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Improved nonlinear analysis method and application of construction mechanics for steel structure

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ABSTRACT

The forming of a structure is a process during the construction, and the loads are applied to the structure step by step along with the construction sequence. The stress state and deformation mode of structure during construction stage are different than the design stage. Based on the characteristics and applicability of a few existing analysis methods of construction mechanics for steel structure and according to the positioning principles of components of steel structure in the actual projects, this study aimed to develop an improved nonlinear analysis method to accurately predict the mechanical changes of structure during the construction process. This method named birth and death element of local configuration constraint is put forward to solve the defect, which is the "drifting" of death element in the direct birth and death element method. It had been applied in the construction mechanics simulation and analysis of the main tower of the Heshi Stupa in Famen Temple during the construction process. The analysis results by the improved method had guided this project successfully. This has indicated that the improved method is an effective analysis method of construction mechanics for steel structure.

Keywords: Construction mechanics; nonlinear analysis; birth and death element method; positioning principle; steel structure.

INTRODUCTION

The traditional design theories of structure only analyze the structural response under different load conditions and combinations during the usage phase of buildings; the results of analysis are the safety guarantee of building structure (Liu et al., 2007). This means that the analysis of structure in design stage depends on the complete structural model. However, a building from the construction stage to the final completion stage has experienced a number of different stages; each stage has different structural configuration and stress patterns.

According to traditional design theories of structure, the structural analysis models of buildings are set up and loaded by one-time applying. On the basis of mechanical models of the structure, the calculation and analysis have begun. However, in practical engineering, structural components are installed according to the construction sequence. The forming of structure is a process during the construction, and the loads are applied to the structure step by step along with the construction sequence (Jiping et al., 2010). So the stress state and deformation mode of structure during construction stage are different than the design stage (Tian et al., 2011). In the past, for a long time, due to the limitation of calculation methods and design theories, structures of buildings were usually simple and regular. For example, the layout of structure, plane or vertical, was regular, the height of building was low, or the structural form of building was not complex. Under these circumstances, the influences of the construction process were insignificant for the structures and could be ignored. So the traditional design theories did not influence the safety of structures and the normal function of buildings.

In recent years, with the development of structural analysis technology and materials science of steel, a large number of new complex steel structures have been designed and built. The application of steel structure is more and more wide, and the buildings of steel structure are higher in height, larger in span, and more complex in structural style. As a result, mechanics analysis and research of the construction process are becoming more and more important. The influences of construction process on these complex steel structures cannot be ignored. The traditional design theories are not applicable to these structures; otherwise, it would lead to structural safety accidents or would not meet the requirements of the normal function of buildings. Therefore, the influences of the construction process on structures must be analyzed by construction mechanics simulation methods of complex steel structure (Case et al., 2014; Agkathidis & Brown, 2013; Hajjar & AbouRizk, 2002; Kanemitsu et al., 2001). According to the result of analysis of construction process, the countermeasure can be considered during the design or construction stage, the construction scheme can be optimized, the safety during construction process can be ensured, and the normal function of buildings can be performed perfectly after the completion of structures.

At the present stage, some analysis methods of construction mechanics are adopted to solve the mechanical problems in the construction process. But the methods have some defects in the application of the actual building projects. For example, the most common methods in commercial finite element software are step-by-step modeling method of multi-stage linear superposition and direct birth and death element method. The defect of step-by-step modeling method of multi-stage linear superposition is that it cannot be adopted to analyze the problem of geometric nonlinearity; that is to say, when it is used to analyze the structure of complex shape, it will lead to an error. The direct birth and death element method, which can be adopted to analyze the problem of the geometric nonlinear, is usually to be used in the construction of bridge engineering. The positioning principle of structural components of bridge engineering is different than building engineering. This method will make mistakes if it is used directly in the steel building engineering. So an improved nonlinear analysis method of construction mechanics for steel structure must be established to solve those problems.

THE SUMMARY OF ANALYSIS METHODS OF CONSTRUCTION MECHANICS

Construction stage is a process involving time (Wang, 2000; C. Q. Li, 1994). The mechanics analysis of construction process belongs to the category of construction mechanics, which is a new interdisciplinary science that has been developed by the combination and intersection of mechanic's theory and civil engineering practice. The research objects of construction mechanics, such as the geometric parameters, physical parameters, and boundary parameters, are all functions of time. It is a four-dimensional mechanical problem coupled with time and space (Cao, 2001; Cruz et al., 1998). So the structure analysis in the construction stage has been changed from traditional there-dimensional mechanical problem to four-dimensional mechanical problem, which increases the time variable. The key mechanical problems coming from the construction of the large complex engineering are how to predict and control the internal force and deformation of the structure in construction process (Guo et al., 2011; Liu & Guo, 2007). To solve such problems is mainly according to the construction scheme to track and analyze the whole mechanical process of construction of the structure. This method can determine the changing process of internal force and deformation of the structure reasonably and accurately during the construction process and provide the guidance and reference for the design and construction (Liu et al., 2007). At present, the common analysis methods of construction mechanics contain step-by-step modeling method of multi-stage linear superposition, direct birth and death element method, and nonlinear step-by-step modeling method, and so forth.

Step-by-step modeling method of multi-stage linear superposition

For buildings of simple structural forms, when the influence of the material nonlinear and geometrical nonlinear factors can be ignored, the analysis method of linear elastic construction mechanics step-by-step modeling method of multi-stage linear superposition can be used (Zhuo & Dong, 2003). This method requires the making of structural analysis models of every construction stage step-by-step. Namely, the internal force and displacement of each construction stage are the linear superposition, which is the sum of the value of internal force and displacement in a previous construction stage and the value in the current construction stage. Because the factor of geometric nonlinear cannot be considered, the step-by-step modeling method of multi-stage linear superposition is used only to analyze the simple structure. The illustrations of analysis methods of design stage and construction stage are shown, respectively, in Figure 1 and Figure 2.

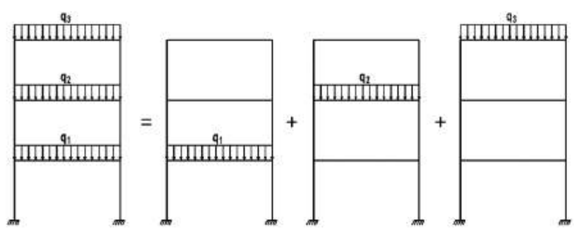


Fig. 1. The analysis method of design stage.

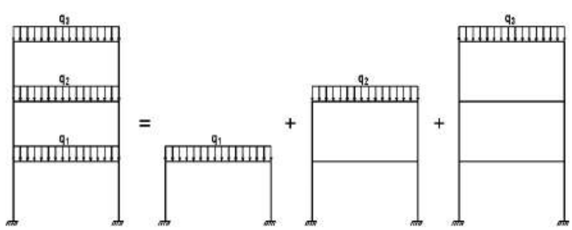


Fig. 2. The analysis method of construction stage.

Direct birth and death element method

The basic principle of birth and death element technology

The removing or adding of material in the finite element model can be simulated by “killing” or “activating” the selected elements; this method is called birth and death element technology (Ye et al., 2016; Mengzhu et al., 2015; Parka & Choia,2009). The “birth” or “death” of elements is not really adding or removing elements in the finite element model. When the element required to “death” in finite element analysis, its stiffness matrix will be multiplied by a minimum factor; at the same time, its mass, element load, damping, specific heat, and other similar effects will be changed to zero, and the strain of elements will be changed to zero.

The analysis process of “birth” element is an inverse process of “death”. It means to reactivate the killed element, that is, to remove the minimum factor in the stiffness matrix of the death element. When the death element is activated again, its element load, mass, damping, specific heat, and so on will restore the original value.

The implementation of direct birth and death element method in the analysis of construction mechanics.

According to the fundamental principle of birth and death element method, it can directly simulate the growing process of elements in structure. The construction process of structure is the installation process of structure component, namely, a process in which structure elements develop from nothing to complete a structure according to a certain construction sequence over time. Direct birth and death element method means to make mechanics analysis in the construction process by using birth and death element technology directly. There is an example that a cantilever beam is installed by cantilever construction method. In this example, the process of the direct birth and death element method can be illustrated.

(1) The finite element model of cantilever beam structure is established according to design configuration. The cantilever beam is divided into three parts, and the installation method is cantilever construction. So the construction process can be divided into three stages: (a) hoisting the first part of beam according to design configuration; (b) hoisting the second part of beam into the position of the tangent line after the installation of the first part of beam; (c) hoisting the third part of beam into position of the tangent line after the installation of the previous two parts of beam. The whole construction process is shown in Figure 3. P2, P3, and P4 are construction loads.

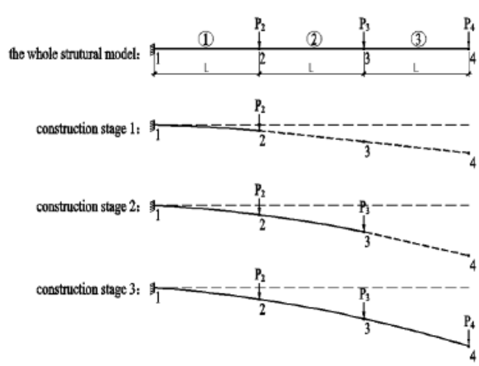


Fig. 3. The cantilever construction method of a three-part cantilever.

(2) All elements are “killed” before the analysis of construction process; namely, the stiffness matrix of all elements is multiplied by the minimum factor, and the node load array is set to zero.

(3) Making the analysis of the first construction stage, the first part of beam will be activated with removing the minimum factor in the stiffness matrix of element ① and restoring the node load P2. The rest of the parts of the beam are still in a state of «death».

(4) Making the analysis of the second construction stage, the second part of beam will be activated with removing the minimum factor in the stiffness matrix of element ② and restoring the node load P3 on the base of the analysis of the first construction stage. The third part of beam is still in a state of «death».

(5) Making the analysis of the third construction stage, namely, making the analysis of the completion stage, the third part of beam will be activated. The last part of beam is installed with removing the minimum factor in the stiffness matrix of element ③ and restoring the node load. Thus, all the parts of beam are activated.

The characteristics of direct birth and death element method

Some characteristics and limitations about direct birth and death element method in construction mechanics analysis can be extracted from the above example.

(1) The finite element model of the whole structure can be established in one time. The installation process of structure components can be simulated by activating elements step by step according to a certain construction sequence after killing all the elements. This modeling method is easy to be achieved.

(2) The influence of material nonlinearity and geometric nonlinearity can be coupled in the analysis process of direct birth and death element method. This method can make nonlinear analysis.

(3) There is a question that the death element will have corresponding “drifting” phenomenon following the deformation of birth element in using direct birth and death element method. As shown in Figure 3, when the first part of beam is activated in the first construction stage, the element stiffness matrixes of the inactivated death element ② and ③ are multiplied by the minimum factor. So the stiffness contribution of the death elements to the analysis of the first construction stage can be ignored; namely, the death elements have no impact on the analysis of birth elements. But death elements in the analysis process of structure exist always. They will be affected by the birth elements. For example, the death elements will make corresponding displacement following the deformation of birth elements and meet the deformation coordination conditions at the common boundary with the birth elements. The death elements shown by the dotted line in Figure 3 are the “drifting” configuration. In the analysis of the second construction stage, death element ② will be activated on the “drifting” configuration, which happened in the first construction stage.

(4) Because of the “drifting” phenomenon of the death element, direct birth and death element method has some limitations on the application of construction mechanics. That is, the components of structure must be installed in the “drifting” configuration of death elements; otherwise, it could not simulate and analyze the mechanical state of structure correctly in the construction process. So it is usually to be used in the construction of bridge engineering.

Nonlinear step-by-step modeling method

Nonlinear step-by-step modeling method is a method in which the finite element model of each construction stage must be established, respectively, according to the actual construction process, considering the nonlinear factors. It can simulate the mechanical changes of each construction stage correctly (Liu, 2008; Liu & Guo, 2008; Guo & Liu, 2008).

Because of using the nonlinear step-by-step modeling technology, the finite element models of every construction stage are established separately. The element stiffness matrix of uninstalled components does not exist in the whole stiffness matrix. So the finite element model of the new structural components of each construction stage can be established according to the actual installing configuration. This method can remove the defect that is brought by the “drifting” of direct birth and death element method. The new components of each construction stage can be installed in the configuration that you want rather than being installed in the “drifting” configuration. The step-by-step modeling method of the multi-stage linear superposition mentioned in the previous section is the linear form of the step-by-step modeling method, and the nonlinear step-by-step modeling method mentioned in this section is the nonlinear form of the step-by-step modeling method.

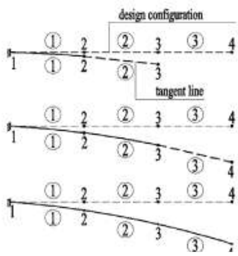
For nonlinear step-by-step modeling method, the finite element model of each construction stage must be established according to the real construction configuration of the current stage. The uninstalled components do not exist in the analysis model of the current construction stage. For the different construction stages, the size of the stiffness matrix of construction mechanics analysis is changed. After the analysis of each construction stage, the solver of finite element will exit, and the resulting analysis data, which usually includes the information of stress and deformation, must be extracted. The resulting analysis data of the previous construction stage will be read during the modeling process of current construction stage. After applying the load and boundary conditions of current construction stage, the analysis can be run. The process will be circulated until all the construction stage analyses are completed. Because this method needs multiple modeling and manual intervention to complete analysis, it is more complicated and tedious than the direct birth and death element method. The calculation amount of this method is very large.

At present, nonlinear step-by-step modeling method is rarely used in practical engineering. The main difficulty is the low modeling efficiency.

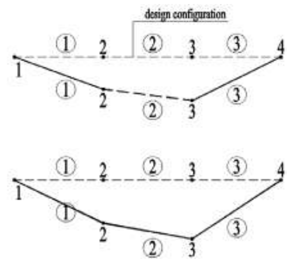
THE POSITIONING PRINCIPLES OF STRUCTURAL COMPONENTS INSTALLATION

In the process of steel structure construction, the configuration of installed structure under the construction load of new components is always changing constantly. The new component will be installed on the current configuration of the installed structure. In construction mechanics analysis, the starting node coordinates of new installed components must be constructed based on the current configuration of structure, which was installed at a previous construction stage, and cannot directly use the node coordinates of the design stage. Otherwise, this would be a large impact on the structural analysis of the subsequent construction stage (Zhang et al., 2004).

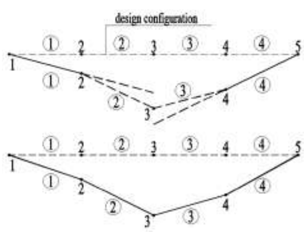
Therefore, a new component of structure needs to be installed on two basis points in each construction stage. One is based on the current configuration of the installed structure; that is, the basis point is the common node of new component and the previous installed component. The other is based on the positioning principle of the new node of the new component; namely, the other basis point is the installation node on the other side of the new component. The positioning principles of structural components in construction must be constructed before installation. There are usually three positioning principles in bridge construction (Xiang, 2001). This paper also puts forward a new positioning principle 4, which is often used in the construction process of steel structure, as shown in Figure 4.



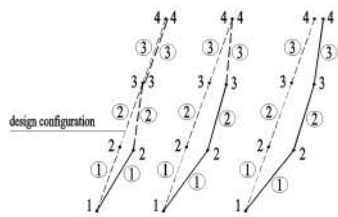
a) The first kind of positioning principle



b) The second kind of positioning principle



c) The third kind of positioning principle



d) The fourth kind of positioning principle

Fig. 4. The positioning principles of structural components in construction.

(1) The first kind of positioning principle is that the new component is installed in position of the tangent line at the end of the previous installed component. As shown in Figure 4(a), member ② is installed at the end of member ① ; member ① has been installed according to design configuration and produced deformation under the construction load; member ② is installed in position of the tangent line according to the current configuration of member ①. The positioning method of member ③ is the same as that of member ②. This is the aforementioned location method of the cantilever construction.

(2) The second kind of the positioning principle is that the new component is installed between the two previous installed components. As shown in Figure 4(b), member ① and member ③ have been installed according to the design configuration and produced deformation under the construction load; member ② is installed in position of the straight line between nodes 2 and 3 according to the current configuration of members ① and ③.

(3) The third kind of positioning principle is that the two new components are installed between the two previous installed components. As shown in Figure 4(c), member ① and member ④ have been installed according to the design configuration and produced deformation under the construction load; member ② is installed in position of the straight line between nodes 2 and 3;

member ③ is installed in position of the straight line between nodes 4 and 3. Node 3 position is at the middle point of the straight line between the end points of the tangent line at the end of the previous installed members ① and ④.

(4) The fourth kind of positioning principle is that the new component is installed according to the configuration of design or a given configuration. As shown in Figure 4(d), member ① has been installed according to design configuration and produced deformation under the construction load; member ② is installed in position of the straight line between nodes 2 and 3 according to the current configuration of member ①. The position of node 3 is at the point of the design configuration (or a given configuration). After the installation of this construction stage, members ① and ② will produce new deformation under the construction load. According to the same positioning principle, member ③ is installed.

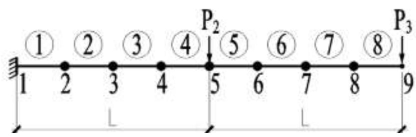
In the four positioning principles, 1 to 3 are used commonly in the application of the bridge engineering. Because the three positioning principles are in line with the activated conditions in which the components are installed on the «drifting» configuration of the direct birth and death element method, the direct birth and death element method can be used to simulate the mechanical changes of the construction process. The fourth positioning principle consists with the actual installation mode of steel structure in building engineering. Using the design configuration as positioning principle of the new installation node of components in the construction process is easy to be implemented and can form a standard of unified control and acceptance. But due to the influence of «drifting», direct birth and death element method will simulate the construction process incorrectly when the fourth positioning principle is adopted in the construction process. So it cannot be used directly.

BIRTH AND DEATH ELEMENT METHOD OF LOCAL CONFIGURATION CONSTRAINT

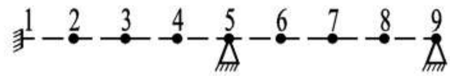
The basic principle of this method

The fourth positioning principle requires a new node of installed components to locate according to the coordinates of design configuration. On this basis, this paper puts forward an improved nonlinear analysis method of construction mechanics for steel structure named birth and death element method of local configuration constraint. The main idea of this method is to apply constraints to a part of nodes of uninstalled «death» elements in order to control the «drifting» of «death» element. The «death» element will be activated on the specified installation position of the corresponding construction stage correctly according to the requirements of the fourth positioning principle. Here, an example of the two-part cantilever beam being installed according to the fourth positioning principle is adopted to illustrate the basic principle of birth and death element method of local configuration constraint.

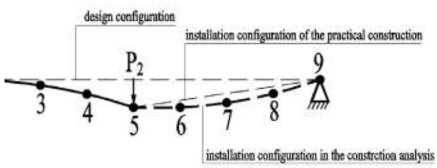
A cantilever beam is divided into two installation parts. In order to improve the accuracy of the finite element analysis, each installation part is divided into four elements. The finite element model of this cantilever beam includes eight elements and nine nodes, as shown in Figure 5(a). Firstly, all elements of this cantilever beam are killed, and the key nodes, which are nodes 5 and 9, are constrained in the vertical direction (see Figure 5(b)). The key nodes are usually the common points or the end points of the installation components, also called installation configuration control points. In the analysis of construction stage 1, the ①~④ elements of the first installation component are activated, the construction load P2 is applied on node 5, and the constraint on node 5 is removed at the same time (see Figure 5(c)). Due to the constraints of partial key nodes, the deformation of "drifting" of dead elements is different than the direct birth and death element method. «Drifting» configuration is shown in Figure 5(c).



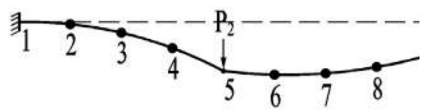
a) The whole FEA model of structure



b) Killing all elements and constraining the key nodes



c) Construction stage 1



d) Construction stage 2

Fig. 5. The method of birth and death element of local configuration constraint.

Figure 5 shows that a «drifting» occurs in «death» element (see the dotted lines). Because of the constraint on the key nodes, the «drifting» configuration has been controlled well; thus, «drifting» configuration is very close to the actual installation configuration and can ensure the second installation component of the cantilever beam to be activated in the relatively correct installation position (see Figure 5(c)). Using the birth and death element method of local configuration constraints can simulate component installation of each construction stage correctly in the construction process. Although there is a little difference in the unconstrained nodes for the reason of «drifting» with the actual installation configuration, this difference, whose value is very small, will not be transferred and accumulated by this method. So the "drifting" of the birth and death element method of local configuration constraints can be controlled within a certain range, and the calculation accuracy can meet the engineering requirements. So this improved nonlinear analysis method solves the problem of the "drifting" defect of the direct birth and death element method and can be used to simulate the construction process correctly of steel structure in building engineering.

The implementation of this method in construction mechanics analysis

The analysis procedure of construction mechanics based on the birth and death element method of local configuration constraints is as follows:

(1) First of all, the whole finite element model of the structure needs to be established according to the design configuration.

(2) The construction process is divided into several construction stages (or called construction step) according to the actual construction scheme. Because the construction of the building is a continuous process, the construction process must be discretized in the analysis of the construction mechanics; the finer the division of the construction stage, the more precise the result of analysis and the larger the calculated amount. So the construction process must be divided reasonably. The main change of structure in the construction process must be reflected in the construction stages. The construction stage, which contains big changes of construction, should be subdivided in the installation process. The discretization of construction process can not destroy the continuity of the construction process as a whole.

(3) Kill all elements of the structure, that is, to multiply the minimum factor to all element stiffness matrixes of the whole stiffness, and set all the load arrays to zero.

(4) Make the installation components in each construction stage as an installation body, according to the fourth positioning principle to make configuration constraints on the key nodes, which are usually the common points or the end points of the installation body of each construction stage.

(5) According to the construction stages in the actual construction, the killed structure elements previously are activated step by step along the construction sequence, and the influence of geometric nonlinear can be coupled in the calculation process. In order to make the installed elements at right configuration after being activated, the constraints of the key nodes applied previously must be removed after the activation of the death elements in each construction stage, and the construction loads made in this stage are applied at the same time.

(6) The elements of structural components in each construction stage are activated constantly along the construction process according to the procedure above, and the constraints of the key nodes in corresponding construction stage are removed gradually. Finally, all elements of structure have been activated, and the mechanics simulation for the whole construction process is over. By this construction mechanics analysis, the results of the mechanical state and deformation mode of structure in every construction stage can be obtained.

THE APPLICATION IN PRACTICAL ENGINEERING

Project summary

Famen Temple, which is located in the Fufeng Town of Baoji City, Shaanxi Province, China, is the famous Buddhism temple whose history of serving the Buddhist relics of Sakyamuni can be traced back to one thousand years ago. The Heshi Dagoba, which is being built due to the rare cultural relic in the underground palace of Famen Temple, will be a center of Buddhism in the world. The Heshi Dagoba, which is a Buddhism architecture, has the height of 147 meters and width of 54 meters (the width of the attached building is 253 meters). The Heshi Dagoba of Famen Temple consists of two towers leaning 36 degrees vertically in one direction. The two towers have the architectural characteristics of bending shape in space and a Xuyuan Bridge joining the two leaning towers at the top. The profile layout is shown in Fig. 6.

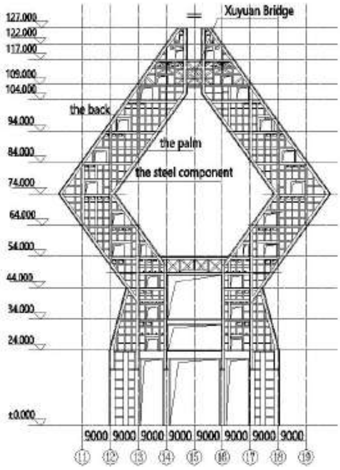


Fig. 6. The structural profile.

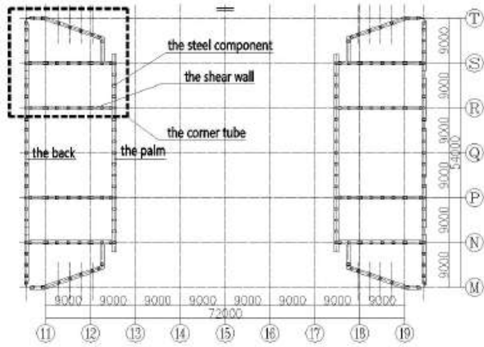


Fig. 7. Plan view of structure at elevation of 64m.

The main structure form of Heshi Dagoba is the combined structure of steel and concrete. The stair rooms, toilet rooms, and elevator rooms, which are connected as a circle, form the core corner tube of shear wall at the four corner of this building. The corners of core tube and the intersecting points of shear walls have the vertical steel skeleton, and the floors have the horizontal steel skeleton. These four corner tubes continue from bottom to the top of Heshi Dagoba. The plane layout is shown in Figure 7. All the beams and columns of this building are designed as the combined structure of steel and concrete. The cross section forms of vertical steel skeleton have rectangular-shape, crossed-shape, L-shape, and so on, and the cross section forms of horizontal steel skeleton have I-shape, box-shape, C-shape, and so on.

At the plane of 54m elevation, the structure has been strengthened by the huge truss in order to increase the stiffness of this flat. Beyond the 54m elevation, the structure of the Heshi Dagoba of Famen Temple is divided into two towers leaning 36 degrees vertically in one direction. And the two towers are bended in space at 74m elevation and connected by the Xuyuan Bridge at the top of this building at 114m elevation. The Heshi Dagoba belongs to space bending and severe vertical irregular structure.

The analysis method of construction mechanics in this project

The structure of Heshi Dagoba is complex and severely irregular. The geometric nonlinear factor may cause great influence in the construction process. The stress state and deformation mode of structure during construction stage are different than the design stage. And it will affect the mechanical state of using phase of the building after the completion of the structure. Therefore, the mechanics simulation of the construction process must be carried on in this project.

The synchronous construction method of space grade separation had been adopted in this project. By this method, the construction surface of steel structure was installed ahead of the construction surface of concrete structure. Because the steel structure and concrete structure can be constructed at the same time, this could increase the construction efficiency. Because of the complexity of the structure system of Heshi Dagoba, and according to the fourth positioning principle adopted in this project for installation, the nonlinear analysis method of construction mechanics named birth and death element method of local configuration constraint is used to simulate the construction process. As shown in Table 1, the practical construction process is divided into 13 stages according to the construction scheme.

Table 1. The construction stages.

Construction stage	Concrete shear wall elevation/m	Steel component elevation/m
1	+34.000	+44.000
2	+44.000	+54.000
3	+54.000	+74.000
4	+64.000	+84.000
5	+74.000	+94.000
6	Installing temporary supporting system	+94.000
7	+84.000	+104.000
8	+94.000	+117.000 (The closure of steel structure)
9	+104.000	+127.000
10	+117.000	—
11	+127.00	—
12	Removing construction live load	—
13	Removing the temporary support system	—

The two construction stages of actual construction according to scheme are shown in Figures 8 and 9. According to the actual construction procedure, birth and death element method of local configuration constraint was adopted to analyze the construction process based on using general finite element program ANSYS. The analysis procedure is as follows.

Fig. 8. The construction stage 6 in the practical project.

Fig. 9. The construction stage 9 in the practical project.

(1) At first, based on the design configuration, the whole finite element model of the main tower of Heshi Dagoba is established. The vital structure of the temporary supporting system, which needs to be added in the main structure in the construction process, also is set up in this finite element model. By this way, the influence of the temporary supporting system can be considered in the analysis of construction. This model is shown in Figure 10.

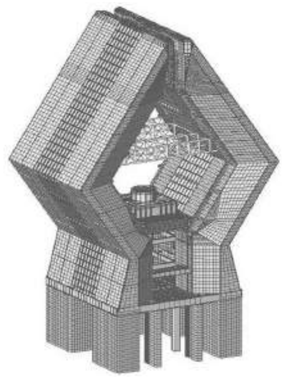


Fig. 10. The whole FEA model of the main tower of Heshi Dagoba.

(2) The construction process is divided into 13 stages according to the actual construction scheme.

(3) The elements of components in the finite element model were divided into 13 groups of installation bodies based on the construction stages.

(4) Kill all elements, that is, to multiply minimum factor to all element stiffness matrixes of the whole stiffness, and set all the load arrays to zero.

(5) According to the fourth positioning principle to make configuration constrain on the key nodes, which are the connection points of the installation bodies at each construction stage.

(6) According to the construction scheme, the previously killed structure elements are activated step by step along the construction sequence in the ANSYS. The influence of geometric nonlinear has been considered in the calculation process. After the activation of the death elements in each construction stage, the constraints of the key nodes applied previously are removed. So it makes the installed elements at the right installation configuration. The construction loads made in this construction stage are applied at the same time.

(7) According to the procedure above, activate or kill the structural components constantly, which will be installed or dismantled in each construction stage. The constraints of the key nodes in corresponding construction stage are removed gradually. Finally, all elements of structure have been activated, and the mechanics simulation for the whole construction process is over. The changes of the mechanical state and deformation mode of structure of Heshi Dagoba in every construction stage can be obtained.

The stress comparison of steel structure

The stress of the key parts in the construction of Heshi Dagoba was tracked and measured during the whole construction process and compared with the theoretical results of construction mechanics simulation. It could be used to judge the correctness of theoretical analysis result, guide the construction, and take corresponding countermeasures. In this paper, just the stress of a representative key point 4 in the A line is extracted for observation. The position of A line and key point 4 in Heshi Dagoba is shown in Fig. 11.

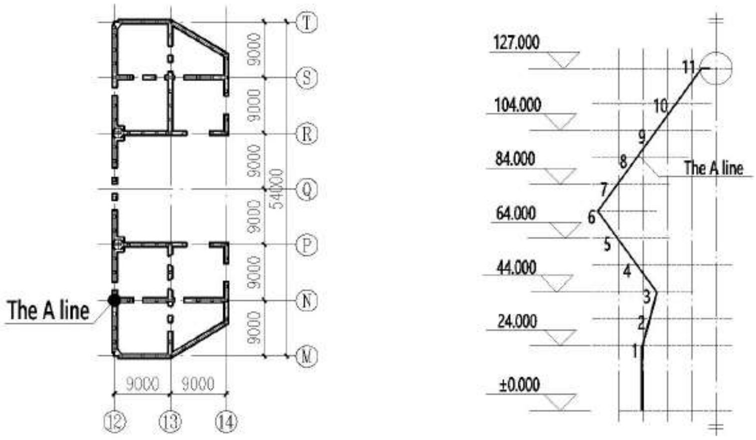


Fig. 11. The position of A line and key point 4 in Heshi Dagoba.

As shown in Figures 12 and 13 (the value of compressive stress is negative), the stress measured values of key point 4 in the A line on the inboard and outboard side of the steel component are compared with the theoretical analysis values. As shown in Figure 14 the deformation measured values of the A line in the horizontal direction are compared with the theoretical analysis values of the three methods. As seen from the curves in Figures 12 and 13, the theoretical values and measured values of key point 4 of the steel component during the construction process have shown the same trend; the values are approximated to each other. So the actual situation in the construction process is reflected accurately by making the construction mechanics simulation analysis on the structure. The theoretical values are less than the measured values slightly in the stress change curve of key point 4 on the inboard side of the steel component (see Figure 12). However, the theoretical value is greater than the measured values slightly in the stress change curve of key point 4 on the outboard side of the steel component (see Figure 13).

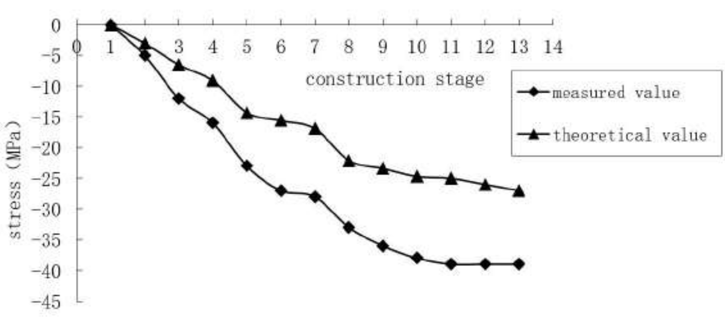


Fig. 12. The stress change curve of key point 4 on inboard side of steel component.

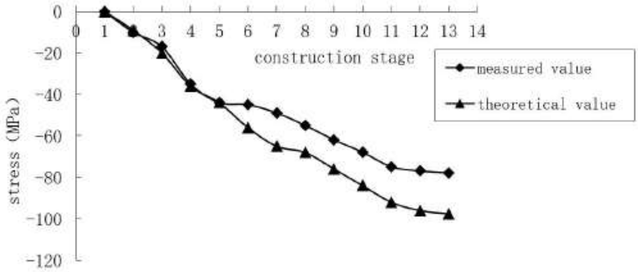


Fig. 13. The stress change curve of key point 4 on outboard side of steel component.

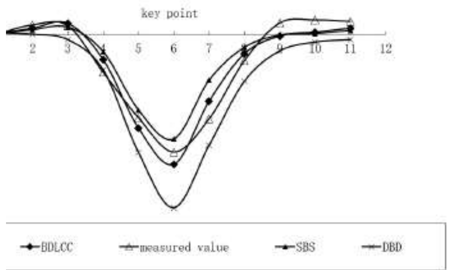


Fig. 14. The deformation curve of the A line in the horizontal direction

(BDLCC- birth and death element method of local configuration constraints;

SBS- Step-by-step modeling method; DBD-Direct birth and death element method).

The main reason for the phenomenon above is that the bigger construction loads are applied in the analysis of construction mechanics. Because of the complexity of the construction loads, the loads cannot be estimated very accurately. In order to improve the safety of structure in the construction process, the construction loads are applied greater than the practical loads. The value of the construction live loads of floor and dead load of structure in analysis may be bigger slightly than the practical value in construction. The key point 4 in the A line is the position of steel component, which lies on the N axis at 54m elevation. This steel component inclines outwards and belongs to the compression-bending member in the structure. The increase of the construction loads in analysis can cause an increase in the axial force and bending moment of this steel component. Therefore, the increase of the bending moment will lead to an increase in the theoretical values of compressive stress on the outboard side and a decrease in the theoretical values of compressive stress on the inboard of this steel component compared with the measured values.

As seen from the curves in Figure 14, the deformation curve by the BDLCC method is the closest to the measured values. The results of the DBD method are larger than the measured values because of the defect of “drifting”. The deformation values by the SBS method is smaller than the measured values because the geometric nonlinear cannot be considered in the analysis. According to the application in the practical engineering, the improved nonlinear analysis method (BDLCC) can be used to simulate the construction process correctly.

CONCLUSIONS

In this work, an improved nonlinear analysis method of construction mechanics for steel structure is established through numerical studies and practical engineering. The following conclusions are drawn from this study.

(1) Based on the study of a few existing analysis methods of construction mechanics for steel structure, direct birth and death element method has some limitations on the application of construction mechanics. Because of the “drifting” phenomenon of this method, the components of structure must be installed in the “drifting” configuration of death elements; otherwise, it could not simulate and analyze the mechanical state of structure correctly in the construction process.

(2) Based on the three major position principles of component installation in bridge engineering, combined with the characteristic and custom in building engineering, the fourth positioning principle, which is applicable to building engineering installation, is proposed.

(3) According to the phenomenon of “drifting” and mechanism in direct birth and death element method, an improved calculation method, birth and death element method, of local configuration constraints is put forward. This method can effectively restrain the “drifting” of the death element in direct birth and death element method; the component element can be activated in a relatively correct installation position. So this improved method solves the problem of the “drifting” defect and can be used to simulate the construction process of steel structure in building engineering correctly.

(4) The improved method is applied to the construction mechanics simulation in the main tower of Heshi Dagoba of Famen temple; the theoretical values are in good agreement with the measured values, which have guided the construction successfully and achieved good effect.

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REFERENCES

Agkathidis, A. & Brown, A. 2013. Tree-structure canopy: A case study in design and fabrication of complex steel structures using digital tools. International Journal of Architectural Computing, 11(1): 87–104.

Cao Zhiyuan. 2001. Construction mechanics and time varying mechanics in civil engineering. Journal of Civil Engineering, 34(3): 41– 46.

Case, F., Beinat, A. & Crosilla, F. 2014. Virtual trial assembly of a complex steel structure by generalized procrustes analysis techniques. Automation Construction, 37(1): 155–165.

C. Q. Li. 1994. Formulation of time-dependent structural serviceability. Computers & Structures, 52(2): 219–226.

Cruz P J S, Mari A R & Roca P. 1998. Nonlinear time-dependent analysis of segmentally constructed structures. Journal of Structural Engineering (ASCE), 124: 277–281.

Guo Yanlin, Tian Guangyu, Zhou Xuhong & Chen Guodong. 2011. Application and research of construction mechanics and new control technology in large and complex steel structures construction. Construction Technology, 40(1): 47–55.

Guo Yanlin & Liu Xuewu. 2008. State nonlinear finite element method for construction mechanics analysis of steel structures. Engineering Mechanics, 25(10): 19–24.

Hajjar, D. & AbouRizk, S. 2002. Unified modeling methodology for construction simulation. Journal of Construction Engineering and Management, 128(2): 174–185.

Jiping Hao, Jiang Zheng, Xiantie Wang & Xiaoli Yang. 2010. Mechanics simulation and analysis of the main palaestra of the world university games during the construction process. Journal of Xi'an University of Architecture & Technology (Natural Science Edition), 42(4): 457–463.

Kanemitsu, T., Kawaguchi, M. & Mitsui, K. 2001. Simulation of construction plan of structure by analysis for construction process optimization. Journal of Structural and Construction Engineering, 148(10): 51–58.

Liu Xuewu. 2008. Analysis and application of construction mechanics of large complex steel structures. Ph.D. Dissertation, Tsinghua University, Beijing.

Liu Xuewu & Guo Yanlin. 2008. Construction mechanics analytical procedures for steel structures in view of the geometric nonlinearity. Journal of Xi'an University of Architecture & Technology (Natural Science Edition), 40(2): 161–169.

Liu Xuewu & Guo Yanlin. 2007. Pre-set construction deformation value and its computational methods for steel structures. Industrial Construction, 37(9): 9–15.

Liu Xuewu, Guo Yanlin, Zhang Qinglin & Liu Luyu. 2007. Analysis of internal force and deformation for the new CCTV headquarters during the construction process. Industrial Construction, 37(9): 22–29.

Mengzhu Diao, Yi Li, Weiming Yan, Xiaowei Cheng & Deyue Li. 2015. Numerical analysis of construction process of large-span half steel plate reinforced concrete roof. Engineering Mechanics, 32(suppl): 240–247.

Parka C M & Choia J T. 2009. Thermal crown analysis of the roll in the strip casting process. Journal of Materials Processing Technology, 209(8): 3714–3723.

Tian Limin, Hao Jiping, Chen Tao, Zheng Jiang & Wang Yuan. 2011. Simulation analysis on erection procedure of main stadium for the Universiade Sports Centre. Journal of Building Structures, 32(5): 70–77.

Wang Guangyuan. 2000. On mechanics of time-varying structures. China Civil Engineering Journal, 33(6): 105–108.

Xiang Haifan. 2001. The Higher Theory of Bridge Structure, China Communications Press, Beijing, China.

Ye Zhiwu, Luo Yongfeng, Chen Xiaoming & Jia Baorong. 2016. Improved method of step by step modeling and its application in construction simulation. Journal of Tongji University (Natural Science), 44(1): 73–80.

Zhang Qilin, Luo Xiaoqun, Gao Zhenfeng & Li Zixu. 2004. Numerical Tracing and Graphic Simulation for Construction Processes of Large Span Pre-Tensioned Steel Structures. Journal of Tongji University: Natural Science, 32(10): 1295–1299.

Zhuo Xin & Dong Shilin. 2003. Construction process internal forces and displacements superimposed analysis method and application. Journal of Zhejiang University: Engineering Science, 37(5): 556–559.

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طريقة تحليل غير خطية محسنة
وتطبيق ميكانيكا البناء للهيكل الفولاذي

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الخلاصة

تشكيل الهيكل هي عملية تتم خلال البناء، ويتم تطبيق الأحمال على البنية خطوة بخطوة مع تسلسل البناء. تختلف حالة الإجهاد وطريقة التشوه في البنية أثناء مرحلة البناء مع مرحلة التصميم. استناداً إلى خصائص وقابلية تطبيق عدد قليل من طرق التحليل الحالية لميكانيكا البناء للهيكل الفولاذي ووفقًا لمبادئ تحديد المواقع لمكونات الهيكل الصلب في المشاريع الفعلية، هدفت هذه الدراسة إلى تطوير طريقة تحليل غير خطية محسنة للتنبؤ بالتغيرات الميكانيكية للهيكل أثناء عملية البناء بدقة. تم وضع هذه الطريقة المسماة «الميلاد» و «الموت» من أجل حل عيوب «الانجراف» في عنصر الموت في تلك الطريقة. وقد تم تطبيقها في محاكاة ميكانيكا البناء وتحليل البرج الرئيسي من Heshi Stupa في معبد Famen خلال عملية البناء. نتائج التحليل بواسطة الطريقة المحسّنة قد عززت هذا المشروع بنجاح. وقد أشار هذا إلى أن الطريقة المحسنة هي طريقة تحليل فعالة لميكانيكا البناء للهيكل الفولاذي.