

Synchronous Control Strategy for Integral Lifting of Large-Scale Structures

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Abstract: A computer-controlled synchronous lifting scheme is often adopted for the integral lifting construction of large-scale structures. In this study, a four-lifting-point mechanical model was constructed which revealed the coupling relationship between the load and displacement of lifting points. It was further clarified that the relative stiffness of lifting points is the core factor affecting the asynchrony effect. Calculations for displacement asynchrony and load asynchrony conditions revealed that when the relative stiffness of lifting points is large, a control strategy primarily based on load synchronization is preferred; in contrast, when the relative stiffness is small, a control strategy primarily based on displacement synchronization is preferred. Furthermore, for lifting structures with complex conditions, a dual-objective control must be adopted to ensure lifting safety. The research results can provide a theoretical basis and technical reference for synchronous control and safe integral lifting construction of large-scale structures.

Keywords: large-scale structure; synchronous lifting; displacement asynchrony; load asynchrony; load synchronization strategy; displacement synchronization strategy; prestressed steel strand

1 Introduction

1.1 Synchronous Lifting Technology

Computer-controlled hydraulic integral lifting is a construction technology that uses flexible steel strands as load-bearing cables and adopts an integrated mechanical-electrical-hydraulic drive control system to lift integrally assembled heavy engineering structures or large equipment to the design elevation and to precisely position and install these structures [1]. This technology is characterized by high control precision and good synchronous performance. It is widely applied for integral lifting of large-span steel space frames and steel truss roofs of stadiums and airport terminals as well as for vertical hoisting of large components such as arch bridges and bridge towers, resulting in integral, smooth and precise positioning of super-large components with large areas, large spans, and large tonnages [2]. Consequently, integral lifting technology has contributed significant economic and social benefits in a series of major construction projects, such as integral lifting of the 10,388 tons steel truss of the Beijing National Digital Library, integral lifting of the 10,000-ton roof of the A380 hangar at Beijing Capital International Airport, and integral lifting of the 74,000 m² steel structure roof of the Shanghai East Station of the Oriental Hub [3-4].

Large components are characterized by excessive weight and large areas, usually requiring the use of multiple lifting points; moreover, the lifting reaction forces among the lifting points may differ significantly. In actual construction processes, owing to mechanical, control, environmental, and design factors, lifted structures cannot achieve absolute synchronous lifting. For instance, minor differences in the sealing performances of cylinders and pistons lead to uneven output under the same oil pressure; sensor and signal delays cause accumulation of local errors; and member installation errors generate additional loads on the

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structure itself. All these factors lead to displacement and load asynchrony during the lifting construction process. In synchronous lifting calculations, an absolute synchronization calculation method may render the distribution of lifting loads at lifting points too ideal. In a near-critical state, the actual load may exceed the calculated load, leading to local buckling or even failure of the lifted structure.

Current research on integral lifting of large-span structures focuses primarily on single-space frame structures [5-7]. This study focuses on a large-span hangar adopting a truss-space frame composite structure. Based on synchronous lifting numerical simulation, it investigates the influence of displacement and load asynchrony during integral lifting, reveals the corresponding relationship between the relative stiffness among lifting points and control strategy, and attempts to propose quantitative criteria for single/dual-objective control, thereby providing a basis for engineering selection of control strategies.

1.2 Synchronous Lifting Mechanical Model

During the lifting process of steel structures, the load and displacement at lifting points are the two most critical indicators. This study analyzes the coupling relationship between the load and displacement of each lifting point during the lifting process of a steel structure by establishing a simple four-lifting-point model.

In the Figure 1, F_A , F_B , F_C , and F_D are loads at lifting points A, B, C, and D, respectively; k is the equivalent stiffness of steel strands; and G is the gravity load of the component. In an ideal lifting process, the lifting speeds of the four lifting points A, B, C, and D are the same, meaning that there is no relative displacement between lifting points and that no stress is generated because of the relative displacement. In an actual lifting process, it is impossible for the lifting speeds of the four lifting points to be the same; consequently, relative displacement occurs between the lifting points. In the four-lifting-point model, lifting point A is initially assumed to have a minor relative displacement Δ_A (Figure 2), and the load change ΔF_{AA} at lifting point A is detected, along with the load changes ΔF_{BA} , ΔF_{CA} , and ΔF_{DA} at points B, C, and D, respectively, caused by Δ_A .

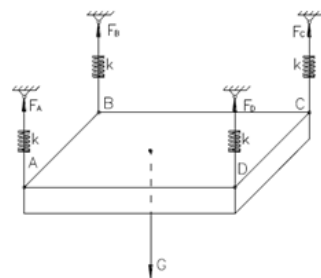


Figure 1 Four-lifting-point mechanical model

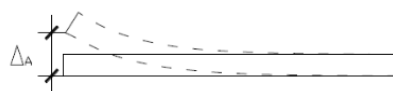


Figure 2 Minor displacement in the plane

Let:

$$\frac{\Delta F_{AA}}{\Delta_A} = K_{AA}, \quad \frac{\Delta F_{BA}}{\Delta_A} = K_{BA}, \quad \frac{\Delta F_{CA}}{\Delta_A} = K_{CA}, \quad \frac{\Delta F_{DA}}{\Delta_A} = K_{DA} \quad (1)$$

where the physical meaning of K_{ij} is the load change at lifting point i caused by a unit displacement at lifting point j —i.e., the relative stiffness of lifting point j to lifting point i . This study primarily focuses on the overall distribution pattern of stiffness among lifting points, without accounting for the tensile deformation of the steel strands (lifting cables) themselves and their stiffness coupling effect with the

space frame. The steel strands used for integral lifting belong to a prestressed load-bearing system. Prior to lifting, the steel strands at each lifting point must be pretensioned to establish an initial prestress for eliminating the nonlinear deformation caused by their relaxation and bending. The pretensioning prestress level will alter the equivalent stiffness of the lifting cables, thereby exerting a certain effect on the load–displacement coupling relationship of lifting points.

Similarly, in cases where only lifting point B has a displacement Δ_B , lifting point C has a displacement Δ_C , and lifting point D has a displacement Δ_D , the following equations are defined:

$$\frac{\Delta F_{AB}}{\Delta_B} = K_{AB}, \quad \frac{\Delta F_{BB}}{\Delta_B} = K_{BB}, \quad \frac{\Delta F_{CB}}{\Delta_B} = K_{CB}, \quad \frac{\Delta F_{DB}}{\Delta_B} = K_{DB} \quad (2)$$

$$\frac{\Delta F_{AC}}{\Delta_C} = K_{AC}, \quad \frac{\Delta F_{BC}}{\Delta_C} = K_{BC}, \quad \frac{\Delta F_{CC}}{\Delta_C} = K_{CC}, \quad \frac{\Delta F_{DC}}{\Delta_C} = K_{DC} \quad (3)$$

$$\frac{\Delta F_{AD}}{\Delta_D} = K_{AD}, \quad \frac{\Delta F_{BD}}{\Delta_D} = K_{BD}, \quad \frac{\Delta F_{CD}}{\Delta_D} = K_{CD}, \quad \frac{\Delta F_{DD}}{\Delta_D} = K_{DD} \quad (4)$$

According to the principle of linear superposition, the following is obtained:

$$\Delta F_A = \Delta F_{AA} + \Delta F_{AB} + \Delta F_{AC} + \Delta F_{AD} \quad (5)$$

$$\Delta F_B = \Delta F_{BA} + \Delta F_{BB} + \Delta F_{BC} + \Delta F_{BD} \quad (6)$$

$$\Delta F_C = \Delta F_{CA} + \Delta F_{CB} + \Delta F_{CC} + \Delta F_{CD} \quad (7)$$

$$\Delta F_D = \Delta F_{DA} + \Delta F_{DB} + \Delta F_{DC} + \Delta F_{DD} \quad (8)$$

By solving simultaneous equations, we obtain the following:

$$\begin{pmatrix} \Delta F_A \\ \Delta F_B \\ \Delta F_C \\ \Delta F_D \end{pmatrix} = \begin{pmatrix} K_{AA} & K_{AB} & K_{AC} & K_{AD} \\ K_{BA} & K_{BB} & K_{BC} & K_{BD} \\ K_{CA} & K_{CB} & K_{CC} & K_{CD} \\ K_{DA} & K_{DB} & K_{DC} & K_{DD} \end{pmatrix} \begin{pmatrix} \Delta_A \\ \Delta_B \\ \Delta_C \\ \Delta_D \end{pmatrix} \quad (9)$$

$$\Delta F = K \cdot \Delta \quad (10)$$

where ΔF is the lifting-point load change matrix, K is the lifting-point relative stiffness matrix, and Δ is the lifting point displacement matrix. The load change ΔF caused by the relative displacement Δ between lifting points is largely related to the relative stiffness K between lifting points. In addition to its own displacement, the displacements of other lifting points cause changes in the load of this lifting point, and the magnitude of the load change entirely depends on the relative stiffness matrix between lifting points.

When extended to the case of n lifting points, the relationship between the lifting point load F and lifting point displacement Δ is as follows:

$$\begin{pmatrix} \Delta F_1 \\ \Delta F_2 \\ \vdots \\ \Delta F_n \end{pmatrix} = \begin{pmatrix} K_{11} & K_{12} & \cdots & K_{1n} \\ K_{21} & K_{22} & \cdots & K_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ K_{n1} & K_{n2} & \cdots & K_{nn} \end{pmatrix} \cdot \begin{pmatrix} \Delta_1 \\ \Delta_2 \\ \vdots \\ \Delta_n \end{pmatrix} = K \cdot \Delta \quad (11)$$

The relative stiffness matrix of lifting points established in this study is based on the principle of linear superposition, which is applicable to small deformations and elastic materials. When large deformations or material plasticity occurs in a structure, the effects of geometric nonlinearity and material nonlinearity become significant, and linear superposition no longer holds true; therefore, this stiffness matrix must be modified before use.

2 Synchronous Lifting Simulation

2.1 Project Overview

The hall of a certain hangar has a building area of 17,065 m², a span of 136 m, and a depth of 68 m; thus, it belongs to the category of large-span roof buildings with a span greater than 120 m. The roof is composed of a giant door truss and a roof space frame. The giant door truss comprises two three-story steel box trusses with a height of 12.2 m. The roof adopts a two-layer orthogonal diagonal space frame with welded hollow spherical joints, and the height of the space frame is 5 m. Both the giant door truss and roof space frame use fixed spherical hinge bearings, and the supporting system comprises reinforced concrete bent columns + double channel steel intercolumn braces. The hangar roof structure adopts an integral lifting construction scheme, with a total lifting weight of approximately 1,275 t and a lifting height of approximately 25 m.

2.2 Lifting Point Layout Scheme

For a large-span over-limit hangar, lifting points can be set at the top of permanent structural columns, and temporary lifting points must be set in the middle of the giant door truss. A total of 21 lifting points, numbered B1–B21, are proposed for lifting this hangar, as shown in Figure 3. Among them, lifting point B11 is a temporary column-top lifting point for the giant door truss, and the rest are permanent structural column-top lifting points.

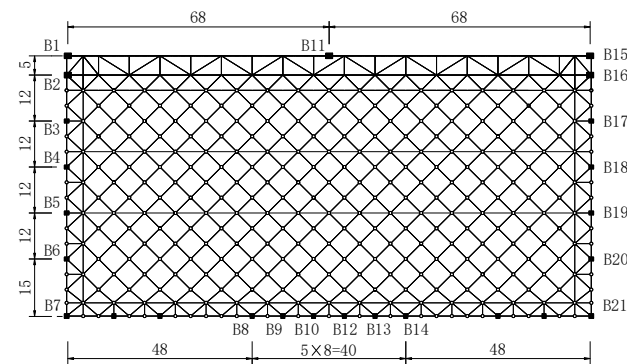


Figure 3 Schematic diagram of hangar lifting points (unit: m)

2.3 Synchronous Lifting Calculation Model

Based on the results of the theoretical analysis and the conditions of the hangar roof space frame lifting project, the MIDAS GEN 2024 software is used to establish a structural integral lifting construction simulation model, as shown in Figure 4.

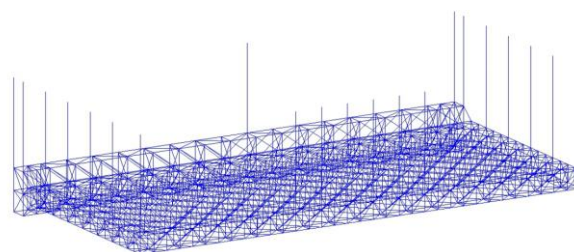


Figure 4 Synchronous lifting calculation model

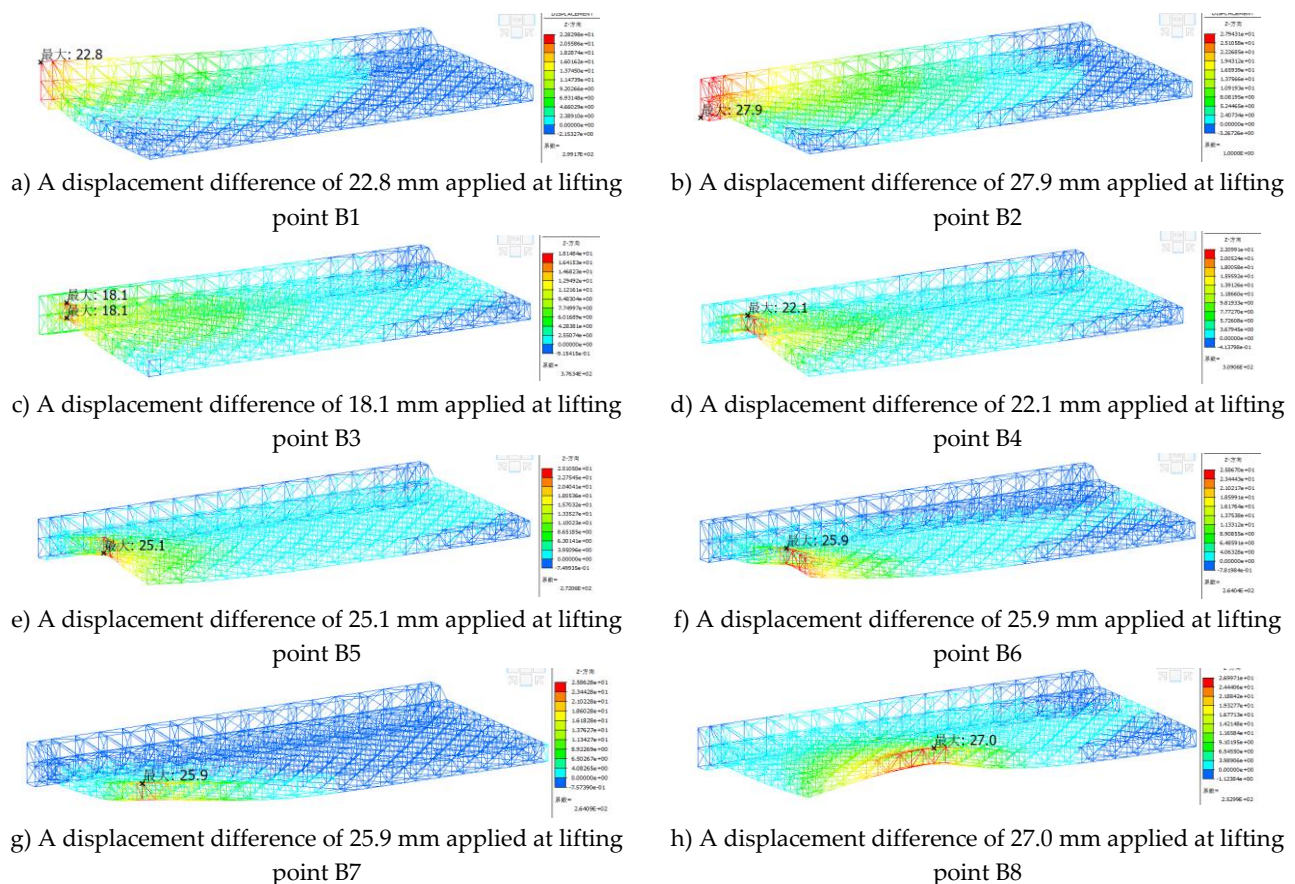
In the model, steel strand elements are established between the upper and lower lifting points, and the top of the steel strands is constrained in D_x , D_y , D_z , R_x , R_y , and R_z . Rotational constraints at both ends of the steel strands are released, and they are set as tension-only truss elements. The length of the steel strands is adjusted through temperature values, thereby adjusting the displacement of the lower lifting points. When the displacements of all lower lifting points approach

zero, the temperature values and lifting point loads are extracted to serve as the initial state of synchronous lifting. In the model, the steel-strand truss element can equivalently simulate the prestressed steel strand lifting cables. Initial state calculation achieves pretensioning of the steel strands through temperature loading, simulating the actual construction process of applying initial prestress to the steel strands and eliminating cable relaxation, reflecting the cooperative mechanical characteristics between the prestressed cables and the main structure.

3 Analysis of Asynchrony Effects

3.1 Analysis of Displacement Asynchrony Effects

According to the *Technical Specification for Space Frame Structures* [9], when hollow hydraulic jacks are used to lift space grid structures, the permissible difference in elevation between adjacent lifting points is 1/250 of the distance between adjacent points, and it should not exceed 25 mm. Based on the synchronous lifting state, the temperature of the steel strands at each lifting point is precisely adjusted to generate a displacement of approximately 25 mm to simulate the displacement asynchrony effect. Owing to the low stiffness of the large-span space frame structure, precisely applying a lifting-point displacement difference of 25 mm requires extensive iterative calculations. Given that the displacement difference does not alter the distribution pattern of relative stiffness among lifting points, this study is based on the effect of a difference in lifting point displacement of approximately 25 mm. The vertical deformation of the hangar space frame is extracted, and the results are shown in Figure 5. Because the structure is fundamentally symmetrical, only the vertical deformation calculation results for lifting points B1–B11 are presented. As shown in the figure, applying a displacement difference to a certain lifting point affects only the deformation of the space frame in the nearby area and has little effect on the deformation of the space frame at farther distances.



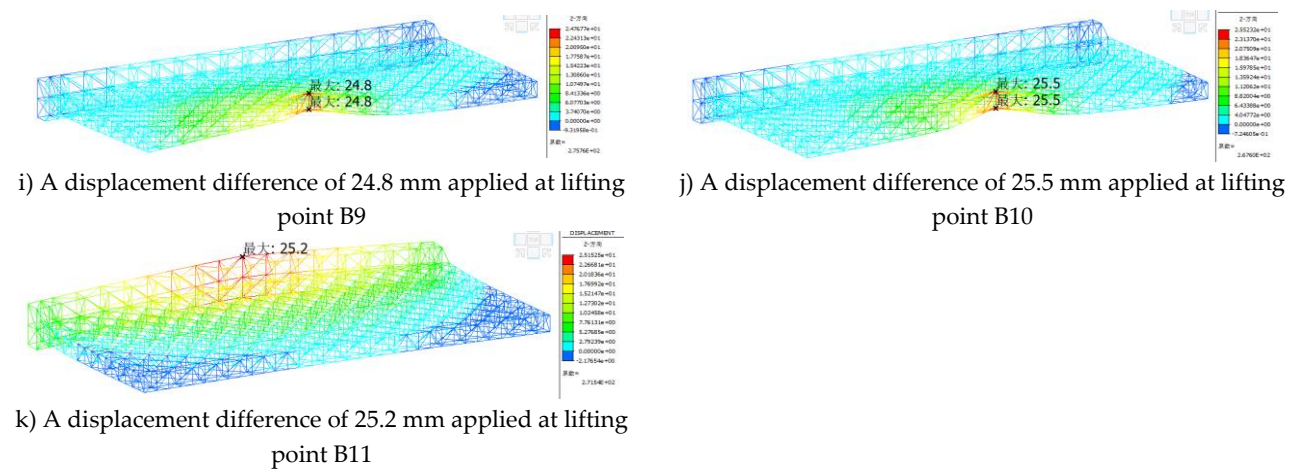


Figure 5 Vertical deformation when a displacement difference of approximately 25 mm is applied at various lifting points (unit: mm)

Under displacement asynchrony conditions, the load changes at various lifting points are extracted, and the results are presented in Table 1. Data presented in bold represent the lifting point load values with a change exceeding 10% after the displacement difference is applied. The lifting points with a load change exceeding 10% are all located near the lifting point at which the displacement difference is applied; meanwhile, the load changes in lifting points at farther distances are minimal.

Table 1 Load conditions at various lifting points during synchronous lifting and when a displacement difference of approximately 25 mm exists at a single lifting point (unit: kN)

Lifting point number	Synchronous lifting point load	Lifting points with an approximate displacement difference of 25 mm applied										
		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	534	909	261	492	532	541	542	538	537	536	537	458
B2	1,895	1,610	2,441	1,768	1,845	1,882	1,896	1,900	1,893	1,894	1,895	1,790
B3	985	943	863	1,315	905	950	972	986	983	984	984	969
B4	1,136	1,133	1,070	1,026	1,373	1,011	1,076	1,127	1,134	1,134	1,134	1,136
B5	421	425	413	398	362	689	365	404	417	418	419	425
B6	387	393	389	377	353	319	583	344	375	382	386	393
B7	201	206	208	202	193	171	137	275	178	194	201	207
B8	1,510	1,514	1,508	1,506	1,508	1,501	1,487	1,481	1,721	1,292	1,379	1,511
B9	433	434	432	432	432	430	429	429	349	840	351	432
B10	362	363	363	362	362	361	361	362	321	296	776	362
B11	4,889	4,748	4,704	4,859	4,890	4,900	4,902	4,898	4,890	4,888	4,887	5,275

3.2 Analysis of Load Asynchrony Effects

Based on the synchronous lifting state, the temperature of the steel strands at each lifting point is adjusted. According to specifications for synchronous construction of large-scale structures [17], a 10% load change is generated at each lifting point to simulate the load asynchrony effect. The vertical deformation of the hangar space frame is extracted, and the results are shown in Figure 6. After the load change at a certain lifting point, only the follow-up deformation of the space frame in the nearby area of the lifting point is relatively large, whereas the follow-up deformation of the space frame at farther distances is small. The load changes at each lifting point under these conditions are listed in Table 2, in which data presented in bold represent lifting points with a load change exceeding 10%.

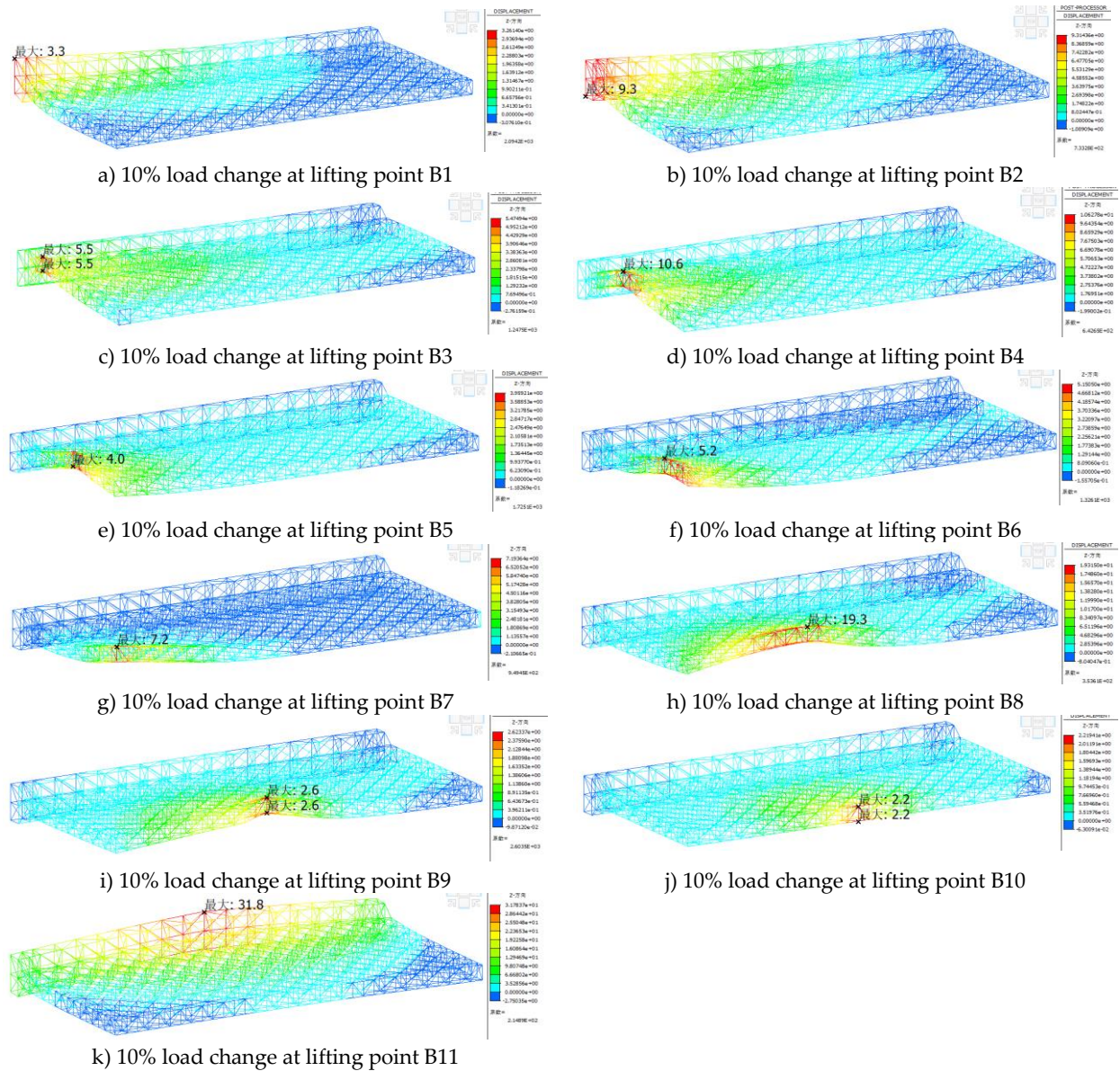


Figure 6 Vertical deformation when a 10% load change is applied at various lifting points (unit: mm)

Table 2 Load conditions at various lifting points during synchronous lifting and when a 10% increase in load occurs at a single lifting point (unit: kN)

Lifting point number	Synchronous lifting point load	Lifting points with a 10% increase in load applied										
		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	534	590	446	524	536	538	538	538	538	537	537	440
B2	1,895	1,858	2,081	1,861	1,875	1,897	1,899	1,900	1,898	1,899	1,899	1,767
B3	985	982	947	1,087	949	982	985	988	986	988	988	967
B4	1,136	1,139	1,118	1,106	1,253	1,120	1,127	1,137	1,138	1,139	1,139	1,140
B5	421	423	419	415	394	464	411	417	419	422	422	427
B6	387	390	389	385	372	378	428	377	380	388	389	396
B7	201	203	205	203	199	198	190	223	186	202	202	210
B8	1,510	1,515	1,514	1,513	1,513	1,513	1,510	1,506	1,665	1,491	1,503	1,516
B9	433	434	434	434	434	434	433	433	374	477	427	434
B10	362	364	364	363	363	363	363	364	334	357	400	363
B11	4,889	4,881	4,840	4,892	4,902	4,903	4,904	4,904	4,902	4,901	4,901	5,389

4 Synchronous Lifting Control Strategy

4.1 Analysis of Relative Stiffness Between Lifting Points

In displacement asynchrony analysis, displacement asynchrony at a lifting point causes load changes at other lifting points. In load asynchrony analysis, load asynchrony at a lifting point also causes displacement changes at other lifting points. By calculating the ratio of the load change to the displacement change between lifting points, the relative stiffness matrix between lifting points can be obtained, as shown in Table 3. Taking $K_{11} = 16.4$ kN/mm as an example, the calculation process is as follows: In Table 2, the reaction force change at lifting point B1 is $909-534 = 375$ kN, and the difference in the forced displacement relative to the synchronous lifting state is 22.8 mm. Therefore, the relative stiffness of lifting point B1 is $375/22.8 = 16.4$ kN/mm. Because the actual hangar roof is a truss-space frame composite system, the structure is not completely symmetrical, and the stiffness coupling effects between lifting points are different; therefore, the relative stiffness matrix exhibits asymmetrical characteristics.

Table 3 Calculation of relative stiffness between lifting points under asynchrony effects (unit: kN/mm)

Lifting point number	Lifting points generating displacement asynchrony or load asynchrony										
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	16.4	-10.0	-2.7	-0.1	0.3	0.3	0.2	0.1	0.1	0.1	-3.0
B2	-12.4	20.1	-8.2	-2.3	-0.5	0.1	0.2	-0.1	0.0	0.0	-4.1
B3	-1.8	-4.5	21.4	-3.7	-1.4	-0.5	0.0	-0.1	-0.1	-0.1	-0.6
B4	-0.1	-2.4	-7.2	10.7	-5.0	-2.3	-0.4	-0.1	-0.1	-0.1	0.0
B5	0.2	-0.3	-1.5	-2.7	10.7	-2.2	-0.6	-0.2	-0.1	-0.1	0.1
B6	0.3	0.0	-0.7	-1.6	-2.7	7.6	-1.7	-0.5	-0.2	-0.1	0.2
B7	0.2	0.2	0.0	-0.4	-1.2	-2.5	2.9	-0.9	-0.3	0.0	0.2
B8	0.2	-0.1	-0.2	-0.1	-0.4	-0.9	-1.1	8.0	-8.9	-5.2	0.0
B9	0.1	0.0	-0.1	0.0	-0.1	-0.1	-0.1	-3.2	16.6	-3.2	0.0
B10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.6	-2.7	16.3	0.0
B11	-6.2	-6.8	-2.0	0.0	0.4	0.5	0.4	0.0	0.0	-0.1	15.1

Table 4 Relative stiffness between lifting points considering distance-weighted average (unit: kN/mm)

Lifting point number	Lifting points generating displacement asynchrony or load asynchrony										
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	16.4	9.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
B2	12.3	20.1	2.8	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.4
B3	0.5	1.7	21.4	1.1	0.3	0.1	0.0	0.0	0.0	0.0	0.1
B4	0.0	0.5	2.4	10.7	1.5	0.5	0.0	0.0	0.0	0.0	0.0
B5	0.0	0.0	0.3	0.8	10.7	0.7	0.1	0.0	0.0	0.0	0.0
B6	0.0	0.0	0.1	0.2	0.8	7.6	0.5	0.0	0.0	0.0	0.0
B7	0.0	0.0	0.0	0.0	0.2	0.7	2.9	0.1	0.0	0.0	0.0
B8	0.0	0.0	0.0	0.0	0.0	0.1	0.1	8.0	2.8	1.9	0.0
B9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	16.6	2.3	0.0
B10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.8	16.3	0.0
B11	0.5	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.1

In Table 3, data presented in bold represent lifting points with a relative stiffness greater than 5 kN/mm; these lifting points are those that are essentially close to each other and those that are giant-door-truss lifting points. Taking

giant-door-truss lifting points B1 and B2 as an example, $K_{21} = 12.4$ kN/mm. When lifting point B1 generates a displacement difference of 10 mm, a 124 kN load change occurs at lifting point B2. This finding indicates that lifting points B1 and B2 are highly sensitive to displacement asynchrony, necessitating very high precision of control for the relative displacement difference between B1 and B2 during the lifting process, which is difficult to achieve in actual construction. Therefore, when the relative stiffness between lifting points is large, adopting load synchronization is a better control strategy.

As shown in Table 3, the relative stiffness between each lifting point and its closer lifting point is relatively large, whereas the relative stiffness between it and a farther lifting point decreases significantly, generally less than 1.0 kN/mm. This further demonstrates that the relative stiffness of lifting points is closely related to the distance between them. Taking space frame nodes B3 and B9 as an example, the distance between the two lifting points is 76 m, and the relative stiffness is $K_{93} = 0.1$ kN/mm. This means that a displacement difference of 100 mm between lifting points B3 and B9 would result in a load asynchrony of only 10 kN. Therefore, the two are not sensitive to displacement asynchrony, and their mutual influence is very weak when a displacement difference exists. Thus, when the relative stiffness between lifting points is small, adopting displacement synchronization is a better control strategy.

4.2 Distance-Weighted Modification of Relative Stiffness Between Lifting Points

To comprehensively determine a control strategy for a single lifting point, the relative stiffness between lifting points considering a distance-weighted average is calculated, and the results are shown in Table 4. The distance weight coefficient is as follows:

$$\omega_{ij} = \left| \frac{L_{ref}}{L_{ij}} \right| \quad (12)$$

where L_{ref} is the average distance between a single lifting point and other lifting points and L_{ij} is the spatial distance between lifting point i and lifting point j .

The modified relative stiffness of the giant-door-truss lifting points B1 and B2 is greater than 10.0 kN/mm (Table 4); therefore, a load synchronization control strategy should be adopted during construction. For the remaining space-frame lifting points B3–B10, the modified relative stiffness with other lifting points is basically less than 1.0 kN/mm; thus, a displacement synchronization control strategy should be adopted during construction. For the middle lifting point B11 of the giant door truss, the structural stiffness at the lifting point is large, but the distance from B11 to other lifting points is large. After modification, the relative stiffness between B11 and other lifting points is less than 0.5 kN/mm. In actual construction, a dual-objective control strategy of both load and displacement can be adopted.

5 Conclusions

Combined with the synchronous lifting construction requirements of the roof of a large-span over-limit hangar, a comprehensive analysis was conducted on synchronous lifting, displacement asynchrony, load asynchrony, and relative stiffness between lifting points. The results reveal that during integral lifting of large-scale structures, a control strategy primarily based on either load synchronization or displacement synchronization should be adopted according to the relative stiffness between adjacent lifting points and the distance between them. When the relative stiffness between lifting points is large, a control strategy primarily based on load synchronization is suitable; when the relative stiffness between lifting points is low, a control strategy primarily based on displacement synchronization is preferred.

If a lifted structure is relatively simple and the relative stiffness is large, a single load synchronization control strategy can be adopted; if the overall structure is relatively flexible, a displacement synchronization control strategy can be adopted. However, in the integral lifting project of complex large-scale steel structures, such as the composite structure composed of a giant door truss and a roof space frame analyzed in this paper, in which the differences in stiffness among different areas of the structure are large, a dual-objective control must be adopted during construction to ensure safety of the lifting.

Conflict of Interest Statement: The authors declare that there is no conflicts of interest regarding the publication of this paper.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

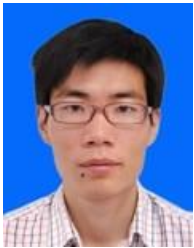
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