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Technology Research on Aluminum Reduction Cell Pre-Stressed Shell

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Abstract

This paper puts forward a new aluminum reduction cell shell technology, specifically a pre-stressed shell. The technology was developed in order to solve the breakage of aluminum reduction shell caused by large deformation. The work is based on pre-stressing technology research and application in the field of steel structures. By pre-stressing the shell cradle, the technology significantly improves the cell structural performance, increases structure safety, reduces materials consumption and is beneficial to prolong the cell life. This paper introduces the design method (force analysis and experimental research), detailed measurements of the pre-stressed shell and gives the application example.

Foreword

The stress system of aluminum electrolysis cell shell is composed of cradle, shell and horizontal shroud, among which the cradle is the most critical stress component. The cradle bears mainly thermal expansion force and horizontal force due to sodium adsorption related expansion of lining materials, all of which are transferred to the shell via the side plates. Under the current operating status of the shell, large horizontal deformation and even tearing of the steel angle of the cradle happens frequently. Domestic and overseas scholars have made improvements and optimization of the design and structure of the cradle, but these generally have high cost or little effect.

To solve this problem, Guiyang Aluminum and Magnesium Design & Research Institute (GAMI) present an aluminum reduction cell pre-stressed shell technology, which improves cell structural performance, and greatly reduces steel consumption of the shell by adding a pre-stressing device and pre-stressing on the traditional cradle. Currently pre-stressed steel structures are more generally applied in the building construction area with big spans and heavy loads. The pre-stressed cell shell is a bold attempt to apply a pre-stressed steel structure to industrial equipment. This technology has been applied in the 160kA cell line of Chalco Guangxi Smelter. The horizontal deformation of the shell was less than that of the comparison cell constructed at the same period and the steel consumption was reduced by about 15%.

This paper is to introduce basic structure, technical principle and application conditions of this technology.

Technical principle

Basic structure

The shell is pre-stressed by adding an “anchor”, “oblique pre-stressing tendons” and “horizontal pre-stressing tendons” to the traditional cradle, as shown in Figure 1. At construction, weld first the end bearing on the cradle, and then fix the pre-stressing tendons on the bearing by bolt and pre-stress the tendons through tightening the bolts. Except for adding the pre-stressing devices, the manufacture of the pre-stressed shell is exactly the same as that of the ordinary cell shell, and the required pre-stressing tendons are purchased easily and manufactured simply. The required pre-stressing force is not very large, so the force can be applied on the pre-stressing tendons manually or by electric torque wrench, which has reliable precision and can be applied safely on a production site.

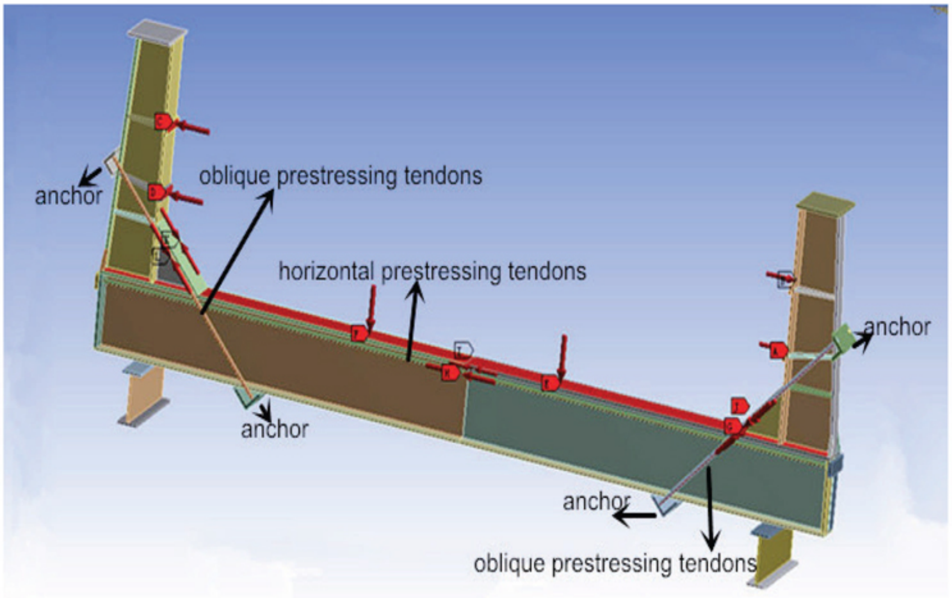

Figure 1 Basic structure of pre-stressed cradle

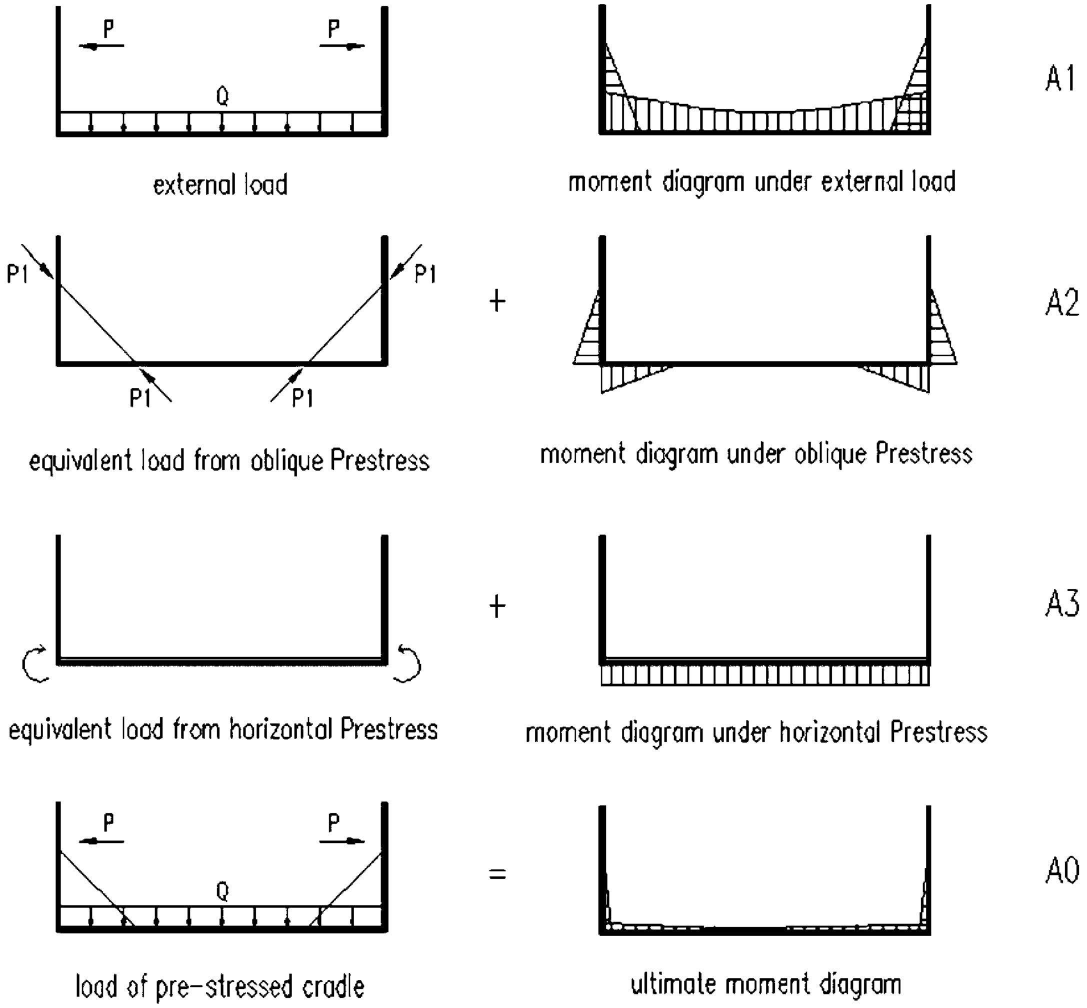

Figure 2 Technical principle diagram of pre-stressed cradle

Technical Principle

First apply stress to the tensile area of the cradle component so as to pre-stress it. The size and distribution of the stress will partially or completely offset the stress of the cradle under load so as to decrease stress amplitude, increase cradle rigidity and reduce deformation of the cradle. The pre-stressing action effects are opposite to the action effects from external load as shown in Figure 2. A1 is the moment diagram of the cradle under external load with cradle under tensile stress; A2 is the moment diagram of cradle under oblique pre-stress with the outside of the cradle corner under tensile stress; A3 is the moment diagram of the cradle under horizontal pre-stress. One group of inwards bending moments are produced due to the eccentric action of horizontal pre-stress on the bottom beam, thus the outside of the bottom cradle is also under tensile stress. A0 is the ultimate moment diagram of pre-stressed cradle under external load, A0=A1+A2+A3.

From Figure 2, the bending moment on the cradle has been obviously reduced. The main reason is that the pre-stressing transfers the bending moment of cradle to axial force of the pre-stressing tendons, and the component is subject to fully axial force, which is the optimal stress state. The pre-stressing tendons used a fine threaded bar with tensile strength of 1080MPa, which is much higher than that of mild steel bar. By pre-stressing, stress is transferred from the mild steel material to the high strength materials to take full use of the material property. For design of pre-stressed cradle, its allowable stress can be indicated as the following equation:

$$\sigma_H = \sigma_0^H + \sigma_1^H \leq f$$

$$\sigma_0^H = -\frac{M_0}{W_j} - \frac{N_0}{A_j}$$

$$\sigma_1^H = \frac{M_1 - M_1'}{W_j} - \frac{N_1'}{A_j}$$

$$\sigma_H = \frac{M_1 - M_1' - M_0}{W_j} - \frac{N_1' + N_0}{A_j} \leq f$$

σ_H-component stress of pre-stressed cradle

σ_0^H-component stress due to pre-stressing

σ_1^H-component stress due to load

M_0-counter moment due to pre-stressing

M_1-bending moment on cradle due to load

M_1'-Counter moment of pre-stressed tendon internal force on cradle due to stressing

N_1'-Axial force pre-stressed tendon internal force on cradle due to stressing

W_j-Net sectional resistance moment of cradle

A_j- Net section area of cradle

f- Allowable stress of cradle steel

Experiment

Component experiment

For this test, two cradle components were manufactured, i.e. old-fashioned cradle and pre-stressed cradle. Compared with the old-fashioned cradle, the pre-stressed cradle had reduced cross section areas for vertical wall and beam, with weight only being 63.7% of the old-fashioned cradle weight. The cradle was stressed by hydraulic jack installed on a reaction frame and with a force sensor at the end to record the actual stress magnitude. The horizontal stress was applied symmetrically at both sides of the cradle. The vertical stress on cradle was simulated by a heavy distributed load. The cradle was placed on the I beam steel stands to simulate the boundary conditions of an actual working cell. Refer to Figure 3 for details.

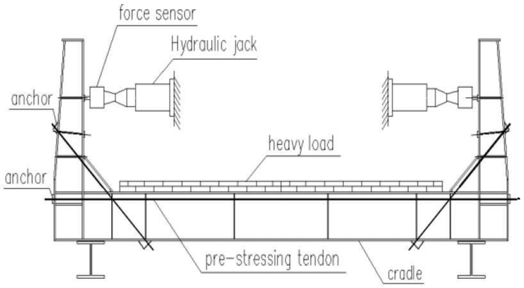

Figure 3 Actual stressing option schematic diagram

Resistance strain gauges were arranged intensively in the cradle bottom area with greatest beam stressing or bigger deformation, and sparsely in the other areas, such as near the stands. Due to the symmetry of structure and stresses, the strain gauges were arranged symmetrically. To know the integral deformation of cradle, the side wall and bottom beam of cradle were arranged uniformly with electronic dial displacement indicators. Refer to Figure 4 for details.

To apply pre-stressing, the end was fitted with a pre-stress pedestal as shown in Figure 5. The pre-stressing was achieved with a car type jack.

N_0-axial force on cradle due to pre-stressing

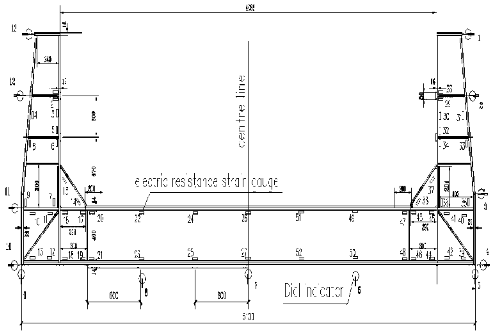

Figure 4 experimental measuring point arrangement

To get the tensile stress of the threaded steel tendon, the end of the threaded steel was installed with a strain pressure sensor for real-time monitoring. To facilitate installation of the strain pressure sensor and transfer of jack stress, a round steel pipe was used as a sleeve as shown in Figure 6.

Figure 5 Pre-stress pedestal

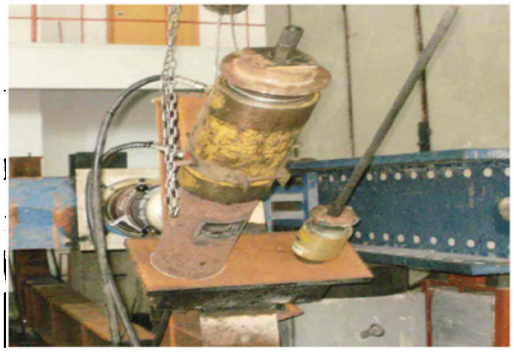

Figure 6 Pre-stress tensile device

As per cradle stressing conditions, the tensile load of a single pre-stressed tendon was defined as 5 tonnes. To ensure stress balance of the pre-stressed tendons on both sides during tension process, the loads on the pre-stressed tendons were not applied in one step but gradually. The strain pressure sensor was used to monitor actual tensile value on the tendons during tension.

The old-fashioned cradle was stressed gradually and strain and deflection were monitored during the test. The cradle kept good stability initially during stressing, but with increase of stress, the stability became poor. When the load reached about 35 tonnes, the jack stress became unstable indicating that local yield had happened in the component. With continuous increase of load, the welded connection between cradle and support cracked with a loud brittle noise. The deflection at the mid span kept increased far beyond the dial indicator measuring range. At this time the load could not be applied and was stopped. By observing the test component, it was found that the connection weld between the right oblique ribbed plate of the cradle and the bottom profile steel beam had cracked. A large amount of 45 degree oblique cross cracks (as seen in Figure 7) had appeared in the bottom profile steel beam location adjacent to the corner, and the final measured ultimate load was about 54 tonnes.

Similarly to the old-fashioned cradle, the strain and stress of pre-stressed cradle was in linear relationship during the primary stressing stage. The cradle kept good stability during continuous stressing but with increase of stress, the stability became poor. When the load reached about 30 tonnes, the jack could not maintain load. With increase of stress, the connection weld between cradle and support cracked noisily. The deflection at mid span kept increasing, far beyond the dial indicator measuring range. By further stressing the component, it was observed that the vertical deformation at bottom profile steel beam increased dramatically, horizontal cracks appeared at the bottom right of cradle (as seen in Figure 8), and the final measured ultimate load was about 51 tonnes.

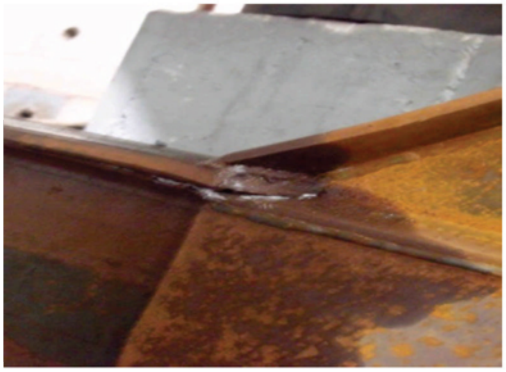

Figure 7 Old-fashioned cradle breaking

Figure 8 Pre-stressed cradle breaking

The test results showed that the ultimate strength of the pre-stressed cradle was equivalent to that of the old-fashioned cradle but with far less steel consumption, as shown in Table 1.

Cradle Type	Breaking load (tonnes)	Weight (kg)
Old-fashioned cradle	54	978
Pre-stressed cradle	51	623

Table 1 Cradle breaking load comparison

By statistics using the cradle strain and deformation conditions, the following curves were obtained: Load-strain curve of cradle corner (Figure 9) and Load-deflection curve of cradle top (Figure 10).

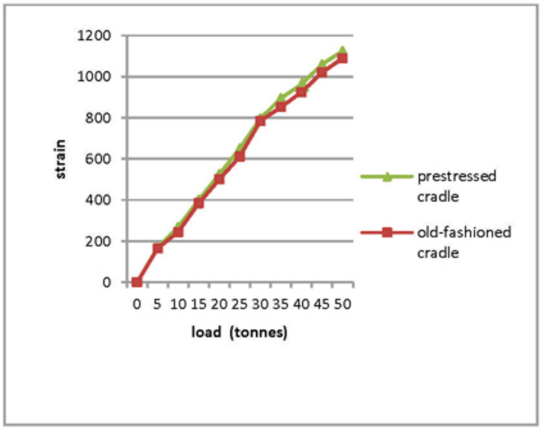

Figure 9 Load-strain curve of cradle corner

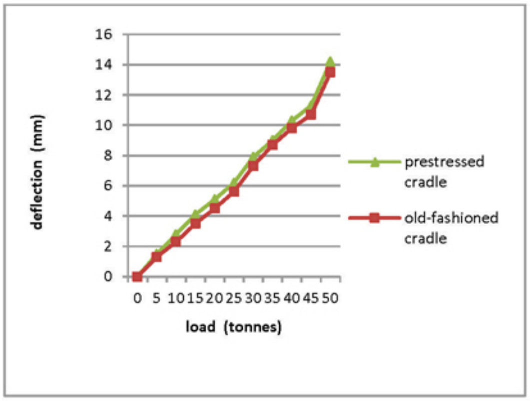

Figure 10 Load-deflection curve of cradle top

It can be seen from these figures that the strain and deflection at the same positions for pre-stressed cradle and old-fashioned cradle, under same loading conditions, are very similar. By pre-stressing, the stressing condition of the cradle corner is clearly improved and the deformation of cradle is also effectively controlled. It is therefore proven that pre-stressing can greatly reduce steel consumption under the same stress conditions and provides good economy.

Simulation analysis

Due to limitation of the test conditions, the impact of temperature on pre-stressed cradle stressing characteristics was not tested. Temperature is one of the key factors influencing shell stressing conditions. With increase of temperature, the impact on structure is obvious. Due to their location, the temperature increase of the pre-stressed tendons is lower than that of cradle so the cradle deformation due to temperature change is also reduced by the pre-stressed tendons, and the tensile stress of tendons is increased. Integrating a variety of effects, finite element analysis has been done on stressing and deformation of 160kA pre-stressed cradle with and without temperature conditions. The design for a 160kA pre-stressed cradle was optimized and reduced steel consumption to 79.8% that of the old-fashioned cradle. The specific analysis results are given in Table 2.

Item	Without considering temperature	Considering temperature
Horizontal deformation of cradle top (mm)	4.1	6.7
Vertical deformation of cradle mid (mm)	2.5	4.9
Tensile load of pre-stressed tendons (kN)	133.8	153.0
Maximum Von Mises stress (MPa)	107.0	130.0

Table 2 Modeled effect of temperature on the cradle

It can be seen from Table 2 that under the actual complicated temperature conditions, the tensile stress of pre-stressed tendons increases with temperature increase. The deformation and maximum equivalent stress of the cradle are greater than those under no temperature consideration, but all can meet application requirements of shell operation and have enough safety margin.

Industry application

This technology has been applied to the 160kA cell line of Chalco Guangxi Smelter (as seen in Figure11)

Figure 11 160kA Pre-stressed cell shell of Chalco Guangxi Smelter

The pre-stressed shell saves 18% steel compared with the original shell. It has operated safely for 2 years with good operating performance, meeting operating requirements and with deformation figures all lower than those of the old cell shell constructed at the same period. The pre-stressed shell is simple to manufacture and is effective. It has no impact on normal operating and various process targets.

Conclusions

The pre-stressed shell technology improves structural performance of aluminum electrolysis cell and reduces construction investment and maintenance cost. Taking the 390 kt/a cell line as example, the application of this technology can save about 2300 tonnes of steel while ensuring enough safety margin for the structures. It also provides effective control of deformation and is beneficial to cell life.

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