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

Zitong Wen[a], Jian Zhou[b], Wenwei Wang[c,*]

a School of Civil Engineering, University of Birmingham, Birmingham, B15 2TT, UK

b Department of Engineering, Durham University, Durham, DH1 3LE, UK

c School of Transportation, Southeast University, Nanjing, 210096, China

Abstract

As an accelerated bridge construction method, the SPMT method is widely used in the installation of bridges. The aim of the work is to improve the structure on the basis of the existing SPMT structure. The rationality of the improvement will be verified by using Midas in the paper. Researches concerning both SPMT and external prestress are presented. The study uses two plane truss structures to simulate concrete trusses and steel-concrete trusses with different sections. According to the calculation assumption of plane truss, Midas is utilized to analyze the internal force of both SPMT with steel brackets and ordinal SPMT. The comparison results show that steel brackets can effectively reduce the tensile stress of the upper chord of the truss. It also shows the reliability and cost savings of the steel bracket.

Keywords: SPMT, Midas, steel bracket, truss, jacking operation, tensile stress

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. SPMT is computer-controlled multiaxle platforms that can pivot, lift, and carry large heavy loads of many types (FHWA, 2017). As a new ABC method, SPMT method shows many outstanding advantages. On the one hand, it can be used as disassembly machine to remove old bridge directly from the original site (Solae, Chorzepa, Durham and Kim, 2020). On the other hand, the prefabricated bridge can be quickly transported from the prefabrication site 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 focus on the study of SPMT structure, such as fixed coupling mode and loose coupling mode (2020).

During the bridge construction, the SPMT method is used to install precast beams. Although the designed precast truss is a simply supported structure, the truss is a cantilever structure during the jacking operation. Therefore, during jacking operations, negative bending moments will be generated near the two fulcrums and tensile stress will be generated in the upper chord. Although its value is not large, it is important to reduce the tensile stress, because the tensile stress can cause on the surface of the concrete. The stiffness and bearing capacity of precast beam will decrease due to cracks (Guangli Chang, Yanyu Meng, and Boyu Niu, 2017). Relevant studies show that, the steel beam and the concrete slab can be prestressed either separately or jointly along the top flange in the negative moment region to prevent cracking (Chen, 2005). However, the application of prestressing on simply supported beam requires additional prestressed tendons on upper flange which causes the increase of construction costs.

In the paper, a new SPMT structure is presented. The new structure is adding a steel bracket to jacking

* Corresponding author
E-mail address: wangwenwei@seu.edu.cn

module of the SPMT and the steel bracket can disperse the force of the truss at the pivot. Thus, the tensile stress of the upper chords can be reduced during the process of jacking and installation. This will effectively reduce the cracks on the concrete surface and ensure the bearing capacity of the precast beam is not affected. At the same time, compared with the original SPMT method, it will reduce the construction cost due to the temporary external prestressing.

Literature review

Cracks are a common defect in structures of civil engineering. Cracks not only affect the structural health but also induce other issues (Gavilán et al., 2011). If cracks not properly sealed, it can increase the risk of corrosion because cracks will undermine bridge appearance, increase maintenance and repair costs, and decrease bridge riding quality and smoothness (Wan 2010; Hopper et al. 2015). Cracking will occur when the internal principal tensile stress in a concrete member exceeds the concrete tensile strength due to the service load, restraint force, or a combination of both (Hopper et al. 2015; Leonhardt 1988). Many factors can cause cracking. Structural design, material design, and construction are three main factors affecting deck cracking (Solae, Chorzepa, Durham and Kim, 2020). For construction techniques, the placement method, curing method, and elevation alignments may cause cracks. The placement method is the most important factor to be considered in the SPMT method because the dynamic forces applied to the structural elements during the transportation can be significant due to the mass of the system (Dorafshan et al., 2019). If the object is lifted off the ground without restraint during the construction, the inertia force of the object will increase the total load on the object (China National Standardization Management Committee, 2008).

In the current, most of the construction reports pointed out that SPMT was equipped with jacks at either end of the superstructure to facilitate lowering and lifting on demand and for precise placement of the new superstructure when lifting the simply supported beam (Ardani, (Shana) Lindsey and Mallela, 2010). However, it is obviously inconsistent with the actual situation because SPMT method needs to leave space for the support at both ends when installing the precast beam. Therefore, the precast beam is a cantilever structure in the process of SPMT jacking operation.

For cantilever beams, cracks are easy to occur in the negative bending region (Y. Dong, Y. Xu, 2019), and the location of the crack is on the upper flange of the beam (Moezi, Zakeri and Zare, 2018). Therefore, in both of the steel-concrete composite beam and concrete beam, the cracking of concrete in the negative moment area of fulcrum is still the focus of research. At present, the falling beam construction is one of the most widely used design methods in concrete anti-cracking design in the construction of continuous beam bridges (Y. Dong, Y. Xu, 2019). The drop height is determined by finite element analysis, and the prestress is applied to the support of the fulcrum, so the concrete deck at the fulcrum of the continuous beam bridge will not generate tensile stress during static load. Moreover, researchers from Tongji University have pointed out 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).

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
f	design value of tensile and compressive strength of steel [MPa]	s	steel strand

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. Methodology

2.1 Introduction of the case

The study analyzes the internal force of the members when the SPMT is jacking up the precast truss under the 'ideal' (clam, cloudless) weather condition (Johnson et al., 1991). The construction site is located in the city, and the flat municipal roads that have been built can be used by SPMT vehicles when transporting precast beams. The data is obtained by using Midas to analyze the internal force of trusses with different member sections.

2.2 The process of software simulation

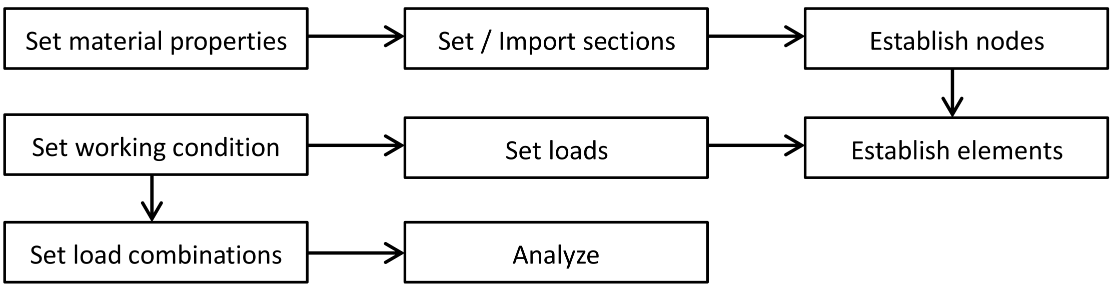


Fig.1 Midas software modeling process

Midas is the software for modeling and finite element analysis. Fig.1 indicates the general modeling process of Midas when simulating the beam.

2.3 Assumption of simulation and calculation

2.3.1 Assumption of truss calculation

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 the study, Midas software also follows the basic assumption when models the truss with different bar sections.

2.3.2 Assumption of internal force of SPMT with steel brackets

In the study, when analyzing the internal force of SPMT with steel brackets, the following assumptions will be utilized: ①The SPMT vehicle and lifting module are regarded as fixed rigid bodies; ②The steel bracket is fixed connected to the lifting module of SPMT; ③The assumption of plane truss is used to calculate the internal force of steel brackets.

2.3.3 Assumption of construction materials in simulation

According to the code in China, 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). Thus, concrete with strength grade C50 and the steel of Q345 were selected to construct prefabricated trusses and steel brackets in the simulation, and the properties of the materials can be seen in Table 1. And the age of the concrete is 90 days.

Table 1

The properties of the materials (Ministry of housing and urban rural development of the People's Republic of China, 2015)

Properties / Materials	Elastic modulus $(\mathrm{kN/m^2})$	Poisson's ratio	Coefficient of linear expansion	Bulk density $(\mathrm{kN/m^3})$
C50	3.45×10^{7}	0.2	1.0×10^{-5}	25
Q345	2.06×10^{8}	0.3	1.2×10^{-5}	76.98

2.3.4 Assumption of truss structure

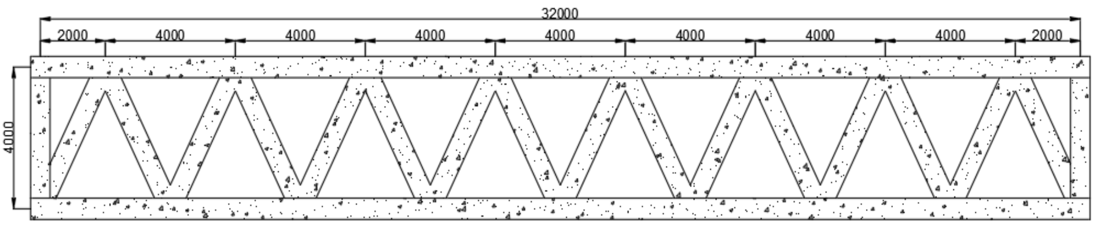


Fig.2 Commonly accepted Warren Truss (unit: mm)

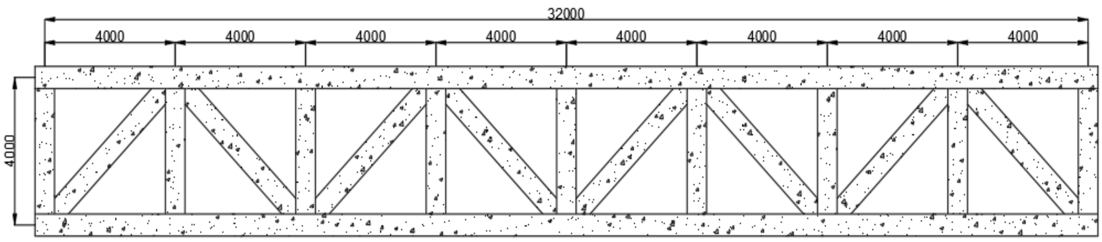


Fig.3 Warren Truss with verticals (unit: mm)

In the simulation, Warren Truss and Warren Truss with verticals (Frank Griggs, 2015) are two common rectangular plane truss structures which selected for analyzing the internal force of simulation shown in Fig.2 and Fig.3. The two structures are widely used in the construction of bridges, such as the Crumlin Viaduct (Jones, Stephen K., 2009) built in 1857.

Table 2

Bar sections of reinforced concrete truss

Type of truss	Type of bar
Warren Truss with verticals	400 mm × 600 mm reinforced concrete member
	Upper and lower chord: 400mm × 600mm reinforced concrete member Web member: 400 mm diameter reinforced concrete column
	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter
	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter
Commonly accepted Warren Truss	400 mm × 600 mm reinforced concrete member
	Upper and lower chord: 400mm × 600mm reinforced concrete member Web member: 400 mm diameter reinforced concrete column
	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter
	Upper and lower chord: 2000 mm × 200 mm reinforced concrete member Web member: reinforced concrete column of 400 mm diameter

Table 3

Bar sections of steel-concrete composite truss

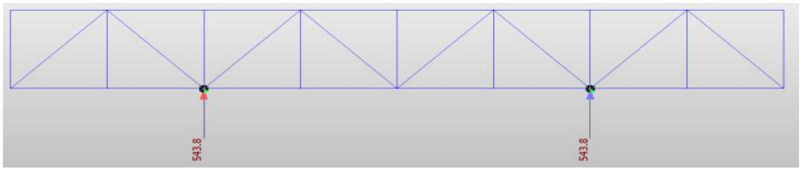
Type of truss	Type of bar
Warren Truss with verticals	Upper and lower chord: 400 mm × 600 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm
	Upper and lower chord: 1000 mm × 200 mm reinforced concrete member Web member: steel pipe with outer diameter of 400 mm and inner diameter of 320 mm
	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
Commonly accepted Warren Truss	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
	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
	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

Fig.2 and Fig.3 show the cross-sectional dimensions of the truss longitudinal bridge in the simulation. Since the research needs to analyze different types of trusses, different materials and cross-sectional forms are used to model the trusses in the simulation, as shown in Table 2 and Table 3. During the construction process, the concrete members need to be equipped with longitudinal steel bars and stirrups. Therefore, in accordance with Chinese standards, five $\mathrm{HRB400}$ steel bars with the diameter of $25\ \mathrm{mm}$ are arranged uniformly on both the upper and lower flanges of the concrete member in the simulation. $\mathrm{HPB300}$ steel bar with diameter of $10\ \mathrm{mm}$ is selected for stirrups whose spacing is $100\ \mathrm{mm}$.

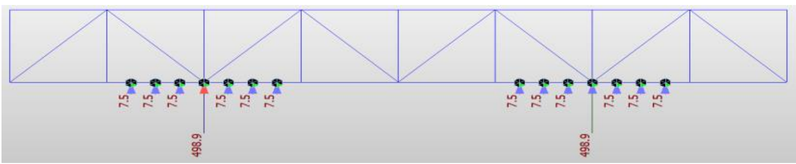
During the process of jacking operation, it assumes that the truss only affected by self-weight load and dynamic effects under the 'ideal' condition. According to the code in China, the self-weight of precast concrete members shall be multiplied by the corresponding dynamic coefficient. And the dynamic coefficient can be taken as 1.5 for hoisting and transportation (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. Thus, the internal force and deflection of the different trusses are analyzed and calculated by utilizing the Midas combining with self-weight load and dynamic coefficient.

2.3.5 Assumption of SPMT vehicle structure with steel brackets

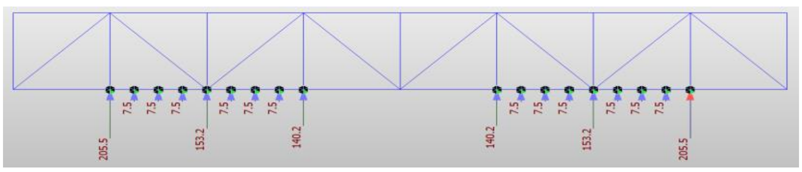
According to the calculation assumption of the plane truss, the load only acts on the nodes of the truss. In this regard, it first used Midas to verify the correctness of the theory. In order to reflect the load distribution, $400\ \mathrm{mm} \times 600\ \mathrm{mm}$ reinforced concrete member were used to simulate the Warren Truss with verticals. The analysis result of the bearing reaction force is shown in Fig.4. Since Midas can only analyze the forces at the nodes, multi-point supports are used in this study to simulate surface supports. In addition, considering the space for installing the supports at both ends of the truss, the point at the quarter span of the truss is selected as the center of the SPMT fulcrum, as shown in the Fig.4 (a).



(a) Fulcrum reaction of two-point bearing



(b) Fulcrum reaction of 6-meters long steel bracket



(c) Fulcrum reaction of 8-meters long steel bracket

Fig.4 Fulcrum reaction of different support forms: (a) two-point bearing; (b) 6-meters long steel bracket; (c) 8-meters long steel bracket (unit: kN)

Combining with the results of simulation, each support between the two nodes of the truss only bears the self-weight of the member and does not bear the load of other bars. Considering that the load on the supports at the non-fulcrum point is very small, it can be considered that it is consistent with the previous calculation assumption. Thus, in order to make the steel bracket play the role of sharing the fulcrum reaction, the length of the bearing surface of the steel bracket must cover at least two truss joints. In the research, the length of the steel bracket is considered as 8 m which built with 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.5 and Fig.6 respectively.

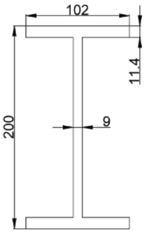


Fig.5 The size of 20B I-beam (unit: mm)

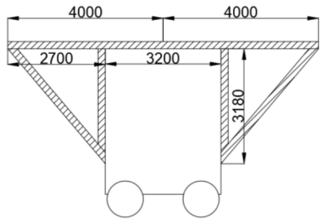


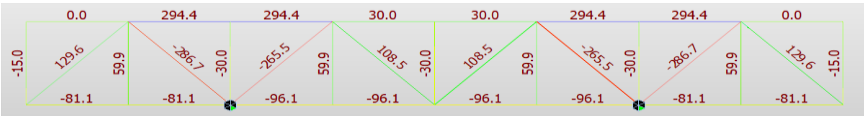
Fig.6 SPMT vehicle structure with steel brackets (unit: mm)

3. Results and discussions

3.1 Results and analysis

3.1.1 Results from modeling of trusses

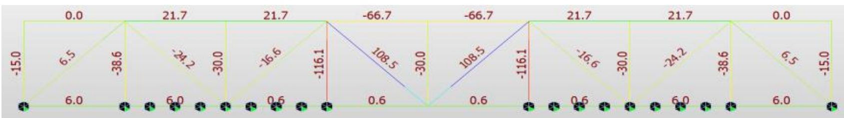
In the research, it analyzed the internal force of the three stages during the truss installation process, namely the lifting stage, the falling stage and the completion stage. At the same time, a control group was set up during the simulation to compare the internal force of the truss members when the SPMT with steel brackets and the original SPMT were used to install the precast trusses, respectively. A reinforced concrete truss with 400 mm × 600 mm reinforced concrete members is used to illustrate the analysis process which can be seen in Fig.7.



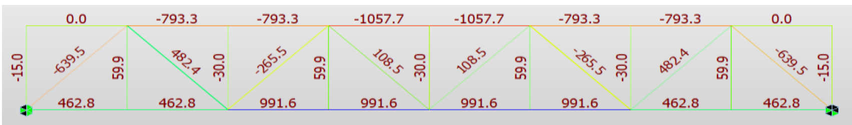
(a) Two-point support during the lifting stage

(b) Two-point support during the falling stage

(c) Surface support during the lifting stage



(d) Surface support during the falling stage



(e) The completion stage

Fig.7 Internal force diagram of truss: (a) Two-point support during the lifting stage; (b) Two-point support during the falling stage; (c) Surface support during the lifting stage; (d) Surface support during the falling stage; (e) The completion stage (unit: kN, negative value represents compression)

Fig.7 clearly shows the construction stages that need to be analyzed in this study. Considering the tensile stress occurs at the upper flange of the negative bending moment zone in the cantilever beam, the maximum tensile stress changes of the upper flange caused by the structural transformation during the installation of the prefabricated truss will be recorded for both the original SPMT and the SPMT with steel brackets, which can be seen in Table 4 and Table 5.

Table 4

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

Type of truss	Truss number	Type of bar	Using common SPMT	Using SPMT with steel bracket	Completion operation
Warren Truss with verticals	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	/
Commonly accepted Warren Truss	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 5

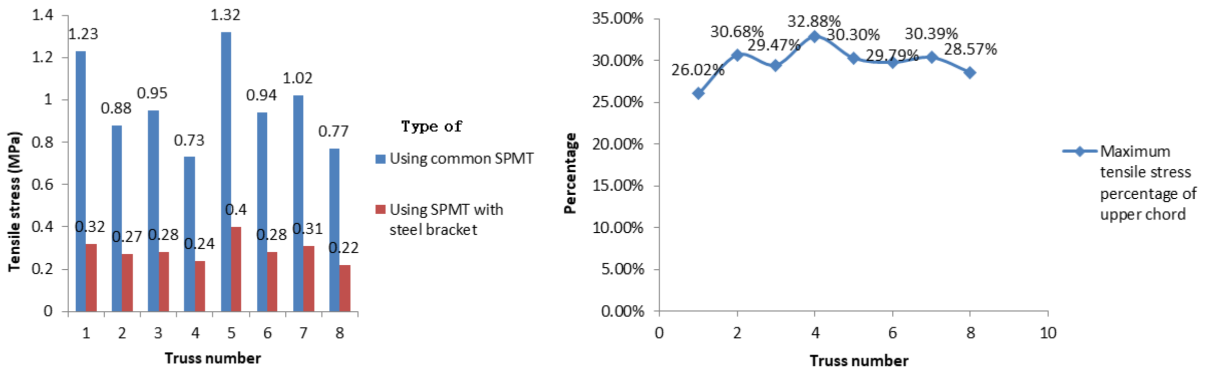
Maximum tensile stress in upper chord of different steel-concrete composite truss (unit: kN)

Type of truss	Truss number	Type of bar	Using common SPMT	Using SPMT with steel bracket	Completion operation
Warren Truss with verticals	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	/
Commonly accepted Warren Truss	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	/

Table 4 illustrates the maximum tensile stress in upper chord of different reinforced concrete truss and Table 5 shows the maximum tensile stress in upper chord of different steel-concrete composite truss. Therefore, the influence of the steel brackets on the internal force of the truss, especially the maximum tensile stress of the upper chord can be obtained.

3.1.2 Analysis and comparison

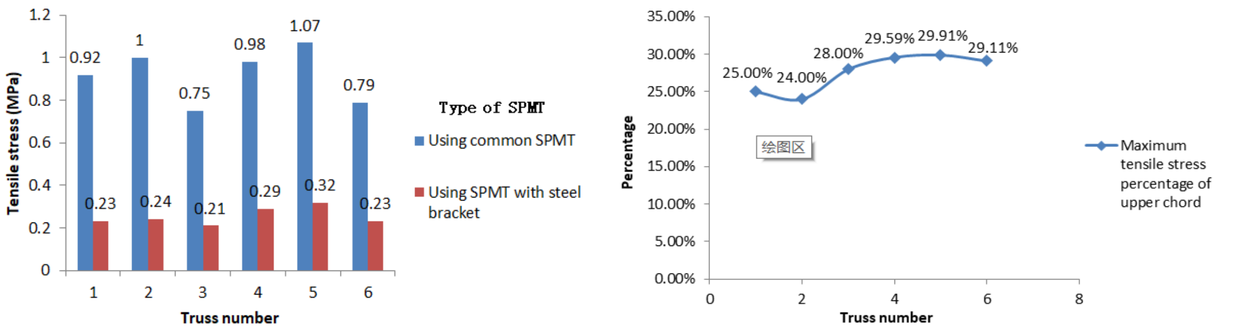
Considering that the upper chord has the biggest tensile stress during the lifting stage, combining with the value in Table 4, the simulation results can be drawn into a chart, as shown in Fig.8.



(a) Bar chart for maximum tensile stress (b) Scatter diagram for ratio of maximum tensile stress

Fig.8 Relationship for maximum tensile stress between SPMT with steel bracket and common SPMT during the lifting stage of reinforced concrete truss: (a) Bar chart for maximum tensile stress (unit: kN); (b) Scatter diagram for ratio of maximum tensile stress

It can be seen from Fig.8 (a) that the maximum value of maximum tensile stress occurs when the $\mathrm{No.5}$ truss is lifted with common SPMT, and the maximum tensile stress on the upper chord is $1.32\ \mathrm{kN}$ at this time. From Fig.8 (b), it can be calculated that the mean value of the ratio of maximum tensile stress between SPMT with steel bracket and common SPMT is 29.76% of that of common SPMT.



(a) Bar chart for maximum tensile stress (b) Scatter diagram for ratio of maximum tensile stress

Fig.9 Relationship for maximum tensile stress between SPMT with steel bracket and common SPMT during the lifting stage of steel-concrete composite truss: (a) Bar chart for maximum tensile stress (unit: kN); (b) Scatter diagram for ratio of maximum tensile stress

For steel-concrete composite truss, Fig.9 (a) indicates the maximum value of maximum tensile stress occurs when the $\mathrm{No.5}$ truss is lifted with common SPMT in Table 5, and the maximum tensile stress on the upper chord is $1.07\ \mathrm{kN}$. The mean value of the ratio of maximum tensile stress between SPMT with steel bracket and common SPMT is 27.60% of that of common SPMT.

Considering the need to calculate the impact of dynamic effect under the most unfavorable construction conditions, it is necessary to analyze the maximum tensile stress under the dynamic effect. 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). Thus, the 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 in China, the value of f_{td} for C50 can be consider as 1.83 MPa (Ministry of housing and urban rural development of the People's Republic of China, 2015). Combining with the value of maximum tensile stress in Fig.8 and Fig.9, it can be obtained that if SPMT only uses two-point support for lifting stage, 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 No. 5 truss in Table 4, 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:

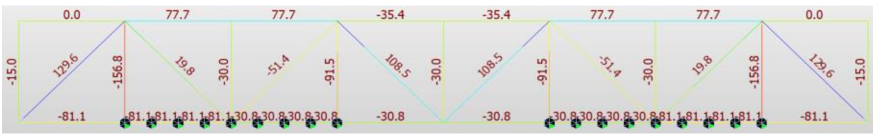
$$\sigma_{t1} = \sigma_{t2} \times \varphi_1 = 1.32 \times 1.5 = 1.98 \text{ MPa} > 1.83 \text{ MPa} = f_{td} \tag{2}$$

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 in Fig.7, it can be considered that the upper chord is only affected by tensile stress during the lifting stage. So the concrete surface is easy to induce cracks when the value of σ_{t1} approaches or even greater than f_{td}. The cracks will reduce the actual compressive area of concrete and increase the risk of corrosion at the completion stage. Thus, it will reduce the bearing capacity of truss members.

The application of steel brackets can effectively reduce the tensile stress generated in the upper chord during the lifting stage. Fig.8 (b) and Fig.9 (b) illustrate that when utilizing SPMT with steel bracket, the mean value of the maximum tensile stress for reinforced concrete truss and steel-concrete composite truss are 29.76% and 27.60% of common SPMT, respectively. Therefore, the application of steel brackets can reduce the effect of cracks by reducing the value of the tensile stress.

3.2 Reliability of steel brackets

In the simulation, in addition to the effectiveness of reducing the tensile stress of the upper chord of the truss, attention should also be paid to whether the load-bearing capacity of the steel bracket meets the requirements. As pointed out in Fig.4, the non-node supports only bear the weight of the current truss member and the value is small enough to be ignored. Moreover, it can be seen from Fig.10 that under the premise that the number of supports at the fulcrum remains unchanged, the number of supports on the rods will not affect the internal force of the truss. Therefore, when verifying the reliability of the steel bracket, the calculation can be simplified by only considering the bearing reaction forces at the nodes.



(a) Truss with multi-point support

(b) Truss which support at the joint points

Fig.10 Internal force: (a) Truss with multi-point support; (b) Truss which support at the joint points (unit: kN, negative value represents compression)

In this research, the maximum reaction force of the joint support is the No. 5 truss in Table 4 and the distribution of the joint reaction force are shown in Fig.11.

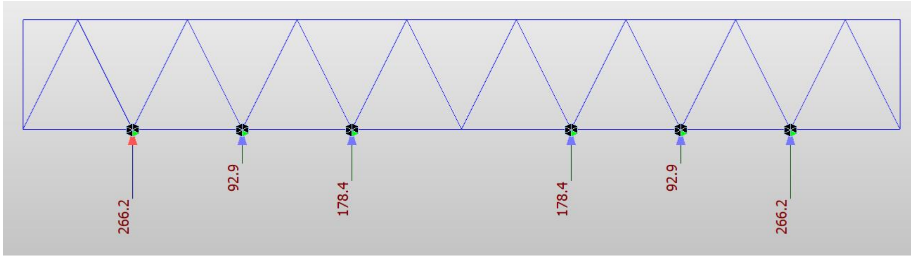


Fig.11 Maximum value of reaction force at joint points (unit: kN)

Combining reaction force at joint points with assumption for steel brackets, it can use Midas to calculate the reaction force of the supports and the analysis result for the internal force of the steel bracket can be seen in Fig.12.

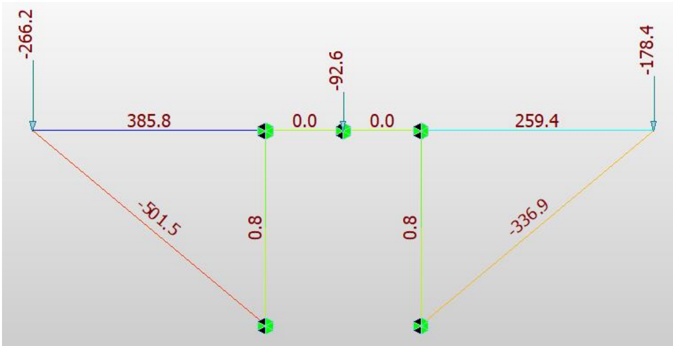


Fig.12 Internal force of steel bracket (unit: kN, negative value represents compression)

In this simulation, the structure of SPMT with steel bracket can be seen in Fig.6. Thus, the section area S of 20B I-beam is $3920.4\ \mathrm{mm}^2$. Considering the standard in China, for Q345 low alloy high strength structural steel, when the thickness of I-beam is less than or equal to $14\ \mathrm{mm}$ and the design value of tensile and compressive strength of steel 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.12, the maximum value of pressure $\mathrm{F}_{c_{max}}$ is $501.5\ \mathrm{kN}$ and maximum value of tension $\mathrm{F}_{t_{max}}$ is $385.8\ \mathrm{kN}$. Thus, with the definition of stress (Zeng Anping and Josephs, 2009), it can get the maximum compressive stress of I-beam f_c and the maximum tensile stress f_t :

$$f_c = \frac{\mathrm{F}_c}{S} = \frac{501.5\times10^3}{3920.4\times10^{-6}} = 127.92\ \mathrm{MPa} < f = 305\ \mathrm{MPa} \tag{3}$$

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

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 also needs to be considered when designing steel brackets. In Fig.13, it shows the deflection distribution of the No.5 truss in Table 4 when utilizing SPMT with steel brackets to lift the truss. the reaction force at joints is applied to the truss. It can be noticed that the maximum value of deflection for the truss is $0.001\ \mathrm{m}$.

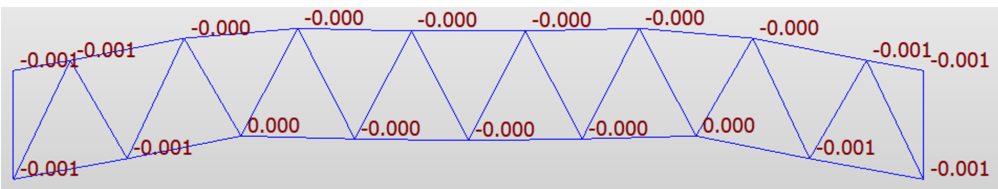


Fig.13 Deflection distribution of lifting stage (unit: m)

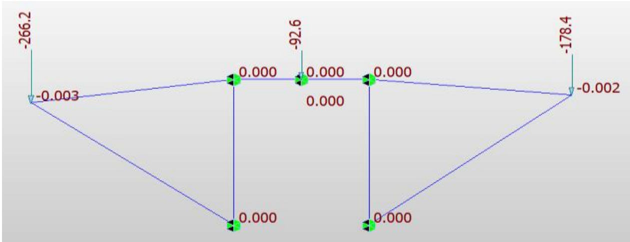


Fig.14 Deflection distribution of steel bracket (unit: m)

If the load borne by the support in Fig.11 is applied to the steel bracket, the maximum value of deflection for the steel bracket is $0.003\ \mathrm{m}$ which can be obtained through modeling, as shown in Fig.14. In practical construction, flexible materials such as rubber and wood block are often laid at the joint, the SPMT and truss are bound with steel cable to fill the displacement caused by deflection. It can ensure steel bracket plays the role of sharing the self-weight of truss.

Combined with the above analysis, when 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 $\mathrm{F} = 305\ \mathrm{MPa}$. And the deflection difference between the truss and the steel bracket is very small, the maximum is $0.002\ \mathrm{m}$. In the actual construction, the influence can be eliminated by laying flexible materials and flexible materials can also reduce the wear of the truss during transportation. Thus, it can be considered that the simulated steel bracket structure is reliable.

3.3 Cost analysis

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 stage and the upper chord of the truss is easy to produce tensile stress due to the negative bending moment. Due to the time simply supported truss simulated in this research, external prestressing tendons can be utilized to reduce the tensile stress of the upper flange of the beam and improve the crack resistance of the beam (Chen, 2005) in normal construction. 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 lifting 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 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:

$$\sigma_1 = \frac{F_m}{\mathrm{A}_s} = \frac{317.4\times10^3}{139\times10^{-6}} = 2283453\ \mathrm{Pa} \approx 2.28\ \mathrm{MPa} \tag{5}$$

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 each $15.24\ \mathrm{mm}$ PC strand cable prestressed anchor is 1.5 dollar (Homepage and Structures, 2020). If it uses the truss in the study to calculate the cost, P_m can be given as:

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

If it considers the construction cost of the temporary external prestressing tendons is 1 dollar per kilogram,

P_c can be obtained as:

$$P_c = 1 \times 35.23 = 35.23 \text{ dollar} \quad (7)$$

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:

$$P = P_m + P_c = 26.46 + 35.23 = 61.69 \text{ dollar} \quad (8)$$

4. Conclusion

In this study, a new SPMT structure is proposed. In the process of modeling, two kinds of truss form are used to be simulated as common structures of bridge truss. In order to obtain analysis data of different member types, it simulates the reinforced concrete truss structure and the steel-concrete composite truss structure with different bar sections by utilizing Midas. Combining with analysis results of different trusses, it compares the internal force of trusses while using SPMT with steel brackets and ordinary SPMT to jack trusses respectively.

According to the results of simulation, when the common SPMT is used to lift the truss, the upper chord of the truss is prone to induce large tensile stress, which leads to concrete surface cracks. The cracks will affect the bearing capacity and structure health of the truss. When the SPMT with steel bracket is used, it can be found that the value of the tensile stress of the upper chord of the truss has changed significantly. The mean value of maximum tensile stress in the reinforced concrete truss structure is only 29.76% of the common SPMT and the mean value of maximum tensile stress in the steel-concrete composite truss is only 27.60% of the common SPMT. Moreover, through the estimation of material cost and labor cost, the cost of each truss can be reduced by 61.69 dollar than the common SPMT. Besides, the simulation also verified the reliability of the steel bracket structure. Even under the most unfavorable conditions, the maximum axial tensile stress and compressive stress are far less than the design values of tensile strength and compressive strength specified in Chinese code.

It is worth noting that in the lifting stage of the truss, it is necessary to ensure that the supporting surface of the steel support covers at least two nodes of the truss during the actual construction process. It is because according to the calculation assumption of the plane truss and the results of simulation, the self-weight load of the truss is mainly supported by the supports at the nodes. And the self-weight load of the support on the rod is very small and can be ignored.

Combining with the above analysis results, it can be considered that the new SPMT structure proposed in this paper is indeed feasible. The new structure can greatly reduce the axial tensile stress of the upper chord of the truss while ensuring that the steel bracket will not exceed its design strength. It can not only avoid the unnecessary construction step which is applying temporary external prestressing tendons to the top chord when SPMT is used to lift the truss, but also ensure the bearing capacity of the truss will not be affected during the lifting stage.

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