Improvement for SPMT in lifting pre-stressed reinforced concrete truss structure and steel-concrete composite truss structure

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Abstract

This paper presents a new SPMT vehicle structure. In order to simulate the actual effect of the new SPMT vehicle structure, based on the calculation assumption of plane truss, this study uses two kinds of plane truss forms to model the reinforced concrete truss and steel-concrete composite truss with different sections, and utilizes Midas software to simulate and analyze. It compares the internal force of different trusses when uses SPMT with steel brackets and ordinary SPMT to jack trusses from joints of lower flange which are not at either end of the truss respectively. Based on the internal force of the trusses, the advantages of using SPMT with steel brackets for jacking and the reliability of the steel brackets are analyzed.

Keywords: SPMT, Midas, steel bracket, reinforced concrete truss, steel-concrete composite truss, jacking operation, tensile stress

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1. Introduction

Due to the increasing traffic pressure in cities at the present stage, the biggest problem encountered in the construction of bridges in cities is no longer the bridge structure itself, but how to minimize the adverse impact of construction on urban traffic. In recent years, accelerated bridge construction (ABC) methods have been developed to reduce traffic disruption (Salem et al. 2018; Yavuz at al. 2017). The ABC method can not only reduce traffic impact and on-site construction time, but also increase safety and construction quality (FHWA, 2008). Self-propelled modular transporter (SPMT) (Culmo et al. 2017) is an important part of ABC method. As a new accelerated bridge construction technology, SPMT method shows many outstanding advantages. On the one hand, it can be used as disassembly machine removes old bridge directly from the original site (Solae, Chorzepa, Durham and Kim, 2020). On the other hand, the prefabricated bridge can be quickly transported to the final position and greatly reduce the impact of traffic jam (Culmo, 2011). The State of Utah in the United States has listed the SPMT method as the recommended construction method and formulated relevant regulations with the SPMT as the core (Utah Department of Transportation, 2008). Therefore, some scholars devote themselves to the study of SPMT vehicles, relevant construction technologies and control procedures, such as fixed coupling mode and loose coupling mode (2020).

However, the SPMT method may affect the integrity and bearing capacity of prefabricated bridges due to the structure of SPMT vehicles when jacking the bridge structure. The beam is a cantilever structure during the jacking operation, because the SPMT method needs to leave enough space at both ends of the precast packaged type simply-supported beam for setting the supports. At this time, tensile stress will appear on the upper flange of the beam in the negative bending region and the stiffness of beam will decrease (Guangli Chang, Yanyu Meng, and Boyu Niu, 2017).

In the paper, it explores a new SPMT vehicle structure which a steel bracket is added to jacking module of the SPMT. Due to the role of steel bracket, when SPMT is used to jack the prefabricated pre-stressed reinforced concrete truss or steel-concrete composite truss, the tensile stress of the upper chords can be reduced. Thus, it can prevent the cracks on the concrete surface caused by the excessive tensile stress during the process of jacking and installation. Besides, it can also ensure the bearing capacity of the truss will not be affected during the jacking and the installation operations.

Nomenclature		Subscripts	
v_q	stable lifting speed [$\mathrm{m\ s^{-1}}$]	min	minimum
f_{cd}	design value of axial compressive strength of concrete [MPa]	max	maximum
f_{td}	design value of axial tensile strength of concrete [MPa]	c	compressive
S	section area of I-beam [$\mathrm{mm^2}$]	t	tensile
t	thickness [mm]	s	steel strand
f	design value of tensile and compressive strength of steel [MPa]		
F_c	compressive force [kN]		
F_t	tensile force [kN]		
f_c	compressive stress [MPa]		
f_t	tensile stress [MPa]		
l	length [m]		
d	diameter [mm]		

A_s	cross section area of steel strand [mm^2]
f_m	maximum tensile stress of top chord [MPa]
F_m	tensile force corresponding to maximum tensile stress of top chord [kN]
P_m	material cost [dollar]
P_c	construction cost [dollar]
P	total cost [dollar]
m_s	required weight of steel strand [kg]
Greek letters	
φ_1	dynamic coefficient of precast concrete members
σ_{t1}	maximum tensile stress of top chord under the most unfavorable condition [MPa]
σ_{t2}	maximum tensile stress of top chord under dead weight [MPa]
σ_1	effective prestress required by structure [MPa]
β_2	grade coefficient of lifting state

2. Simulation of structure jacking process

2.1 Purpose of Simulation

Utilizing Midas software modeling to research the internal force of prestressed reinforced concrete truss and the steel-concrete composite truss when using SPMT with steel brackets and ordinary SPMT to jack trusses as shown in Fig.1. On this basis, it compares the differences of the internal force between using SPMT with steel brackets and using ordinary SPMT when the type of bar section is different.

Fig.1 SPMT jacking truss bridge (2018)

2.2 The process of software simulation

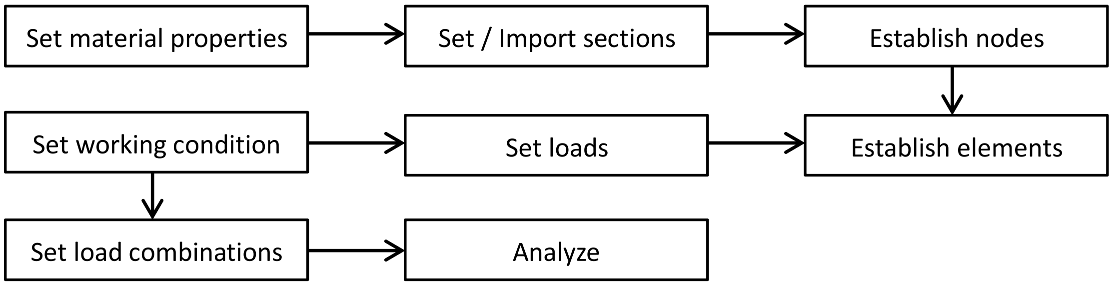

Fig.2 Midas software modeling process

Fig.2 indicates the general modeling process of Midas software. In this modeling, concrete with strength grade C50 was selected. The elastic modulus of concrete, Poisson's ratio, coefficient of linear expansion and bulk density are $3.45 \times 10^7\ \mathrm{kN/m^2}$, 0.2, 1.0×10^{-5}, $25\ \mathrm{kN/m^3}$ respectively (Ministry of housing and urban rural development of the People's Republic of China, 2015). Also, the steel of Q345 is selected in the simulation, its elastic modulus of concrete, Poisson's ratio, coefficient of linear expansion and bulk density are $2.06 \times 10^8\ \mathrm{kN/m^2}$, 0.3, 1.2×10^{-5}, $76.98\ \mathrm{kN/m^3}$ respectively (Ministry of housing and urban rural development of the People's Republic of China, 2015).

After importing different types of the bar section, elements of truss can be established by utilizing the nodes which have already set up in Midas before. In this modeling, two common rectangular plane truss structures are selected for calculating the result of simulation shown in Fig.3 and Fig.4.

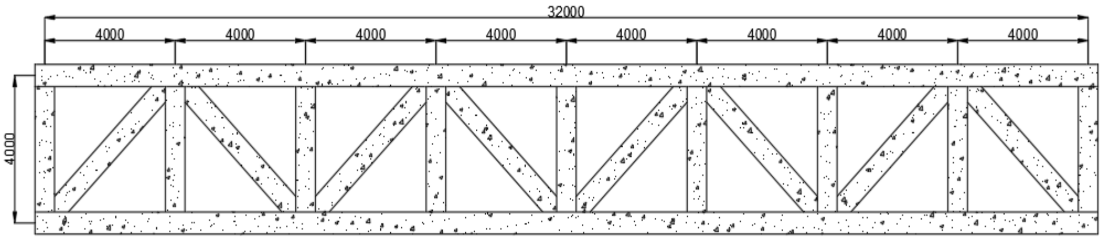

Fig.3 Rectangular plane truss with vertical bar (unit: mm)

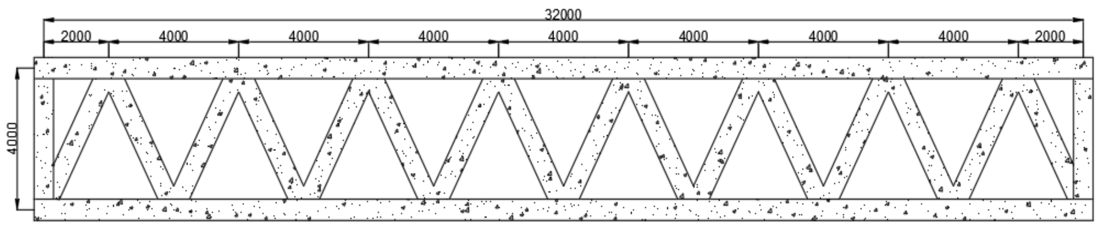

Fig.4 Rectangular plane trusses with few vertical bars (unit: mm)

In this simulation, the length and the height for trusses are 32 m and 4 m respectively. As shown in Fig.3, for the rectangular plane truss with vertical web members, a vertical bar member is arranged every 4 m from the left end of the truss. The diagonal bar members are in the shape of 'Λ', which are arranged by relying on the joints between vertical bar members and chords. There are 4 'Λ' in total, and the length of each diagonal bar member is 5.66 m. For the rectangular plane truss structure with few vertical bar members, only the left and right ends have one vertical bar member, and no other vertical bar members are arranged in the middle of the truss. As shown in Fig.4, each diagonal bar member is 4.47 m long and there are 8 'Λ' in total.

After the truss model is established, the self-weight load is applied to the model according to the bulk density of building materials. During the process of jacking operation, the truss is only affected by its self-weight load, so the internal force and deflection of the structure are analyzed and calculated according to the self-weight load of the structure.

3. Methodology

3.1 Introduction and calculation assumption for plane truss

In engineering, a truss is a structure which consists of two-force members only, where the members are organized so that the assemblage as a whole behaves as a single object (Plesha, Michael E., Gray, Gary L., Costanzo, Francesco, 2013). When the axis of each member is in the same plane and the external force is also in the plane, then the truss called a plane truss (Hibbeler, Russell Charles, 1983).

In the calculation diagram of plane truss, the following assumptions are usually used: ① All members are connected only at their ends by frictionless hinges; ② The axis of each bar in the truss is absolutely straight, and the axis passes through the center of the hinge; ③ The external load on the truss acts on the node and is located in the plane of the truss (Assumptions for Analysis of Trusses, 2020).

In this simulation, Midas software also follows the above basic assumption when models the truss with different bar sections.

3.2 Software limits and length selection for steel bracket of SPMT

Since the modeling object is a truss, according to the calculation assumption of truss, all external forces act on the central plane of truss and act on the joints. In this case, the truss members can be regarded as two-force bars which only transfer the axial force. The support sets at the non-node of the bar only bears the self-weight of the truss, and does not bear the force transmitted by the other bar members.

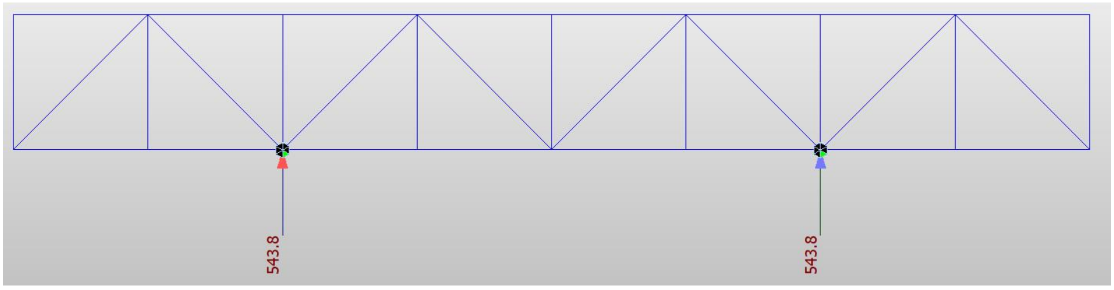

Fig.5 Counter-force of two-point bearing (unit: kN)

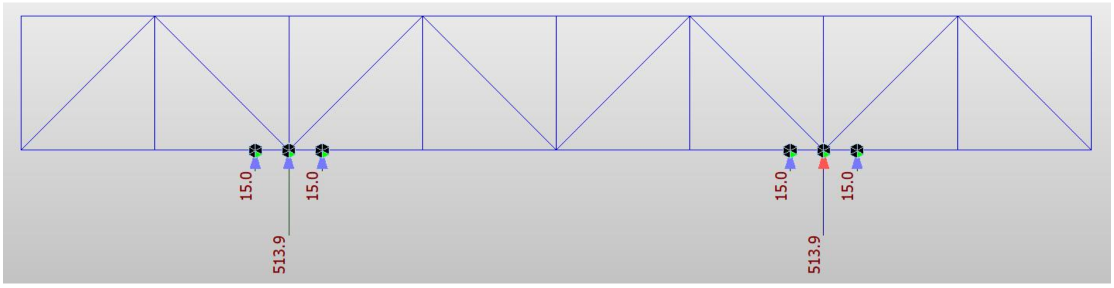

Fig.6 Counter-force of 2-meters long steel bracket (unit: kN)

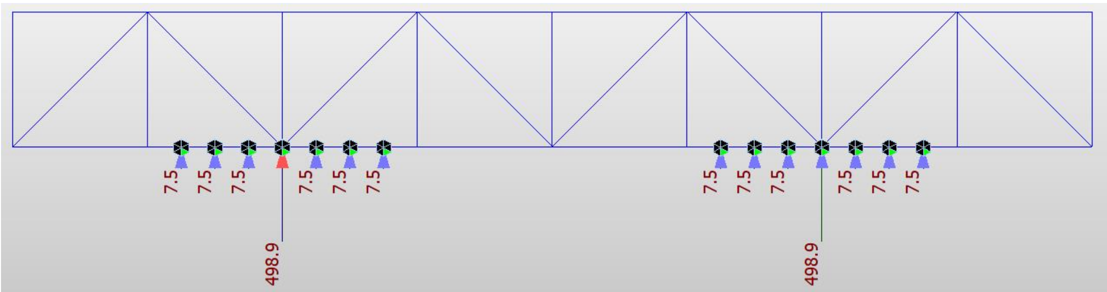

Fig.7 Counter-force of 6-meters long steel bracket (unit: kN)

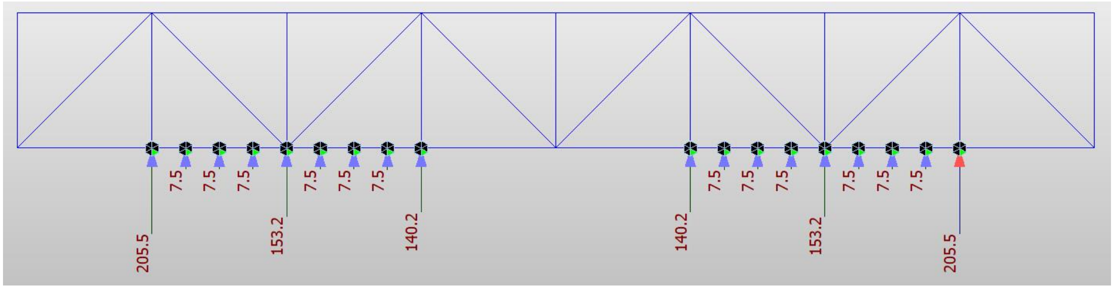

Fig.8 Counter-force of 8-meters long steel bracket (unit: kN)

We select the rectangular plane truss structure with vertical bar members in Fig.3 for modeling. The cross section of the member is $600\ \mathrm{mm} \times 400\ \mathrm{mm}$, and the material is $\mathrm{C50}$ concrete. At this time, the counter-force of the supports at different positions of the truss is shown in Fig.5-8. According to the simulation results, each support between the two nodes of the truss only bears the self-weight of the member and does not bear the effect of other force from other bars.

Due to the limitation of the software, it can not establish a plane support in the truss structure to perfectly simulate the influence of steel bracket on the internal force of the structure. However, considering the basic assumption of plane truss calculation, it can be deduced that the support between the two nodes of the truss only bears the self-weight of the bar member and does not bear the effect of other forces. The truss members can be regarded as two-force bars that only transfer the axial force. Therefore, under the support system shown in Fig.8, the method of multi-point support simulating plane support has no effect on the internal force of truss members. In fact, the main load-bearing point is the support located at the node position, so the method of setting multiple supports and simulating surface support with multi-point support can be used in modeling, and the similar calculation results can be obtained.

Due to the mechanical characteristics of the truss structure and the simulation results in Fig.5-8, in order to make the steel bracket play the role of sharing the counter-force at the truss node, the length of the bearing surface of the steel bracket must cover at least two truss joints. Therefore, in this simulation, the length of the steel bracket is $8\ \mathrm{m}$ which built with $\mathrm{20B}$ I-beam (China National Standardization Administration Committee, 2008) and each steel bracket covers three truss joints. The size of I-beam and the structure of steel bracket are shown in Fig.9 and Fig.10 respectively.

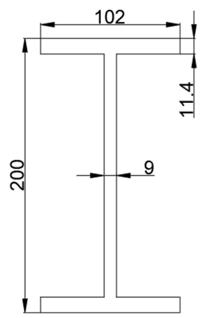

Fig.9 The section of 20B I-beam (unit: mm)

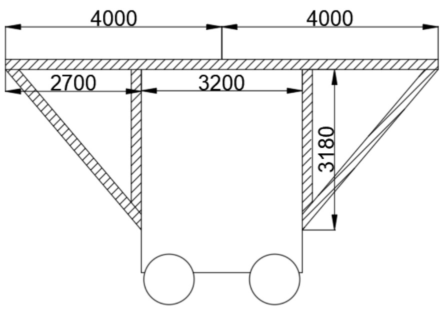

Fig.10 SPMT vehicle structure with steel brackets (unit: mm)

3.3 Calculation assumption of internal force of SPMT vehicle structure with steel brackets

①The SPMT vehicle and jacking module are regarded as fixed rigid bodies.

②The steel bracket is fixed connected to the jacking module of SPMT.

③The assumption of plane truss is used to calculate the internal force of steel brackets.

3.4 Modeling and computational analysis of different bar sections

In this simulation, it considers two kinds of plane truss forms in Fig.3 and Fig.4 and combines with reinforced concrete truss and steel-concrete composite truss when analyzing the structural internal force under different bar sections. During the process of analysis, considering the actual construction processes, it analyzes the internal force of truss in the three stages of jacking, installation and completion respectively. It can compare the influence of the effect of steel brackets on the internal force of the structure. The self-weight effect of the truss only considered in the analysis of the internal force, the specific analysis processes are as follows:

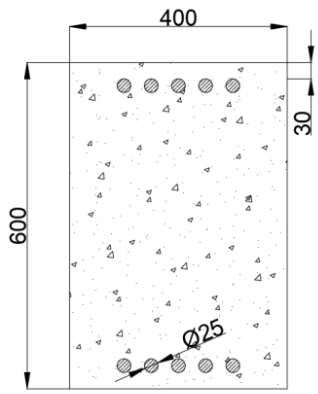

Fig.11 Dimension drawing of truss member with $400\ \mathrm{mm} \times 600\ \mathrm{mm}$ section (unit: mm)

Firstly, the reinforced concrete truss with $400\ \mathrm{mm} \times 600\ \mathrm{mm}$ bar section is modeled, and the rectangular plane truss structure in Fig.3 is selected as the truss form. According to the code for design of concrete structures in China, the concrete strength grade of reinforced concrete structure shall not be lower than C20; the concrete strength grade of prestressed concrete structure shall not be lower than C40 and shall not be lower than C30 for reinforced concrete members bearing repeated load (Ministry of housing and urban rural development of the People's Republic of China, 2015). Therefore, it can be considered the concrete strength grade of this modeling is C50 and the age is 90 days. Five HRB400 steel bars whose diameter are $25\ \mathrm{mm}$ are arranged at both top and bottom concrete member, and the thickness of concrete cover is $30\ \mathrm{mm}$ which shown in Fig.11. HPB300 steel bar with diameter of $10\ \mathrm{mm}$ is selected for stirrup whose spacing is $100\ \mathrm{mm}$.

In this paper, the internal force of prestressed reinforced concrete truss analyzed when SPMT method used for jacking operation when utilizing only two supporting points to support the truss. The analysis results are shown in Fig.12 and Fig.13, respectively.

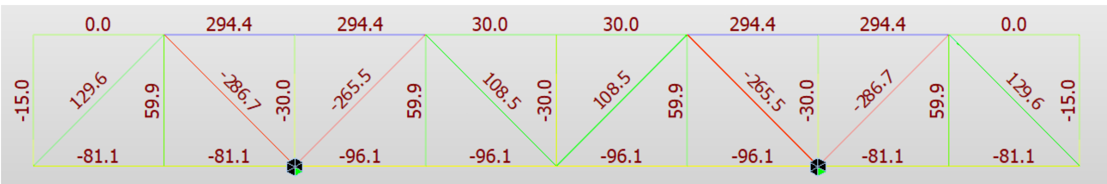

Fig.12 Internal force diagram of truss during jacking operation for two-point support (unit: kN, the negative value represents compression)

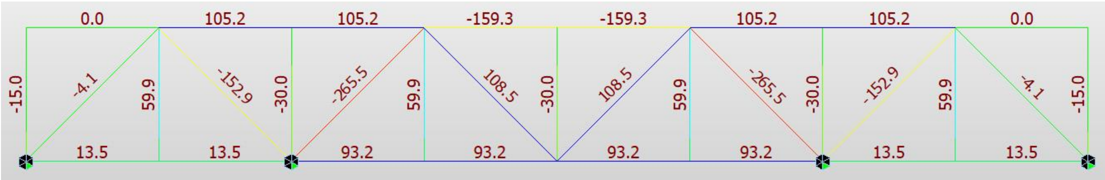

Fig.13 Internal force diagram of truss during installation operation for two-point support (unit: kN, the negative value represents compression)

Secondly, the internal force of the reinforced concrete truss is analyzed when using the SPMT equipped with steel bracket for jacking operation. The analysis results of the structural internal force are shown in Fig.14 and Fig.15.

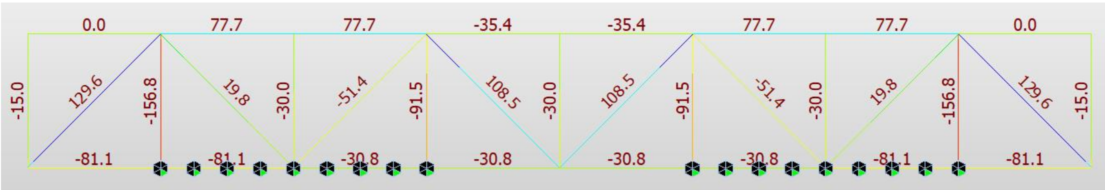

Fig.14 Internal force diagram of truss during jacking operation for multi-points support simulated surface support (unit: kN, negative value represents compression)

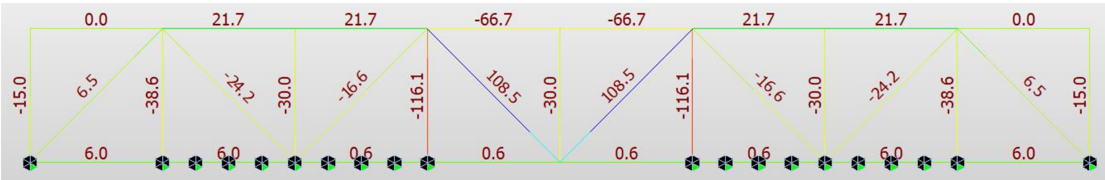

Fig.15 Internal force diagram of truss during installation operation for multi-points support simulated surface support (unit: kN, negative value represents compression)

It is clear to see from the above four graphs that the maximum internal force of the top chord appears in the jacking operation during the process of truss installation. Moreover, all the maximum value is positive value which represents tension. In addition, the comparison of the analysis results in Fig.12 and Fig.14 shows that the installation of steel bracket for SPMT can effectively reduce the tensile force in the top chord.

Finally, the internal force of the reinforced concrete truss under the completion operation is modeled and analyzed by the software, and the analysis results are shown in Fig.16.

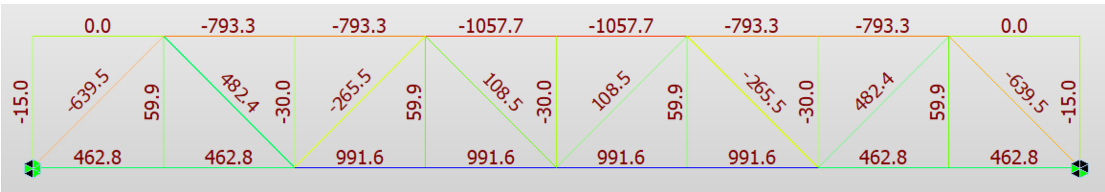

Fig.16 Internal force diagram of truss for completion operation (unit: kN, negative value represents compression)

The result of simulation illustrates it is no tensile force in the top chord of the simply supported truss in completion operation which can be seen in Fig.16. Combining with the internal force of jacking operation and installation operation shown from Fig.12 to Fig.15, this proves it has a structural conversion from cantilever structure to simply supported structure during the construction of the beam.

Depending on the method of changing the section of truss member, the maximum value of tensile force of top chord with different section during jacking operation can be obtained, as shown in Table 1 and Table 2. In the table, the strength grade of concrete is considered as C50, the reinforcement used is taken as HRB400, and the steel used for steel-concrete composite truss selects Q345.

Table 1

Maximum tensile force of upper chord of different reinforced concrete truss (unit: kN)

Rectangular plane truss with few vertical web members				Rectangular plane truss with vertical bar members				Type of truss	
Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	Upper and lower chord: 400mm × 600mm reinforced concrete member Web member: 400 mm diameter reinforced concrete column	400 mm × 600 mm reinforced concrete member	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	Upper and lower chord: 400mm × 600mm reinforced concrete member Web member: 400 mm diameter reinforced concrete column	400 mm × 600 mm reinforced concrete member	Type of bar	
306.9	203.9	224.5	317.4	290.6	190.8	210.8	294.4	Jacking operation	Using common SPMT
80.0	65.2	68.8	109.7	75.4	62.1	65.3	105.2	Installation operation	
89.2	61.1	66.7	97.1	95.2	56.0	64.0	77.7	Jacking operation	Using SPMT with steel bracket
15.5	12.6	13.3	21.3	17.5	13.6	14.6	21.7	Installation operation	
/	/	/	/	/	/	/	/	Completion operation	

Table 2

Maximum tensile force of top chord of different steel-concrete composite truss (unit: kN)

Type of truss	Type of bar	Using common SPMT		Using SPMT with steel bracket		Completion operation
		Jacking operation	Installation operation	Jacking operation	Installation operation	
Rectangular plane truss with few vertical web members	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	317.1	108.2	92.5	20.9	/
	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	214.1	80.5	64.5	15.8	/
	Upper and lower chord: 400 mm × 600 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	234.7	86.7	70.1	16.9	/
Rectangular plane truss with vertical bar members	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	299.8	102.0	84.8	21.5	/
	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	199.9	76.6	47.6	14.5	/
	Upper and lower chord: 400 mm × 600 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	219.9	82.3	55.1	16.1	/

Table 3

Maximum tensile stress of upper chord of different reinforced concrete truss (unit: MPa)

Type of truss	Truss number	Type of bar	Using common SPMT	Using SPMT with steel bracket	Completion operation
Rectangular plane truss with vertical web members	1	400 mm × 600 mm reinforced concrete member	1.23	0.32	/
	2	Upper and lower chord: 400mm × 600mm reinforced concrete member Web member: 400 mm diameter reinforced concrete column	0.88	0.27	/
	3	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	0.95	0.28	/
	4	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	0.73	0.24	/
Rectangular plane truss with few vertical web members	5	400 mm × 600 mm reinforced concrete member	1.32	0.40	/
	6	Upper and lower chord: 400mm × 600mm reinforced concrete member Web member: 400 mm diameter reinforced concrete column	0.94	0.28	/
	7	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	1.02	0.31	/
	8	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter	0.77	0.22	/
Maximum			1.32	0.40	/

Table 4

Maximum tensile stress of upper chord of different steel-concrete composite truss (unit: MPa)

Type of truss	Truss number	Type of bar	Using common SPMT	Using SPMT with steel bracket	Completion operation
Rectangular plane truss with vertical web members	1	Upper and lower chord: 400 mm × 600 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	0.92	0.23	/
	2	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	1.00	0.24	/
	3	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	0.75	0.21	/
Rectangular plane truss with few vertical web members	4	Upper and lower chord: 400 mm × 600 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	0.98	0.29	/
	5	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	1.07	0.32	/
	6	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm	0.79	0.23	/
Maximum			1.07	0.32	/

Since the size of section members has been determined, the maximum value of tensile stress for trusses can be calculated from the known maximum tensile force of the upper chord in Table 1 and Table 2. The maximum value of tensile stress for upper chord of different trusses shows in Table 3 and Table 4.

According to the code for design of concrete structures in China, the self-weight of precast concrete members shall be multiplied by the corresponding dynamic coefficient: for demoulding, overturning, hoisting and transportation, the dynamic coefficient can be taken as 1.5, and for temporary fixation, it can be taken as 1.2 (Ministry of housing and urban rural development of the People's Republic of China, 2015). It is because when the object is lifted off the ground without restraint, the inertia force of the object will increase the dynamic load of the lifting load, (China National Standardization Management Committee, 2008). In this study, the truss is prefabricated, so the dynamic coefficient φ_1 can be taken as 1.5 .

Combining with Design Rules for Cranes in China, the dynamic effect is taken by the dynamic coefficient multiplied by the self-weight effect of the structure (China National Standardization Management Committee, 2008). Under the most unfavorable condition, the jacking operation needs to consider both the self-weight of the truss and the inertial force of SPMT. Thus, maximum tensile stress of top chord under the most unfavorable condition σ_{t1} can be obtained as:

$$\sigma_{t1} = \sigma_{t2} \times \varphi_1 \tag{1}$$

According to code for Design of Concrete Structures in China, the value of f_{td} for $\mathrm{C50}$ can be consider as $1.83\ \mathrm{MPa}$ (Ministry of housing and urban rural development of the People's Republic of China, 2015). Combined with Table 3 and Table 4, it can be seen that if SPMT only uses two-point support for jacking operation, the tensile stress of the upper chord of truss will be close to the maximum tensile stress specified by the code which can be borne by the structure. Even for the truss with $400\ \mathrm{mm} \times 600\ \mathrm{mm}$ cross-section as members which has few vertical web members in Table 3, the maximum tensile stress of the top chord exceeds the design value of tensile strength under the most unfavorable conditions, which can be seen as:

$$\sigma_{t1} = \sigma_{t2} \times \varphi_1 = 1.32 \times 1.5 = 1.98\ \mathrm{MPa} > 1.83\ \mathrm{MPa} = f_{td} \tag{2}$$

Because of the low tensile strength of concrete, cracks will appear on the surface of reinforced concrete members even when the external force is not very large. Moreover, when the component cracks, the concrete at the crack section will completely withdraw from the work (Ye, 2014). According to the results of simulation, it can be considered the top chord is only affected by tensile stress during the jacking operation and only affected by compressive stress during the completion operation. So when σ_{t1} approach or even greater than f_{td}, the concrete surface is easy to induce cracks, which reduces the actual compressive area of concrete in the completion operation. Thus, it will reduce the bearing capacity of truss members.

3.5 Reliability of SPMT steel bracket

Because of the calculation assumption of plane truss, both of the load of truss and support reaction force act on the joint. It can be seen from Fig.7 that the support between two nodes only bears the self-weight of one member and its reaction force is far less than the support reaction at the nodes. Moreover, when use vertical web member with $400\ \mathrm{mm} \times 600\ \mathrm{mm}$ section in simulation, Fig.17 and Fig.18 indicate that whether there are other supports between the two nodes does not affect the value of the internal force for the truss. Therefore, when verifying the reliability of the SPMT steel bracket and only consider the support on the node, the calculation can be simplified by attributing the weight of the members between the two nodes to the support at the joint point.

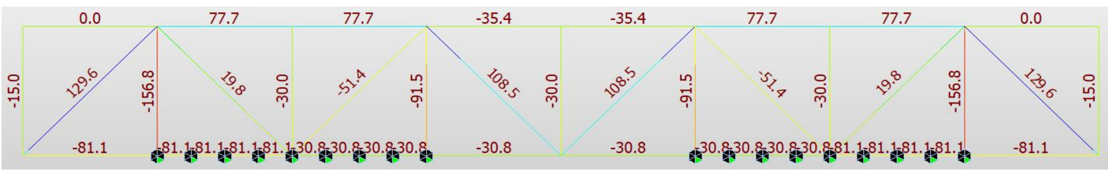

Fig.17 Internal force of truss with multi-point support (unit: kN, negative value represents compression)

Fig.18 Internal force of truss with only supporting truss joints (unit: kN, negative value represents compression)

In this research, the maximum reaction force of the joint support is the reinforced concrete truss with $400\ \mathrm{mm} \times 600\ \mathrm{mm}$ section with few vertical web members as shown in Table 3. The joint reaction force for the supports are shown in Fig. 19.

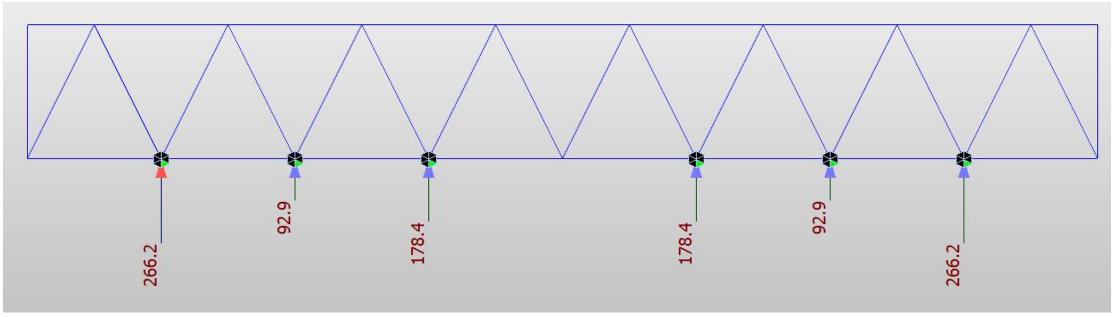

Fig. 19 Reaction force at joints of reinforced concrete truss with $400\ \mathrm{mm} \times 600\ \mathrm{mm}$ section with few web members (unit: kN, negative value represents compression)

Since the SPMT jacking module was assumed to be a rigid body, the steel bracket was fixed on the jack up module, and the steel bracket was built with 20B I-beam. It uses Midas to simulate the steel bracket and applied the reaction force of the supports shown in Fig.19 to the steel bracket. The analysis result for the internal force of the steel bracket can be seen in Fig.20.

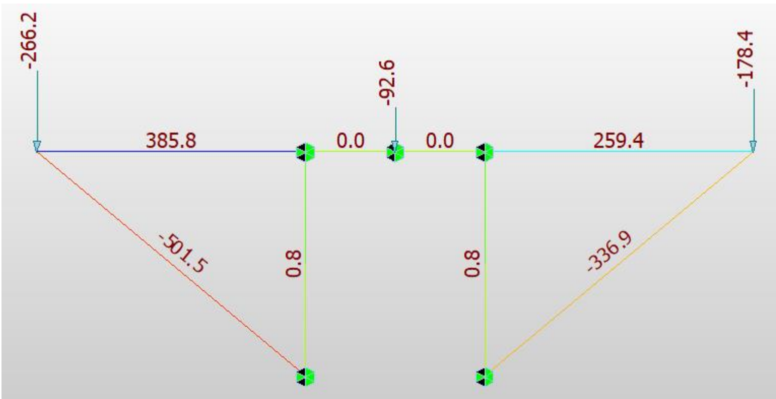

Fig.20 Internal force diagram of steel bracket after bearing reaction force at joint point (unit: kN, negative value represents compression)

In this simulation, it can know the total length of the steel bracket is $8\ \mathrm{m}$ from Fig.10. 20B I-beam with steel grade of Q345 is used for construction whose section area S is $3920.4\ \mathrm{mm}^2$. The cross section of 20B I-beam and the structure of SPMT with steel bracket are shown in Fig.9 and Fig.10. Considering Standard for Design of Steel Structures in China, for Q345 low alloy high strength structural steel, the value of t should be less than or equal to 14mm and the value of f is $305\ \mathrm{MPa}$ (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2017). As can be seen from Fig.20, the maximum value of pressure $F_{c_{max}}$ is $501.5\ \mathrm{kN}$ and maximum value of tension $F_{t_{max}}$ is $385.8\ \mathrm{kN}$. Thus, with the definition of stress (Huston and Josephs, 2009), it can get the maximum compressive stress of I-beam f_c and the maximum tensile stress f_t :

$$f_c = \frac{F_c}{S} = \frac{501.5\times10^3}{3920.4\times10^{-6}} = 127.92\ \mathrm{MPa} < f = 305\ \mathrm{MPa} \quad (3)$$

$$f_t = \frac{F_t}{S} = \frac{385.8\times10^3}{3920.4\times10^{-6}} = 98.41 \text{ MPa} < f = 305 \text{ MPa} \tag{4}$$

All the results are less than the design value of tensile and compressive strength and meet the requirements of design standards in China.

Secondly, the deflection of the truss with the largest reaction force at the joint support is compared with that of the steel bracket with the support reaction force at the joint. As shown in Fig.21 and Fig.22, when the truss adopts two-point support during the jacking operation, the maximum deflection of the structure is 0.001 m, while for the steel bracket with bearing reaction force at the joint, the maximum deflection is 0.003 m. In practical construction, flexible materials such as rubber and wood block are often laid at the joint position, and the SPMT and truss are bound and fixed with steel cable to fill the displacement caused by deflection, so as to ensure that the bearing at the joint of truss and steel bracket plays a role of sharing the weight of truss.

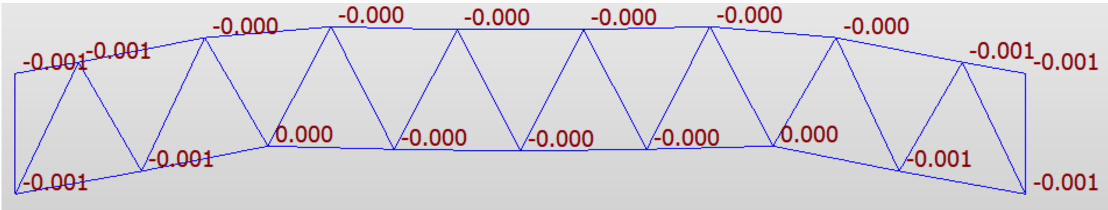

Fig.21 Deflection of each node of truss during jacking operation with two-point support (unit: m)

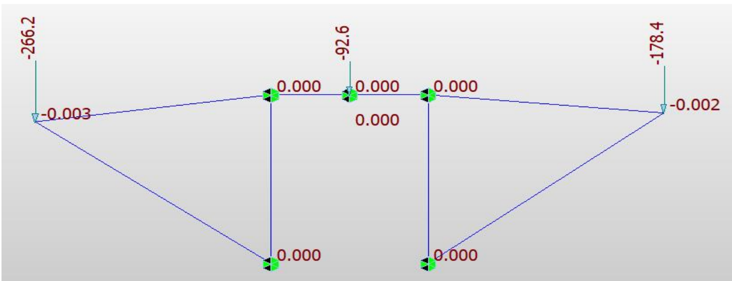

Fig.22 Deflection of each joint of steel bracket after bearing the joint reaction force (unit: m)

The above analysis is based on the fact that only one I-beam is used to support the truss with the largest reaction force at the joint. In Fig.8, the width of bar for 20B I-beam is 102 mm, while the minimum width of bottom chord of each truss in Table 1 and Table 2 is 400 mm. Therefore, in fact, when the width of each bottom chord is 400 mm, the truss can be supported by three 20B I-beams side by side in the transverse direction. Fig.23—26 show the internal force and deflection of the steel bracket obtained by Midas software modeling and analysis when two or three I-beams of 20B are used to share the weight of the truss with the largest reaction force at the joint. It can be seen that the maximum internal force and maximum deflection of I-beam decrease with the increase of the number of I-beams which share the weight of truss transversely. Moreover, when the truss is supported by three or more 20B I-beams in the transverse direction, the maximum deflection is only 0.001 m, which is equal to the maximum value of the joint deflection when the truss is supported by two-point support, so the influence of deflection on the bearing force transfer at the joint can be ignored.

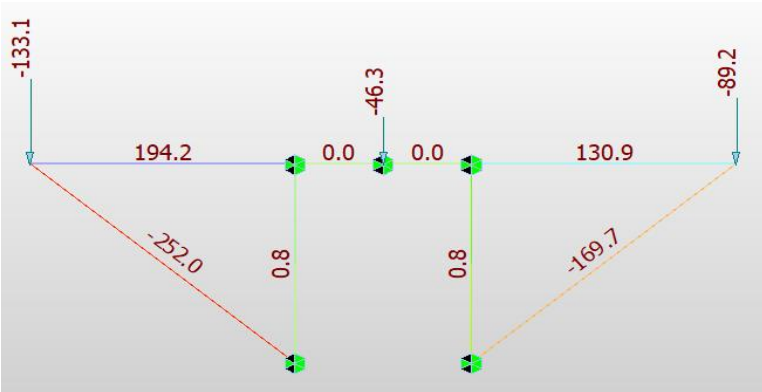

Fig.23 Internal force of one I-beam when two 20B I-beams are arranged side by side horizontally (unit: kN, negative value represents compression)

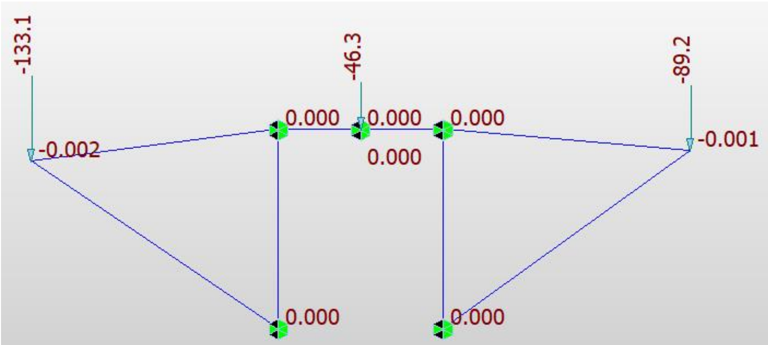

Fig.24 Deflection of one I-beam when two 20B I-beams are arranged side by side horizontally (unit: m, negative value represents vertical downward direction)

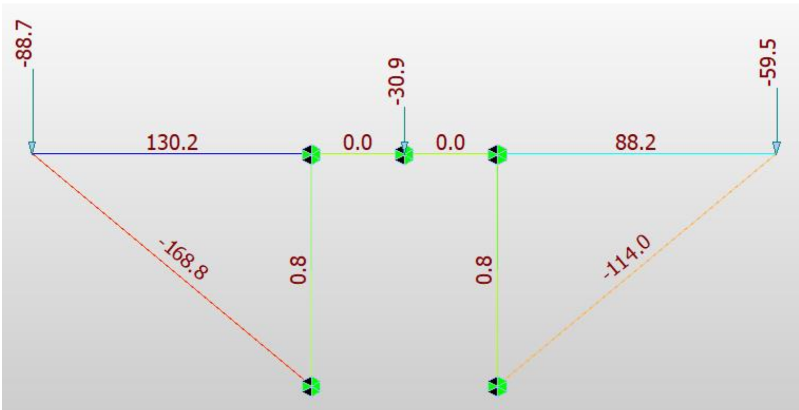

Fig.25 Internal force of one I-beam when three 20B I-beams are arranged side by side horizontally (unit: kN, negative value represents compression)

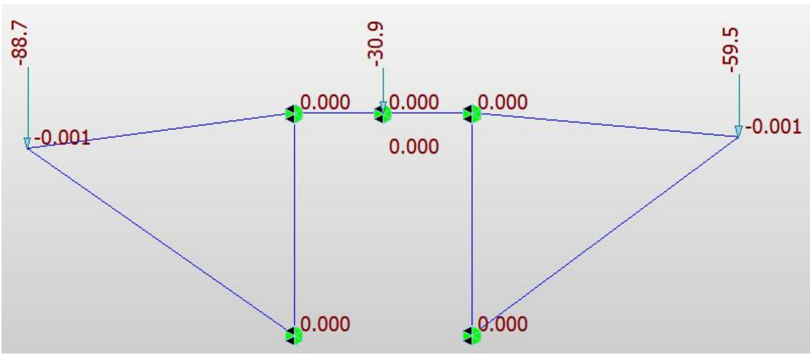

Fig.26 Deflection of one I-beam when three 20B I-beams are arranged side by side horizontally (unit: m, negative value represents vertical downward direction)

Combined with the above analysis, when SPMT steel bracket supports the truss with the largest reaction force at the joint, the maximum tensile stress and compressive stress under the most unfavorable conditions are far less than the $F = 305\ \mathrm{MPa}$. And the deflection difference between the truss and the steel bracket is very small, the maximum is $0.002\ \mathrm{m}$. In the actual jacking operation, the influence can be eliminated by laying flexible materials, so it can be considered that the simulated steel bracket structure is reliable.

4 Advantages, limitations and future work

4.1 Advantages

4.1.1 Reduction of maximum tensile stress on top chord

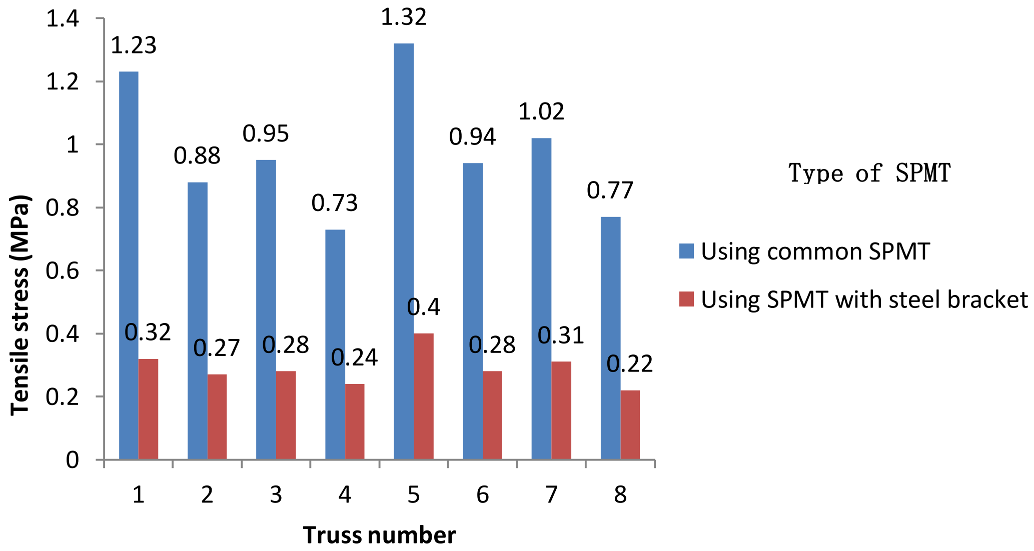

Fig.27 Bar chart of maximum tensile stress of upper chord of SPMT with steel bracket and common SPMT during jacking operation of reinforced concrete truss

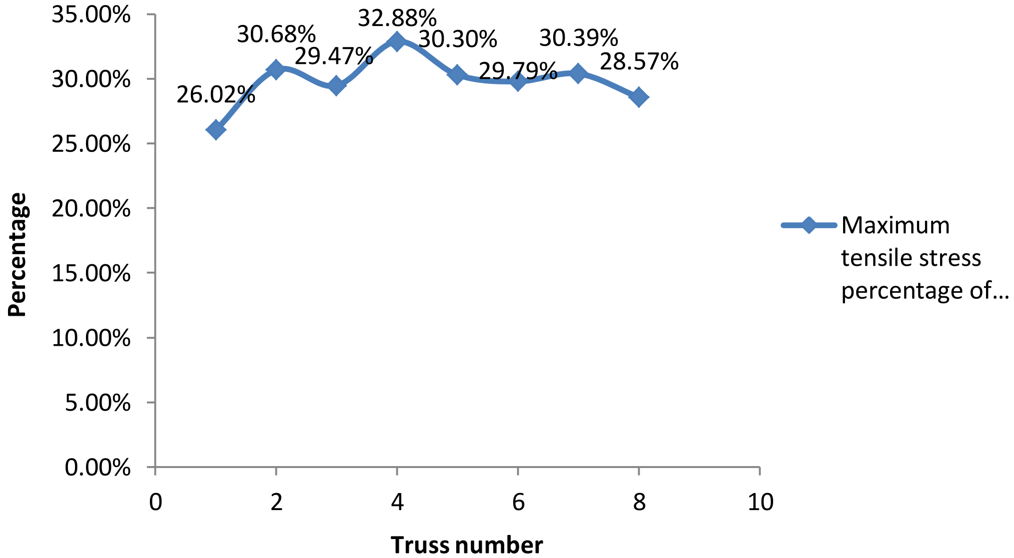

Fig.28 Scatter diagram of maximum tensile stress percentage of upper chord of SPMT with steel bracket and common SPMT during jacking operation of reinforced concrete truss

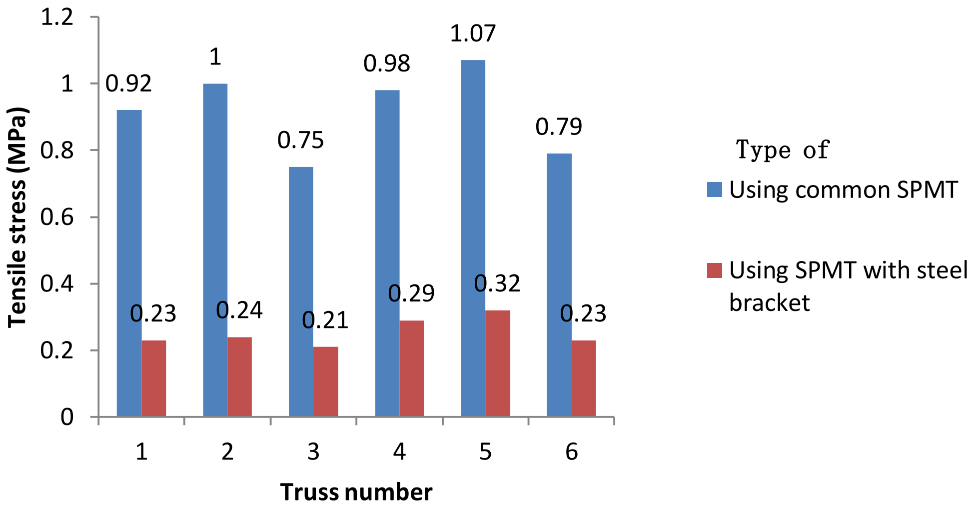

Fig.29 Bar chart of the maximum tensile stress of the top chord of SPMT with steel bracket and common SPMT during jacking operation of steel-concrete composite truss

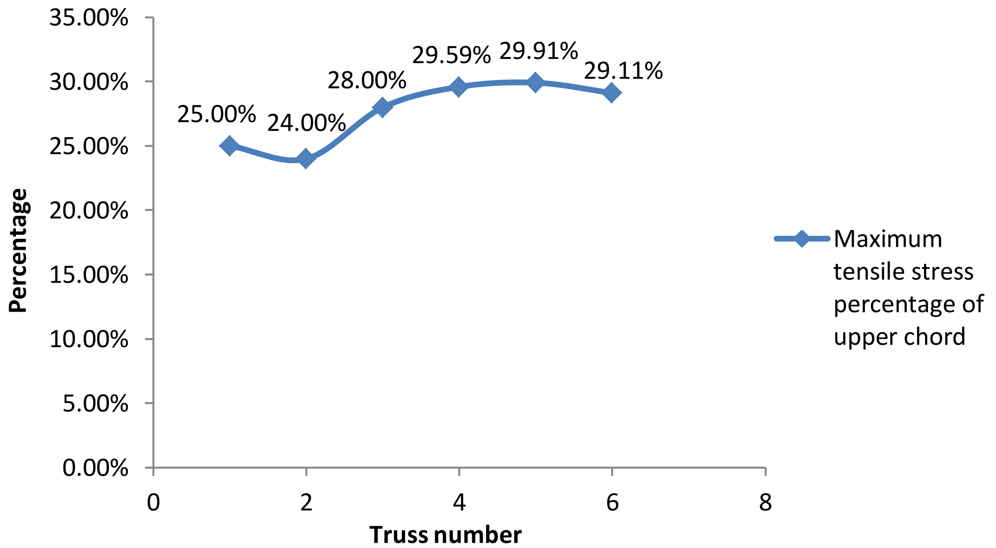

Fig.30 Scatter diagram of maximum tensile stress percentage of upper chord of SPMT with steel bracket and common SPMT during jacking operation of steel-concrete composite truss

Combined with Fig.27—30, it can be seen that when supporting surface of SPMT with steel bracket is covered with the three joints of truss is used for jacking the truss, the maximum tensile stress of upper chord of truss is quite different, and the maximum tensile stress of upper chord in reinforced concrete truss structure is only about 30% of that of common SPMT, and the maximum tensile stress of the top chord of the steel-concrete composite truss is only about 28% of that of the common SPMT. Therefore, when SPMT with steel bracket is used to jack up the truss, the tensile stress on the top chord can be greatly reduced.

4.1.2 Reduction of construction cost

In the actual construction, in order to reduce the concrete surface cracks caused by the tensile stress to the members of truss, a certain amount of prestress is often applied to the tension members to form the prestressed concrete tension members, so as to improve the crack resistance performance of the members of truss (Ye, 2014). According to the above analysis, the beam is cantilever structure during the lifting operation, the hogging moment regions appear adjacent to the supports of the beam. The upper chord of the truss is easy to produce tensile stress due to the negative bending moment. Relevant studies show that the use of external prestressing tendons can reduce the tensile stress of the upper flange of the beam and improve the crack resistance of the beam under negative bending moment (Chen, 2005). Therefore, it is necessary to consider the cost of setting external prestressing tendons in order to prevent tensile stress in the upper chord of truss during jacking operation.

It assumes that temporary external prestressing tendons are set on the upper chord of truss in the original construction process. According to the code in China, the 1×7 steel strands which $f_{pk} = 1860\ \mathrm{MPa}$, $l = 32$, $\mathrm{d} = 15.2\ \mathrm{mm}$ and $\mathrm{A}_s = 139\ \mathrm{mm}^2$, are adopted as temporary external prestressing tendons (Ministry of Transport of the People's Republic of China, 2018). The maximum tensile stress of the upper chord in Table 3 and Table 4 is $f_m = 1.32\ \mathrm{MPa}$ whose tensile force F_m is $317.4\ \mathrm{kN}$. Thus, the tensile stress of the steel strand is as follow:

$$\sigma_1 = \frac{F_m}{\mathrm{A}_s} = \frac{317.4 \times 10^3}{139 \times 10^{-6}} = 2283453\ \mathrm{Pa} \approx 2.28\ \mathrm{MPa} \quad (5)$$

Therefore, if it considers that no tensile stress in the upper chord when the temporary prestressed tendon tensioned, one 1×7 steel strand is required. If the calculation is based on one prestressed tendon, the required weight of steel strands $m_s = l \times 1.101 = 32 \times 1.101 = 35.23\ \mathrm{kg}$. According to the market information, the price of the 1×7 low relaxation steel strands with $\mathrm{d} = 15.2\ \mathrm{mm}$ can be consider as 666 dollar per ton (15.2mm 7 Wire Pc Steel Strand Price Low Relaxation Steel Strand For Post Tension - Buy Pc Steel Strand Price,7 Wire Pc Strand,15.2mm Pc Steel Strand Product on Alibaba.com, 2020) and the price of one $15.24\ \mathrm{mm}$ PC strand cable prestressed anchor is 1.5 dollar (Homepage and Structures, 2020). If it designs one truss with a span of $32\ \mathrm{m}$, P_m can be given as:

$$\mathrm{P}_m = 666 \times \frac{m_s}{1000} + 2 \times 1.5 = 666 \times \frac{35.23}{1000} + 3 = 26.46\ \mathrm{dollar} \quad (6)$$

If it considers the construction cost of the temporary external prestressing tendons is 1 dollar per kilogram, P_c can be obtained as:

$$\mathrm{P}_c = 1 \times 35.23 = 35.23\ \mathrm{dollar} \quad (7)$$

Therefore, if SPMT with steel bracket is used for jacking operation, it is unnecessary to apply the temporary external prestressing tendons on the top chord before the jacking operation starts because the tensile stress of the top chord is greatly reduced. At this time, the total cost P of applying temporary external prestressing tendons which can be saved while jacking one truss is:

$$\mathrm{P} = \mathrm{P}_m + \mathrm{P}_c = 26.46 + 35.23 = 61.69\ \mathrm{dollar} \quad (8)$$

4.2 Limitations

In this modeling, the steel bracket added by SPMT is fixed with the jacking module of SPMT. In the actual use of SPMT, the steel bracket can not be disassembled freely, so there are higher requirements for ground traffic conditions when transporting SPMT. Moreover, this kind of SPMT structure is not suitable for the method of jacking operation at both ends, and the steel bracket plays a very limited role for reducing the internal force of the top chord of the truss. In addition, the SPMT construction method itself is not suitable for the two ends jacking operation mode because SPMT needs to reserve enough length at both ends of the truss to facilitate the construction in the falling stage, as shown in Fig.1.

4.3 Future work

At present, due to the limitation of SPMT jacking action point, SPMT construction method can not replace the traditional construction method of both ends hoisting. Therefore, in the future, the application scope of SPMT construction method can be expanded by improving the overall structure of SPMT or the structure of SPMT jacking module. We can also start with SPMT jacking module, adding different types of detachable steel structure to SPMT jacking module to meet the requirements of different conditions of jacking operation.

5 Conclusion

In this study, a new SPMT structure is proposed. In the process of modeling, two kinds of truss forms are used, and Midas software is used to simulate and analyze the reinforced concrete truss structure and the steel-concrete composite truss structure with different bar sections. It compares the internal force of different trusses when uses SPMT with steel brackets and ordinary SPMT to jack trusses from joints of lower flange which are not at either end of the truss respectively.

According to the results of modeling and analysis, when the common SPMT is used to jack up the truss, the upper chord of the truss is prone to produce large tensile stress, which leads to concrete surface cracks, and then affects the bearing capacity and durability of the overall structure of the truss. The maximum tensile stress of the top chord in the reinforced concrete truss structure is only about 30% of that of the common SPMT, and the maximum tensile stress of the top chord in the steel-concrete composite truss is only about 28% of that of the common SPMT, and the cost of each truss can be reduced by 61.69 dollar. Moreover, this simulation analysis also verified the reliability of the steel bracket structure. Even under the most unfavorable conditions, that is, when only one I-beam bears the dead weight of truss laterally, the maximum axial tensile stress and compressive stress are far less than the design values of tensile strength and compressive strength specified in Chinese steel structure design standard.

According to the above modeling analysis results, it can be considered that the new SPMT vehicle structure proposed in this paper is indeed feasible, which can not only avoid the unnecessary construction steps of applying temporary prestress to the top chord when SPMT is used to jack up the truss, but also ensure that the bearing capacity of the whole truss is not affected during the jacking operation.

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