, the safety in operation, the reduction of labor, and the maximal automation of the working processes of the formwork.

The rigidity of the formwork structure directly influences the flatness of the concrete surface after casting.

The climbing process of multiple formworks, as well as the closing or opening process of various formwork shells, can be carried out simultaneously.

These solutions can be applied either to improve the available climbing formwork or to manufacture a new one.

The application can be made individually or simultaneously on a self-climbing formwork.

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