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Construction analysis on integral lifting of steel structure by the vector form intrinsic finite element

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Abstract: A new numerical method based on vector form intrinsic finite element (VFIFE) is proposed to simulate the integral lifting process of steel structures. First, in order to verify the validity of the VFIFE method, taking the steel gallery between the integrated building and the attached building of Nanjing Mobile Communication Buildings for example, the static analysis was carried out and the corresponding results were compared with the results achieved by the traditional finite element method. Then, according to the characteristics of dynamic construction of steel structure integral lifting, the tension cable element was employed to simulate the behavior of dynamic construction. The VFIFE method avoids the iterative solution of the stiffness matrix and the singularity problems. Therefore, it is simple to simulate the complete process of steel structure lifting construction. Finally, by using the VFIFE, the displacement and internal force time history curves of the steel structures under different lifting speeds are obtained. The results show that the lifting speed has influence on the lifting force, the internal force, and the displacement of the structure. In the case of normal lifting speed, the dynamic magnification factor of 1. 5 is safe and reasonable for practical application.

Key words: integral lifting; vector form intrinsic finite element (VFIFE); steel gallery; whole process of construction; dynamic magnification factor

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In recent years, novel space structures with long-spans are becoming more prevalent. The integral lifting construction technology as one of the key technologies of building and installing long-span space structures has been widely used, such as the integral lifting of the main truss in Macao Comprehensive Gymnasium[1], Shanghai Pudong Boeing Hangar Roof[2], and the International Exhibition in Zhuhai Cross Gate[3]. Integral lifting refers to a process that initially assembles constructional elements on the ground, and then lifts them integrally to the design-elevation. Compared to the traditional steel structure installation scheme, the integral lifting dispenses with the erection of high and large scaffolding, and aerial work is greatly reduced. Therefore, construction quality and safety are strictly ensured. Meanwhile, integral lifting has many other advantages, such as a short construction period and high work efficiency. However, this method is suitable for the installation projects under a tight schedule, high weight and high installation. More importantly, the lifting of the steel structure is a dynamic process, which involves the displacement of a rigid body, so the risk of the lifting the construction into the air is greater.

Therefore, it is necessary to carry out a detailed analysis of the construction process. Guo et al. [1] used the ANSYS software to analyze several intermediate states in the integral lifting process of the main truss, and observed the change tendency of the internal force and deformation in the full-process. Chen et al. [2] adopted the MIDAS software to simulate integral lifting, and analyzed the change regulations of the internal force and the displacement of the nodes in the two lifting process. The static analysis of the steel gallery was carried out by using the ANSYS software in Ref. [4], and the non-synchronization problem in the lifting process was checked. Most of these simulations are based on the traditional finite element theory only for linear static analysis. In order to take the dynamic effect into account, the internal force and deformation of the structure can be obtained, and then they are multiplied by the corresponding dynamic amplification factor. However, this is an approximate method, and it cannot track and simulate the whole process of lifting. In addition, the safety and effectiveness of the power amplification factor have not been verified.

VFIFE was first put forward by Ting et al. [5-8] at Purdue University, which is a new finite element analysis method based on a combination of vector mechanics and numerical calculation. The VFIFE can effectively deal with continuum geometric deformation, nonlinear and discontinuous material constitutive relationships, rigid body motion and the coupling behavior of all types of complicated situation. Thus, there is a good application prospect in the study of engineering problems involving large deformations, fractures, collisions and other strong nonlinearities. Currently, this method has some related applications in the field of structural analysis based on the

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concepts of Ting et al. [5-8], Wu et al. [9] who analyzed the nonlinear behavior of the planar flexible truss structure. Wang et al. [10] studied the elastoplastic large deformation behavior of the three-dimensional truss. Zhu et al. [11-12] analyzed the static space structure and the whole process of the steel strand rupture using the VFIFE method. Yao et al. [13] adopted C++ language to compile the VFIFE calculation program for the structure of the bar system, obtained the wind-induced response of the transmission tower, and then analyzed the collapse mechanism of the transmission tower under wind loads.

The steel gallery is very popular in modern high-rise building design due to its capability to connect two independent buildings and its attractive design. Therefore, the steel galleries have gained popularity among many domestic and foreign designs, for instance, the steel gallery in Shanghai Jinhongqiao International Center[14] and the steel gallery in Changsha Zhongtian Plaza. In this paper, the integral lifting of a steel gallery is simulated using the VFIFE program in Matlab and the corresponding results are compared with those obtained by the traditional finite element method. The impact of the internal force and displacement in the whole lifting process of the steel gallery is discussed. Moreover, the value of the dynamic magnification factor is studied for practical application.

1 Assumptions of VFIFE

VFIFE is a generalized and systematic calculation method, which can be used to compute the position change caused by internal/external force and geometric deformation. In the VFIFE model, the structure is regarded as a collection of multiple particles with masses and elements without masses. The basic concepts of this method, which is the description of the point value and path element, greatly simplify the motion description of the structure. Meanwhile, the structure behavior is described by a clear physical model and a particle motion control equation. A numerical calculation method is introduced to avoid complex iterative calculations. There is a great advantage in the nonlinear and discontinuous behavior of the structure without establishing a stiffness matrix in the solution process.

1.1 Equations of motion

Every component of the structure is divided into two particles and a spatial connecting element, as shown in Fig. 1.

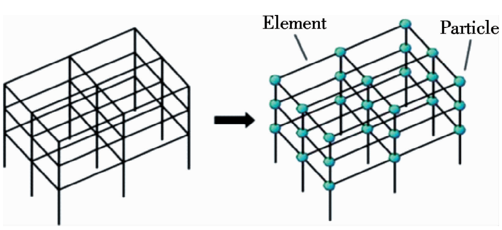


Fig. 1 The VFIFE model

According to classical mechanics, the motion equations can be expressed as

$$m\ddot{d} + a\dot{d} = F \quad (1)$$

$$I\ddot{\theta} + \alpha\dot{\theta} = M \quad (2)$$

where α is the damping factor; m, $\dot{d}$, $\ddot{d}$ and F represent the mass, velocity, acceleration of the particle and resultant force vectors, respectively; and I, $\dot{\theta}$, $\ddot{\theta}$ and M are the mass moment of inertia, angular velocity, angular acceleration and resultant bending moment vector. According to the central difference formulas, we obtain

$$\dot{d}_n = \frac{d_{n+1} - d_{n-1}}{2h} \quad (3)$$

$$\dot{\theta}_n = \frac{\theta_{n+1} - \theta_{n-1}}{2h} \quad (4)$$

$$\ddot{d}_n = \frac{d_{n+1} - 2d_n + d_{n-1}}{h^2} \quad (5)$$

$$\ddot{\theta}_n = \frac{\theta_{n+1} - 2\theta_n + \theta_{n-1}}{h^2} \quad (6)$$

Therefore,

$$d_{n+1} = \frac{F_n}{m}h^2 c_1 + 2d_n c_1 - d_{n-1}c_2 \quad (7)$$

$$\theta_{n+1} = \frac{M_n}{I}h^2 c_1 + 2\theta_n c_1 - \theta_{n-1}c_2 t_n \quad (8)$$

where d_n, θ_n, h are the displacement of a particle at t_n, the angular rotation at t_n, and the time increment, respectively; $c_1 = 1/(1 + \alpha h/2)$; and $c_2 = c_1(1 - \alpha h/2)$.

The computational procedure of the VFIFE is illustrated in Fig. 2.

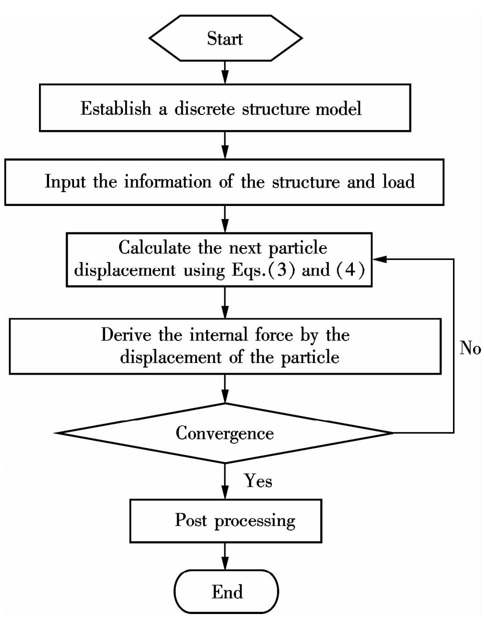


Fig. 2 Computational procedure of the VFIFE

1.2 Internal force of tension cable element

Assuming that element AB moves from the initial location A_1B_1 to the adjacent location A_2B_2 (see Fig. 3), the full process includes translation vector $\boldsymbol{u}$ and rotation vector $\boldsymbol{\theta}$. The internal force at A_2B_2 is expressed as

$$f_{A_2B_2} = \left(f_{A_1B_1} + E_a A_a \frac{\Delta l}{l_{A_1B_1}} \right) e_{A_2B_2} \tag{9}$$

where $e_{A_2B_2}$ is the directional vector of A_2B_2.

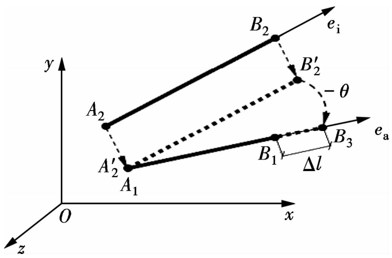


Fig. 3 Virtual inverse motion of tension cable element

After obtaining the internal force of the element, according to the law of actions and reactions, the force of each particle can be obtained. The external force acting on the structure is loaded on each particle according to the principle of equivalent force. Therefore, we obtain the resultant force of a particle. Then, the resultant force F and M are substituted into Eqs. (7) and (8) to calculate the position of the particle.

Assume that A_1B_1 is the state of the element without prestress before tensioning. Due to the fact that the deformation of cable in the tension process is always within the elastic range, ignoring the change of section, Eq. (9) is simplified as

$$f_{A_2B_2} = \left(E_0 A_0 \frac{l_{A_2B_2} - l_0}{l_{A_1B_1}} \right) e_{A_2B_2} \tag{10}$$

where l_0 is the length of the initial state of the element; A_0 is the initial state section; and E_0 is the elastic modulus. The cable element cannot be compressed, so when $f_{A_2B_2} > 0$, $E_0 = 0$.

In the whole lifting process, the effective length of the steel wire is shortened, and the VFIFE model is correspondingly shortened to the original length of the steel strand, which can reflect the change in the force and shape of the steel strand in the tension process:

$$l_0 = vnh \tag{11}$$

where v is the tension speed, and n is the total time steps in the tension process.

2 Static Analysis of the Steel Structure

2.1 Project description

As shown in Fig. 4, there is a steel gallery between the integrated building and the attached building of Nanjing Mobile Communication Buildings. The span of the gallery is 47 m, width is 8.375 m and the total weight is 170 t. The composite floor with the profiled steel plate is used, and the H-bar with the maximum size of H1000 mm × 400 mm × 24 mm × 35 mm is employed in the upper and lower chord bars, and also the horizontal bars of the gallery. The square steel tube is used in the vertical bar.

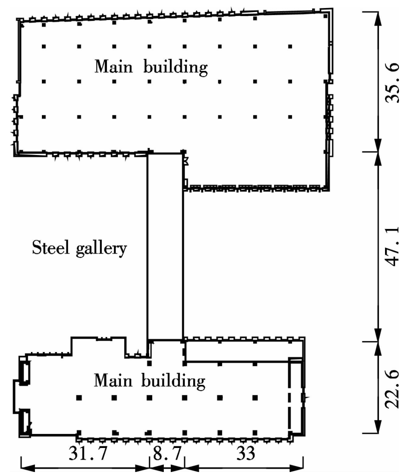


Fig. 4 Layout of the steel gallery (unit: m)

Due to the fact that the section size, structural weight and the span of the engineering components are large, the approach of dispersed assembly at high altitude may lead to a high risk. After the field analysis of the construction, assembling the steel structure gallery in the basement roof can be directly realized with the auto crane. The upper lifting point is arranged in the concrete bracket, and the corresponding lower lifting point is arranged in the gallery of bottom I-beam end of the steel structure. The lifting sketch is shown in Fig. 5.

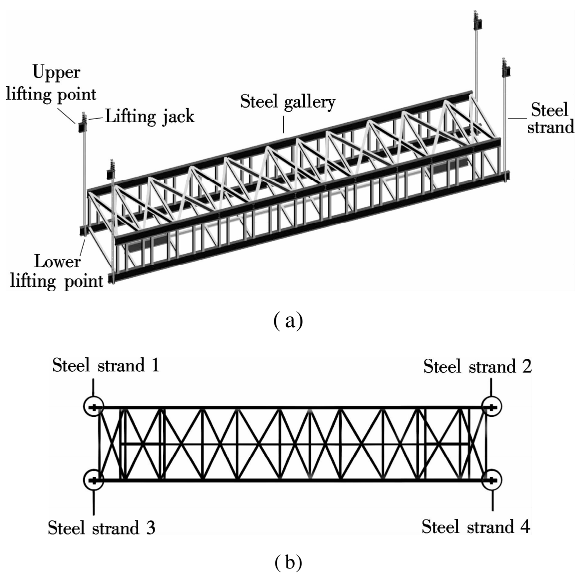


Fig 5. Sketch of integral lifting and lifting point. (a) Integral lifting; (b) Lifting point

2.2 Static analysis

The static analysis is carried out directly by the traditional finite element method. The influence of the dynamic response in the lifting process is simulated by the dynamic magnification factor. In the ANSYS model, BEAM188 is used to simulate the beam element, while LINK10 is used to simulate the steel strand element. The VFIFE method is applied to establish the static analysis model, and truss rods are simulated by the beam elements. While the steel strand is simulated by the tension steel strand element, the time step is 2×10^{-5} s. In order to make the calculation converge to the stable solution as soon as possible, the virtual damping coefficient of 23 is used. Based on the above settings, the static analysis results under gravity are calculated.

The calculation comparison on displacement and internal force by VFIFE and ANSYS is shown in Tab. 1 and Fig. 6. The maximum vertical displacement is 85.45 mm, and the internal forces of the steel strand are around 402 and 419 kN, respectively. Fig. 7 illustrates the time history curves of the internal force in the process of lifting the steel strands. Owing to the virtual damping coefficient, the internal force and vertical displacement of the VFIFE model converge rapidly to a stable solution. The internal force curve is coincident with the ANSYS results.

Tab. 1 Calculation comparison of the displacement and internal force

Methods	Displacement/mm	Internal force of midspan element/kN	Internal force of steel strands/kN			
			SS1	SS2	SS3	SS4
ANSYS	85.447	628.0	402.0	402.0	419.0	419.0
VFIFE	85.452	625.8	401.4	401.4	418.5	418.5

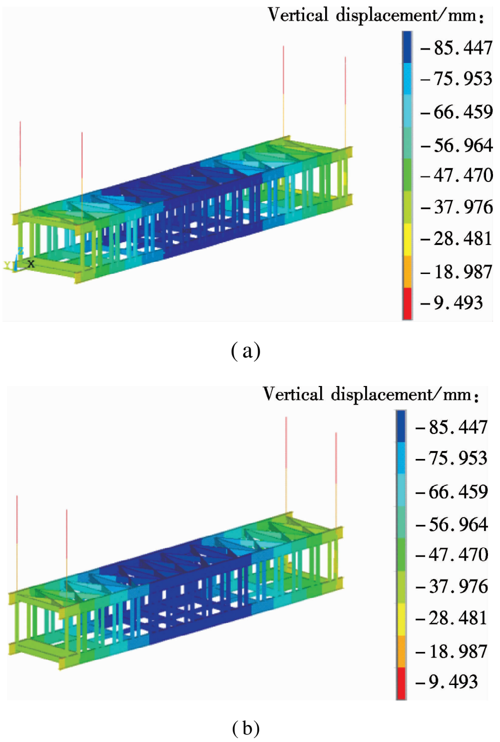


Fig 6. The comparison of the vertical displacement by ANSYS and VFIFE. (a) ANSYS; (b) VFIFE

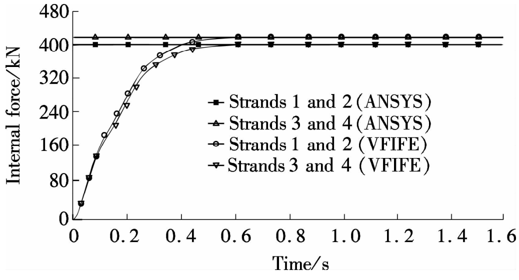


Fig. 7 Time history curves of internal force of steel strands

3 Dynamic Response to the Whole Process of Integral Lifting

According to the actual construction process, the steel gallery is assembled on the ground frame first. Then the steel strand is hung on the lifting point, and the integral lifting is carried out through the jack in the upper lifting point. In practice, the lifting speed of the jack is generally 1.5 to 2.5 min per stroke. The jack stroke is 200 mm, so the lifting speed is approximately 2 mm/s. The lifting process is divided into many stages according to the jack stroke, and the first stroke and the second stroke of the lifting of the jack is selected to be tracked and simulated in this paper. Then, we can establish the VFIFE model, and the time step is 2×10^{-5} s. Due to the large number of elements, the dynamic response of each element cannot be separately considered. In addition, the small internal force does not have a representative. We examine rods with large internal forces in the whole structure and the rods are located in the mid-span. The internal forces of steel strands, the time history curves of the internal forces and the vertical displacements in the mid-span are also obtained (see Fig. 8 and Fig. 9).

The entire analysis process lasts 204 s. To be specific, the first stroke is divided into four stages. The first stage is the initial stage, and the gallery is only under the gravity load, which is on the lower part of the temporary supports. At this stage, the initial lifting state is obtained by setting the virtual damping. The internal force and vertical displacement of the mid-span, and the internal forces of the steel strands are equal to zero in this procedure (see Fig. 8 and Fig. 9). The second stage is the beginning of the lifting stage. Without the virtual damping coefficient, the whole dynamic lifting process can be tracked by gradually changing the initial length of the steel strand element. In this stage, when the jack starts working, the steel strands are tensioned, and then elastic deformation occurs. Since the internal force of the steel strand has not been sufficient to enhance the steel gallery yet, the vertical displacement of the mid-span is still equal to zero (see Fig. 8), and the steel gallery remains motionless (see Fig. 9). The third stage is the lifting stage. The internal force of the steel strand increases to the same weight of the steel gallery. The maximum stress of the steel strand increases to 420.9 kN. The lifting of the steel gallery reaches a speed of 2 mm/s. The fourth stage is the holding stage. The jack stops moving, and the steel structure stops rising. The maximum internal force of the steel strand is 418.5 kN in static balance. The second stroke starts from the end of the second stage of the first stroke. The process of lifting and unloading is repeated. The maximum internal force of the steel strand is 420.9 kN.

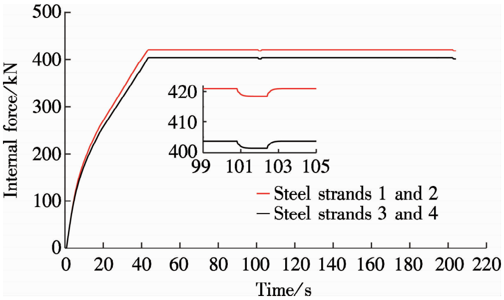
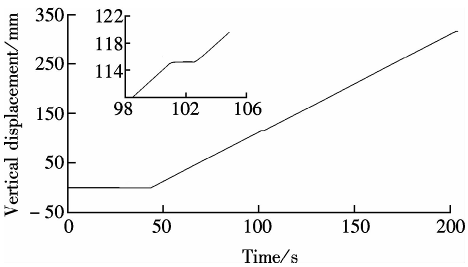
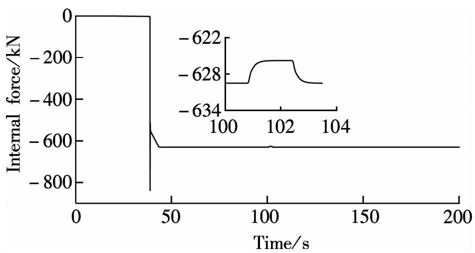


Fig. 8 Internal forces of steel strands



(a)



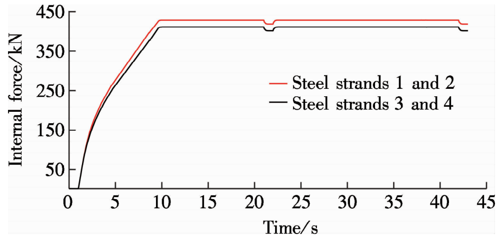
(b)

Fig. 9 Vertical displacement and internal force of the mid-span. (a) Vertical displacement; (b) Internal force

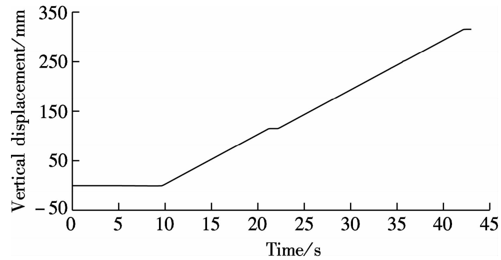
4 Influence of Lifting Speed

In the integral lifting construction process of steel structures, the lifting speed is an important parameter. In order to ensure the safety of the construction process, the structure should be lifted within a certain speed range. To theoretically verify the relationship between speed and dynamic response in the actual construction process, three speeds of 2, 10 and 100 mm/s are considered in this paper. We track the integral lifting construction process of the steel structure at these three different speeds, respectively.

Figs. 10(a) and (b) are the time history curves of the internal forces and vertical displacement of the mid-span in the integral lifting construction of the steel gallery at the speed of 10 m/s. Figs. 11(a) and (b) are the time history curves of the internal forces and the vertical displacement of the mid-span at the speed of 100 m/s. It is apparent that the relationship between the line-type and lifting speed is basically the same as that at 2 mm/s. However, the peak value of the internal force of the steel strand is different at various speeds. The maximum internal force of the steel strand is 428.3 kN when the lifting speed is 10 mm/s; in contrast, it is 516.9 kN when the lifting speed is 100 mm/s. However, the maximum internal force of the static state is all 418.5 kN. The internal forces of the steel gallery rods are 841.1, 842.9 and 883.5 kN, respectively, at three different speeds (see Fig. 12). It can be found that the influence of the lifting speed is limited to the internal force, and the dynamic magnification factor is no more than 1.5.

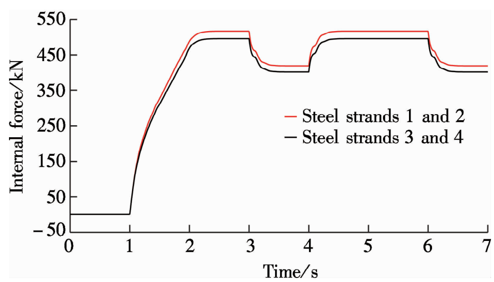


(a)

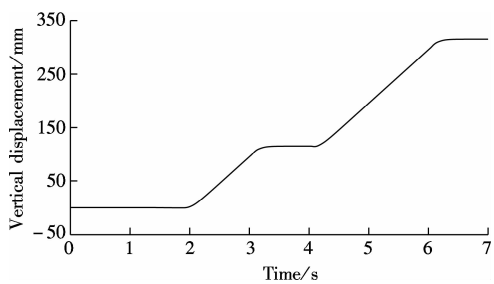


(b)

Fig. 10 Internal forces and vertical displacement at 10 mm/s. (a) Internal forces of steel strands; (b) Internal force of the mid-span



(a)



(b)

Fig. 11 Internal forces and vertical displacement at 100 mm/s. (a) Internal forces of steel strands; (b) Internal force of the mid-span

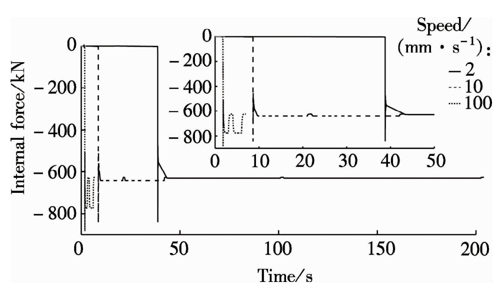


Fig. 12 Internal forces of the mid-span at different speeds

5 Conclusions

1) Based on the basic theory of the VFIFE, we derive the formulae for the internal force of the tension steel strand element. A program is then developed to simulate the tension steel strand elements and beam elements using Matlab. The results of the internal force and displacement are consistent, which verifies the validity of the theoretical derivation and the program.

2) The whole process of the steel gallery lifting construction is realized. It is simple to achieve the displacement and internal force time history curves of the whole construction integral lifting process of the steel gallery. Thus, the VFIFE is effective and accurate in the analysis of both traditional structures and unconventional structures, including the construction procedure with mechanisms and rigid body motions.

3) Different lifting speeds are selected to analyze the static performance. It can be found that the impact of the lifting speed on the internal force of the steel strand is significant. The preliminary analysis shows that the safety factor 1.5 can meet the engineering requirements in the case of normal lifting speed.

References

[1] Guo Y L, Miao Y W, Lou J J, et al. Integral lift design of the main trusses in Macao Gymnasium and analysis of the latticed hoist tower[J]. *Journal of Building Structures*, 2005, **26**(1): 17－24. (in Chinese)

[2] Chen D D, Yao G, Yuan X D, et al. Integral lifting technology of boeing hangar roof at Pudong Airport[J]. *Journal of Chongqing Jiaotong University* (*Natural Science*), 2010, **29**(4): 650－653. (in Chinese)

[3] You Z W, Yu R, Li M, et al. The integral lifting construction of international exhibition in Zhuhai cross gate [J]. *Construction Technology*, 2014, **43**(14): 44－46. (in Chinese)

[4] Dong Y, Liang C Z, Feng D B, et al. Analysis of key problems about integral lifting of long-span huge steel vestibule[J]. *Building Science*, 2014, **30**(9): 107－111. (in Chinese)

[5] Ding C X, Wang Z Y, Wu D Y, et al. Motion analysis and vector form intrinsic finite element [R]. Taoyuan, China: Bridge Engineering Research Center of National Central University, 2007. (in Chinese)

[6] Ting E C, Shih C, Wang Y K. Fundamentals of a vector form intrinsic finite element: Part Ⅰ. Basic procedure and a plane frame element [J]. *Journal of Mechanics*, 2004, **20**(2): 113－122. DOI: 10.1017/s1727719100003336.

[7] Ting E C, Shih C, Wang Y K. Fundamentals of a vector form intrinsic finite element: Part Ⅱ. Plane solid elements[J]. *Journal of Mechanics*, 2004, **20**(2): 123－132. DOI: 10.1017/s1727719100003348.

[8] Shih C, Wang Y K, Ting E C. Fundamentals of a vector form intrinsic finite element: Part Ⅲ. Convected material frame and examples[J]. *Journal of Mechanics*, 2004, **20**(2): 133－143. DOI: 10.1017/s172771910000335x.

[9] Wu T Y, Wang R Z, Wang C Y. Large deflection analysis of flexible planar frames[J]. *Journal of the Chinese Institute of Civil Hydraulic Engineering*, 2006, **29**(4): 593－606. DOI: 10.1080/02533839.2006.9671156.

[10] Wang R Z, Chuang C C, Wu T Y, et al. Vector form analysis of space truss structure in large elastic-plastic deformation[J]. *Journal of the Chinese Institute of Civil Hydraulic Engineering*, 2005, **17**(4): 633－646.

[11] Zhu M L, Dong S L. Application of vector form intrinsic finite element method to static analysis of cable domes [J]. *Engineering Mechanics*, 2012, **29**(8): 236－242. (in Chinese)

[12] Zhu M L, Dong S L, Yuan X F. Failure analysis of cable domes due to cable slack or rupture[J]. *Advances in Structural Engineering*, 2013, **16**(2): 259－272. DOI: 10.1260/1369-4332.16.2.259.

[13] Yao D, Shen G H, Pan F, et al. Wind-induced dynamic response of transmission tower using vector-form intrinsic finite element method[J]. *Engineering Mechanics*, 2015, **32**(11): 63－70. (in Chinese)

[14] Gao L L, Wang L P. Hydraulic integral hoisting technology of steel corridor in Shanghai Jinhongqiao International Center[J]. *Construction Technology*, 2012(S2): 222－225. (in Chinese)

基于向量式有限元的钢结构整体提升施工过程分析

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摘要:基于向量式有限元提出一种新型数值计算方法对钢结构整体提升进行模拟分析. 首先,以南京移动通信综合楼和附楼之间的钢连廊为例,对其进行静力分析,并与传统有限元求解结果比较,验证向量式有限元方法的有效性. 针对钢结构整体提升动态施工的特点,引入张拉索单元,该向量式有限元方法避免了刚度矩阵的迭代求解以及奇异等问题,实现了钢结构的整体提升施工全过程跟踪模拟分析. 通过使用向量式有限元方法得到了不同提升速度下钢结构节点的位移和单元内力时程曲线. 结果表明,提升速度对提升力、结构内力和位移有一定影响,在正常提升速度情况下,动力放大系数取为1.5是安全合理的.

关键词:整体提升;向量式有限元;钢结构连廊;施工全过程;动力放大系数

中图分类号:TU393.3;TU745.2